DIGITALIZATION RELATED TO ENERGY CONSUMPTION IN BUILDINGS

Introduction

Digitization is the process of converting information into a digital (i.e. computer-readable) format. In relation to buildings, it is obtaining and processing of data for e.g. gaining insight into the energy consumption of a building, obtaining an overview of the energy efficiency and thermal characteristics of a country's buildings stock, controlling the energy consumption and the indoor environment in buildings, adjusting the energy consumption of buildings in order to improve the stability of the power grid, etc.

Digitalization will in the following be divided into three main areas based on the nature of the utilized data:

- Static and semi-static data
- Historic time series
- Real-time data

The document is not a thorough review of what digitalization in the built environment is, and possible can be in the future. The aim of the review is to give the reader an impression of the diversity and different levels of digitalization, and how it can be utilized. This will be done by describing specific examples, but the list of examples is not exhaustive.

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When dealing with digitalization in relation to buildings, privacy and security are very important topics. It is further necessary to acknowledge that measured data from a building belong to the customer. Measured data may be misused. Online measurements of e.g. the power consumption can by burglars be used to detect if anyone is present in a house or an apartment. Control systems may be hacked and overtaken for e.g. blackmail purposes. The EU General Data Protection Regulation (GDPR) sets the rules for protecting private data and much work have been or are being done in order to create secure channels for exchange of data. Data privacy and data security will not be dealt with in this document, however, when reading the document always have in mind that data privacy and data security are essential parts of the described examples.

Static and semi-static data

Static data for a building are typically information about the layout of a building, descriptions of the constructions and installations, intended use of the building and expected energy demand. It can also be aggregated information in the form of Key Performance Indicators (KPIs) like EPCs and SRIs (see below). All these data are static until the building is changed in some way e.g. in the form of renovation of the building where constructions are modified or installations are replaced. This may also change the KPIs.

In the following, five examples will be given on static/semi-static data:

- Building Information Models (BIMs)
- Energy Calculation Models
- The Danish Building and Housing Register (BBR)
- Energy Performance Certificates (EPCs)
- Smart Readiness Indicators (SRI)

Building Information Models (BIMs)

BIM is an integrated method for digitizing the construction process. Throughout the entire construction life cycle, from idea to demolition, digital building models are here the focal point for all the activities in a building project and the cooperation between the various parties. BIM is both a model and a working method. A BIM contains all the blueprints of the buildings, information on construction and installations incl. changes, maintenance instructions, etc.[1]

[1] https://www.bim.byg.dtu.dk/bimlab/hvad-er-bim (in Danish)

BIM means close cooperation between parties and extends to every actor participating in a project. The deep branching means both that full implementation of BIM can be cumbersome and at the same time that a single actor who has no knowledge of BIM will be unable to participate in an integrated project process.

Energy calculation models

Programs for calculation of the energy demand of buildings come in many different forms and levels of details. From very simple tools (requiring a minimum of input from the user) to very detailed simulation programs (where building components and systems have to be specified in a very detailed way). Although the level of details differ, energy simulation programs are less detailed than BIMs, however the energy simulation model needs beside BIM data also information on the thermo-physical and optical properties of the used materials, detailed information on the installations in form of efficiencies, power demand, flow rates, etc., and use pattern.

The simplest calculation tools typically only gives the annual energy demand of the considered building, while the larger simulation models give results as time series on hourly (or even on sub-hourly) basis. These latter programs can also give time series of other states of the buildings, like temperatures, humidity, heat flows, air flows, power demand for installations, etc. Larger simulation programs are thus capable of also evaluating the indoor climate of a considered building. Many larger simulation programs show a geometric drawing of the buildings when constructions are applied to the model.

Be18

Only one energy calculation tool will be considered here; The Danish program Be18, which is used to determine if a building comply with the energy requirements of the Danish Building code for obtaining building permits. The calculation engine of this program is also used by certified energy consultants when they issue Energy Performance Certificates (EPCs) (see below) for a building. If the calculation for the EPC does not comply with the energy requirements of the Danish Buildings Code, a use permit cannot be issued before modifications to the building has been carried out so that the EPC comply with the requirements in the Building code.

Be18 is like a spread sheet type of program with predefined sheets where rather detailed information on opaque surfaces (walls, roofs and floors), transparent surfaces (e.g. windows), ventilation, heating, renewable energy systems, etc. can be filled in. The program calculates the heating and primary energy demand on a monthly basis and gives the annual primary energy demand per m^2.[2]

The Danish Building and Housing Register (BBR)

BBR is an online register that contains publicly available information about properties and buildings in Denmark[3]. One of the main purposes of the register is to be able to provide information to the property valuation authority in connection with property taxation. The register was established in 1977-1978. For the ordinary citizen, the creation of BBR meant that it was no longer necessary to fill in questionnaires about housing conditions in connection with population and housing censuses. The data in BBR are considered quite reliable, however, as it is the

[2] https://build.dk/anvisninger/Pages/213-Bygningers-energibehov-4.aspx (in Danish)
[3] https://bbr.dk/file/665225/bbr-arkitekturoverblik.pdf (in Danish)

building owner who is responsible for ensuring correct information in BBR, some wrong information are unavoidable. Feedback of data from energy labeling of buildings (EPC – see below) could possible further increase the quality of the stored building data.

For each building, BBR contains information about type of use, location, ownership, built-up area, heated floor area, main materials, source of heating, any installed renewable energy systems, number of floors, number of rooms besides kitchen and bathrooms, etc. These information are public available. Together with EPCs, BBR contains important information for assessing the current energy state of the Danish building stock – see below.

From 2010, BBR further contains information on measured consumption of electricity, gas, oil and/or district heating. This information is only available for the owner of the building and for the municipality, utilities and researchers that utilize the data in an anonymized form.

The Danish building stock

Based on data from BBR and issued EPCs an analysis has been carried out to estimate the energy savings to be expected until 2050, if buildings and building components are being upgraded according to the requirements laid down in the Danish Building Code from 2010, when they have to be replaced or renovated for other reasons[4].

The result of the analysis was: when retrofitting buildings due to termination of service life for the building components (thermal envelope), this will by 2050 result in savings of about 30 % of the 2011 national energy use for heating in buildings.

If in addition balanced mechanical ventilation with heat recovery is implemented in residential buildings with a sloping roof (and enough free space in the attic to install the ventilation system) in combination with roof retrofit, the potential savings will increase to 47 %.

Boliganalysen – housing analysis and broadcast

Based on BBR the tool Boliganalysen (housing analysis)[5] has been developed to help the municipalities achieve energy savings and transition to climate-friendly heating in private homes and rental properties. Boliganalysen provides an opportunity to communicate purposefully to individual homeowners about the potential of e.g. replacing an oil or gas boiler or energy renovate the home. The tool also uses content and calculations from https://sparenergi.dk/ (one-stop-shop for home owners with information on e.g. how to perform energy renovation) to generate unique customized direct information to individual homeowners, thereby creating actual and usable information for the homeowners.

Energy Performance Certificates (EPCs)

The Danish setup for Energy Performance Certificates (EPCs) was established in 1997. With the EU Energy Efficiency Directive (EED) in 2006, EPC schemes became mandatory for all EU countries. The normal EPC ranking goes from G to A, where A is for the best energy performing buildings. In Denmark the A ranking is subdivided into A2010, A2015 and A2020. A2010 and A2015 refer to the energy requirements in the Danish Building code from 2010 and 2015

[4] https://build.dk/Assets/Potential-heat-savings-during-ongoing-renovations-of-buildings-until-2050/sbi-2016-04-1.pdf
[5] https://boliganalysen.dk/ (in Danish)

respectively. A2020 refers to the Voluntary energy class in the Danish Building Code from 2018, which is the nearly Zero Energy Buildings (nZEB) standard requested by the EU.

To issue an energy performance certificate, an inspection of the building by an energy consultant from a certified company is necessary. The consultant assesses the building's energy performance and grades it on a scale from A to G. All EPCs are registered in a central database[6] and displayed on a public website. In Denmark, a total of around 70,000 new EPCs are registered annually. It is anticipated that the quality is high due to few complaints received from tenants and buyers.

The EPCs from 130,000 Danish detached houses has been compared with measured heat consumption[7]. The comparison showed good agreement for label C and D. The measured consumption was higher than given in the EPC for label A and B, while lower for label F-G, where the mean consumption for label G buildings were only half than given by the EPCs. The reason for the latter is that people in houses with poor EPC labels tend to have a lower mean temperature in the buildings and possible have wood stoves. Higher measured consumption in A and B houses is due to a higher indoor temperature than assumed in the EPC. Further, some buildings have a higher EPC due to PV, which reduces the primary energy demand (which the EPC is based on) without decreasing the heating demand. Better agreement between EPC and measured energy consumption can possible be achieved if measurements are available at high frequency – e.g. as hourly data. Please see the section on Energy Signatures.

A survey from 2016[8] reveals a high awareness of the EPC among Danish house owners. Nine out of 10 respondents recognize that they have received an EPC when purchasing their property. In addition to that, 92% have read parts of the report, and more than half have read the entire report. The survey also showed that the recommendations for cost-effective renovations in the EPC report are particularly relevant to owners with properties marked as either D, E, F or G. Among these, 39% have acted on the recommendations in the EPC report and have carried out energy renovations.

It has been analyzed that a better EPC leads to a higher selling price for a building, which encourage to perform some if not all of the energy saving measures recommended in the EPC[9].

Smart Readiness Indicators (SRI)

Smart Readiness Indicators (SRIs) was introduced in the 2018 revision of the European Energy Performance of Buildings Directive (EPBD). This indicator allows for rating the smart readiness of buildings, i.e. the capability of buildings to adapt their operation to the needs of the occupant, also optimizing energy efficiency and overall performance, and to adapt their operation in reaction to signals from the grid (energy flexibility).

The SRI for a building is calculated based on an inspection of the building where 9 energy system types: heating, cooling, domestic hot water, ventilation lightning, dynamic building envelope, electricity, EV charging and monitoring and control are giving the scores between 0

[6] https://sparenergi.dk/forbruger/vaerktoejer/find-dit-energimaerke (in Danish)
[7] https://doi.org/10.1080/09613218.2018.1426810
[8] https://ens.dk/sites/ens.dk/files/Energimaerke/brugerundersoegelse_af_energimaerkeordningen.pdf (in Danish)
[9] https://finansdanmark.dk/nyheder/2020/energirenoverede-huse-saelges-hurtigere-og-til-hoejere-pris-men-der-er-ikke-nok-af-dem/ (in Danish)

and 3 in the 7 areas: energy savings, maintenance and fault prediction, comfort, convenience, health and wellbeing, information to occupants and grid flexibility and storage. All of these 63 combinations are given predefined impact criterion of between 0 and 100 %. Based on this the SRI is calculated, which can be a percentage or a label from A to E. For more information see [10] below.

The argument against SRI is that it is not really possible to characterize a highly dynamic system with only one number[11]. However, the audit performed in order to obtain the SRI will reveal important information about the installations and control of these in the building.

Historic time series

Measurements from buildings have typically been energy consumptions. Formally, in the form of manually, annually readings from billing meters or in case of oil, the amount of oil from each time oil was delivered to the building. Such readings give a good idea of the annual energy demand of a building, but it is not possible to determine why the building has this energy demand. For this, much more granulated readings are needed, preferably as hourly or even more frequent readings. Much valuable information are embedded in such high-resolution data as exemplified below.

Today most Danish power billing meters are smart meters as requested by the EU. One of the features of smart meters is that the power utilities can access these meters remotely and automatically retrieve time series of the measured electricity consumption and the quality of the delivered power. This enables the utilities to better predict the electricity consumption of their customers and thereby more precisely to bid in to the day ahead electricity market. The power utilities further make it possible for their customers to display their own electricity consumption and its evolution over time, so that it is possible for the building owner to detect if e.g. there is an electricity consumption at times where there should not be.

The power utilities are by law obliged to release relevant data to the national database: the **Data Hub** managed by the Danish TSO Energinet.dk. These data have to meet specified requirements. The objective of the Data Hub is among other to provide market participants with a more efficient and data driven basis for developing electricity market products. The newest data in the Data Hub are typically several days old.

The Building Hub – A digital test facility. The purpose is to develop and test a platform that provides easy and comprehensive access to data on electricity and district heating consumption for buildings, data on buildings from public registers, such as the Building and Housing Register (BBR), the EPC database and data on local weather conditions from the Danish Meteorological Institute (DMI). The benefit of the Building Hub for users of data is that all the above data can be obtained from one place only and in a specific format. This can facilitate both existing work, as well as contributing to the development of new solutions.

Historic time series can come from other sources than billing meters. BEMSs (Building Energy Manage Systems – see the next chapter) perform many real-time measurements of the states in a building and its installations - e.g. temperatures, lux, humidity, flows, pressure, etc. Based on

[10] file:///C:/Users/b076081/Downloads/MJ0320413ENN.en.pdf
[11] https://annex67.org/media/1470/position-paper-energy-flexibility-as-a-key-asset-i-a-smart-building-future.pdf

measurements commands are released to the actuators in the building. In most BEMSs, these measured states and commands are not stored, although they contain important information on the performance of the building as seen below.

As stated several times above: historic time series of data contain typically important information on the system from where the data are obtained. In the following five examples are given:

- Display of time series of data
- Performance testing
- Heat pumps on subscription
- Energy signatures
- Development of simple low-order models

Display of time series of data

In the project Characterization and optimized control by means of multipara meter controllers[12] 957 data points where logged and stored each 5 minutes in a five floor 21,200 m^2 office building. The logged data points were: local weather data, data from the heating system, data from the ventilation system, data from the cooling system, data from the offices and the 1,182 m^2 atrium. The data points were temperatures in the offices and installations (both set points and actual temperatures), valve settings, speed of fans and rotating heat exchangers, bought district heating and electricity used totally and by the cooling system, etc. The data were obtained from and logged by the BEMS.

The building was known for having a higher energy demand than expected and overheating problems. The overheating problems were mainly related to large areas of glazing, however, the control strategy of the building did not make this better.

Many of the historic time series of data points were in the project displayed on graphs and often combined with each other. This gave valuable insight into why the building was performing badly. Some examples on this is given in the following.

Heating and cooling at the same time

The control system was programmed so that the fresh air from the ventilation system always should be 21ºC, even if a lower fresh air temperature would decrease the overheating problem. Example: On the morning of a spring day the ambient temperature was below 10ºC, so first started the rotating heat exchanger in the ventilation system up. As this could not cover the necessary heating, the heat exchanger for district heating started up and together these two units could deliver the desired fresh air temperature of 21ºC. However, as part of the building still was overheating after a previous sunny day (and because the feature of night cooling using the ventilation system did not function) the cooling system stared up. Although cold outside air could have cooled the building down, the cooling system was instead used to remove heating from the district heating system. No wonder that the building used more energy than expected.

12 https://www.buildvision.dk/pdf/characterization_and_optimized_control_by_means_of_multiparameter_controllers.pdf

No utilization of free cooling in the cooling system

Free cooling means that a cooling system below a certain ambient temperature can supply the necessary cooling without starting the compressor. Only the pumps between the outdoor heat exchanger and the indoor heat exchanger are running. This saves a lot of electricity. The cooling systems of the considered building were equipped with free cooling, however, the measured time series of electricity consumed by the cooling systems showed that free cooling was not utilized.

Constant speed of fans

Time series also revealed that the fans of the heating systems were always running at a constant speed between 4:00-6:00 and 20:00 although variable speed based on CO_2 was possible. This led to both a higher electricity and heating demand.

Wrong location of temperature sensors

Temperature sensors need to be located correctly. It was discovered that one temperature sensor was located so that colder air from the ventilation system was blown directly onto it. The BEMS did, therefore, not detect the overheating problem in the room. A bookcase was located in front of another sensor, so that the BEMS measured a larger overheating than in reality.

Lessons learned

The above problems were not detected by the technical staff because: 1) they were too busy solving other problems in the building, 2) they did not know how to operate the BEMS. Even if the building had been operated correctly from the start, problem fixing due to e.g. complaints caused after replacements of desks were tried solved by symptom fixing, which causes unbalance in the system, which again leads to new complains, and so on. When changes are introduced to such a system, time series of measurements should always be evaluated for detecting any unbalance in the system. This can either be done manually or automatically, however, a continuous automatically evaluation is preferable. The latter enables automatically fault detection.

The total system needed a rework. This was done based on the above findings for a rather low price with a payback time of few months. The building then performed better, however, there are no measurements to prove how much better, as the project had ended by that time.

Performance testing

Most construction and renovation projects have critical flaws in the technical installations at the time of completion. This may lead to a higher energy consumption than expected as well as a poor indoor climate.

In order to prevent flaws, the Danish Building Code from 2018 (BR18) requires that the energy performance of new technical installations (also in existing buildings) is tested and verified in a performance test before the building is taken into use. The performance tests are carried out on the below shown installations using short-term measurements, which following are evaluated[13].

One-family houses:	Multi-story and office buildings (larger buildings):
• Heating system • Boiler / District heating system • Heat pumps • Solar cells • Ventilation system	• Heating system (large) all types • Ventilation systems (large) • Cooling system • Lighting system • Solar cells • Elevators • BEMS system (building automation systems)

The building owner is responsible for carrying out the performance tests and also for ensuring that the results of the tests comply with the requirements in the Danish Building Code for the specific technical installations. The measured values need to be used in a re-run of the energy calculation for the building. If the new predicted energy demand of the building is higher than the requirements in the Building code, a user permit will not be issued until the problems have been fixed.

Heat pumps on subscription

In the concept of "Heat pumps on Subscription" or "Heat as a Service", the heat pump is owned and serviced by an energy service company and not by the house owner. The homeowner pays a sign-on fee (typically much lower than the price of the heat pump), for the delivered heat and for the maintenance of the heat pump. This is similar to the conditions in district heating systems. For a detailed description of a trial on this concept see [14] below.

The energy service company measures the electricity consumed by the heat pump and the heat delivered to the customer. These measurements are retrieved as time series by the energy service company. The heat measurements are primarily for billing the customer. However, having time series for both the electricity consumed and the heat delivered by the heat pump, it is possible to follow the efficiency of the heat pump over time and thereby detect when the heat pump needs maintenance. The energy service company is very much interested in the efficiency of the heat pump being as high as possible, as this maximizes the profit of the installation.

Energy signatures

It is possible to characterize the thermal performance of a building based on time series of heat consumption and the surrounding climate. The thermal characteristics include the response of the building to changes in temperature (UA-value), solar radiation (gA-value), and wind (wA-value). The effect of the wind is characterized both in terms of the wind speed and the wind direction, implying that wA-values are estimated for different wind directions. The wA-value gives an impression on how leaky the building is.

13 https://ens.dk/sites/ens.dk/files/Globalcooperation/performance_testing_of_technical_installations_in_denmark.pdf

14 https://ens.dk/sites/ens.dk/files/Globalcooperation/final_ens_heatpump_as_a_service_lores_web.pdf

The concept was first presented and documented in[15]. In this work heat consumption from 56 houses located in the district heating system of the Danish town Sønderborg were analyzed. However, the heat demand of a house consists of two values: heat demand for space heating and heat demand for domestic hot water (DHW). Space heating is closely related to the climate and thus predictable, while the heat demand for DHW is highly stochastic and, therefore, often less predictable. Methods for separating the heat demand for space heating and DHW have been developed – see e.g. [16] below.

The above described method has the potential to lead to automated generation of EPCs based on measurements, however, at the time of development (2007-2010) measurements of heat consumption from district heating were seldom in the form of time series. This has over the last years started to change, so that at least the larger district heating companies have started to use smart heat meters with remote access. The concept has, therefore, been taken up in a new project also in Sønderborg[17] where the energy signature for a building e.g. is used for estimating how specific energy renovation measures will affect the heating demand.

Energy signatures for heat pump heated houses are more tricky as the heat demand is not known - unless for heat pumps on subscription. So, an estimation of the varying efficiency of the heat pump is needed here.

The method is also utilized in the EU project: the Nordic Energy Efficient Mortgage Hub, which aims to scale-up lending to energy renovations in the Nordics[18].

Development of simple low-order models

There are several ways of creating models for estimating the energy performance of a building:

- White box models
- Black box models
- Grey box models

White box models

White box models typically contain many differential equations describing the different processes in a building. It takes time and skill to develop good models, which may and may often not give the same results as later measurements. The latter because the parameters of the differential equations are mainly based on assumptions and not on measurements. These models often have a long runtime so that simulating one hour may even take more than one hour to simulate. Such models are thus seldom used for control. Be18 (see earlier) is a white box model, although having a very fast calculation engine, the program cannot be used for control as the output is monthly average values.

White box models are very useful when designing a building, as it is possible to run parametric analysis in order to test, which energy measures have the largest effect.

[15] www.researchgate.net/publication/233400389_Analysis_of_energy_consumption_in_single_family_houses
[16] https://backend.orbit.dtu.dk/ws/portalfiles/portal/126768981/kernelPaper2.pdf
[17] https://www.exray.dk/
[18] https://neemhub.eu/

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Black box models

Black box models are purely data driven and may be created in many different ways e.g. in the form of neural network programming. The model is fitted to the measurements so that it is able to give a good estimate of the actual energy consumption of the buildings. The problem with this type of models is, that even if they give the right answers it is not possible to define which processes in the building are main responsible for the energy consumption. So, it is not possible to use this type of models for giving recommendation of e.g. energy renovation measures.

Grey box models – simple low-order models

Grey box models combine the two above methods. The model is like black box models data driven, which in this case means that the parameters of the model are identified using historic data. However, the models are developed in such a way that the parameters of the model have physical meaning in the form of e.g. thermal capacity and UA values. These models are typically developed like an electrical network with R and C components and some external measured influencing parameters like ambient temperature, solar irradiation and wind. Such a RC model is shown below. How many R and C components are needed depends on the complexity of the building, however, often rather few are needed in order to represent the main information contained in the measurements, the model is fitted to. Statistical tools are applied to define which number of states (number of R and C components) are necessary for obtaining the statistically best fit. For further information please see [19], [20] and [21] below.

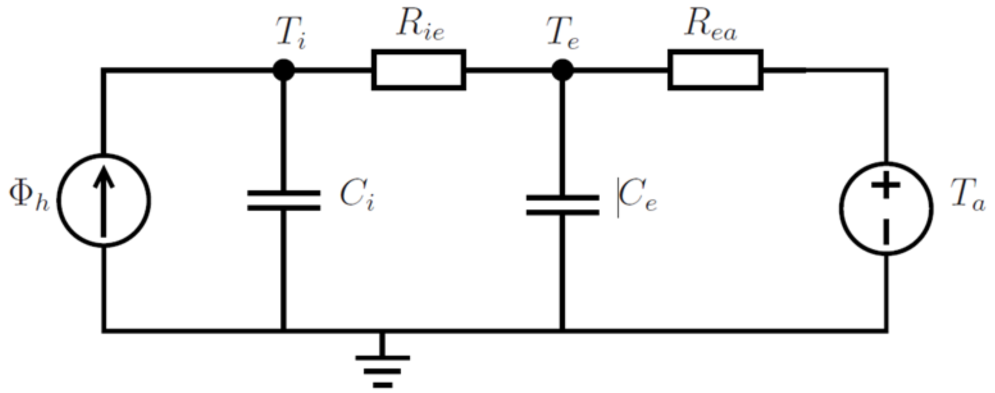

Figure 1: Example of a RC model where the building is represented by two resistances (Rs) and two capacities (Cs).

The benefit of grey box modelling is that the models are fast to run and, thereby, well suited for control purposes. As the parameters of the models (R and C values) are identified based on measurements, the models can continuously be tuned using online measurement for always obtaining the best possible fit to the actual conditions, even if these changes over time – the performance of a building is different day compared to night and different winter compared to summer. It is this type of models, that are utilized in the above described project in Sønderborg.

[19] http://henrikmadsen.org/wp-content/uploads/2014/10/Report_-_2010_-_Experiments_and_Data_for_Building_Energy_Performance_Analysis.pdf
[20] https://bwk.kuleuven.be/bwf/projects/annex58/
[21] https://bwk.kuleuven.be/bwf/projects/annex71/

Summary

White box models are valuable during the design of a building as no measurements are needed and that it is possible to perform parametric analysis to determine the optimal combination of energy saving measured for obtaining a good indoor climate and a low energy consumption.

Grey and black box models are well suited for control purposes as they are fast to run and can continuously be tuned based on measurements to give a correct picture of the actual energy consumption. Grey box models have the benefit that the parameters of the models have a physical meaning, which can be utilized for detecting problems in certain area of a building.

Real-time data

Online control is necessary in order to maintain good indoor comfort in a building. Many years ago, it was human interpretation of the indoor temperature that defined when it was necessary to put more wood in the stove. Since mid-1900s it became natural in Denmark to control the indoor temperature by applying analog thermostats on the radiators, where the desired level of the indoor temperature was set by manually adjusting the setting of the thermostat. Later these thermostats became programmable (= digital), but the connection to the valve was still analog based on the pressure of a liquid in the thin tube between the thermostat and the radiator valve.

For many years BEMS has been utilized in larger buildings, while first with the appearance of wireless communication in the form of both proprietary protocols and IoT (Internet of Things) HEMS (Homer Energy Manage Systems) has started to concur market shares in private homes. BEMS have still typically a wired connection between sensors and actuators.

The control in building uses real-time data to control the states of the building. A sensor measures e.g. the room temperature. Based on this, the BEMS or HEMS determine if a valve on the radiator in the room should open or close. Rule-based control is still the most commonly used control principle, however new principle are emerging. In the following, some way of control will be described:

- Rule-based control
- Model predictive control (MPC)
- Energy flexibility
- Advanced heat pump control

Rule-based control

Rule-based control are in principle based on if-then sentences:

- **If** the temperature in a room is below a certain threshold **then** open the valve on the radiator
- **If** the solar irradiation on the façade is above a certain threshold **then** close the blinds
- **If** the temperature in a room is above a certain threshold **then** start the cooling system
- **If** the CO_2 in a room is above a certain threshold **then** increase the ventilation rate

This is quite simple when one sensor controls one actuator, however, when many sensors and actuators are combined in a BEMS, it gets complicated:

- **If** the temperature of a room get above a certain threshold **then**:
    - Close the valve on the radiator
    - **If** it is sunny conditions, **then** maybe close the blinds
    - **If** the ambient temperature is lower that the indoor temperature **then** maybe increase the ventilation rate **else** start the cooling system also **if** increased ventilation does not give sufficient cooling

So, rule-based control also utilize if-then-else sentences.

If not programmed correctly and taking into account all eventualities it can go very wrong as seen in the above example in the section Display of time series of data.

Typically rule-based control does not have the ability to automatically adjust to new conditions in a building, as the rules are hardcore programmed into the system. The parameters of the rules are not continuously identified as in the above described low-order models.

Model predictive control (MPC)

Model predictive control is a multivariable control algorithm that uses:

- an internal dynamic model of the process – e.g. the above described low-order models
- forecasts – e.g. weather forecast and forecast of occupant behaviour
- a cost function – e.g. reducing the energy demand without jeopardizing the comfort
- an optimization algorithm minimizing the cost function

A MPC thus not only control based on the present states of the building it also considers the future development in the local climate and when the building is possibly occupied. So, if sunny conditions are forecasted the MPC may start to reduce the heat to a room before the sun starts to deliver heat to the buildings, however, not compromising the constraint that the indoor temperature should not drop too much and too fast if the building is occupied. In this way, the controller is able to lower the energy demand of the building but still maintain sufficient good indoor comfort.

Due to the ability to take future (forecasted) conditions into consideration, this type of controller is well suited to obtain energy flexibility from a building – see below.

Energy Flexibility

Denmark is shifting more and more towards renewable energy. However, energy sources such as wind and solar power have an intrinsic variability that can seriously affect the stability of the energy networks if they account for a high percentage of the total energy generation. Therefore, future high penetration of variable renewable energy sources forces a transition from “generation on demand” to “consumption on demand” in order to match the instantaneous energy generation. In practice, this means that the energy consumption needs to be flexible.

Consumption on demand calls for sector coupling in the form of e.g. electrification of the heating sector. Electrification of the heating sector can be obtained by large heat pumps in district heating systems and small individual heat pumps in private homes.

Buildings are expected to play a central role in this transition, where consumers and "prosumers" (e.g. buildings with PV) become energy flexible in order to satisfy the generation and/or storage needs of the energy grids (both power and district heating grids).

One option for generating flexibility is to make use of the thermal mass in the building structures. Depending on the amount, distribution, speed of charging/discharging, etc. of the thermal mass it is possible to shift the heating or cooling demand in time for a certain period without jeopardizing the thermal comfort for the occupants. The time constant of buildings varies between a few hours to several days depending on the amount and exploitability of the thermal mass together with the heat loss, internal gains, user pattern and the actual climate conditions. In addition, many buildings use different kinds of distributed energy storages (e.g. hot water tanks and electrical batteries), which may add to the energy flexibility of the buildings.

Control of energy flexibility from buildings

There are two main ways of utilizing the energy flexibility from buildings (and other DERs (Distributed Energy Resources)): direct and indirect control:

- In direct control: the entity interested in harvesting the energy flexibility has direct access to the building – e.g. the heat pump. Here the entity controlling the device measures the states of the device, calculates the available energy flexibility and send the proper control signal to the device. This method demands for two-way communication.
- In indirect control: the entity interested in harvesting the energy flexibility has no direct access to the building. Instead a control signal (often named Penalty signal) is broad casted to a large number of buildings. The buildings have their own controllers, which try to optimize the performance of the building in order to e.g. minimize the energy bill, if the control signal is a price signal. This method demands only one-way communication.

As indirect control is one-way communication this method needs less communication and thus less server capacity and, therefore, less electricity consumption compared to direct control.

Aggregator

Indirect control is best suited for harvesting energy flexibility from buildings as the available energy flexibility from a single building is low. Direct control is better suited for large controllable energy consumptions as in e.g. industry. As the available energy from a single building is low, it is not possible to bit this energy flexibility directly into a flexibility market. Here there is a need for a new market player: the aggregator. The aggregator is able to generate energy flexibility by broadcasting a control/penalty signal and bit this possible energy flexibility into a flexibility market. The below figure shows such a setup in a power grid.

MPCs (see the section above) are well suited to deliver energy flexibility based on signals from an aggregator. The reason for this is that this type of controllers can, based on forecasts of weather and occupancy, predict the energy need several hours ahead. This can further be enhanced with a forecasted control signal from an aggregator. Based on the broadcasted time series of the control signal, the MPC will try best possible to dispatch the energy consumption to periods when the energy price is lowest (if the control signal is an energy price), but maintaining the comfort. In its simplest form the control signal can be day ahead electricity prices, however, the aggregator may want to deviate from this price due to knowledge about e.g. predicted bottlenecks in the power system or locally produces power from PV. The aggregator can thus broadcast different time series of prices or time series of energy consumptions to be met for different local areas.

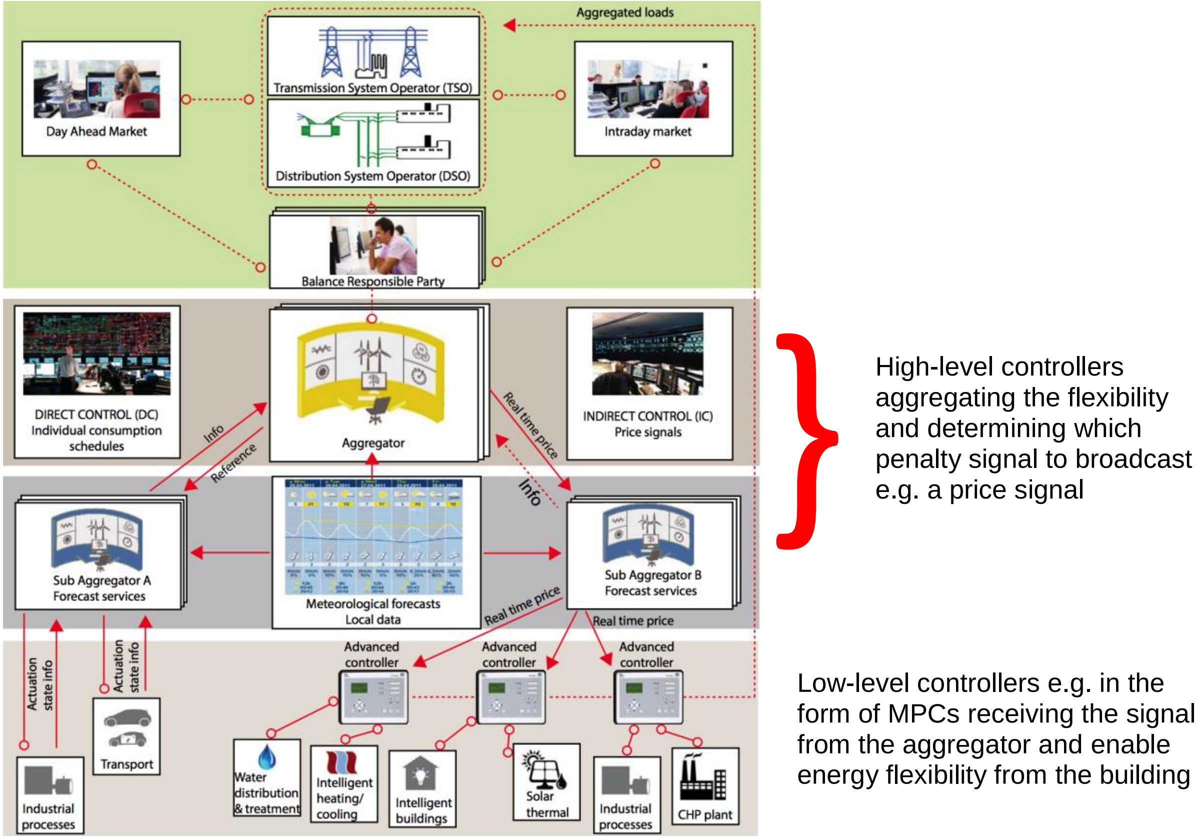

Figure 2: Control hierarchy in a power system where utilization of energy flexibility from DERs are enables via dedicated controllers.

Flexibility function

On the other end, the aggregator do not really know how much energy flexibility is available due to the only one-way communication. The aggregator needs to have knowledge of what a given control signal will lead to. This is not simple to obtain as the amount of available energy flexibility cannot be expressed with a single number as it can for energy consumption. However, IEA EBC Annex 67[22] have suggested a methodology for characterizing energy flexibility by quantifying the amount of energy a building can shift according to an external forcing factor (control/penalty signal), without compromising the occupant comfort conditions as well as accounting for the technical constraints of the building and its HVAC system. It acknowledges that the penalty signal acts as a boundary condition for the building. The below figure shows an example of the aggregated response of buildings when receiving some sort of penalty signal – here a sudden (not in advance known) increase in the energy price. In a real energy grid, the penalty signal will not be this type of step signal but typically a temporal varying signal. The figure further shows the parameters describing the response to the signal.

Consequently, the energy flexibility of a building is not a fixed static value, but varies according to environmental conditions, occupants' use of the building, the current state of the building as well as the penalty signal. A building's energy flexibility is determined by its ability to shift the

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instantaneous energy demand to minimize the effect of the penalty signal. This ability to shift the energy demand can be described by a dynamic Flexibility Function – e.g. giving the curved line in the below figure, which describes how the building reacts to a penalty signal. For simulations, the Flexibility Function is found based on the difference between the performance of the penalty aware building and the penalty unaware building, as a function of the penalty signal, which vary over time. For real buildings, only the penalty aware performance is measured, so more advanced mathematical methods are necessary in order to derive the Flexibility Function from measurements of the system's/building's response to the penalty signal. For further information on the Flexibility function, please see [23] below.

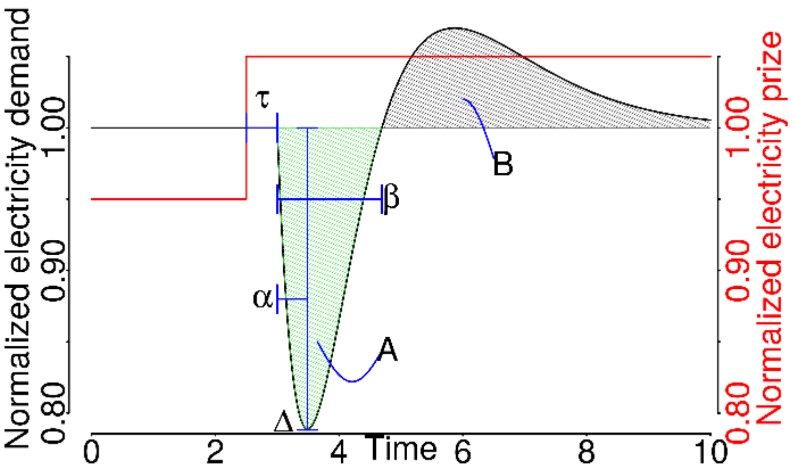

Figure 3: Example of aggregated response when some buildings receive a penalty signal – here a price signal. The parameters in figure are: τ is the time from the signal being submitted to when an action starts, α is the period from the start of the response to the max response, ∆ is the max response, β is the duration of the response, A is the shifted amount of energy, and B is the rebound effect for returning the situation back to the "reference" situation. [24]

The aggregator can utilize the Flexibility Function in order to gain knowledge of the systems in the portfolio and to predict available energy flexibility in the system. The Flexibility Function is developed based on historic data of the energy demand in the system, and can continuously be tuned to obtain an increasingly better forecast of the available energy flexibility for any given time. Flexibility Functions are not only restricted to buildings but may be developed for any system having the possibility to shift energy consumption in time. EU DG Connect is considering to promote Flexibility Functions for use in the control of the future energy systems. Eventually there is thus a possibility that calculation of Flexibility Functions may be part of future EPBD requirements.

Smart Energy OS

The Smart-Energy Operating-System[25] [26] (SE-OS) (see figure 2) is a framework for digitalization and implementation of smart energy solutions using Flexibility Functions as Minimal Interoperability Mechanisms (MIMs). The SE-OS is able to handle different kinds of DERs e.g. buildings, and water and food processing systems. The SE-OS framework consists of both

[23] https://annex67.org/media/1919/characterization-of-energy-flexibility-in-buildings.pdf
[24] https://www.sciencedirect.com/science/article/pii/S0306261918307
[25] https://orbit.dtu.dk/en/publications/smart-energy-operating-system
[26] https://www.opendei.eu/case-studies/data-spaces-for-energy-home-and-mobility/

direct and indirect (mostly price-based) control of the electricity load, heat load, etc. in integrated energy systems. The SE-OS has embedded controllers for handling ancillary service problems in both electricity and heat grids using the concepts of Flexibility Functions as MIMs. The entire setup of the SE-OS includes all levels of computing (cloud, fog, edge). The distributed setup of computing and data includes edge computing at the DERs.

SE-OS are utilized by Center Denmark[27] to control among other heat pumps.

Advanced heat pump control

The main factor, that influence the efficiency of a heat pump, is the temperature difference between the ambient heat source (air or ground) and the necessary forward temperature from the heat pump to the house for keeping the building sufficiently warm. For each increase of 1ºC in this temperature difference, the efficiency of the heat pump will decrease with 2-3 %.

The necessary forward temperature is given by the heat-emitting system of the buildings for covering the heat demand of the building. The room needing the highest forward temperature determines the efficiency of the heat pump. If the heat-emitting system is in unbalance – i.e. one heat-emitter has a too low pressure loss, this heat-emitter will receive a too high flow rate leaving the other heat-emitters with a too low flow rate. For still delivering sufficient heat to the rooms, the heat-emitters with the too low flow rate need a higher forward temperature. This leads to a decrease in efficiency of the total system.

In an ideal world, the thermostatic controlled valves on the radiators or in the underfloor heating circuits are controlled in a coordinated way. The valve of the room needing the highest forward temperature should be fully open, while the other valves are only partly open in a coordinated way to decrease fluctuations of the flow in the system. This will make it possible to run the system at the lowest possible forward temperature, which will increase the efficiency of the heat pump. In order to achieve this, there is a need for a more advanced combined control of the heat-emitting system and the heat pump. This is possible by using e.g. Model Predictive Control (MPC).

The same type of MPC can be utilized for making a heat pump deliver energy flexibility to the power grid. This can help stabilize a power grid with much fluctuating wind and solar power. It may also reduce the need for a reinforcement of the power cables. Even with a smart grid ready controller in the heat pump, the heat pump can only deliver energy flexibility by being switched off during a low power (high price) situation in the power grid. It is not possible to excess run the heat pump during a high power (low price) situation as the thermostats of the heat-emitting system are not controlled to increase their set point. With a MPC controlling the heat-emitting system, a low power situation may be predicted due to forecasts embedded in the controller. The settings of the thermostats may thus be increased before the low power situation allowing for a higher indoor temperature and thus for storing of heat in the internal constructions of the rooms or in e.g. a domestic hot water (DHW) tank. When the low power situation follows, the heat pump can be switched off for a longer duration due to the stored heat in the constructions and/or the DHW tank.

House owners have an increased interest in investing in PV systems. The production of electricity from PV systems is, however, often out of phase with the demand of the household. Part of the produced electricity, therefore, needs to be sold to the grid at low or no cost. The

[27] https://www.centerdenmark.com/

above described MPC can (besides being able to increase the efficiency of the heat pump and deliver energy flexibility to the power grid) also maximize the own-consumption of electricity from a PV system connected to the house. The heat pump may be forced to run during sunny conditions and store heat for the evening, however, still respecting the comfort in the house.

If a battery is included in the system it will further increase the own-consumption of PV produced electricity. It will also make it possible to buy electricity from the grid during low price situations and decrease the import from the grid during high price situations. This will besides an economic benefit for the house owner also enhance the energy flexibility, the house is able to deliver to the power grid. Appropriate control of the charging and discharging of the battery can be combined with the above described MPC.

The above type of control is studied and developed by Aalborg University in cooperation with commercial partners in the research project OPSYS 2.0 lead by Danish Technological Institute[28].

Conclusion

Digitalization related to energy consumption of buildings comes as shown above in many different forms and for many different purposes. The above examples is just a small fraction of all the ways building related data can be processed and utilized. And we have not yet seen the end. It is foreseen that much more data will become available leading to even more advanced processing and utilization of data.

The present document propose to create an overview by dividing digitalization into three main areas based on the nature of the utilized data:

- Static and semi-static data
- Historic time series
- Real-time data

Static and semi-static often are used for characterization of buildings or for simulation of the performance of the buildings.

Historic data are often used to investigate the pattern of the energy performance of and states in the building. Such time series are very valuable when trying to pinpoint why a building e.g. has a higher energy consumption or a poorer indoor climate than expected. Historic data can thus be used for fault detection. However, time series can also be used to characterize a building by e.g. creating energy signatures or by developing simple data-driven models of the building.

Real-time data are mainly used for control, however, by logging and storing these data, they become historic data. Control also comes in many different forms ranging from one sensor only controls one actuator, to complex rule- or model-based control where many systems are controlled in an integrated way. Forecast can improve the control as the controller, dependent on the quality of the forecasts, may predict what will happen in the nearer future and act upon this. Predictive controllers are foreseen to play a major role in the transition of the energy systems from fossil fuels to varying energy production from renewable energy sources.

[28] https://www.teknologisk.dk/projekter/projekt-opsys-2-0/40581 (in Danish)

However, digitalization on all the above mentioned levels have their important role to play in the transition towards sustainable energy systems.

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