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Olsson, D., Filipsson, P., Trüschel, A. et al (2026). MPC Using a Digital Twin Versus Simpler Traditional Heating Control in Swedish Multi-Family Buildings—A Measurement-Based Study. Energies, 19(20). http://dx.doi.org/10.3390/en19204857

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MPC Using a Digital Twin Versus Simpler Traditional Heating Control in Swedish Multi-Family Buildings—A Measurement-Based Study

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Abstract

Our buildings must become more energy efficient. Multi-family buildings account for a significant part of the total energy use. However, many energy-saving measures are very costly and require extensive effort. In this context, improved heating control is a cost-effective supplement. Over the past decade, sensors, machine learning, and related technologies have enabled more advanced heating control. Much of the development relates to model predictive control (MPC), but feedback control (FBC) remains useful on its own and as a stabilising component in various MPC strategies. This field study's novelty lies in comparing two neighbouring, similar Swedish multi-family buildings with traditional feedforward heating control (FFC). One building was equipped with an established pure FBC strategy and the other with a pure MPC strategy. The latter is based on a tailor-made digital twin with continuous input of real-time weather and household electricity data, etc. In the MPC building, the savings amounted to 11 kWh/m^2, and in the FBC building to 6 kWh/m^2. The FBC results are consistent with a recent similar field study in the same city. However, the MPC results are unique as they are based on a highly detailed digital twin. The results indicate that, under similar conditions, MPC strategies should involve FBC sparingly if energy efficiency is a high priority.

Keywords: model-based control; white-box principle; feedback control; heating; energy; indoor temperature; radiator system

1. Introduction

Large parts of today's building stock are not energy-efficient and will continue to account for a major share of the total energy use. Achieving climate goals therefore requires reductions in energy use in existing buildings. So, the possibility of quickly and effectively reducing energy use in existing buildings is highly relevant.

More advanced heating control results in minor fluctuations around the indoor temperature set point, enabling temperature levels close to the lowest permissible level and thus saving heating energy [1]. However, how much energy is generally saved, and what is the potential? For a property owner, it can be difficult to relate published results to their own portfolios. And the answers from companies that provide control-related services often vary, as results depend on control strategy, building performance, initial indoor temperature, local climate, etc. By studying the impact of different, well-defined control

Check for updates

Academic Editor: Christian Inard

Received: 11 August 2026
Revised: 28 September 2026
Accepted: 1 October 2026
Published: 14 October 2026

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strategies in equivalent buildings with equivalent indoor temperatures at the same location, differences and conclusions can be clarified.

In principle, heating control can be divided into three different strategies:

- Feedforward control (FFC): Traditional heating control that generally only takes outside temperatures into account. Also known as rule-based control (RBC).
- Feedback control (FBC): Control that considers both outdoor and indoor temperatures and thereby indirectly considers internal heat from people, solar radiation, appliances, etc.
- Model-predictive control (MPC): This control strategy is driven by algorithms, often based on standardised digital twins of typical buildings, fed with weather data. It can also consist of, or include, a self-learning process based on analysis of, for example, previous supply and indoor temperatures.

MPC strategies are often categorised as white-box, black-box, and grey-box principles. The white-box principle is physics-based and often uses detailed, advanced calculation models to handle heat balance, heat storage, HVAC, etc. The main advantage is that the input-output relationships are interpretable, and parameters can be adjusted with high resolution [2]. The disadvantage, however, is that it is time-consuming. Critics argue that it should be emphasised mainly as an alternative when historical data is missing. Depending on the design of the calculation models, it may require large amounts of input data, which, so far, makes it a non-scalable approach [3]. On the other hand, proponents argue that digital twins improve both energy savings and indoor thermal comfort during the operational phase [4].

The data-driven black-box principle, as distinguished by Chen et al. 2022 [2], is characterised by the fact that little or no physical building data is required, as it is based primarily on historical data and mathematical methods to derive relationships, e.g., between heating requirements and the building design and user patterns. Data-driven models are beneficial when sufficient historical data from existing buildings is available. The disadvantage of the principle is that it usually requires large amounts of historical data and a long time to train the model, and that the results are difficult to explain [2].

The grey-box principle is a hybrid of white-box and black-box approaches, characterised by a simplified physical model and a data-driven part based on readily available historical data. According to Chen et al. 2022 [2], the main disadvantages are that the principle is difficult to develop and spans two scientific domains.

Although no international studies have been identified in which the proportion of buildings with advanced or in some way demand-adapted heating control could be quantified, there is no doubt that there are many research studies on the subject. Likewise, it is clear that data models are increasingly created and used during planning, design, construction, operation, and even demolition of buildings. Models are also used to evaluate different control strategies. Digital twins may also be used for efficient fault detection [5], proactive maintenance [6], and/or continuous optimisation of HVAC system set-points in the building. The latter is an example of MPC, and its potential has been amply demonstrated during the last decades in different studies [7–10]. Rapid growth in MPC research is partly driven by improved capabilities (e.g., increased computing power and connected sensors) and increased benefits (e.g., more use of energy storage systems, more intermittent energy sources, and more volatile energy prices). While some studies highlight the time and cost required to set up a sufficiently sophisticated model [11,12], other studies conclude that even the simplest MPC outperforms traditional non-predictive control [13]. Weather forecasts are integral to most MPC studies and are sometimes considered a major contributor to the benefits [14]. On the other hand, others conclude that short-term weather forecasts are just a cheaper alternative to on-site weather measurements [15], and some

MPC systems do not include weather forecasts at all [16]. While many simulation-based studies assume perfect weather forecasts, others, such as Hedegaard et al. 2018 [15], investigate how stochastic imperfections affect the performance of MPC. It is rare not to include weather forecasts at all. Still, weather forecasts, compared with real-time local weather data, yielded only a minor performance improvement in one study investigating that alternative [17].

Many researchers have summarised the existing research on MPC, with the most comprehensive example entitled "All you Need to Know About Model Predictive Control for Buildings" [18]. Despite the large number of studies in the field, research on practical applications is still in its early stages and warrants further attention. Drgona et al. 2020 [18] note that several studies have reported that advanced HVAC control reduces energy use in buildings by an average of 13% to 28%, corresponding to 8000–18,000 TWh per year for the global building stock, according to the authors. In a summary of different strategies for heating control, the same conclusion was drawn, after which the authors requested high-quality evidence in the form of long-term experiments in real buildings [19]. A review of building energy management strategies concluded that previous research on MPC has primarily focused on the non-residential sector [20]. Another study, also summarising existing research in the field [21], distinguishes between online predictions and offline predictions, where the strategy in the present study would be classified as offline because it is not connected to a weather forecasting service (nor to an energy trading market). Serale et al. 2018 [21] note that only 19% of research on MPC concerns offline predictions; research focuses mainly on commercial buildings (24% residential), and simulation dominates over field measurement (19% in real buildings), and energy savings from MPC generally average between 15–20%. Although the focus of previous research has been on non-residential buildings, the potential may be no smaller in residential buildings. A Polish study [22] conducted a long-term field evaluation of a low-cost MPC system installed in seven residential and three commercial buildings. The average heat demand reduction was 13.4% in residential buildings and 10.7% in commercial buildings. In Finland, a field study [23] was conducted with 27 student residential buildings in which traditional feedforward control (FFC) was replaced with a weather-forecast-based control that also included feedback control (FBC), resulting in an average 9% reduction in heating energy use. However, it did not separately report how much of the saving may have been due to the forecast or the FBC.

In a recent review article [24] based on 104 peer-reviewed papers and published open-access datasets, the authors state that a large body of research suggests that model predictive control (MPC) and machine learning can reduce energy costs, pollutant emissions and grid stress. In the field studies they analysed, savings in multi-family buildings averaged about 22%. Despite this, large-scale implementation of the technology in the real estate sector is lacking. The authors speculate on the reason for this, noting that the lack of field studies and real-world data is a contributing factor. Only 4% of the 2892 papers found were based on field studies. The authors argue that more field studies are needed to accelerate implementation by providing real and relevant data that support the business benefits of implementation.

In addition to what is summarised above, the review of previous studies showed that MPC-based studies do not quantify or problematise the built-in FBC part of MPC. However, this can be difficult, especially in field studies, since the FBC component ensures that indoor temperatures remain at desired levels. The question, nonetheless, is how much of the observed MPC effect is actually due to FBC? Could pure MPC, where FBC serves only as passive backup, save more energy without indoor temperatures reaching unacceptable levels? To answer this question, several studies are required; this article reports on one

such study, divided into two stages. Both stages, referred to as Studies 1 and 2, were carried out to evaluate pure FBC and pure MPC in typical Swedish multi-family buildings:

Study (1): A simulation-based evaluation of pure FBC and MPC (the latter with and without weather forecast). The simulations were carried out using IDA ICE by EQUA [25], and Olsson published the results in a licentiate thesis in 2014, later summarised in an article [17]. As part of the study, the authors developed a strategy for using a digital twin.
Study (2): A follow-up field study in which the strategy in Study 1 was applied. Study 2 evaluated the practical performance of pure white-box MPC without FBC and compared it with an established pure FBC strategy. The study was planned, implemented, and reported to involved stakeholders from 2016 to 2019 and is now summarised in this article.

The novelty of Study 2 lies partly in comparing two similar, neighbouring buildings equipped with pure FBC and pure MPC, respectively, and partly in the MPC strategy's reliance on a tailor-made, highly detailed digital twin continuously fed with real-time weather and household electricity data. By comparing the two strategies in their pure forms, certain conclusions can be drawn about the results. If the FBC building's energy efficiency is greater than or equal to that of the MPC building, it indicates that FBC can be used instead of MPC and that MPC is not negatively affected by built-in FBC functions. If, instead, the MPC building achieves a clearly better result, it may indicate that MPC strategies should not involve FBC more than necessary if energy efficiency is a priority. Possibly only for temporary adjustment when the indoor temperature falls outside certain limits.

Since the evaluated white-box MPC strategy is unique, this article focuses mainly on MPC. Note that, as pure FBC provides little room for optimisation and has been applied in many buildings for decades, the control strategy was studied only in its established commercial form.

2. Materials and Methods

Studying pure FBC is relatively unproblematic, as the FBC strategy is entirely focused on achieving an average indoor temperature equal to the setpoint. A system that only controls one parameter has a high chance of success. The property owner takes almost no risk, which is, of course, a major advantage of FBC systems.

To evaluate white-box MPC, without elements of active adjustment with respect to indoor temperature, a more complex and somewhat riskier approach is needed, as it depends on the system's algorithms and digital twin being so well-designed and calibrated that it can generate an indoor temperature within given limits on its own. Here, the property owner takes a risk which must be managed through indoor temperature monitoring, alarms, and, if needed, temporary countermeasures.

There is, therefore, a fundamental difference here: pure FBCs target a setpoint through continuous measurements of indoor temperature, while pure white-box MPC relates to a setpoint in an algorithm/digital twin.

Study 2, which tested both alternatives, was conducted 2016–2019 in collaboration with the real estate company Stena Fastigheter in Gothenburg, which provided two neighbouring, technically equivalent multi-family buildings from the early 1950s. A smaller (24 apartments on 3 floors) for MPC and a larger (44 apartments on 4 floors) for FBC. The average apartment size in both buildings is nearly identical (60 m^2), and both are thermally heavy, with the same type of concrete frames and plastered facades. They were renovated in the same way in the late 1990s when facades and attic floors were insulated, and windows were replaced with triple glazing, etc.

Moreover, the buildings are oriented in the same direction, with long sides running north/south, and shading from other buildings and surrounding trees is similar but minimal.

Like most Swedish multi-family buildings, they are supplied with district heating connected to hydronic heating systems (radiators). Additionally, all apartments, basements, and stairwells are mechanically ventilated with exhaust air ventilation and can generally be considered typical in Sweden.

2.1. Installation, Preparations and Prerequisites for the Established FBC

Early in the process, wireless temperature sensors were installed in the apartments in the FBC building and connected to a cloud service for compilation and communication. (The same type of sensors were also installed in the MPC building; see E—Table 1.) Before activation, the building automation control system (Direct Digital Controller, DDC) was programmed. The actual temperature was measured every 30 min and defined as the average of the apartments' measured temperatures, excluding the three warmest and coolest apartments.

Table 1. Compilation of measurements and other on-site activities related to modelling.

What	Why (Apart from Input Data and Baseline Calibration)
(A) HEAT GAIN FROM PIPES. Surface temperatures were measured with thermography in the basement and vertical shafts. The measurements were made partly on exposed but insulated heating pipes, and partly on wall and floor surfaces where heating pipes passed internally. Quantity: ten measurement places.	
(B) HEAT GAIN FROM TOWEL DRYERS. Temporary temperature sensors installed on supply and return pipes to hydraulic towel dryers. To improve measurement precision, the sensors were coated with a thermally conductive paste, firmly attached with stripes, and thermally insulated. Same water flow as (C) below, calculated per apartment. Quantity: three apartments, six sensors.	Basis for heat source at apartment level
(C) HOT WATER CIRCUIT—FLOWS AND TEMPERATURE. Temperature sensors on water pipes to log supply and return temperatures periodically. Same approach for increased measurement precision as in (B) above. The water flow was measured with a TA-SCOPE instrument branched to a fixed valve on the hot water circuit. Quantity: two sensors.	Basis for heat source at building level
(D) HOUSEHOLD ELECTRICITY. Optical sensors on electricity sensors. Quantity: 17 sensors.	
(E) INDOOR AIR TEMPERATURE. (A) Temporary temperature sensors in all rooms in six apartments. Quantity: 20 sensors. B) Permanent temperature sensors in apartments, in the attic, in stair wells and in the basement. Quantity: 29 sensors.	(A) Verify the representativeness of the hall temperatures for other parts of the apartments
(F) PEOPLE. The number of residents in each apartment was obtained through public Internet-based sources. Approximate attendance patterns were noted during several on-site observations and conversations with residents.	
(G) RADIATOR PERFORMANCE. The model designation for all the building's radiators was identified. Quantity: 152 radiators.	Quantification of heating power at different temperature conditions.
(H) RADIATOR SYSTEM—HEAT ENERGY AND POWER DEMAND. An energy meter (ultrasound) with a temperature sensor was installed on the system's return pipe (a temperature sensor was also installed on the supply pipe).	
(I) RADIATOR SYSTEM—RESET. All radiator valves in both buildings were reset to projected kv-values (expresses the water flow in a valve). Quantity: 152 radiator valves, 22 stem valves and branch valves.	To obtain more equal indoor temperature levels between apartments (preliminary balancing)

Table 1. *Cont.*

What	Why (Apart from Input Data and Baseline Calibration)
(J) THE BUILDING. Geometry, material, surrounding shading, etc. Information obtained from drawings and status assessments on-site.	
(K) TRICKLE VENTS (WINDOW). Opening area, etc., noted during visits in apartments (three visits in each apartment).	
(L) WEATHER. A weather station was installed on the roof to measure air temperature, wind direction, humidity, and global solar radiation. A pyranometer with a shadow ring was also installed for diffuse solar radiation.	
(M) VENTILATION FLOWS. Exhaust air flow was measured in all apartments. In some apartments, supplementary measurements were also made to determine the impact of window slit valves (see K above). Quantity: 23 apartments.	
(N) WINDOW AIRING, CURTAINS, AND BLINDS. User patterns, opening area, etc., were visually inspected from outside approximately ten times during the heating season.	

The FBC strategy was PI-controlled. In the P-block, the gain factor was set to 3 °C/°C, which means that if the room temperature deviates by 1 °C from the setpoint, the supply temperature shifts by 3 °C. In the I-block, the integration time was set to 1 min. According to the company that provided the FBC installation, these values were the practice for the prevailing conditions. Furthermore, the room temperature setpoint was 21.3 °C, in accordance with the property owner's guidelines for the building, and the supply temperature adjustment was limited to ±6 °C relative to the FFC curve, in line with the housing company's practice for similar buildings with FBC. Otherwise, the activation of the Feedforward Control (FFC) did not involve any other steps.

2.2. Digital Twin Modelling and Preparation for MPC

The chosen strategy contained a digital twin modelled in IDA ICE (https://www.equa.se/en/ida-ice) (accessed on 6 September 2026), provided with various measurement data. IDA ICE is a well-established dynamic building simulation program used to calculate building energy performance and indoor climate conditions. Comparisons with other established simulation tools show that the program yields results of the same order of magnitude as other advanced calculation engines when using equivalent input data [26].

The model had ideal room-level heating control, always keeping the desired indoor temperature in the digital twin (when heating was needed). With prior knowledge of a reference occasion, a proper supply temperature was continuously calculated using a practically useful physical relationship between supply temperature and heat demand, described in a thesis by Kärkkäinen [27] and presented by Olsson et al. 2024 [17]. The reference occasion can be selected at any time, provided there is a heat demand and the radiator system is active. At that occasion, the heating system's actual heat output, water temperatures (supply and return) and the logarithmic average temperature difference between the radiator and the indoor temperature are noted.

The article by Olsson et al. 2024 [17] describes how the chosen control principle was implemented in Study 1. Later, in the field study (Study 2), the same principle was used, but with the addition of practical measurement-data handling and communication with the real building, as illustrated later. In short, the digital twin was first given properties that mimicked the real building (geometry, materials, technical installations, human presence, air leakage, etc., see Table 1). An important difference, however, was that the digital twin (as mentioned above) had perfect heating control in each room, resulting in constant

indoor temperatures at the set point as long as there was a heat demand. This was done to ultimately achieve more precise heat control in the real building. The digital twin was then connected to continuously updated measurement data on weather and household electricity; see Section 2.3. A separate administration program handled receiving measurement data and updating the digital twin, as this could not be done in IDA ICE 4.8.

In the administration program, a suitable supply temperature was also calculated at frequent intervals based on the relationship described by Käärkinen, with the only variable being the digital twin's heat demand (kW). This was simulated and communicated to the administration program, which in turn sent the calculated supply temperature to the real building's automation control system.

Commercial MPC strategies generally use weather forecast data as input, which undoubtedly facilitates the process, as forecast data can be easily purchased from weather institutes for a wide range of locations. Nonetheless, to specifically study the practical potential of MPC, weather forecasts were avoided as they are inevitably subject to errors and, therefore, require large safety margins. For example, direct solar radiation (a required input to the model's simulation tool, IDA ICE) often changes from approximately 900 to 0 W/m^2, or vice versa, in a few seconds when a cloud obscures the building. In this context, it should be emphasised that Study 1 showed that weather forecasts provide only a small additional benefit on an annual basis compared to real-time data, even with perfect weather forecasts. It also showed that incorrect forecasts can lead to indoor temperatures that are either too low or too high. This is generally compensated for by an FBC element with indoor temperature sensors, meaning that most MPC strategies are, in practice, hybrid.

Even though the MPC strategy was free of FBC, each apartment in the MPC building had temperature sensors to record indoor temperatures, primarily for later analysis, to trigger alarms (in case of too-low indoor temperatures), and to manually adjust the heating control if necessary. However, it turned out that such adjustments were only needed a few times during an entire heating season.

Several measurements were taken on-site to ensure the digital twin was given accurate information. This included the preparation and execution of numerous long- and short-term measurements, etc.; see compilation in Table 1. Later, in Table 3, the instruments used for continuous measurement are specified.

Since the primary purpose of any form of heat control is to maintain the desired indoor temperature, this aspect was prioritised during the digital twin's calibration, although energy consumption and heating power demand were naturally also important parameters. As solar radiation strongly and rapidly affects the building's heat balance and indoor temperature, specific measures were required to calibrate this parameter with high time resolution. This had to be done on sunny yet sufficiently cold days, and special attention had to be paid to occupant habits, as residents generally tend to open windows for ventilation and use blinds more frequently under such conditions. Although multiple external observations of the building were required, it must be noted that such habits—characterised by rapid changes—cannot be fully replicated in digital twins. Nevertheless, a close approximation can be achieved.

The calibration process involved feeding a version of the digital twin (though without ideal local heating control) with data on measured weather parameters, household electricity consumption, estimated occupancy, observed routines, and so on. The model's simulated outputs regarding indoor temperatures, energy consumption, and heating power demand were then compared with measurement data from the actual building.

Once the digital twin was calibrated, sensitivity analyses were conducted, particularly on solar radiation and household electricity consumption. First, the digital twin (the version with ideal heating control at room level) was fed with modified input data for the

parameters subject to sensitivity analysis. In a second step, the resulting supply temperature from Step 1 was applied to the heating system of the identical digital twin, this time without ideal heating control at room level. The room temperatures in the latter digital twin were then compared with actual measured values.

Sensitivity analyses focused primarily on solar irradiance and household electricity consumption; the latter was best analysed during periods without sunlight that would otherwise disturb the results. The digital twin proved sensitive to inaccuracies in both areas. For instance, if household electricity consumption in the digital twin was set to zero in December, the discrepancy between the modelled and measured average indoor temperature increased by about 0.4 °C. Accurate, continuous household electricity input data are therefore crucial, which justifies point (D) in Table 1. Conversely, when the digital twin was fed with manipulated weather data—such as zero solar irradiance for December—the modelled average indoor temperature became virtually identical to the corresponding measured values. This is unsurprising given the very limited number of sunshine hours in Gothenburg during December, as well as the low solar intensity when the sun is actually visible. Naturally, however, the solar irradiance parameter becomes more significant during periods with more sunlight. In October, for example, the difference between measured and modelled indoor temperature increased by an average of approximately 0.5 °C when the digital twin was fed with data deviating by 50% from measured values. This justifies point (L) in Table 1

Figure 1 presents results from one high-resolution calibration test, focusing on indoor temperature during a sunny day in April. In addition to precise hourly weather data, the analysis also considered household electricity consumption (D—Table 1), the use of trickle vents (K—Table 1), and window airing, as well as the use of blinds and curtains (N—Table 1). Figure 2 shows a photograph of the building and a screenshot of its digital twin, created in IDA ICE.

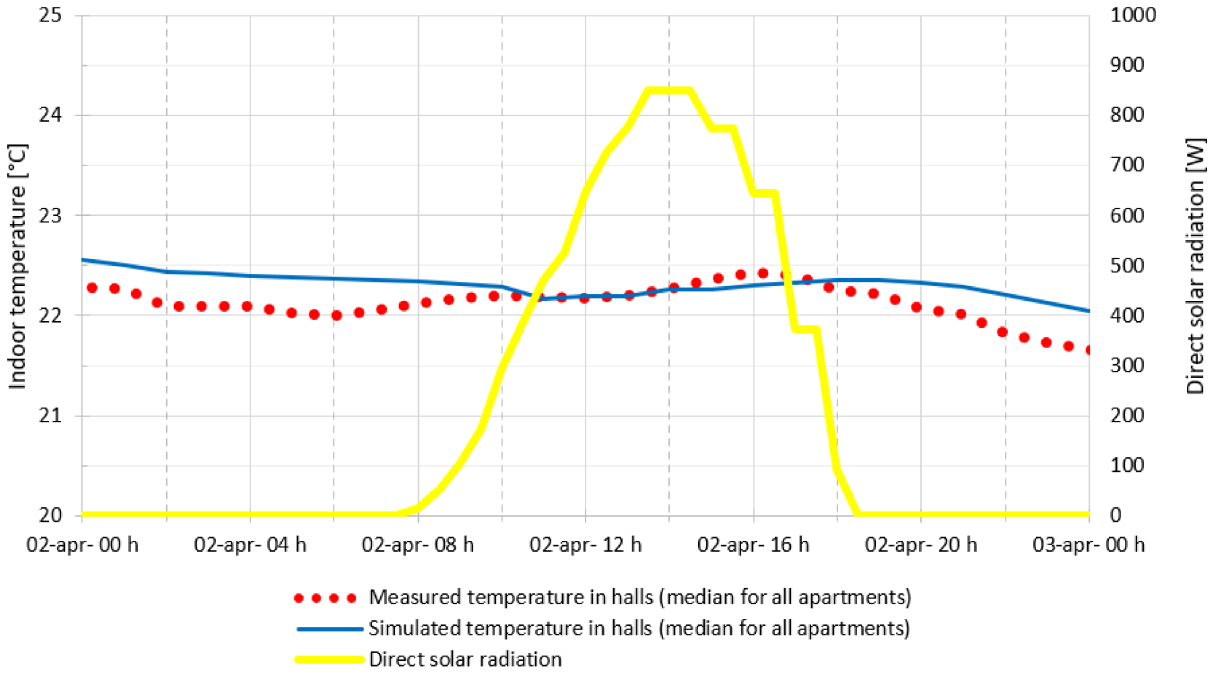


Figure 1. Measured direct solar radiation and median values for the indoor temperature of all apartments. The graph was used as a tool for high-resolution calibration of the digital twin. Here, an example is given for a sunny April day. The outdoor temperature was 2–12 °C.



Figure 2. The real building and its digital twin.

All impacts quantified refer to differences between before and after FBC and MPC were activated. The reference period (baseline) stretches back to April 2016, when the radiator systems in both buildings were adjusted (I—Table 1). In this context, it should be noted that all thermostats in both buildings were replaced with manual knobs a few months before the two control strategies were activated. This occurred outside the study's control and likely resulted in impaired heating control at room level. However, no significant indoor temperature differences were observed (E—Table 1). It should be mentioned, though, that other similar multi-family buildings in the area, with their thermostats replaced by manual knobs, showed increased energy use during the same period (see Section 3.1).

2.3. Technical Setup for Heating Control with a Digital Twin

As mentioned in the beginning of Section 2, to enable the developed MPC strategy, the digital twin had to receive, handle and communicate real-time data with the building's existing Direct Digital Controller (DDC). Table 2 reports the measurements that continuously delivered real-time data to the digital twin, and Figure 3 shows communication paths between them and other related equipment and software.

Table 2. Compilation of continuous real-time measurements for heating control (MPC).

What	Why (Apart from Continuous Input Data to Digital Twin)
HOUSEHOLD ELECTRICITY. Optical sensors on electricity sensors. Quantity: 17 sensors [1] (see D—Table 1).	
INDOOR AIR TEMPERATURE. Temperature sensors in apartments (halls), in the attic, in the stair wells and in the basement. Quantity: 29 sensors (Same as E—Table 1).	Monitoring and long-term adjustments (not heating control)
OUTDOOR AIR TEMPERATURE. Permanent temperature sensor since before, for FFC.	For FFC as a backup if the MPC fails.
WEATHER. A weather station was installed on the roof to measure air temperature, wind direction, humidity, and global solar radiation. A pyranometer with a shadow ring was also installed for diffuse solar radiation (required for the simulation tool IDA ICE) (see L—Table 1).	

[1] Written consent was required from the residents, which was obtained from 17 of the building's 24 households. For the other seven apartments, separate monthly schedules with hourly resolutions were created by analysing historical measurement data from the electricity supplier.

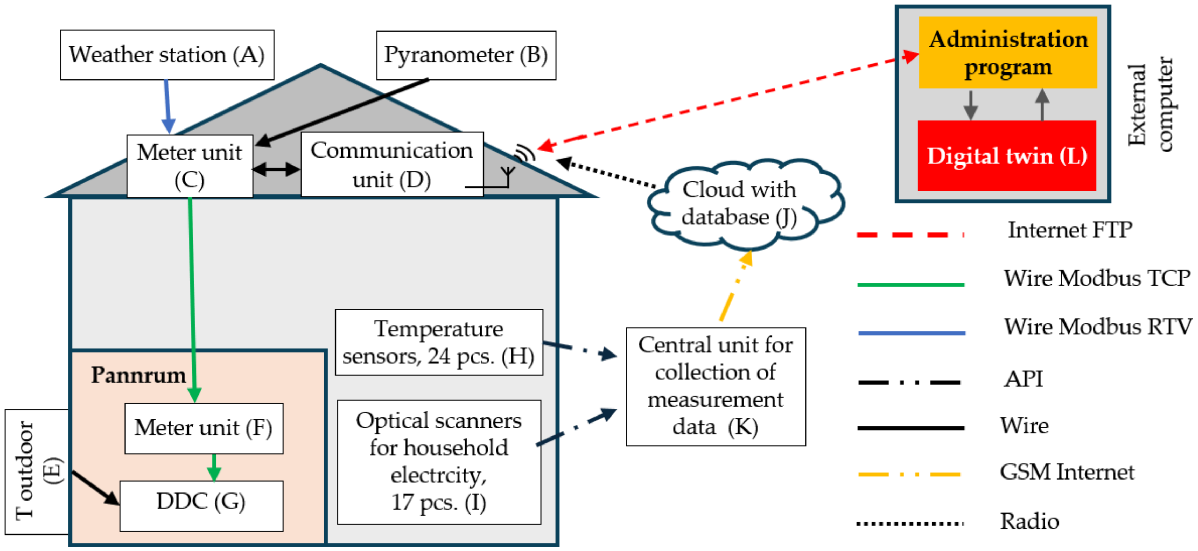


Figure 3. Principal sketch of equipment and communication paths. (A) Kipp & Zonen WS501, (B) Kipp & Zonen CM11, (C) Adam 4018, (D) Opto 22 OptoEMU-SNR-DR2, (E) KTC OTS 100, (F) Adam 6024, (G) Direct Digital Controller DDC—KTC SRD3211B, (H) EcoGuard TS02, (I) EcoGuard EcoReader, (J) EcoGuard Databasserver, (K) EcoGuard EcoCom, and (L) IDA ICE 4.8.

All information was collected in a communication unit (D in Figure 3), which communicated bidirectionally with the digital twin via an administration program developed for the study. The administration program also started and stopped the model simulation in IDA ICE every 30 min (L in Figure 3). Thus, the building received updates on set values for optimal supply temperature every 30 min. Please note that the indoor temperature sensors (H in Figure 3) were not used for heating control but for monitoring and alarms (in case of too-low indoor temperatures).

In Figure 4, photos of the described sensors are shown.



Figure 4. Sensors for real-time measurement for the digital twin. From left to right: (1) Weather station. (2) Pyranometer with shadow ring for measuring diffuse solar radiation. (3) Optical pulse counter for reading electricity sensors. (4) Indoor temperature sensors.

The administration program was also designed to handle deviant events, such as missing measurement values and too-low indoor temperatures, set to 20.8 °C by the real estate company Stena Fastigheter. In the event of such deviations, the MPC was automatically replaced by the same traditional heating control as before (FFC). The MPC

was then manually restarted when the indoor temperature returned to the desired levels. During the MPC pauses, minor indoor temperature setpoint adjustments were made in the digital twin to adjust the supply temperature. This backup procedure was an essential requirement from the property owner.

Table 3 presents the technical specifications for the instruments used to report results and for real-time heating control in the MPC building, and Table 4 summarises measurements conducted to provide a basis for result analyses.

Table 3. Technical specifications for measurement instruments in the MPC building (continuous measurements only).

What	Sensor	Principle	Accuracy	Sampling Rate
Diffuse solar radiation (roof)	Kipp & Zonen CM 11	Pyranometer	±2% [1]	1 min
Electricity (apartment)	EcoGuard Ecoreader	Optical (pulse)	n.a.	15 min
Heating energy (radiator system)	Kamstrup Multical 402	Ultrasonic + temp.	±<5%	15 min
Global solar radiation (roof)	Kipp & Zonen WS501	Pyranometer	±5%	5 min
Indoor temperature (apartment)	EcoGuard TS02	NTC	±0.15 °C	15 min
Outdoor temperature (roof)	Kipp & Zonen WS501	NTC	±0.2 °C	5 min
Relative humidity (roof)	Kipp & Zonen WS501	Capacitive	±2% RH	5 min
Pipe temperature (multiple places)	EcoGuard WL RT-1004-1	NTC	±0.5 °C	15 min
Wind direction (roof)	Kipp & Zonen WS501	Ultrasonic	<3°	5 min
Wind speed (roof)	Kipp & Zonen WS501	Ultrasonic	±0.3 m/s	5 min

[1] Excluding the impact of shadow ring.

Kipp & Zonen is a Dutch manufacturer based in Delft, The Netherlands. Their products used in Study 2 were purchased from distributors in Sweden. EcoGuard is a Swedish manufacturer of measurement equipment and monitoring systems, based in Örebro, Sweden. There units were purchased directly from the manufacturer in Sweden. The Adam 4018 and 6024 units in Figure 3 are from the Taiwanese company Advantech Co., based in Taipei, Taiwan. The former is an 8-channel thermocouple input module for industrial data acquisition, while the latter is an I/O module for acquiring analogue and digital signals. There units were purchased from distributors in Sweden. The gateways unit for data collection, OptoEMU-SNR-DR2, Figure 3 was purchased in Sweden but manufactured by Opto 22 in Temecula, CA, USA. Kamstrup is a Danish manufacturer situated in Stilling, Denmark. There unit was purchased from EcoGuard in Sweden. Finally, KTC is a Swedish company based in Gothenburg Sweden that manufactures direct digital controllers for building (DDCs). There unit was installed in the building several years before Study 2 began.

Table 4. Compilation of measurements carried out for result analysis.

What	Why
INDOOR AIR TEMPERATURE. Temperature sensors (E—Table 1). Quantity: 29 sensors (23 in apartments, one in attic, two in stair wells, three in basement).	Follow-up of temperature level and fluctuation
RADIATOR SYSTEM—HEAT ENERGY AND POWER DEMAND. An energy meter was installed on the system's return pipe (temperature also on supply) (H—Table 1).	Follow-up of energy and heat demand
RADIATOR SYSTEM—TEMPERATURES. Temperature sensors installed on the radiator system's supply and return pipes for continuous measurements (H—Table 1). Quantity: two sensors.	Follow-up of supply temperature

In the FBC building, the control strategy continuously sorted out the three warmest and coldest apartments. However, in the MPC building, where heating control is based on the building's overall heat balance, no corresponding exclusion was made.

2.4. Measurement Period and Typical Mean Year Correction

Comparisons and analyses of energy statistics must always be preceded by separating energy unaffected by outdoor climate and normalising the rest. This process is generally called the Typical Mean Year Correction, or simply the TMY correction. Since the MPC building was equipped with a separate energy meter (H—Table 1) for the radiator system since 2016, no reduction was required for domestic hot water. However, the FBC building did not have a radiator energy meter or hot water meter, so the input for the TMY correction of that building was based on measured heat statistics (district heating) for the entire building, but reduced by measured heat demand during the summer months when the radiator system does not need any heat.

There are various TMY correction methods, but in this study, the method had to account for the fact that FBC and MPC were active for less than a year (40 and 22 weeks, respectively) and experienced some technical interruptions. The choice fell on the energy signature method, which enables an upscaling of energy use to a full-year basis as it is based on power demand in relation to outdoor temperatures rather than time periods. Of course, a comprehensive measurement basis is preferable and increases the accuracy. However, when this was not possible, the energy results were instead compensated with a larger deviation range, as described in Section 2.5 and quantified in Section 3. Note, however, that the results for both buildings are calculated using the same time periods, with common interruption periods to make the comparisons more equivalent.

Despite the advantages, only a few scientific field studies use the energy signature for TMY correction. One of them [28] describes the energy signature and justifies why the TMY method was chosen. Cholewa et al. [22] also use it, although without describing why. There are, of course, more examples, but overall, the state of knowledge about this TMY method justifies a more detailed description. The Energy-Signature method is based on a measured relationship between the building's heating demand and outdoor temperature. In the process, the average heating power demand (kWh/h) is derived for periods with a suitable resolution (here, two weeks). This is then set in relation to the average temperature for the respective period, whereupon a regression line is obtained. The more comprehensive the energy statistics, the more stable the regression line in this case. See the current regression line equations in the coloured boxes in Figure 5.

The regression lines in Figure 5 follow a typical pattern, where improved heating control results in a steeper slope, while, e.g., thermal insulation typically generates a parallel downward shift. For the FBC building, the outcome was similar but with a lower slope difference between the regression lines.

Once the equations of the regression lines are known, annual upscaling and TMY correction can be performed by replacing measured mean outdoor temperature with official TMY temperatures for the location. Finally, the heating power usage (kW) is multiplied by the number of hours for the selected time resolution, after which a TMY-corrected energy use (kWh) is obtained.

According to the Swedish Meteorological and Hydrological Institute (SMHI), the reference period was, on average, about 1.3 °C colder and had about 18% lower global solar radiation than during the period with upgraded heating controls. Even though the difference in outdoor temperature is largely addressed through TMY correction, exact equivalence cannot be achieved, which is further discussed in Section 5.

The coloured boxes in Figure 5 also show the regression lines' R^2 values, which indicate how much of the variation in the dependent variable the regression model explains. If the value is 1.0, the regression model explains 100% of the variation. As can be seen from Figure 5, the R^2 values indicate that more than 90% of the variation can be explained by the relationship between power demand and outdoor temperature. In the context of building energy, this is a very strong relationship.

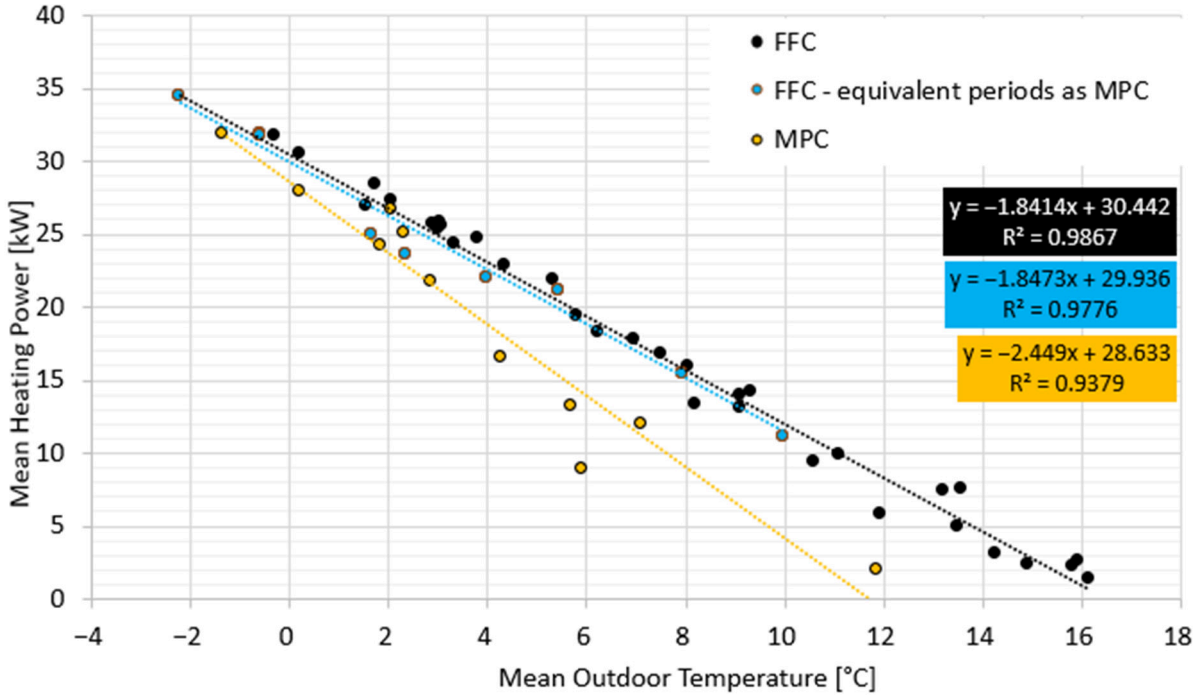


Figure 5. Energy signatures for MPC and FFC in the MPC building (Study 2). Each filled dot represents a two-week average value. The regression lines form functions with outdoor temperature as the variable.

2.5. Energy Calculation

The total reference period with FFC was more extensive than the period with MPC, which explains the larger number of black-filled dots in Figure 5. The blue-filled dots also represent FFC during the reference period, but only for the corresponding periods with active MPC (same dates as MPC but different years). For equal comparison, the same reference period was used for the FBC building, resulting in four functions/relations (and associated R^2 values in parentheses):

The FBC building (A)

- With FFC

$$P_{A,FFC} = -3.76 \cdot t_{out} + 63.78 \quad (R^2\text{: } 0.96) \tag{1}$$

- With FBC

$$P_{A,FBC} = -4.16 \cdot t_{out} + 62.11 \quad (R^2\text{: } 0.99) \tag{2}$$

The MPC building (B)

- With FFC

$$P_{B,FFC} = -1.85 \cdot t_{out} + 29.94 \quad (R^2\text{: } 0.98) \tag{3}$$

- With MPC

$$P_{B,MPC} = -2.45 \cdot t_{out} + 28.63 \quad (R^2\text{: } 0.94) \tag{4}$$

where

$P_{A,FFC}$ and $P_{A,FBC}$:heating power demand—two-week mean value, FBC Building (kW).
$P_{B,FFC}$ and $P_{B,MPC}$: heating power demand—two-week mean value, MPC Building (kW).
t_{out}: measured outdoor temperature—two-week mean value (°C).

Uncertainty in the calculated energy performance was quantified using a non-parametric bootstrap procedure. That procedure is particularly useful for non-large samples. The method uses repeated resampling with replacement from the observed data. The original regression dataset was resampled with replacement 20,000 times. For each bootstrap sample, the regression model was refitted and the annual energy performance recalculated. A 95% confidence interval was obtained from the 2.5th and 97.5th percentiles of the bootstrap distribution, following Efron [29].

When the control strategy's impact on heating energy was finally calculated as described in Section 2.4, based on Equations (1)–(4), double confidence intervals were obtained (one for the baseline FFC strategy and one for the FBC or the MPC strategy respectively). Adding their confidence intervals would give a large margin of error. However, as the uncertainties were independent (uncorrelated), error propagation according to the root-sum-square method (RSS) could be used; see Equation (5).

$$u = \sqrt{u_1^2 + u_2^2 + \ldots + u_n^2} \tag{5}$$

where

u_{1-n}: independent uncertainties.

2.6. Indoor Temperature

Finally, the impact on indoor temperature was also studied in terms of level and fluctuation, using hourly analyses of apartment average temperatures (E—Table 1). Fluctuations in the measured indoor air temperatures were quantified by weekly analysis of the standard deviations (deviations from the mean value) using Equation (6).

$$\sigma = \sqrt{\frac{\sum(t_h - t_w)^2}{n-1}} \tag{6}$$

where

t_h: hourly measured mean indoor temperature for all apartments.
t_w: weekly mean value of t_h.
n: number of measured values (168 values per week).

3. Results

As previously mentioned, the white-box MPC results could be considered close to the strategy's practically feasible potential under the given conditions. The results in Table 5, further explained in Sections 3.1 and 3.2, refer to the impact of control strategies on two similar, neighbouring multifamily buildings from the 1950s in Gothenburg. However, even if they can be considered representative, it should be emphasised that all buildings and their conditions are unique.

The FBC and MPC strategies turned out to have a clear impact on the supply temperature. The most significant difference was generally obtained on cold but sunny days. In commercial designs of FBC and MPC, the deviation from the setpoint (offset) is often limited. Hence, the tested FBC strategy was limited to an offset value of ±6 °C compared to FFC, as mentioned in Section 2.1. However, the tested MPC strategy had no limitations, as the aim was to investigate its potential. Figures 6 and 7 show the impact on the supply temperatures in the two adjacent multifamily buildings.

Table 5. Summary of results. Traditional heating control (FFC) as the baseline for the comparison with FBC and MPC.

What	Unit	MPC Building	FBC Building
Changed annual energy use (heat) [1]	kWh/m^2	-11.0 ± 1.9	-6.1 ± 2.5
Changed indoor temperature level (heating season) [2]	°C	−0.54	−0.32
Changed indoor temperature fluctuation [3]	%	−1	−10
Multi-family buildings	Quantity	1	1
Area	m^2	approx. 2400	approx. 3600

[1] TMY-corrected for Gothenburg, Sweden, with energy signatures (See Sections 2.4 and 2.5) based on periods with active MPC. Uncertainty intervals derived as described at the end of Section 2.5. [2] Mean values. Refers to periods when the MPC was active. [3] Percentage difference in standard deviation on a weekly basis (Equation (6)) compared to the corresponding standard deviation with FFC.

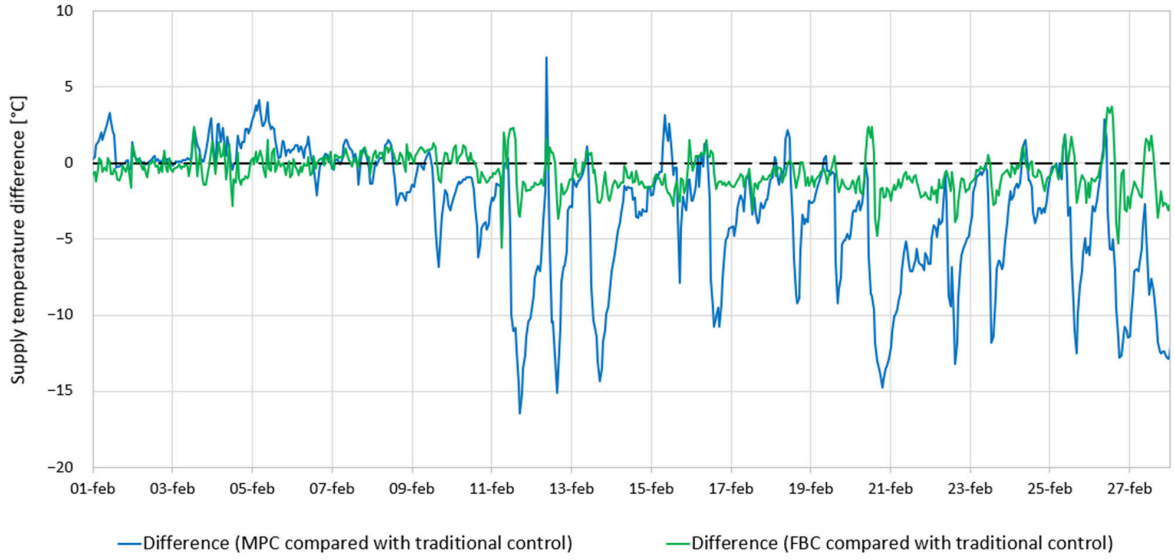


Figure 6. Impact on supply temperatures. Difference between measured supply temperature for both tested control strategies, compared to calculated supply temperature for FFC. February 2019. Negative values mean that the MPC or FBC strategies resulted in a lower supply temperature. Please note that the graphs are not necessarily fully comparable, as they refer to two separate buildings with unique predetermined FFC supply temperature curves.

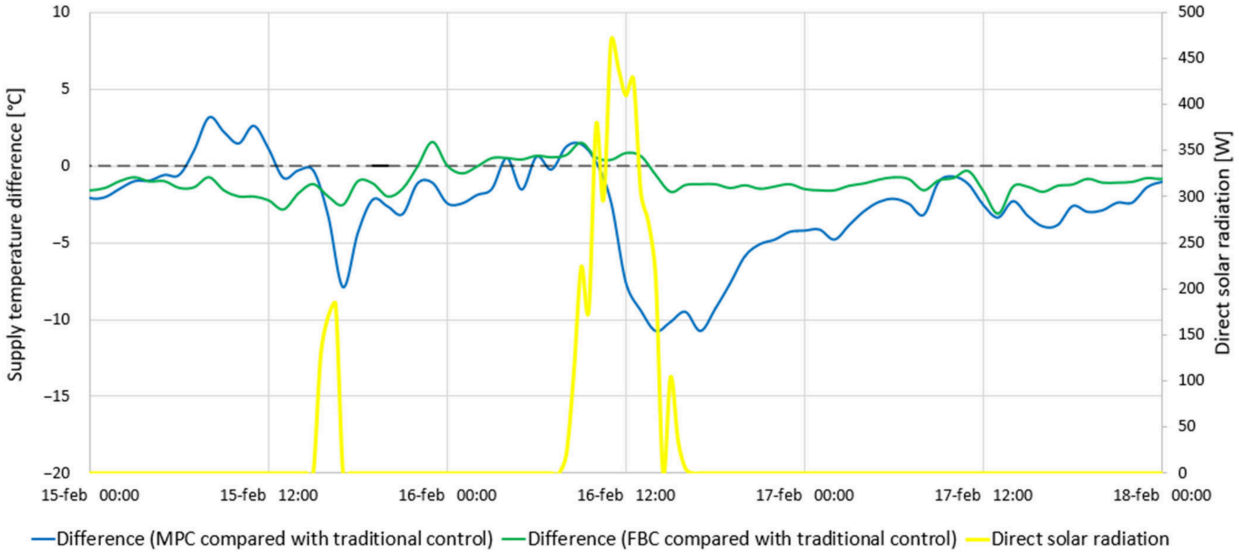


Figure 7. Impact on supply temperature. Zoomed in for two days from Figure 6, completed with measured direct solar radiation.

As shown in Figures 6 and 7, MPC has the most significant impact on the supply temperature. The mean outside temperature in February was about −4 °C at the beginning of the month and about +10 °C at the end. During the three zoomed-in days in Figure 7, the outdoor temperature was +4.5 ± 2 °C. In February, the supply temperature was reduced by an average of about 0.5 °C with FBC and about 3.5 °C with MPC. The impact was smaller in January (little sunshine) but larger in March (more sunshine). The figures also show that FBC was generally not much affected by the mentioned ±6 °C limitation. The FBC was limited only during a handful of brief occasions from January to March. In April, however, the limit was often reached.

The measured results are summarized in Table 5. Sections 3.1 and 3.2 supplement the results and relate some of them to previous studies.

3.1. Impact on Energy Use

Using Equations (1) and (2) and entering TMY values for all months of the year, TMY-corrected annual energy use was obtained in the FBC building for FFC and FBC. Using the same process for Equations (3) and (4), the corresponding energy use in the MPC building was determined. The energy changes (improvements) were calculated as the difference between the previous FFC and FBC and between FFC and MPC, respectively.

As noted in Section 2.5, Equations (1)–(4) were based on the period during which the MPC was active. This was done to ensure an equivalent comparison.

If the reference period with FFC had instead been chosen for a more extensive period (the regression line for the black-filled dots in Figure 5), the savings in the MPC building would have been 12.5 kWh/m^2 (instead of 11.0 kWh/m^2). A corresponding extension for the FBC building reduces the savings slightly to about 5 kWh/m^2 (instead of 6.1 kWh/m^2)

In several studies referenced in the literature review, energy savings were reported as percentages; however, they did not always clarify whether hot water was included. The percentage savings achieved in the FBC building correspond to approximately 9% of that building's heating energy, excluding domestic hot water. In the MPC building, the corresponding saving was approximately 20%.

To ensure that the applied control strategies caused the energy savings, energy use was also examined in three nearby multi-family buildings. These had FFC but were otherwise similar to the FBC and MPC buildings in terms of year of construction, size, ventilation systems, materials, etc. In addition, they had the same property owner and the same overall operating organisation. It turned out that the three neighbouring buildings showed increased heating demand during the same period: +10%, +15%, and +13%, respectively (TMY-corrected), excluding domestic hot water.

The reasons for their increase were not investigated. However, as mentioned in Section 2.2, the thermostats were replaced with manual knobs also in these buildings at the same time. That measure is likely to have led to poorer local heat control, which could explain the increase in energy use.

3.2. Impact on Indoor Temperature

The two buildings were warmer during the heating season than required by national regulations/guidelines. The FFC building was initially 22.1 °C, and the MPC building was initially 21.8 °C. This is in line with previous Swedish studies [30–33], which indicate that 22.0–22.5 °C is the Swedish average indoor temperature in multifamily buildings during the heating season.

As shown in Table 5, room temperatures were reduced when FBC and MPC were activated. Fluctuations were also reduced with FBC but not with MPC. The difference in fluctuations is probably mainly due to the fact that the indoor temperature is an important

control parameter in FBC strategies, unlike the tested MPC strategy, which did not use it as an active control parameter. However, the difference can also be partly explained by the fact that the supply temperature under MPC was allowed to deviate freely from the set value, whereas it was limited (and thus more stable) in the FBC strategy.

No evaluation of the residents' experiences in the two buildings was conducted. Instead, the agreement with the property owner was to monitor differences in the number of temperature-related complaints received. No impact on this was reported. One anecdotal detail, however, was that a property technician with an office in the MPC building reported cold radiators on two occasions during cold weather. It was quickly determined, however, that the indoor temperature in his office and the other apartments was at the required level, and that the low supply temperature was due to MPC compensation for solar gain and internal heat.

Finally, it could be noted that two of the three similar but out-of-scope buildings mentioned above, which also had their thermostats replaced with manual knobs, had temperature sensors showing an elevated indoor temperature of about 0.9 °C on average.

4. Discussion

The literature review shows that MPC and FBC have been studied many times. However, this article links a simulation study to a detailed field study in which the effects of pure FBC and pure MPC strategies in comparable adjacent multi-family buildings were investigated, which is unique. The MPC strategy in Study 2 was based on a tailor-made, detailed digital twin, developed through multiple on-site inspections and measurements to reflect the design, technical installations, occupancy patterns, etc. What also distinguishes Study 2 from previous work is the use of real-time weather data instead of weather forecasts. Furthermore, none of the previous field studies have used direct and diffuse solar radiation, even though these components are highly variable and crucial to the heat balance of buildings.

Obtaining permission to control the heating system of an occupied multi-family building using an unproven MPC technology is not a trivial matter (especially not without an active FBC component), which further underscores the study's novelty.

FBC and MPC in Study 2 were first activated in March 2018. MPC was deactivated in mid-April the same year as it required modification and more secured technical communication. The MPC operation restarted in mid-December and continued until mid-May 2019; in total, the MPC was active for almost six months. Unfortunately, as the building was scheduled for renovation, the measurement period could not be extended into the following season—a fact that naturally disadvantaged the study. Fortunately, the energy signature method could address the lack of data for a full season.

In addition to the long shutdown in 2018, the MPC technology automatically disconnected on three occasions as the indoor average temperatures dropped slightly too low (below 20.8 °C), requiring manual restarts. These three interruptions lasted 2.5 h, 72 h, and 18 h, respectively—a negligible amount in this context. The middle stop took so long because of technical communication problems.

In the MPC building, the heating system had a dedicated energy meter (Table 1, item H), the optimal approach for monitoring heating energy. Unfortunately, resources for a similar installation in the FBC building were lacking; consequently, heating energy there had to be estimated by deducting values based on measured heat demand during the summer months (see Section 2.4). Naturally, this latter method is less precise. A comparison of the methods was therefore conducted in the MPC building, revealing that the difference was relatively small—approximately 9%.

Moreover, the impact of the number of floors has not yet been discussed. This is partly because it is difficult to quantify, and partly because it is considered small, as the control technologies' impact on energy and temperature is relative to their baselines. However, differences are conceivable depending on the area exposed to the weather. Thus, the general heating requirement is slightly higher per square meter of living area in the lower MPC-building than in the higher FBC-building. A comparison between two completely identical neighbouring buildings would have been preferable but unfortunately was not possible in this study.

Since today's commercially available white-box MPC solutions use generic building models, they largely rely on FBC, which can thus improve indoor temperature stability but also inhibit the energy-saving potential of MPC. Unless indoor temperature levels are set as inviolable at all times, more advanced and tailor-made white-box solutions without active FBC should be able to offer greater savings potential. On the other hand, such white-box solutions are currently too expensive to be rolled out on a scale in the market. However, it is conceivable that tools for creating digital twins will be simplified in the future through sensors, image processing, drawing conversion, etc., which, in that case, would make the technology more accessible than it is now.

In parallel, solutions for black-box MPC are being developed, using machine learning that certainly requires a lot of history but can be implemented relatively quickly at scale. However, they are continuously dependent on FBC, which in many cases probably inhibit savings.

Regardless of the MPC principle, tools are now also being developed to handle fluctuating energy prices, peak power shaving, etc., which have great potential [34].

In addition to improved heat control at the building level, there is potential for improvement at the room level, with electronic PI- or PID-controlled thermostats on each radiator. In Sweden, electronic thermostats are not yet used in multi-family buildings but are becoming increasingly common in houses. A Swedish study examines the conditions for developing electronic thermostats for multi-family buildings [35], and future studies are likely to investigate whether they can complement or serve as an alternative to advanced central heating control.

5. Conclusions

The initial simulation study (Study 1) resulted in savings of 7 kWh/m^2 for FBC (compared to FFC) with a P-controller. The corresponding savings for MPC were 8–10 kWh/m^2, depending on whether it used real-time weather data or perfect weather forecasts. It should be noted, though, that simulation studies have difficulty fully replicating real (non-perfect) heating control, especially at the room level, where thermostats' functions and placements vary greatly.

The measurement in this follow-up study (Study 2), summarised in Table 5, shows that significant energy savings can be achieved when the heating control adapts to current conditions and demand. In this specific case, savings of approximately 11 kWh/m^2 with a white-box MPC strategy, while 6 kWh/m^2 with the specific FBC approach, were achieved. The energy savings for the MPC, as well as the FBC, building are approximately in line with the results of the simulation-based study mentioned above, in which the same type of digital-twin-based heating control was applied to a multi-family building featuring similar thermal insulation and ventilation performance and using climate data for the same city (Gothenburg). The results with the FBC strategy regarding energy and indoor temperature are entirely in line with the larger field study by Olsson et al. [28] (similar buildings and the same city), where it was concluded that pure FBC reduced the heating demand in general by 6–7 kWh/m^2 and generated a more stable indoor temperature. However, whether the

achieved temperature difference is significant enough to be perceived by occupants is less certain and has not been investigated.

It should be noted that the buildings in this study (Study 2) and in the larger FBC field study by Olsson et al. are owned by large housing companies with extensive organisations managing their properties, which may explain why the buildings had lower indoor temperatures than average multi-family buildings in Sweden. Facilities managed by small organisations are likely to be less optimised and thus have greater savings potential.

It should also be noted that though matched on construction era, structure, retrofit history, ownership, and location, building-specific factors (occupant behaviour and features beyond obvious control) cannot be fully separated from the control-strategy effect.

Finally, the studies show that white-box MPC—using a detailed digital twin under the given conditions—can save more energy than FBC. Based on the study's findings, white-box MPC strategies should rely on FBC only as much as necessary if energy efficiency is a high priority. However, creating detailed digital twins still requires extensive (and costly) effort to replicate actual buildings accurately; otherwise, they must rely heavily on FBC. Given that the study involved only one building using this type of MPC, further similar studies are needed to confirm the validity of the conclusion.

Author Contributions: Conceptualization, methodology, validation and formal analysis, D.O. and A.T.; writing—original, D.O. and P.F., draft preparation, project administration and funding acquisition, D.O.; writing—review and editing, J.-O.D.; supervision, A.T. All authors have read and agreed to the published version of the manuscript.

Funding: The Swedish Energy Agency funded this study through the research program E2B2, Project number P2021-00217.

Data Availability Statement: Contact the corresponding authors for further documentation.

Acknowledgments: The following actors assisted in various parts of the work: Stena Fastigheter, CIT Renergy, EQUA, EcoGuard and Processkontroll.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results. Authors Daniel Olsson and Peter Filipsson were employed by CIT Renergy and industrial Phd students at Chalmers University of Technology.

Abbreviations

The following abbreviations are used in this manuscript:

DDC	Direct Digital Control
FBC	Feedback Control
MPC	Model Predictive Control
TMY	Typical Mean Year

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