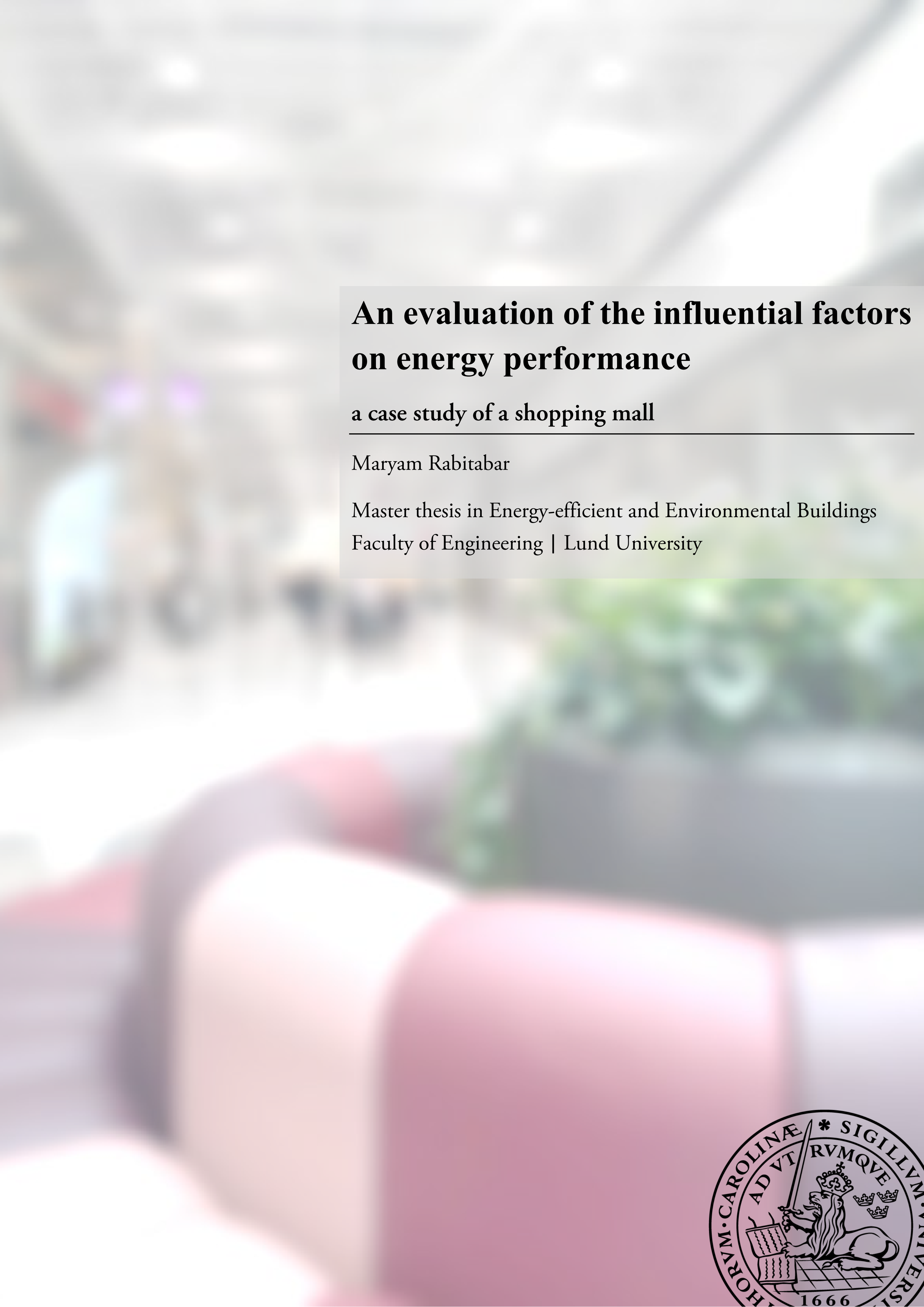

An evaluation of the influential factors on energy performance

a case study of a shopping mall

Maryam Rabitabar

Master thesis in Energy-efficient and Environmental Buildings
Faculty of Engineering | Lund University

1666

Lund University

Lund University, with eight faculties and a number of research centers and specialized institutes, is the largest establishment for research and higher education in Scandinavia. The main part of the University is situated in the small city of Lund which has about 112 000 inhabitants. A number of departments for research and education are, however, located in Malmö. Lund University was founded in 1666 and has today a total staff of 6 000 employees and 47 000 students attending 280 degree programmes and 2 300 subject courses offered by 63 departments.

Master Programme in Energy-efficient and Environmental Building Design

This international programme provides knowledge, skills and competencies within the area of energy-efficient and environmental building design in cold climates. The goal is to train highly skilled professionals, who will significantly contribute to and influence the design, building or renovation of energy-efficient buildings, taking into consideration the architecture and environment, the inhabitants' behaviour and needs, their health and comfort as well as the overall economy.

The degree project is the final part of the master programme leading to a Master of Science (120 credits) in Energy-efficient and Environmental Buildings.

Examiner: Dennis Johansson (Division of Building and Services)

Supervisor: Victor Fransson (Division of Building and Services)

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Abstract

Shopping malls are becoming more prevalent throughout the world. They have been identified as having high energy use, which is less explored than other building types. There are 357 shopping centers in Sweden, which has doubled in the last five years. Regardless of national differences in shopping mall tenants' demands, shopping malls always tend to have high lighting loads, high population density, and, therefore, a significant air conditioning demand. Therefore, exploring the influential parameters determining shopping malls' energy demand demonstrates how well the building performs. Considering the above, this study aims to analyze a three-year hourly energy demand time series recorded in a relatively large shopping mall in south Sweden. This research aims to fill a gap in the literature as there is a lack of evidence of an in-depth analysis of shopping malls' energy demands and their relationship with independent variables. Energy use data and meteorological data were obtained from a BEM system. The analyses focused on determining the annual energy demands in occupied and unoccupied hours and investigating the correlation between outdoor temperature, cooling degree hour, heating degree hour, occupied/unoccupied hours, time of day, tenant electricity, and observed energy use. A Pearson coefficient correlation was used to estimate the correlation between investigated variables. For distinguishing extreme conditions, clusters of warm months, warmest week, cold months, and coldest week were made.

The results indicated that each usage of each energy carrier is dependent on its application and has been impacted by particular parameters. Moreover, analysis of clusters revealed that more extreme conditions affect the strength of correlations. The number of influential parameters is higher in warm conditions than in cold ones. Annual energy demand is even less affected by the studied parameters than the cold conditions. Based on annual assessments, district heating is primarily related to heating degree hours, while in cold conditions, it is mainly dependent on working hours, time of day, and supply airflow. The cooling electricity is positively correlated with cooling degree hour, supply airflow, and negatively correlated with heating degree hour on a yearly basis assessment. Under warm conditions, cooling is correlated to working hours, cooling degree hours, property electricity, tenant electricity, and supply airflow. The property electricity is influenced by working hours, tenant electricity, and supply airflow. Additionally, it is highly correlated with district heating flow in cold conditions and electricity for cooling in warm conditions. The results of this study can be used to assess shopping malls' energy performance by considering the most influential factors in design phases and energy management.

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1 Introduction

Today, the European Commission has adopted a package of proposals to reduce net greenhouse gas emissions by at least 55% by 2030, compared to 1990 levels. Together with industry, buildings and transport use the most energy and produce the most greenhouse gases. To achieve climate neutrality, energy supply and demand must be decarbonized("Directive on the Energy Performance of Buildings" 2018). According to amending Energy Performance Directive, buildings account for 40 % of total energy use in the Union. Moreover, the sector is expanding, which will increase energy use. The International Energy Agency has identified the building sector as one of the most cost-effective sectors for reducing energy use(International energy Agency 2010). Analysis of EU Climate Target Plan pointed out that building energy use of new and existing buildings required to be reduced through regulation to make buildings use the least amount of energy and reflect the carbon cost in the energy mix. Energy efficiency would reduce emissions, deal with energy poverty, reduce people's susceptibility to energy prices and promote economic recovery ("Answers on the Revision of the Energy Performance of Buildings Directive" 2021). Evaluation of energy efficiency at a building level could be performed by both mandatory energy policies and voluntary benchmarking tools. Energy Performance of Building Directive (EPBD), Eco-design of Energy Using Product Directive, the energy Labelling Directive, Energy Efficiency Directive, and the promotion of Renewable Energy Sources are European energy policies and Building Research Establishment Environmental Assessment Method (BREEAM) and Leadership in Energy and Environmental Design (LEED) are voluntarily benchmarking tools.

The EPBD is the main legislative instrument for improving the energy performance of buildings on a European level. EPBD includes a template for Energy Performance Certificates (EPCs) with a minimum number of common energy and GHG emissions indicators, complemented with several voluntary ones, such as charging points, indoor air quality, and Global Warming Potential based on the building's life-cycle carbon emissions. The Objective of EPBBD is to achieve a zero-emission and fully decarbonized building stock by 2050("DIRECTIVE (EU) 2018/844 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL" 2018).

Buildings that are occupied by public authorities or commonly visited by the public, such as shops and shopping centers, supermarkets, and restaurants, should disseminate to public by clearly displaying the energy performance certificates. According to IEA reports, the commercial building sector accounts for 32% of the final electricity use in OECD countries(Yildiz, Bilbao, and Sproul 2017).

The Commercial Buildings Energy Consumption Survey (CBECS) is a national sample survey that collects information on the stock and their energy-related characteristics and energy consumption, categorized buildings based on the main activity, which involves the primary business, commerce, or function carried out within each building(Smitha S.D. et al., 2013, as cited in Justo Garcia Sanz-Calcedo et al., 2019), whereas the national energy statistics in Sweden do not treat shopping malls separately. It is well-established that heating demand is dominant in residential buildings, while energy use for air treatment, space cooling, and fan and pump operation are dominant in commercial buildings. Therefore, significant energy is required to remove surplus heat and provide required hygienic airflow as heating, ventilation, and air conditioning (HVAC) are considered the dominant part of the overall energy demand in commercial buildings, utmost efforts are made to predict the consumption and optimization of building energy systems (Lazos, Sproul, and Kay 2014). Electricity for lighting and devices are usually classified as tenants' energy use, which is not considered in buildings primary energy in Sweden. The most common type of shops in shopping malls are clothing stores, which are high electricity use consumers due to the extensive interior lighting ; consequently, a shopping mall's tenant electricity accounts for 40 % to 75 % of its total energy use (Stensson 2014).

A distinctive characteristic of commercial buildings' energy loads is that they vary regularly throughout the day, week, and year. Moreover, environmental factors, such as humidity, solar radiation and wind speed strongly influence building energy loads(Bianchi, Mendoza, and Tran 2017). Analyzing the system's behavior would provide a pattern to find the crucial factors in a building's energy loads. According to Gould and Sutton a distinction between commercial buildings and other types of buildings is observed on a daily, weekly and seasonal basis. On a daily basis, the load profile consists of a baseload followed by a morning boost, an afternoon peak, and an evening decline to the baseload. There is usually a reduction in load profiles during weekend. Seasonal variations are depended on the local climate (Lazos, Sproul, and Kay 2014). According to Lazos, Sproul, and Kay, having a centralized management system, a broad range of scheduling options and interaction with grids, more consistent energy profile due to occupancy patterns and predictable activities would provide an opportunity to improve the building's energy performance.

In general, buildings include a huge set of variables related to energy consumption, including the types of activities conducted in the building, weather conditions, geographic location, building materials, HVAC system, energy suppliers rates, occupancy time (Smitha, Savier, and Chacko 2013) lighting and external weather conditions(González et al. 2011a). Sensitivity analysis is commonly conducted when calibrating and optimization a model and can identify critical factors in a multidisciplinary setting. Yang Shen & Matthew Yarnold determine how uncertainty in the dependent variable of a model (numerical or otherwise) can be caused by different sources of uncertainty in its independent variables(Yang Shen and Matthew Yarnold, 2021). Kapetanakis et al. assessed methods of selecting variables like weather, indoor temperature, occupancy, and schedule from historical data from the BEM of an office building by regression, ANN, and SVM data-driven models. Research shows that input variables correlate differently with thermal loads depending on building types and climate zone. In all humid climates, Ambient Relative Humidity is not correlated to heating load due to the constant Ambient Relative Humidity. Based on analysis of 102 cases. The relationship between ambient temperature and thermal loads was the most consistent one(Kapetanakis, Mangina, and Finn 2017).

In order to improve the energy performance of existing buildings, it is necessary first to determine their energy performance. It is challenging to obtain detailed information on existing buildings to conduct energy performance assessments. A method to measure a building's energy performance is benchmarking by comparing its energy performance with previous results, similar buildings, or a performance indicator (Capozzoli et al., 2016, cited in (Grolinger et al., 2018). It is essential to consider the operational hours in benchmarking methodologies. For instance, office buildings may show different behavior during working and non-working hours. Although benchmarking categorized the most similar types of buildings, some aspects of a building are still overlooked in this system. It is crucial that a building that operates 12 hours a day should not be penalized for consuming more energy than another building that operates only 8 hours a day. Therefore, to make a fair evaluation, the operational requirements and limitations of each building should be considered. Grolinger et al. assign data of energy use to different time slices to assess consumption patterns independently, which provides a way of determining low-performing periods and assists in identifying opportunities to find new opportunities for improvement and cost reduction (Grolinger et al. 2018).

In general, the concept of a building's performance, as it determines how well a building meets the needs of its users, can be developed to encompass more of what the building must do and how it must be defined as a requirement of the building. This has been related to quantification, including how metrics, indicators, and measures can be used to capture performance. Even though “metrics, measures, and indicators” are commonly used as synonyms in the building performance field, each term has different implications (de wilde 2018). 'Metrics usually represent how performance changes over time or in different dimensions. 'Measures' are the values or quantities that represent the performance. 'Indicators' are usually summed-up values that provide an easy-to-understand overview rather than raw operational measurements(Occuphan, Zhe, and Tianzhen 2021).

Key performance indicators (KPIs) are well-recognized goal-based numerical indicators in performance management systems for different industries(J. Li, Wang, and Zhou 2020). The critical project goals are measured with KPIs such as economic, social, and environmental KPIs, which are particularly useful when dealing with complex contexts(McGinley, Moran, and Goggins 2022). In addition to measuring performance, good KPIs are also objective and functional ("what gets Measured Gets Done: Key performance Indicators" 2010), so managers and owners can measure what is most critical for their goals. For example, having a goal of reducing CO_2 emissions will not be accomplished by using only energy performance indicator since energy carrier plays an essential role in this regard. Since two buildings with identical energy consumption but different energy sources can have district performance in reducing carbon dioxide.

KPI is ideally practical for performance estimations,that provide crucial information and help evaluate and track the critical aspects of determining performance(Y. Li et al. 2017). Performance indicators may be normalized. Normalization is a process that changes the value of a particular variable to be on an equal scale with other variables while maintaining patterns within the range of the variable(Occuphan, Zhe, and Tianzhen 2021). However, CIBSE (2012: Section 19.5) cautions that normalization should only be used if relationships can be proved to avoid introducing unhelpful distortions. Normalization can easily be abused, and normalized indicators can be confused with raw ones (Bordass 2020). In order to compare KPIs fairly, normalization must be performed to eliminate the influence of irrelevant factors. According to Occuphan, Zhe, and Tianzhen, KPIs' denominators are categorized into three types: (1) spatial normalization factors (e.g., floor area, number of rooms/zones), (2) occupant normalization factors (e.g., number of occupants, occupant equivalent total hours), and (3) weather normalization factors (e.g., degree hours, degree days).

Volume is a spatial denominator used in some sectors to calculate Energy use per volume (m^3) (i.e., UK used volume for health buildings, although its justification was unclear). The weakness of this denominator is that it is not commonly recorded. This was not found to be helpful in for all types of buildings; it could be productive in sectors where height can contain proper volume (i.e., warehouses) (Bordass 2020).

In addition to volume, the internal floor area is a simple energy performance indicator (Wang, Yan, and Xiao 2012) as a starting point because it is recorded and is easier to audit than the area of the occupancy. Energy use intensity (EUI), which represents annual energy use normalized by floor area, is one of the most widely used metrics in energy benchmarking (Esteban Estrella Guillén, Holly W. Samuelson, and Cedeño Laurent 2019). The way floor area is measured and defined (i.e., gross, net, usable, internal, external, conditioned) differs considerably between sectors and countries. An example of the various definitions of floor area related to energy statistics is A_{temp} used in STIL2 and energy declaration, while rentable area (LOA) is used in SwedEs. Boverket defines A_{temp} as floor area in temperature-controlled spaces intended to be heated to more than 10 °C, enclosed by the inside of the building envelope. This definition is defined by the Swedish National Board of Housing, Building, and Planning *[Boverket]*. LOA is the rentable area in non-residential buildings. Staircases and corridors are not included, which means heated areas in larger in reality than in the statistics. Thus, making a comparison between them impossible.

While a fair comparison of different building sizes can be made with this method instead of considering energy alone, EUI leaves out often-important building characteristics(Esteban Estrella Guillén, Holly W. Samuelson, and Cedeño Laurent 2019).Even if a comparison of EUI between similar types of commercial buildings seems reasonable, it could be significantly impacted by other variables such as occupancy, climate, schedule, and envelope. In addition, an issue with EUI puts smaller buildings at a disadvantage. A study of comparing electricity use for thermal energy of four houses showed that although household use increases with house size, EUI decreases with increasing house size. The large house yielded a 30% lower EUI than the smallest (Ueno 2010).

Another suggested KPI is energy use normalized by occupancy instead of floor area, based on the belief that the ultimate aim of energy use is to provide occupants' comfort. Occupants are the primary recipients of the services provided by building systems and play two roles in buildings; first, they are the reason of building system operation. Second, occupants release sensible and latent heat that requires a ventilation system, which contributes to a building's heating, cooling, and ventilation HVAC loads (Occuphan, Zhe, and Tianzhen 2021). The number of occupants or workstations, or occupancy hours indicates productivity. Even though energy use per person is an excellent secondary indicator, it is challenging to count reliably (Bordass 2020). Kontokosta indicates that occupancy variables are critical drivers of building energy performance. Hence, understanding and controlling for occupant density and the operational hours of a building are crutial for the reliable and effective identification and comparison of buildings. Research indicates that the weekly operating hours and worker density are positive and highly correlated. Also, a quadratic term is included in the model to calculate non-linear relationship between operating hours and EUI (Kontokosta 2015).

The reliance on simple metrics, such as EUI, does not account for the significant variation across other characteristics and variables of a case (Kontokosta 2015). The relevant factors could be used as denominators if a relationship is proved. For example, one of the energy consumption indicators commonly used for hospitals is kWh per bed, although a low correlation was detected between energy use and the number of beds (Garcia-Sanz-Calcedo, Gómez-Chaparro, and Sánchez-Barroso 2019). Justo Garcia Sanz—Calcedo et al. studied energy efficiency indicators in hospitals based on healthcare activity. Kontokosta developed a predictive model to provide the basis for a multivariate energy performance index and normalized multiple building worker density, operation hours and number of personal computers per 1000 ft^2 to quantify energy performance more precisely. The floor area of the building has no relation to the source EUI. After exploring for other variables in the model, larger buildings were not found to have a statistically significant different EUI than smaller buildings. However, the results indicate that lower and more compact constructed buildings are more efficient than towers with small footprints relative to lot size (Kontokosta 2015).

McGinley et al. normalized energy data from a case study using heating degree day (HDDs) based on external temperature during the periods the heating data represented. Then normalized heating energy data was multiplied by the average of HDDs during the heating season for each phase to estimate an annual heating energy use. It is assumed that no heating is required in buildings at a base temperature of 15.5 degrees to maintain comfortable indoor temperatures(McGinley, Moran, and Goggins 2022). Ueno calculated the kBtu/sf·year·Heating Degree Day to provide normalization based on the local climate loading. However, since it assumes that heating loads are the primary energy consumers, it can be calculated explicitly for cooling loads.(Ueno 2010).

Esteban Estrella Guillen et al. calculated Normalized EUI, EUI per person, and EUI per person-day using occupancy information. Moreover, two metrics called Cold and Hot Discomfort Degree Days is also used to measure discomfort. For every day in the analyzed period, the average difference in degrees between indoor temperature and respective adaptive comfort thresholds (lower or upper) is calculated for each time step with a temperature outside the adaptive comfort range. In this case, since the number of monitored units and monitoring length varied for the case study buildings, an average of Daily Hot and Cold Discomfort Degree Days was calculated by diving at the average of monitored days per unit (Esteban Estrella Guillén, Holly W. Samuelson, and Cedeño Laurent 2019).

Energy Efficiency Index (EEI), which is sometimes referred to as Building Energy Index (BEI), is another KPI for tracking and comparing energy use in buildings. Generally, EEI can be viewed as the ratio of the energy input to the factor related to the energy-use component, denoted in Eq. 1 (Abu Bakar et al. 2015). González et al. defines EEI as the ratio between the energy use or carbon dioxide emissions of an actual building with those of a reference building. Also, an energy efficiency index (EEIB) is proposed to develop a quantitative energy efficiency metric based on the actual measurement and an accurate energy prediction. When real data are not available, simulation tools can be used to derive data. The EEIB is calculated as the ratio between the performance of an actual building to that of a reference building, either in terms of energy use or carbon dioxide emissions (González et al. 2011b).

$$\text{EEI} = \frac{Energy\ input}{Factor\ related\ to\ the\ energy\ using\ component} \qquad \textit{Eq. 1}$$

1.1 Shopping malls in Sweden

Since 1948, Swedish regulations cover energy management in new and renovated buildings. EPBD is implemented in national legislation and building codes by January 2006 in Sweden. New laws are introduced to require energy declarations for all buildings. The purpose was to assess measures to reduce the energy use of the building by conducting an energy audit. Energy Performance Certification is called energy declaration in Sweden, that is valid for 10 years. The energy performance is not only calculated but also measured. All energy declarations are stored in a central database at the Swedish National Board of Housing, Building, and Planning *[Boverket].*

1.1.1 BBR requirements for shopping malls:

BBR contains mandatory requirements for the energy use of buildings that should be calculated during the design and operation phase. BBR has different requirements for residential and non-residential buildings. Furthermore, its requirements differ depending on the energy carrier of the heating system.

Table 1: Maximum permitted primary energy, installed electrical power for heating, average heat transfer coefficient, and average air leakage for premises.

	Energy performance is expressed as the primary energy number (EP_{pet}) / (kWh / $m^2_{A\text{temp}}$)	Installed electrical power for heating / kW	Average heat transmission coefficient (Um) / (W / (m^2 K))	Average air leakage at 50 Pa pressure difference
Premises	70 $^{1)}$	4.5+1.7 (F_{geo}-1) $^{2,3)}$	0.50	In accordance with 9:26

1) Addition made by 40($q_{average}$ - 0.35). When indoor airflow in temperature-controlled spaces increases, hygienic reasons are greater than 0.35 l/s per $m^{2,}$ of which $q_{average}$ is the average specific outdoor airflow during the heating season and may not be credited up to a maximum of 1.00 l/s m^2.

2) With 4.5+1.7 (F_{geo}-1) (A_{temp}-130) as A_{temp} is greater than 130 m^2. If geographical adjustment factor is less than 1.0, it is set to 1.0 when calculating the installed electrical power.

3) Addition maybe made with (0.22 + 0.2(F_{geo} – 1) (q – 0.35) A_{temp} when the outdoor air flow extended continuous hygienic reasons are greater than 0.35 l/s m^2 in temperature-controlled spaces. Where q Is the maximum specific outdoor air flow at DVUT. If the geographical adjustment factor F_{geo} is less than 1.0, it is set to 1.0 when calculating the installed electrical power.

9:26: The building's climate envelope shall be so air-tight that the requirements of the building's primary energy number and installed electric input for space heating are met. *(BFS 2017:5).*

1.1.2 Energy statistic reports of shopping malls in Sweden

According to Stensson, several scientific papers deal with energy efficiency in shopping malls with a focus on HVAC systems, operation, and controls. A number of these papers included case studies in their methodology. Some of the studies involved modeling and simulations of subsystems in shopping malls. A study of the whole building calculation model for a shopping mall in Sweden was performed to compare STIL2, SwedES-09, energy declaration, and a case study (Stensson 2014).

1.1.2.1 Energy statistics of shopping malls in Sweden

An overview of two reports covering energy statistics in shopping malls and/or retails are provided in bellow.

1. Energy use in retail trade STIL2-09, provide detailed results than ordinary national energy statistics. STIL2 includes reports concerning energy use in retail trade, offices, schools, hospitals, and sports facilities. Retail Trade is categorized as shopping malls, supermarkets, and other retail trade.
2. Energy statistics of non-residential premises in 2020 is given in SweEs-20. Energy use of supermarkets and other retails are reported yearly in the Swedish energy Statistics report.

Table 2 Energy statistics for non-residential premises ("Energistatistik För Lokaler 2020 Kvalitetsdeklaration" 2020)

	Number of non-residential properties	Heated area of non-residential premises / km^2	Use of energy for heating and hot water / (kWh / m^2)	Use of energy for heating and hot water (corrected for temperature) / (kWh/m^2)
Grocery store	2 734	4.60	129	142
Other trade	6 063	11.76	102	112

* For the statistical year 2020, no statistical collection was carried out. Data on energy used in 2020 are estimates based on 2019 energy use data. The statistics for 2020 have been compiled regarding differences in temperature between the years and changes in the stock of local buildings.

According to Stil2-09, the total average energy use (including building electricity and thermal energy) in shopping malls is 262 kWh_a/m^2 in Sweden. However, the total energy use in other retail trade is considerably lower, with 182.9 kWh_a/m^2.

Shopping malls use considerably more electricity than other retail trade in Sweden. Therefore, it can be questioned why a shopping mall, which would generally have similar activities to other retail trade, would need more building electricity. In below some results extracted from STIL2 are presented (STIL2 cited in Stensson & Chalmers tekniska högskola. Building Services Engineering., n.d.):

- Lighting is the most significant part of the business electricity in shopping malls and other retail trade. Furthermore, electricity is considerably higher in shopping malls than in other retail trade.
- Electric heating, including heat pumps, is higher in other retail trade than in shopping malls in Sweden.
- The HVAC electricity used for comfort cooling is higher in shopping malls than in other retail trade. The lighting and comfort cooling interact since lighting affects the internal heat load and surplus heat that must be removed from the building.
- Energy use for pumps and fans is rarely measured and reported in energy statistics for buildings. However, it is included in Stil2-09, and the result shows that pumps and fans account for approximately 20 % of the building electricity; hence their energy use is not negligible.
- According to Stil2-09, shopping malls use both more district heating and more district cooling than other retail trade. In Sweden district heating is the most common source of energy used for heating. However, it is strange that in the SweES-09 for other retail trade, district heating is reported to be nearly twice as high, 115 kWha/m2, as for retail trade in Stil2-09 66.5 kWh_a/m^2.

In SweES-20 for other retail trade, district heating is reported to be 95 kWh_a/m^2, district heating combi is 109 kWh_a/m^2 and an average of different resources is 102 kWh_a/m^2. However, based on data of corrected temperature energy use In SweES-20, district heating is reported to be 104 kWh_a/m^2, district heating combi is 120 kWh_a/m^2 and average of different resources is 112 kWh_a/m^2.

1.2 Research gap and Objective

According to Swedish Shopping Center Directory (HUI,) which deals with energy use in buildings, shopping malls have been identified as having high energy use, which is less explored than other buildings type. There are 357 shopping centers in Sweden, which has doubled in the last five years. Various measures such as rising electricity prices and greenhouse gas emissions, and a growing number of commercial buildings are incentives to decrease the energy demand. Therefore, it is vital to manage energy demand via energy efficiency and produce energy onsite. Energy efficiency in shopping malls is a developing research area; exploring the definition of energy efficiency meters is unavoidable to perform successful energy conservation. The energy performance indicator or energy usage intensity (EUI) is simple for ranking sampled buildings and understanding energy usage levels according to descriptive statistics values, such as the mean and quantile values of EUI(Juaidi et al. 2016). Commonly used EUI measures include energy use per unit area, per person, and unit (Kim and Srebric 2017). However, the main drawback of EUI is that it does not consider other essential energy incentives, such as occupancy and the HVAC system, leading to unreliable results. Although analysis of energy use has been made in previous studies, comprehensive research is becoming increasingly important.

This research aims to describe the energy use of the studied shopping mall and determine the influential parameters based on data-driven statistical analysis considering dependent and independent variables. The case study is a shopping mall located in Skåne, Sweden.

1.3 Research questions

Based on the objectives, the main research questions in this work are:

- What is the most appropriate method to assess the performance of a complex building such as a shopping mall?
- What information can be obtained from the building control system to evaluate the building's energy performance? What is the time frame for the majority of the data series available?
- How are the monthly occupied and unoccupied hours' energy demand related to outdoor temperatures?
- What method can be used to identify the relationship between building energy demand and influential variables?
- How does the energy performance of cold and warm weather conditions differentiate from an annual assessment?
- What are the most influential factors for the studied shopping mall?

2 Methodology

Case study research allows the exploration and understanding of complex issues. As energy consumption pattern of a building involves large set of characteristic and uncertainties, a comprehensive, in-depth investigation can be achieved by involving a holistic analysis a large data base of numerous case-studies of building type. An understanding of the process and outcome of a phenomenon can be gained by including quantitative case study through complete observation, reconstruction, and analysis of the investigated cases within a specific context to acquire representative statistics of that building type. Dynamic measured data coming from automated metering infrastructure provides valuable information to evaluate the effect of energy conservation strategies. As simulation of a complex building needed several input data and assumption as well as simplifications, a data-driven approach is a solution to reduce the dimensions of the characteristics of a sampled building. A data-driven method is used since it can exploit extensive amounts of information for assessing energy use. In this research a single case study of a regional shopping mall located in Skåne in the south of Sweden was selected due to the availability of data and time-limitation. For confidentiality reasons, the precise location and name of the facility cannot be disclosed. The building has been extended in several stages with the most recent extension in 2011. Distribution of leased to property area is 26% and 74% respectively with Total A_{temp} area of 71800 m^2. The main building is divided into nine sections. Working hours of the shopping mall are 10:00 to 20:00 on weekdays and 10:00 to 18:00 on weekends.

2.1 Research Workflow

The methodology workflow in the present study is demonstrated in Figure 1. The study started with a literature review to identify the latest research and achievements in energy performance indicators. Then, the data collection phase was performed by investigating the architectural plans, HVAC plans, and building management system. Moreover, the responsible company provided other project descriptions to add to the data collection phase. As the case study was a complex building that includes multiple AHUs, chillers, and district heating plants, available data must be sorted using the relation between each category. Then, the periods were found in which most of the data are available and eliminate the rest. The cleaning process was conducted using Python. The next step was to determine the periods and extreme weather conditions of those, followed by evaluating each category and comparing them on a weekly, seasonally, and yearly basis. A dummy data was made by reindexing time indices to find the monthly demand pattern. Finally, relevant performance indicators were identified by finding the most influential factors.

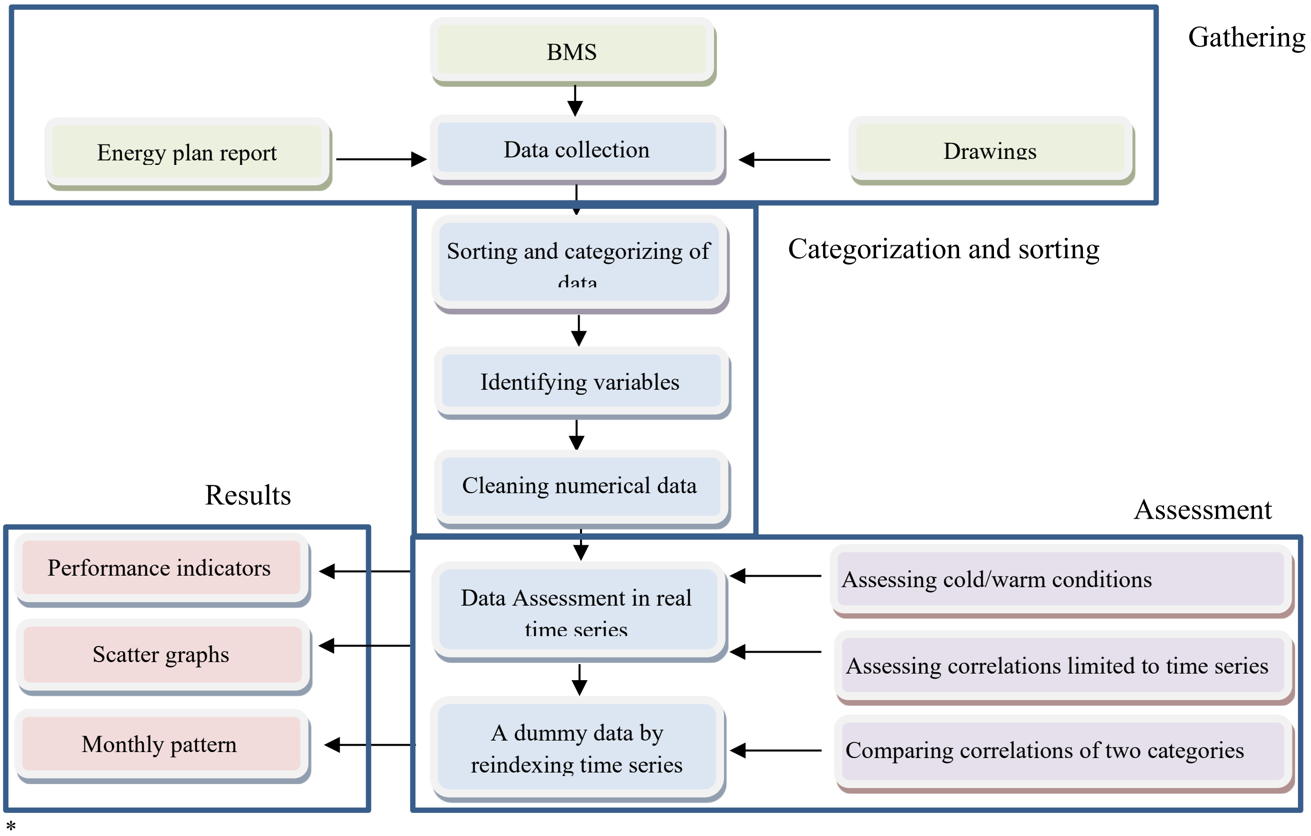

Figure 1 Work flow

2.2 Data gathering method

There were two main phases of data collection to address the research questions:

Energy Plan report and drawings – The report contains basic facts, statistics, energy distributions, and meter structure from an energy survey conducted in 2015. In addition, the building's characteristics, meter structure, district heating plants' service plan, and chillers' service plans are collected from the report. The district heating plant's plan, cooling units, chillers' plan, and service area of each AHU are obtained from drawings.

Metering system - Building energy use can be measured in various ways, ranging from a simplified energy bill to detailed end-use monitoring and sub-metering systems. However, energy bills can only provide the total use of a whole building within a long-time interval; In contrast, disaggregated data from energy bills appear to provide some end-user consumption details, but the accuracy and details remain quite limited. More accurate and detailed information regarding energy use can be gathered by utilizing more sophisticated metering systems.

BMS-based: The available data from properly designed and maintained BMS (Building Management System) are usually sufficient to determine how much energy HVAC systems use on a typical basis. However, when BMS monitoring is not adequate, dedicated monitoring devices, such as electricity meters and temperature loggers can be used. Therefore, it will be possible to identify and gather data on HVAC systems at a very low or even negligible cost(Wang, Yan, and Xiao 2012). In this research, the primary source of information has been a platform called "Navigator" which is a part of the Building Management System (BMS). The platform is a detailed information bank supplemented with information from the plant's settings, installation descriptions, flow charts, and building services. Hourly simultaneous district heating and electricity are obtained from the navigator. Drawing-based property inventory is carried out using documents of ventilation units, district heating plants, cooling systems, air handling units, and architectural plans. Energy statistics are presented for the entire building, including tenant electricity use. As data for a part of the facility were not available, the side building is demarcated in analysis. Data from the metering system is divided into six parts, including outdoor climate, cooling systems, heating plants, air handling units, energy meters, and billing energy meters. Data were extracted from 2019 to 2022. Electricity use is divided into the property, tenants, and cooling subcategories.

Meter structure - The assessment of building performance can be conducted at three levels that correspond with the hierarchical nature of building services (i.e., the whole-building level, the system or service level, and the component or equipment level. Therefore, studying the meter's structure is essential to grasp the level of available measured data. Figure 2 present structure of a system that monitors and controls a building's electrical and mechanical equipment such as lighting, pumps, heating, and ventilation. Energy meters are available at building and system levels, while operational parameters and settings are existing at components level. To coordinate measure energy use and systems' operational settings and modes, it is necessary that all information be available at the same level, or they should be converted to a specific level.

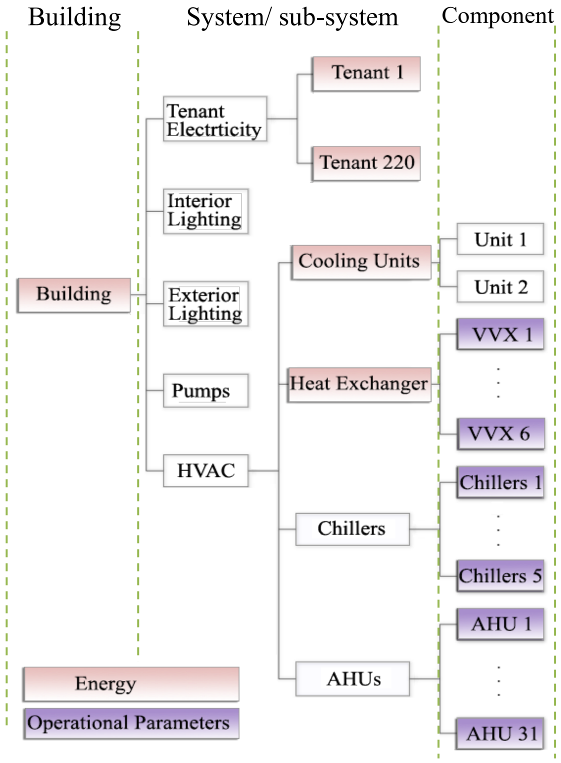

Figure 2 Meter's structure

2.3 Sorting and categorization

An enormous amount and variety of data series are collected from building's control system together with data collected from the report and drawings. The handling of the building's control system data is challenging, since building automation has faced interoperability challenges due to various systems and technologies. In addition, the high density of sensors and increased sensing frequency, which allows for more precise observation and control of equipment, has resulted in large quantities of data. In this study, approximately 1200350000 rows of data were extracted from the control system (Table 3). Due to the limitation on exporting the parameters, 220 parameters were exported one at a time. Making data sets from several data series required sorting and categorizing, identifying variables, determining time series, and data cleaning to adjust the intended data series to datasets. The data series is arranged into two categories of independent and dependent variables (Table 3). Independent variables are assumed to have a direct impact on dependent variables.

Table 3 data sets' quantity

	Number of categories	**Total parameters**	**Duration**	**Interval**	**Variables**
Chillers	5	59	3 years	Hourly	Independent
Energy	1	5	3 years	Hourly	Dependent
District heating plant	12	120	3 years	Hourly	Independent
Property	1	16	3 years	Hourly	Dependent
Tenant	1	220	3 years	Hourly	Dependent
AHUs	54	800	2 years	Hourly	Independent
Weather	1	9	1 year	Hourly	Independent

Data cleaning – Moreover, accuracy, thoroughness, and neatness are essential in datasets. Combining multiple data series into one dataset requires finding a common time frame among them, in addition to refilling minor inconsistencies. A timeline graph summarizes availability of measured parameters, that blue parts of the bars determine two periods potentially suitable for further studies (Figure 3). Periods are determined by availability of AHUs' and chillers' parameters since they are the incomplete data series. The first period starts from September 2019 to August 2020, and the second one is from March 2021 to Feb 2022. Available parameters of AHUs vary from one period to the other one. Negligible inconsistency due to the missed hourly values in each period is refilled by value from the next hour. Detailed information of all measured parameters, their units, types, starting and ending dates are provided in Appendix A.

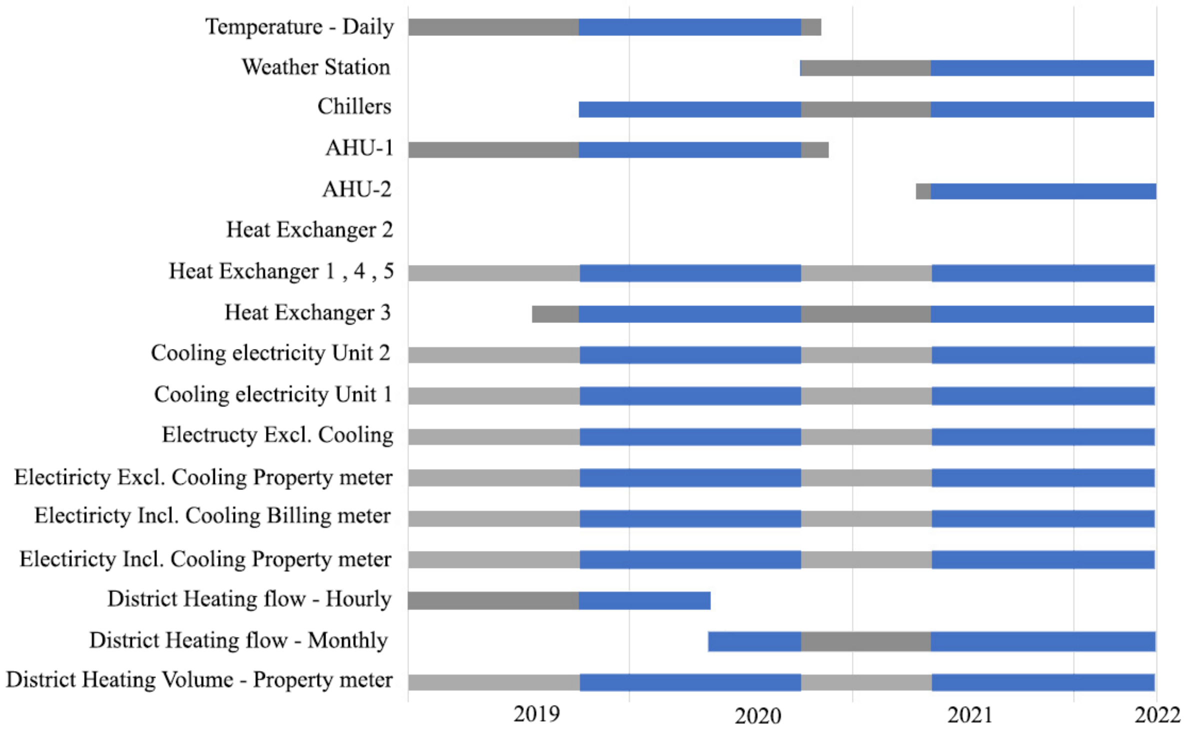

Figure 3 timeline of measured data and

Identifying variables – As District heating flow, property electricity, and cooling electricity use are essential to measuring a building's energy performance, these are chosen as dependent variables. In addition, the selected independent variables are weather, and AHUs based on literature reviews and data availability. In this case, tenant electricity is also an independent variable that can impact dependent variables. Following, more discussion regarding independent variables will be made in each section.

2.3.1 Dependent variables

2.3.1.1 District Heating

The property is first and foremost heated by the air handling units and a few radiators. As the portion heated by radiators is so small, this part of the heating system is disregarded from further investigation on AHUs. The building is connected to the local district heating network. District heating is used for heating the entire building and domestic hot water. Data on district heating is provided in property billing and energy meters, which are available in energy with the unit of kWh and MWh and volume in m^3 (Table 4). An hourly plot of district heating demand shows that only March of 2019 to April of 2020 are reported hourly. In contrast, the rest is presented using the monthly mean value (Figure 4). Since information from the billing meter covers cold months in the first period, it is used in later analysis stages.

Table 4 Available district heating dataset

	Meter	Type	Unit
Energy meter	District heating (A)	Volume	m^3
	District heating (A)	Flow	kWh
	District heating (F)	Volume	m^3
	District heating (F)	Flow	kWh
Property billing meter	District heating	Flow	kWh
	Heat	Flow	MWh

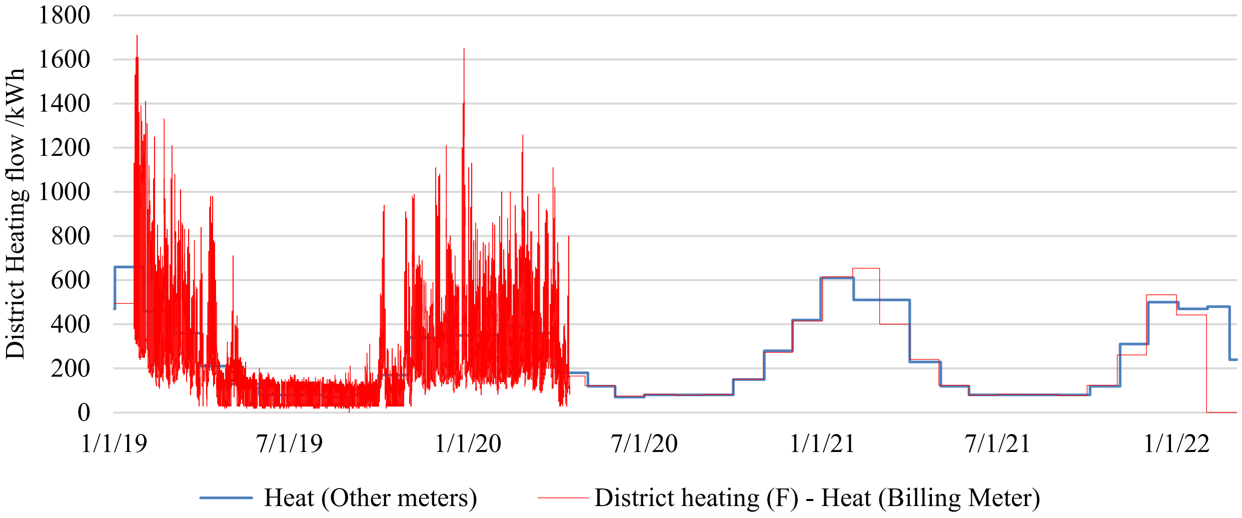

Figure 4 Hourly volume of consumed district heating

2.3.1.2 Electricity

Electricity use of the building includes required energy for chillers, ventilation systems, interior lighting, pumps, exterior lighting, and tenant electricity. Recorded measurements for cooling are extracted from three meters, one property meter, and two meters of cooling units. The sum of these two cooling unit meters calculates electricity for cooling.

Property electricity comprises energy for the ventilation system, pumps, extra exhaust fans, and interior lighting. The facility is run all year round. The average year contains 114 public holidays and weekends and 251 weekdays, multiplied by the working hours resulting in 3422 open hours. Measured property electricity is approximately 26.5 kWh/m^2 considering 71800 m^2 floor area and working hours (Figure 5).

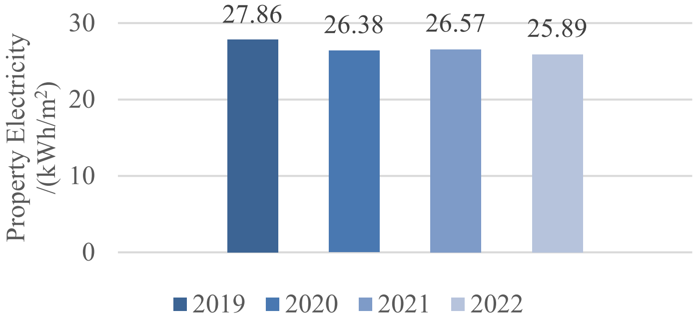

Figure 5 Property electricity per square meter of lease area

Tenant electricity is measured by 178 meters from March 2019 to February 2022. Electricity demand extracted from Navigator is plotted on. Total tenants' electricity use is divided by each year's annual occupancy time and floor area. Figure 6 provides how tenants' electricity use changed in four years. Estimated tenant electricity is approximately 36 kWh/m^2 considering 3422 working hours and 53125 m^2 lease floor area.

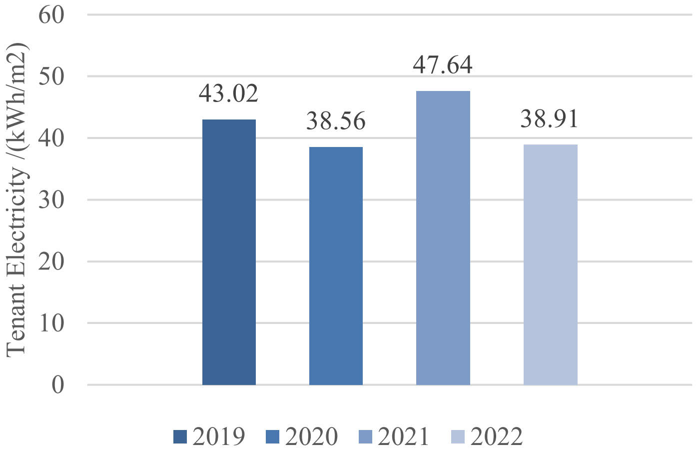

Figure 6 Tenants' electricity uses per square meter of lease floor area

Cooling - The building is cooled through the ventilation, and five chillers generate cooling. The cooling units are liquid-cooled and are thus connected to five large coolant coolers placed on the roof. In addition, two cooling units are in the basement. Cooled air is distributed through the air handling units. The operation of the cooling units follows the need. It is stepped in sequentially according to a predetermined outdoor temperature curve. The annual cooling energy use of the first period is 950 MWh, and the second period is 760 MWh. Although the electricity use of two cooling units is measured separately, no further measurement is provided for cooling units.

2.3.2 Independent Variables

Independent variables are comprised of sets of operational data from air handling units, district heating plants, and chillers which assumed have direct impact on dependent variables.

2.3.2.1 Weather data

Parameters were obtained from a weather station at the shopping mall, a meteorological station seven kilometers from the mall, and outdoor temperature loggers provided for each AHU. The weather station located at the center measures dew point temperature, outdoor air temperature, outdoor air enthalpy, relative humidity, rainwater, wind direction, and wind speed. Although measured outdoor temperature from the buildings database is provided hourly, further investigation shows that from April 2020, values are constant during the day, which means data are converted from daily to hourly. Since other data are collected hourly, another data source is needed to retrieve hourly outdoor air temperature. In addition to the main meter, each AHU has a meter to record the outdoor temperature. Although recorded temperatures from AHUs are perpetually higher than the weather station, the overall trend between the two sets is similar.

Moreover, data from Sweden's meteorological and hydrological institute (hereafter SMHI) of the closest weather station are plotted in Figure 7. As the weather station, R-squared is calculated by daily data since the time interval for the first period is daily. As a result, the R-squared of SMHI and shopping center's weather station data is 0.45, while the calculated R-squared between the average temperature of AHUs and weather station is 0.96. Therefore, it has been decided to use the average hourly mean AHUs meter as the outdoor temperature in the first period.

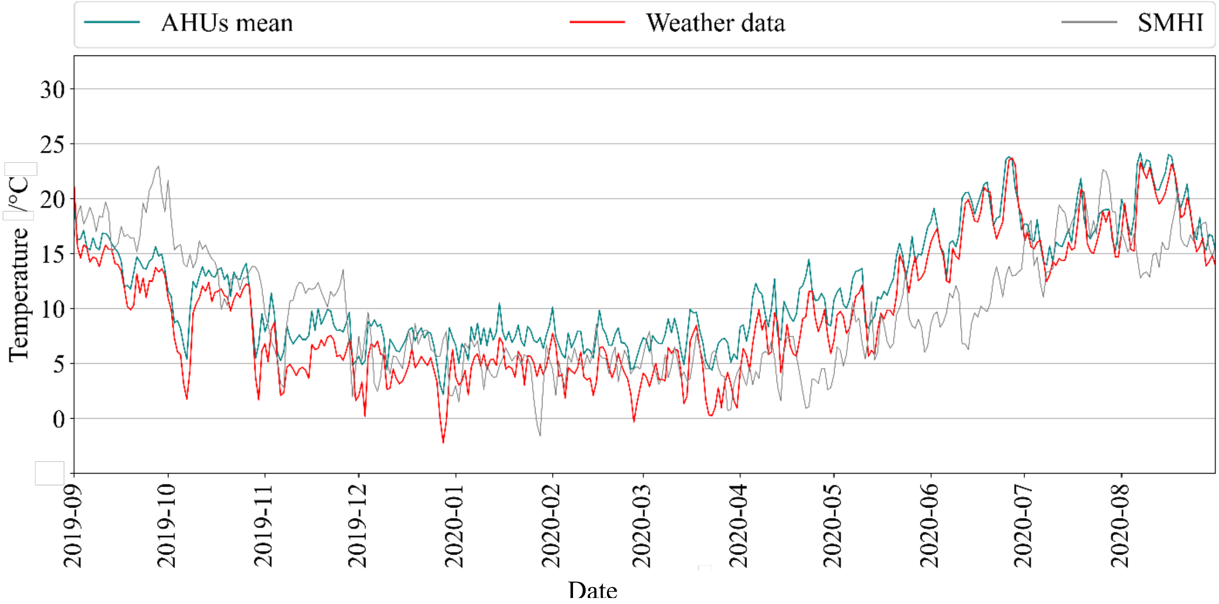

Figure 7 Hourly outdoor temperature of the first period 2019-2020

However, outdoor air temperature is measured in hourly intervals by shopping mall's weather station meters in the second period; a comparison between average recorded temperature by AHUs and SMHI has been conducted. Figure 8 outlines the difference between the three datasets. The variance between temperature from the weather station and SMHI is negligible, while a time lag is observed over recorded data from AHUs and two other data sets. Therefore, measured temperature from the outdoor temperature main meter is selected to conduct further investigations.

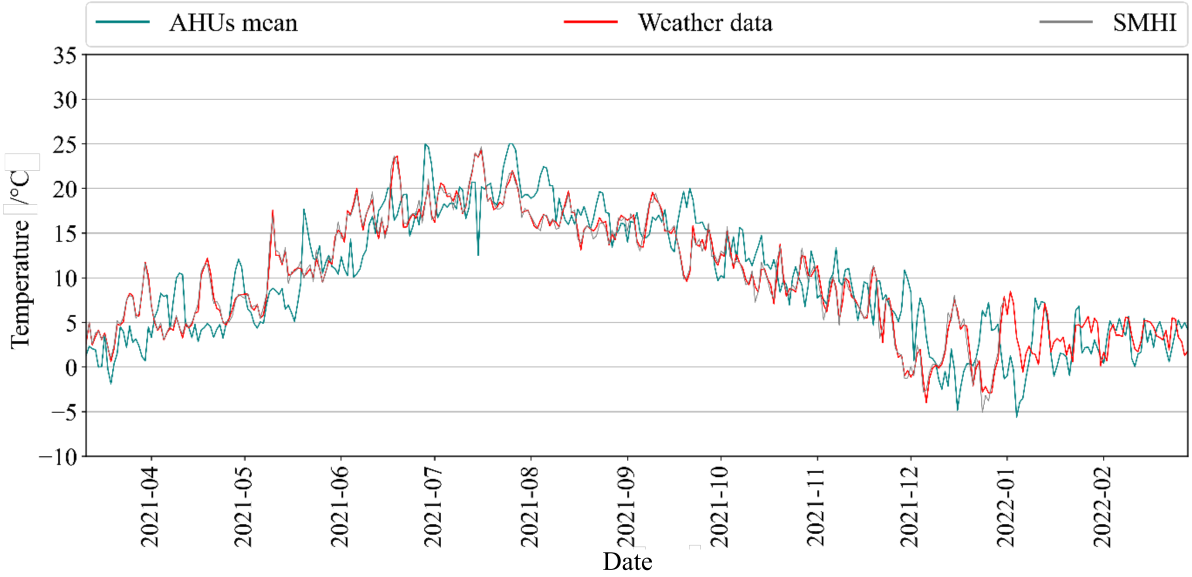

Figure 8 Hourly outdoor temperature of the second period 2021-2022

Degree hours - The current climatic design standards used for Heating, Ventilation, and Air Conditioning (HVAC) units (ASHRAE 2017) state that Cooling Degree Hours (CDH) and Heating Degree Hour (HDH) affect the energy system operation; thus, HDH, CHD, and temperature are chosen to be assessed as independent variables. Heating and Cooling Degree hours are calculated as the differences between the hourly average temperature and the base temperature with the threshold value of 18.3 °C for heating and 23.3 °C for Cooling (ASHRAE 2017). A sum of the hourly degree hour is used to calculate HDH and CDH during a month or year. The reason for using temperature in addition to degree days is the fact that used thresholds are not local. Therefore, the temperature is also included in the assessment to examine the base temperatures.

2.3.2.2 Air handling units

The major energy use of the center is property energy use which also includes electricity for air handling units. Electrical energy is used for ventilation operations, such as fans. Most of the comforting heat and all comfort cooling are distributed through the ventilation. Therefore, it is essential to know how the ventilation system works and what has a significant impact on them. The Control system includes operational data of 31 AHUs. Although the system consists of several extra exhaust fans, operational data are not measured. As the shopping center has been expanded in different stages, the units are varied in size, age, and efficiency. Table 5 summarizes the basic information of each air handling unit.

Table 5 Summary of basic information on air handling units

Heat exchanger	Unit	Heat exchanger efficiency / %	Re-ventilation	Shops / m^2	Walking path / m^2	Services / m^2	Total Area / m^2
VVX[1]1	TA-01		*	1951			1951
	TA-02	71.9		885		100	985
	TA-03	75		1662	238		1900
	TA-04		*	945	199		1144
	TA-05	75		962		110	1072
	TA-06	75		1497			1497
	TA-07		*	1383	1165		2548
	TA-08	75		3007	705	227	3939
	TA-09	75		1802		100	1902
	FTX-15	75		100			100
	TA-26	50		800		140	940
	TA-28	56.8		3885	447	303	4635
	Floor Heating						-
	Floor Heating						-
	Floor Heating						-
VVX3	TA-17		*	3502		255	3757
	TA-31	50		6503	1263	540	8306
VVX4	TA31 V4			6479.4			6479.4
	TA31 V5						
	Castillo TA30						-
	Floor Heating						-
VVX5	FTX-10	75	*	2132	1219		3351
	TA-11		*	2323	209	334	2866
	FTX-12	75	*	2762	882		3644
	TA-13	74		3957		200	4157
	FTX-14	75		485			485
	FTX-25	75	*	482			482
	TA-29	50		1285		125	1410
	FTX-39	75	*	2202			2202
	FTX-40	75	*	2374	1194	80	3648
	FTX-41	75	*	1750			1750
	FTX-42	75	*	3039			3039
	FTX-44	75		280		160	440
	Floor Heating						-
	Floor Heating						-
VVX6	FTX-32	75	*	4693	1893	400	6986
	FTX-33	75	*	5670			5670
	FTX-34	75	*	1269			1269
	FTX-35	75	*	653			653
	FTX-36	75	*	1041		185	1226
	FTX-37	75	*	2177	1943		4120
	FTX-38	75	*	2967		267	3234
	FTX-43	75		194			194
	Floor Heating						-

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[1] Värmeväxlare

As areas are obtained from drawings, they should not be regarded as an accurate value. For example, in this table, the store area is calculated 55700 m^2, and the actual lease area is 53125 m^2, a margin of error of 4.8 %.

For AHUs, two datasets are obtainable from the control system (AHU1, AHU2 section). The number of operational and functional data sets and their attainable period differ from one AHU to another. The first step is to categorize data. All available AHUs in the control system have been divided into two periods from 2019 to 2022. Then, the available dataset of AHUs was studied separately (appendix 1). Table 6 summarizes operational sets and the corresponding number of AHUs in those sets.

Table 6 operational data and its availability

Category 1	
Operational data	**No. of AHU**
Cooling Coil Valve Command/Position	**29**
Cooling Demand Status	16
Cooling Setpoint	14
Exhaust Air Damper Command/Position	15
Exhaust Fan Start/Stop Command	14
Exhaust Air Temperature	**28**
Exhaust Airflow	11
Exhaust Fan VFD Speed Command	10
Decoupler Temperature	16
Heat Recovery Coil Valve Position	16
Heat Recovery Coil Leaving Air Temperature	22
Heating Coil Valve Position	19
Heating Demand Status	15
Heat Demand Setpoint	15
Heating Setpoint	15
Mixing Box Dampers Position	15
Outdoor Air Damper Position	16
Outdoor Air Temperature	**30**
Return Air CO2	12
Return Air Temperature	**30**
Return Airflow	18
Supply Fan Differential Pressure	13
AHU/Supply Air Fan/Command	15
Supply Air Velocity Pressure	14
Supply Air Temperature	**29**
Supply Air Temperature Cooling Setpoint	16
Supply Air Temperature Heating Setpoint	14
Supply Air Temperature Setpoint	14
Supply Airflow	**29**
Supply Fan VFD Speed Command	27
Unit Operational Mode	14
Operational Mode Manual	13

Category 2	
Operational data	**No. of AHU**
Cooling Coil Pump Command	**30**
Cooling Coil Valve Command	**31**
Cooling Demand Status	**31**
Cooling Setpoint	**29**
Exhaust Fan Start/Stop Command	26
Exhaust Air Temperature	**29**
Exhaust Airflow	21
Exhaust Fan VFD Speed Command	23
Heat Recovery Coil Efficiency	27
Heat Recovery Coil Leaving Air Temperature	21
Heat Recovery Coil Speed Command	**28**
Heating Demand Status	**31**
Heat Demand Setpoint	**31**
Heating Setpoint	**31**
Preheat Coil Freeze Protection Water Temperature	**28**
Preheat Coil Pump Start/Stop Command	26
Outdoor Air Temperature	**31**
Room CO2	13
Room Temperature	20
Return Air Temperature	**30**
AHU/Supply Air Fan/Command	**30**
AHU/Supply Air Temperature	**31**
Supply Air Temperature Cooling Setpoint	14
Supply Air Temperature Heating Setpoint	12
Supply Air Temperature Setpoint	**29**
Supply Airflow	**29**
Supply Fan VFD Speed Command	**28**
Unit Operational Mode	**29**
Operational Mode Manual	**28**

An alternative method has been investigated to estimate the energy demand of each AHUs and consequently corresponded heat exchanger when the energy demand of each AHU is not metered. Therefore, operational data from the control system has been evaluated, and service areas have been obtained from the drawings. Actual airflows, percentage of engine speed, and operating are required to be extracted from the control system.

$$Energy\ use = Operation\ time \cdot number\ of\ days\ (supply\ air\ power + exhaust\ air\ power) \qquad Eq.\ 2$$

$$P = \dot{V} \cdot \Delta p / (1000 \cdot \eta e) \qquad Eq.\ 3$$

Where $\dot{V}$ is airflow rate in m^3/s, Δp is the total pressure difference across fan in Pa, and ηe is total system static fan efficiency

According to Eq. 2, operation time is varied from unit to unit and from one day to another day. Fan motors are also varying in size and power. To estimate supply and exhaust fan power, airflow rate, differential pressure, and system static fan efficiency are required for each AHU (Eq. 3). As too many assumptions should have been made regarding data that have not been measured, the scope of analysis is limited to the entire building.

Supply Airflows

The total air exchange varies greatly depending on the outside temperature. Therefore, projected flow is assumed to be in the order of magnitude. It is one of the crucial measures to be evaluated in this research. Initial information regarding supply airflow is only obtained for 29 of the 31 units through the plant's control system. As the main concern of this project is to evaluate performance during two specified periods, it is crucial to determine which AHU supply airflows are recorded in both periods. Table 7 provides information regarding the availability of supply airflow meter for each AHU; black color means not measured. The grey color means that although data are available, the lack of data for the other period made us overlook those AHUS. Therefore, 24 AHUs' supply airflow are considered for the rest of the study. Regarding the service area for each AHU, data for supply airflow are provided for 92.5% of the total AHU service area. Moreover, the ventilation system has 29 extra independent exhaust fans, which measurement has not been found in the control system.

Table 7 availability of supply airflow

AHU	FTX10	FTX12	FTX14	FTX25	TA13	FTX15	FTX32	FTX33	FTX34	FTX35	FTX36	FTX37	FTX38	FTX43	FTX39	FTX40	FTX41	FTX42	TX44	TA01	TA02	TA03	TA04	TA05	TA06	TA08	TA09	TA26	TA31	TA17	TA30	TA28	TA29
Period 1	■			▨																▨	■	■	■										■
Period 2	■			■																■	■	■	■										▨

2.3.2.3 District Heating Plants

The district heating plant is located in the basement, where heat is distributed to different building parts. The plant consists of six heat exchangers. A diagram of the building's nine sections and the connected district heating plants are depicted in Figure 7. Each plant is connected to one or more sections. In addition to radiators and AHUs, floor heating systems are installed in four entrances. Table 14 in the result section summarize four heat exchangers and their respective service area.

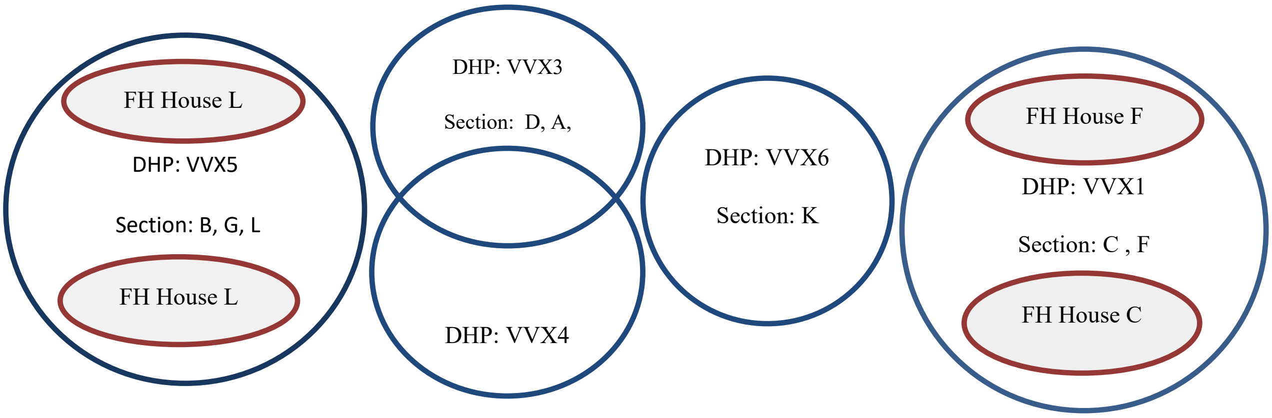


Figure 9 Sections and district heating plants and connected floor heating systems

The Control system recorded several operational sets for VVX1 to VVX5 and floor heating systems (FH). Table 8 shows all extracted data series from the control system and the period when series are available. A solid filled data bar is used to indicate the start, end, and length of availability (i.e., the Heating Demand Status series of FH2 is available from 2/18/21 to 10/3/2022; on the table, while the whole cell indicates the period between 1/1/2019 to 10/3/2022, black bar shows period and amount of the data.)

Table 8 Availability of heat exchangers and floor heating systems operational parameters

	VVX1 (C , F)	**VVX3 (D , E)**	**VVX4 (A)**	**VVX5 (B)**	**FH* (F)**	**FH (C)**	**FH1 (L)**	**FH2 (L)**
Heating Demand Status	■	■	■	■	■	■	▪	▪
Heat Demand Setpoint	■	■	■	■	■	■	▪	▪
Heating Circuit Supply Temperature Setpoint	■	■	■	■				
Heating Circuit Supply Temperature	■	■	■	■			▪	▪
Heating Circuit Return Temperature	■	■	■	■			▪	▪
Mixing Circuit Temperature Setpoint	■	■	■	■	■	■		
Mixing Circuit Supply Temperature	■	■	■	■	■	■	▪	▪
Mixing Circuit Return Temperature	■	■	■	■			▪	▪
Mixing Circuit Pump Start/Stop Command	■	■	■	■	■	■	▪	▪
Mixing Valve Command Circuit A	■	■	■	■	■	■	▪	▪
Mixing Valve Command Circuit B	■			■				
Unit Operational Mode	■	■	■	■	■		▪	▪
Operational Mode Manual	■	■	■	■	■	■		
Outdoor Air Temperature			■		■	■	▪	▪

* Floor Heating

2.3.2.4 Chillers

On the control system, the operation of five chillers is recorded. Table 9 shows the start and length of availability of collected Chilled water temperature setpoint, entering cold water temperature, leaving cold water temperature, condenser temperature setpoint, evaporator temperature setpoint, and electrical efficiency using a data bar on each cell. Each cell indicates a period of 2019 to 2022. Black cell means data is not available.

Table 9 Availability of chillers' operational parameters

	Chiller 1	Chiller 2	Chiller 3	Chiller 4	Chiller 5
Chilled Water Temperature Setpoint	■	■	■	■	■
Chiller Entering CW Temperature	■	■	■	■	■
Chiller Leaving CW Temperature	■	■	■	■	■
Chiller Entering CHW Temperature	■	■	■	■	■
Chiller Leaving CHW Temperature	■	■	■	■	■
Condenser Temperature Setpoint	■	■			
Condenser Temperature Setpoint-Circuit A			■	■	■
Condenser Temperature Setpoint-Circuit B			■	■	■
Chiller Evaporator Temperature Setpoint	■	■	■		
Chiller Evaporator Temperature Setpoint-Circuit A			■	■	■
Chiller Evaporator Temperature Setpoint-Circuit B			■	■	■
Operational Mode Manual	■	■	■	■	
Electrical Efficiency	■	■	■	■	■
Electrical Efficiency Circuit A			■	■	■
Electrical Efficiency Circuit B			■	■	■
Operational Mode Manual	■	■			

2.3.3 Selected parameters and Limitations

To analyze the influence of parameters on building energy performance, district heating flow, cooling, and property electricity use are selected as dependent variables; outdoor air temperature, CDHs, HDHs, airflow and tenant electricity are chosen as independent variables to perform a further assessment on correlations.

As discussed in section 2.3.1, the building's property electricity and district heating are measured by one meter for the entire building; Therefore, it is not applicable to evaluate the relations at component level between the energy use of each heat exchanger and the measured operational data. As illustrated in **Error! Reference source not found.**, each section is connected to a specific heat exchanger and AHUs, therefore measuring the district heating and electricity use separately would provide required information to compare each section's energy performance. Installation of new energy meter to AHUs, chillers, and heat exchangers to measure both district heating flow and electricity are recommended to make a detailed evaluation of energy performance of each building part. Moreover, although property electricity is measured separately in meters structure, aggregated value is recorded as property electricity excluding cooling in the control system.

An alternative approach is to use an aggregated value from AHUs, heat exchangers, or chillers and a relevant denominator to perform a whole building scale calculations (i.e., a sum of multiplication of supply airflow by supply air temperature of each AHUs divided by total airflow from all AHUs will provide an average supply air temperature implied in correlation assessment). Although the approach is applicable, a unique method is required to convert measured operational and functional values on equipment level to aggregated value on entire building level. Due to the limitations in time, more investigation is suggested in further studies.

2.4 Measured Data analysis

Information plays a crucial role in energy quantification and influences decision-making regarding building performance. As storage capabilities have exponentially increased and data collection methods have changed, enormous data has become readily available. As a result, new ways were needed to handle and extract value and knowledge from these abundant raw materials. Having such large, diverse, and rapidly changing data required a new type of big data analytics. Big data describes datasets that grow too large to be handled by traditional database management systems(Elgendy and Elragal 2016). Utilizing advanced analytics makes it possible to significantly improve decision-making, minimize risks, and uncover insights from the data that would otherwise not be discovered (Manyka James et al., 2011). Every step of the significant data analysis pipeline has its challenges and decisions. The decisions range from what data to acquire, which format to use for analysis after cleansing, integrating, and extracting data from the source, and how to make decisions based on those results (Elgendy and Elragal 2016).

2.4.1 Data analysis tools

Python, as a high-level, general-purpose interpreted programming language, is widely used in scientific and numerical computing. In the first place, Python is known for its clean and easy-to-understand code syntax. The readability of a code improves its maintainability, which results in fewer bugs and rapid code development. Additionally, it contains a wide range of Python packages for scientific computing. Apart from the technical reasons why Python provides a suitable environment for computational work, it is also significant that Python and its scientific computing libraries are free and open source, eliminating economic constraints on when and how applications developed environment can be deployed and distributed by its users. Aside from the technical reasons why Python is a good environment for computational work, being free and open source eliminates economic constraints on when and how applications developed with the environment can be deployed and distributed by its users(Johansson 2018).

Pandas is an open-source Python library for data analysis. Data can be loaded, transformed, manipulated, aligned, split, merged, and manipulated quickly and easily using spreadsheet-like data. Python introduced two new data types to enhance its features: Series and DataFrame. The DataFrame will represent the entire spreadsheet or rectangular data, whereas the Series is a single column of the DataFrame. A Pandas DataFrame can also be considered a dictionary or collection of Series(Chen Daniel Y. 2018). Time-series analysis is an essential field in statistical modeling that deals with analyzing and forecasting future values of data observed as a function of time. The Pandas library is an extension of NumPy; it complements features that are particularly useful when handling data, such as labeled indexing, hierarchical indices, data alignment for comparison and merging of datasets, handling missed data, and much more. However, the library contains only limited statistical modeling support (linear regression). For more detailed statistical analysis and modeling, other packages such as statsmodels, patsy, and scikit-learn are available (Johansson 2018).

2.4.2 Data analysis method

Energy quantification is the foundation for any numerical energy performance evaluation, which determines the amount of energy used by a building or its energy performance indicator based on collected data. To account the impact of energy influential factors, benchmarks have been constructed using a regression-based model(Wang, Yan, and Xiao 2012). Although calculation-based methods are the only option for new construction, energy quantification, using measured data, is more convenient for existing buildings(Lee, Yik, and Burnett 2007). One of the approaches to quantifying the energy use of an existing building is the Inverse modeling approach. Utility bills, building audit data, sub-metering systems or BMS monitoring systems, and computer simulations are typical sources to calculate building energy uses.

2.4.2.1 Weather data analysis

According to provided data in section 2.3.2.1, the average, minimum, and maximum outdoor temperature recorded from AHU meters have been assessed to determine the Warmest and coldest month of each period. December is the month with the coldest, while August is the warmest month in the first period. January and July are the coldest and warmest months in the second period, respectively.

Table 10 Mean Average, Min. And Max outdoor temperature of all AHUs

Date			Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
First period - (Sep. 2019 - Aug. 2020)	AHUs mean	Avg. /°C	7	7	7	10	13	19	17	20	15	11	8	7
		Min. /°C	3	1	1	4	6	10	10	12	9	3	2	-1
		Max. /°C	12	12	14	19	24	30	28	31	22	16	13	11
Second period (Mar. 2021- Feb 2022)	AHUs mean	Avg. /°C	2	3	2	6	9	16	20	18	16	11	8	2
		Min. /°C	-8	-3	-7	-2	0	4	9	8	5	3	1	-7
		Max. /°C	9	8	9	21	27	34	33	29	27	21	14	11
	Weather station	Avg. /°C	3	4	4	6	11	18	20	16	15	11	7	1
		Min. /°C	-2	-1	-4	-1	2	10	14	10	6	4	-4	-6
		Max. /°C	9	8	17	19	23	30	29	24	25	18	13	9

First period's Extreme weeks

For the rest of the study, weeks are decided to start from Monday. Extreme conditions are chosen by observing weeks that temperatures are extremely high or low for at least three consecutive days. In the first period, cold and warm weeks are from February 24 to March 1 and August 10 to 16. Figure 10 compares recorded hourly temperatures from AHUs and weather stations. The graph indicates that the daily deviation of temperature is smaller on coldest days than on warmest days.

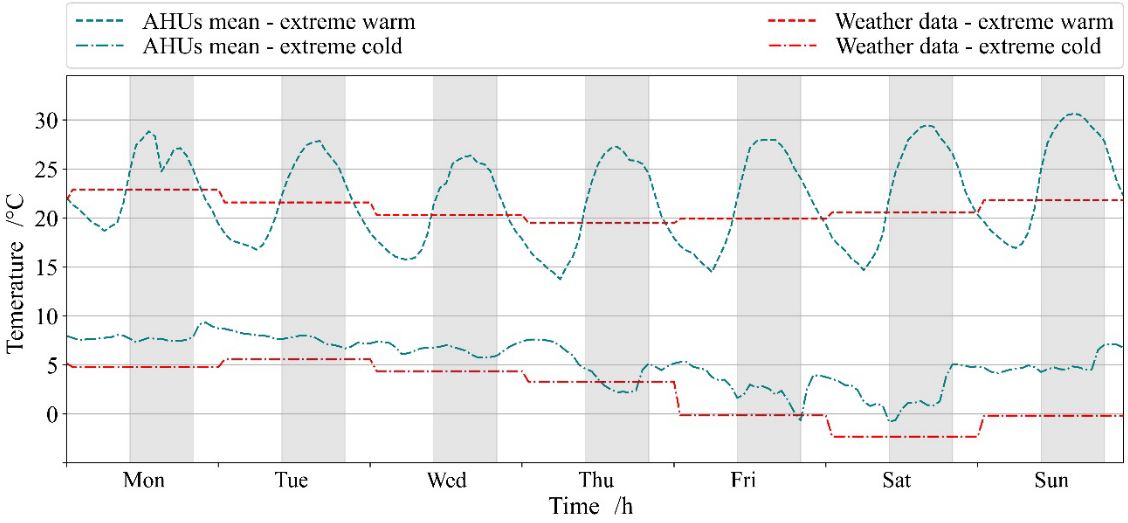


Figure 10 First period extreme conditions

Second period's Extreme weeks

Mean, Min and Max recorded temperature of AHUs' meters show the coldest and warmest weeks are January 3 to 9 and 28 June to July 4. Figure 6 indicates that the warmest hour of the day is the night, which is not a logical pattern. Furthermore, due to the lack of valid data and provided hourly data from the weather station at the shopping mall, it has been decided to use weather data for outdoor temperature in the second period. As illustrated in Figure 7, even though the recorded high temperature is lower in the AHUs dataset, the daily pattern of outdoor temperature looks more comparable.

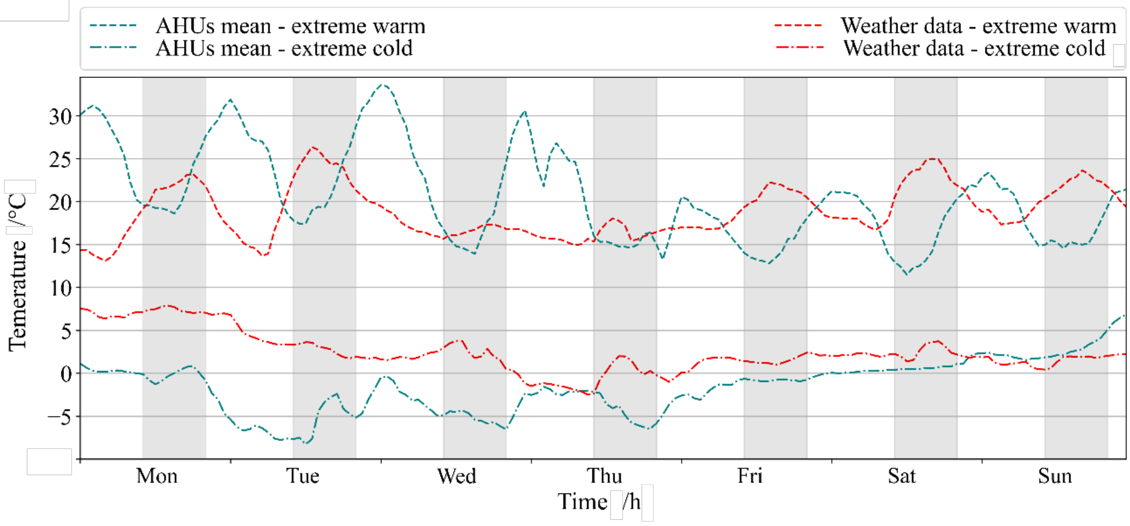


Figure 11 Second period extreme conditions based on data from AHU meters.

The increasing temperature overnight during summer from AHU meters corroborates uncertainty about the recorded temperature (Figure 12). The approximate variance on the warmest day over the first period is 13 °C, while over the second period, it is 11 °C. The highest recorded temperature is 2 degrees higher in the first period. Table 11 shows the determined time frame for further investigations.

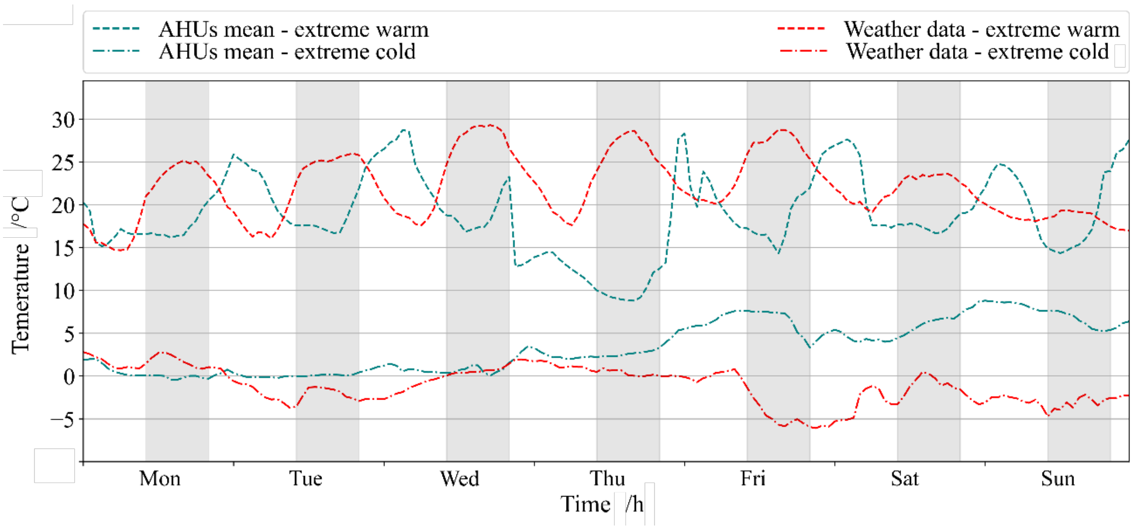


Figure 12 Second period extreme conditions based on recorded temperature from the weather station and AHU meters of the shopping mall.

Table 11 suggests the time frame of analysis periods

	Duration	Coldest months	Coldest week	Warmest months	Warmest week
Period 1	Sep. 2019 -Aug. 2020	Dec-Mar	24 Feb-1 Mar	Jun-Aug	28 Jun-4 Jul
Period 2	Mar. 2021-Feb 2022	Dec-Mar	20 -26 Dec	Jun-Aug	12 - 18 Jun

2.4.2.2 Demand pattern

Generally, there is extensive literature on energy demand in buildings. Energy demand has been discussed from various perspectives and with multiple objectives. Despite this, a limited number of studies are dedicated to analyzing energy demand patterns using data from existing buildings. Considering the above, actual energy use is utilized to explore energy demand patterns. This part uses actual energy use to investigate typical energy demand patterns. The monthly demand is analyzed to understand the load fluctuations and how they can be used in performance assessment.

The annual pattern is investigated by sorting out all dependent variables, mean temperature, and airflow from January to December regardless of their order because each period starts at a different month. Therefore, a new index has been set to datasets. District heating, cooling, property, tenant, and airflow are provided in monthly use during occupied and unoccupied hours. In addition, outdoor temperatures are calculated as a mean of each month. Presented graphs are stack bars in which each bar comprises both occupied and unoccupied hours values. The weekly pattern of heating and cooling are analyzed over extreme warm/cold weeks in both periods. In addition, daily assessment is implemented on the most extreme cold and warm days. It should be mentioned that as district heating is constant during the second period, weekly and daily investigations are not consequential.

2.4.2.3 Inverse modeling approach.

The inverse modeling approach establishes a correspondence between energy performance indicators and critical energy influential factors (e.g., weather conditions, floor area). The first step is identifying a model coefficient considering the structure or physical properties of a building or a system by statistical analysis or regression analysis. Fixed coefficients are commonly established for steady-state inverse modeling, which is used at either whole building level or HVAC system levels. The simplest way of calculating building energy performance is inverse modeling for the entire building level. The whole building energy use can be regressed against several important influencing parameters using the method. Linear, change-point linear, and multiple regressions are widely accepted techniques to correlate energy use with weather data and/or other influential variables. Using the whole-building energy model involves creating a whole building model and several different regression models for the particular building(Wang, Yan, and Xiao 2012). This formula will use the best explanatory variables among the candidate variables. In the most cases, the whole-building inverse uses multiple linear regression from Eq. 4:

$$E = C + B_1V_1 + B_2V_2 + \ldots + B_nV_n \qquad \textit{Eq. 4}$$

E is the estimated energy, and C is a constant term in energy units. B_n represents the regression coefficient of an independent variable V_n.

Each step introduces the most significant variable, checks whether the selected variables in the model are substantial or not, and removes the insignificant variables from the candidate explanatory variables based on specific criteria. An example of utilizing this method is the U.S. Energy Star benchmarking system. Energy use intensity (EUI) is calculated by a simple linear regression model that explains the relationship between building operational characteristics and primary energy consumption.

2.4.2.4 Pearson Correlation

A data-driven approach is a solution to reduce the dimensions of the building characteristics of sampled buildings, and regression analysis is most widely used to assess building energy performance. To select the most appropriate type of EUI for the sampled buildings, the Pearson correlation coefficient (r) is adopted to obtain a building energy-influencing factor that is more significantly correlated with total energy use than the other factors. The degree of correlation between the building energy use and various influencing factors can be measured by the equation Eq. 5.

$$r = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})}\sqrt{\sum_{i=1}^{n}(y_i - \bar{y})}} \qquad \textit{Eq. 5}$$

where, r ranges between (−1, + 1). When r is less than 0, it indicates a negative correlation, and there is a positive correlation in the opposite case. In addition, the larger the value of | r |, the stronger the correlation between the two variables; otherwise, the weaker the correlation between the two variables(Ding and Liu 2020).

With Pearson coefficients of correlation, caution is advised, as their value can only indicate the existence of certain relationships among variables, not the causal connection. Further, Pearson correlation only measures linear relationships between variables and does not consider a non-linear relationship (Mikulik 2018). Although regression analysis is easy to apply and accepted by engineers and policymakers, there are still significant limitations. First, residuals from a regression model represent relatively inefficient items in buildings and contain random items, including measurement errors, statistical noise, and the effects of unexplained factors. Additionally, large sample size and comprehensive explanatory variables are needed for linear regression analysis since the analysis is sensitive to outliers. Furthermore, linear regression models are not likely to capture the non-linear nature of building energy use and its drivers (Ding and Liu 2020).

Pearson correlation coefficient has been calculated in three scales among dependent and independent variables on two datasets, including the day of the week, working hour, working time, outdoor temperature, heating degree hour, cooling degree hour, electricity for cooling, district heating demand, property electricity, tenant electricity, and airflow. As mentioned in Table 11, the time frame is implemented over two periods (P1 and P2). Correlations study implemented on three scales of entire year, warm/cold months, and warmest/coldest week. The workflow of investigation of variables based on an hourly interval is illustrated in Figure 13.

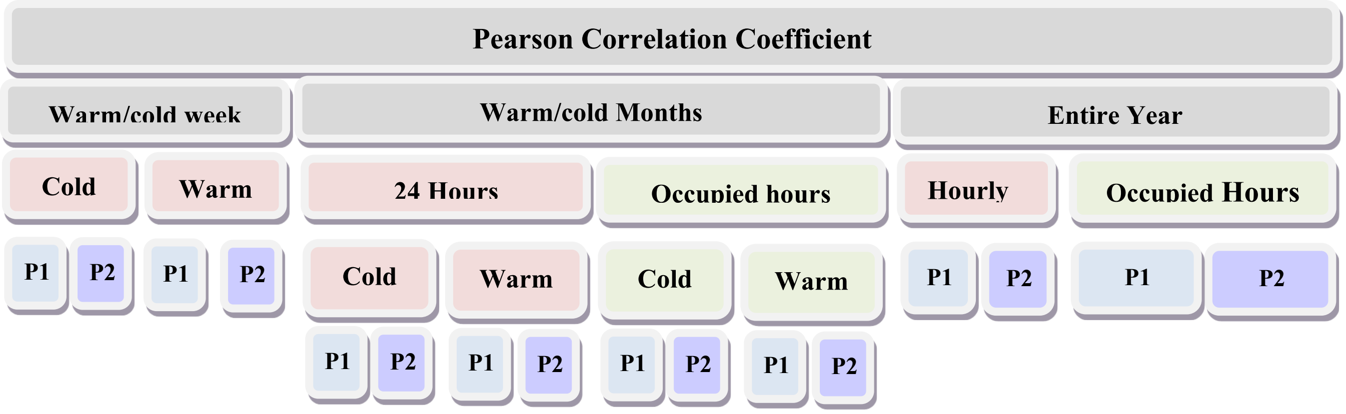


Figure 13   Pearson's correlation coefficient calculation workflow

- Day of Week: numbers from 0 to 6 have been set to each day of a week. Weeks start from Monday. This term cannot be assessed in a monthly-based calculation since time intervals are longer than a day.
- Working Hour: the working hour is determined as a binary number, 1 for an occupied hour and 0 for an unoccupied hour. To calculate daily/monthly bases correlation coefficient, a summation of hourly data in the interval is used.
- Time of Day: Time of day illustrates how each hour of a day is correlated to other parameters.
- Outdoor Temperature (OT): according to a study of measured outdoor temperature, the average measured temperature from all AHUs and measured temperature from the building's weather station

are used for P1 and P2, respectively. As all the initial data are in hourly intervals, in daily and monthly assessments, the average of the determined interval is used as a representative temperature.

- HDH: heating degree hours are calculated for hourly calculations; daily and monthly based assessments are equivalent to the summation of hourly HDHs.
- CDH: the same process as HDH is implemented on CDH.
- District Heating, cooling electricity: As the main focus of the research is to evaluate energy performance, these factors are considered dependable variables. Thus, the impact of other parameters is studied on district heating and cooling demand.
- Property El.: Property electricity includes AHUs, pumps, and fans electricity use; it is selected as a dependent variable.
- Tenant El.: Tenant electricity is considered an independent variable affecting thermal comfort energy use.
- Supply Airflow: Though supply airflow depends on independent factors such as temperature and ventilation in this research, it is accounted for as an independent variable to analyze its relationship with thermal comfort energy use.

Although ‘Time of Day’ shows the correlation of time to other parameters in every hour of a day, from 0 to 23, the impact of the occupied and unoccupied hour is aggregated in other correlation factors. Splitting the data into an occupied hour and occupied hour is an approach to filtering the datasets.

A correlation matrix is used to present correlation coefficients among a group of variables. The objective of an investigator is to discover patterns of interesting associations among bivariate combinations of a set of variables(Chernick and Friis 2003).

Table 12 presents a matrix of all dependent and independent variables and their corresponding correlation coefficients. The table's down left and top right gives the correlation coefficient of period one and period two, respectively. In addition, scaled color from white to blue or purple is utilized for better presentation. White means correlation is 0, while dark blue-purple means correlation of either -1 or 1. Thus, darker color means a stronger correlation.

Table 12: A template to present the result of the Pearson Correlation Coefficient

	Day of week	Working Hour	Time of Day	OT	HDH	CDH	District Heating	Cooling El.	Property El.	Tenant El.	Supply Airflow
Day of week	1										
Working Hour		1									
Time of Day			1						P2		
OT				1							
HDH					1						
CDH						1					
District Heating							1				
Cooling El.			P1					1			
Property El.									1		
Tenant El.										1	
Supply Airflow											1

As mentioned in 2.3.1.1 from April 2020, district heating demand is reported monthly, and other data are recorded hourly. Therefore, results from hourly intervals are not comparable to the mean value of the months. Thus, a sensitivity analysis was implemented to determine how changing intervals affect the Pearson correlation coefficient. In addition, a study with monthly intervals would represent the relation of mean district heating demand with the average temperature of each month, which is a more accurate method than comparing data with two different intervals.

When data has a nonlinear relationship, Pearson's r can be misleading. While the terms "strong" and "weak" do not have a precise numerical definition, a relationship described as "strong" will be more linear, with points clustered more closely around a line drawn through the data, than data described as "weak"(Boslaugh et al. 2013). Therefore, reporting correlation coefficients and naming their strength should be conducted with the utmost care to prevent misunderstandings. Correlation coefficients with a magnitude between 1.0 and 0.98 indicate variables that can be considered **perfectly correlated.** Correlation coefficients whose magnitude is between 0.65 and 0.98 indicate variables regarded as **very strongly correlated.** Correlation coefficients whose magnitude is between 0.35 and 0.65 indicate variables that can be considered **strongly correlated.** Correlation coefficients whose magnitude is between 0.25 and 0.35 indicate variables with a **moderate correlation.** Correlation coefficients whose magnitude between 0.15 and 0.25 is weak, magnitude between 0.15 and 0.02 indicate variables with a **negligible correlation and** less than 0.02 have **not correlated,** if any (linear) correlation(Akoglu 2018).

2.4.2.5 Normalized energy

In order to consider influential factors in the energy analysis, a normalized energy use index with the uncommon factors was to be developed by analyzing the relationship between energy use and these inputs(Juaidi et al., 2016). In This study, the climatic variables chosen for analysis are Heating Degree Days (HDD) and Cooling Degree Days (CDD) since other factors were unavailable for both periods. There are many citations for these variables in the literature (Wang, Yan, and Xiao 2012). Their effect on the operation of assets and the current climatic design standards used for Heating, Ventilation, and Air Conditioning (HVAC) units were pointed out.

Climate adjustment of energy use

Climatic conditions could affect the building energy use, so to make a fair comparison, the effect of climatic conditions on the energy use should be eliminated. In order to do this, the Degree Day method has been developed by using Heating Degree Day and Heating Degree hour(Juaidi et al. 2016). HDDs measure the cold climate for a specific day below a threshold value; CDDs measure how warm the weather is for a given day above a threshold value (Brown et al., 2022). The degree-day method assumes that solar and internal heat gain offsets heat losses when the mean outdoor temperature is 18 ◦C (base temperature) and that the rate of heat gain or loss is proportional to the difference between the mean daily temperature and base temperature(Wang, Yan, and Xiao 2012).

In the equation below, η is the climate adjustment coefficient; HDD_1 is the cooling degree days of the typical year. HDD_2 is the cooling degree days of the observation year(Juaidi et al. 2016):

$$\eta = \frac{HDD_1}{HDD_2} \qquad \textit{Eq. 1}$$

The method increases the level of accuracy than the simple average method, reflecting the actual energy use(Juaidi et al. 2016). However, some limitations still exist when these methods are applied. For example, normalizing a EUI using the degree-day method relies on the assumption that, like building energy use and heating/cooling degree-days have a linear correlation, energy disaggregated indicators do not consider the effects of occupancies.

3 Results and discussion

3.1 Energy Use

Below in Figure 14, the properties of energy use are summarized in a few key energy demands. The specific energy use for the different energy carriers and applications is calculated as energy per total service area (A_{temp}). The data from the references were normalized by area. Table 13 compares the energy use intensity of a case study in two study periods, a report on energy use of the shopping mall from 2013 and comparative data taken from the Swedish Energy Agency, Energy in retail premises, published in 2010. Unfortunately, the report has not had a newer version.

Table 13 Specific energy use by type of energy and application

EUI /(kWh/m^2)	Period 2	Period 1	2013	Swedish energy Agency (2010)
District Heating	28	26	46	86
Cooling El.	13	11	18.4	21.7
Tenant El.	114	113	117	104
Property El.	20	32	64.1	45

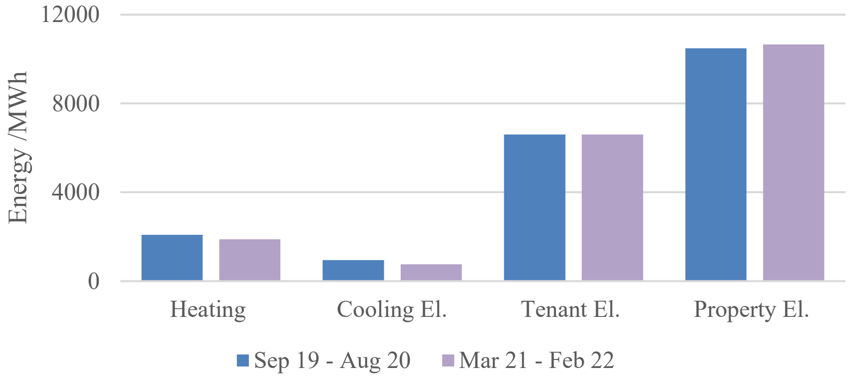


Figure 14 illustration of energy demand

Electricity use is divided into the property, tenants, and cooling subcategories. Figure 14 shows the electricity use of subcategories of two studied periods.

District heating

Data extracted from the billing meter and energy meter are compared in Table 14; the maximum difference is 269 kWh. The absolute difference is 358,442 kWh from April 2020 to December 2021, about 10 % of the total district heating demand.

Table 14 District heating demand descriptions

		DH (A) - (Other meters)	DH (B) - (Billing Meter)
Heat /kWh	mean	223	225
	std	178	184
	min	70	75
	25 percentiles	80	82
	50 percentiles	120	123
	75 percentiles	310	273
	max	610	653
	Total	3347790	3378931

Heat exchanger	Service Area /m^2
VVX1	18879
VVX2	DHW
VVX3	10005
VVX4	6479
VVX5	23071
VVX6	18664

3.2 Demand pattern

A summary of demand patterns and degree days over cold months, warm months, and the whole year is provided in Table A 1-3. Below, district heating, cooling, property, and airflow are shown over a year during occupied and unoccupied hours.

3.2.1 District heating

The monthly district heating flow over two periods is presented in Figure 15. Over June and August, heating demand during unoccupied hours is higher than occupied hours. Also, energy use is constant from May to September during both periods. Comparing variations in mean monthly temperatures shows that district heating demand follows a reverse trend. The only exception is in October when heating use is higher regardless of the higher monthly mean temperature.

In the first period (blue), from December to March, heating energy use is notably higher over occupied hours, contrary to the second period (purple). Less energy was needed during occupied hours. In the first period mean monthly temperature was higher than in the second period; thus, the probably higher temperature at night caused less demand during unoccupied hours. Moreover, another reason could be a low setpoint over an unoccupied hour compared to the second period. The reason behind the pattern of the second period could be higher heating degree hours during nights when the temperature is lower than on middays. In addition, low internal gain due to the unoccupied hours and buildings require more energy to reach the determined setpoints. The following provided data and discussion are according to a comparison between period one and period two.

June to August - The heating Degree hour of the occupied hour of the second period is 4.5 times higher than the first period. This means that cumulative HDH is 4.5 times more than the first period during the shopping mall's working hours. Consequently, it results in 36% of district heating use over an occupied hour in the second period. On the other hand, the heating Degree hour of the unoccupied hour is 1.17 times higher than in the first period, whereas district heating use was 4% higher than in the first period.

December to March - Although HDH over the occupied hours of period two is almost equal to period 1, heating demand increased by 45%. On unoccupied hours, the difference between HDH of the second and first periods is 7700-degree hour. During the second period, nights were warmer, which resulted in about 50% less energy demand. There could be other incentives to this, but it is assumed that part of a decline in district heating use is due to the warmer nights.

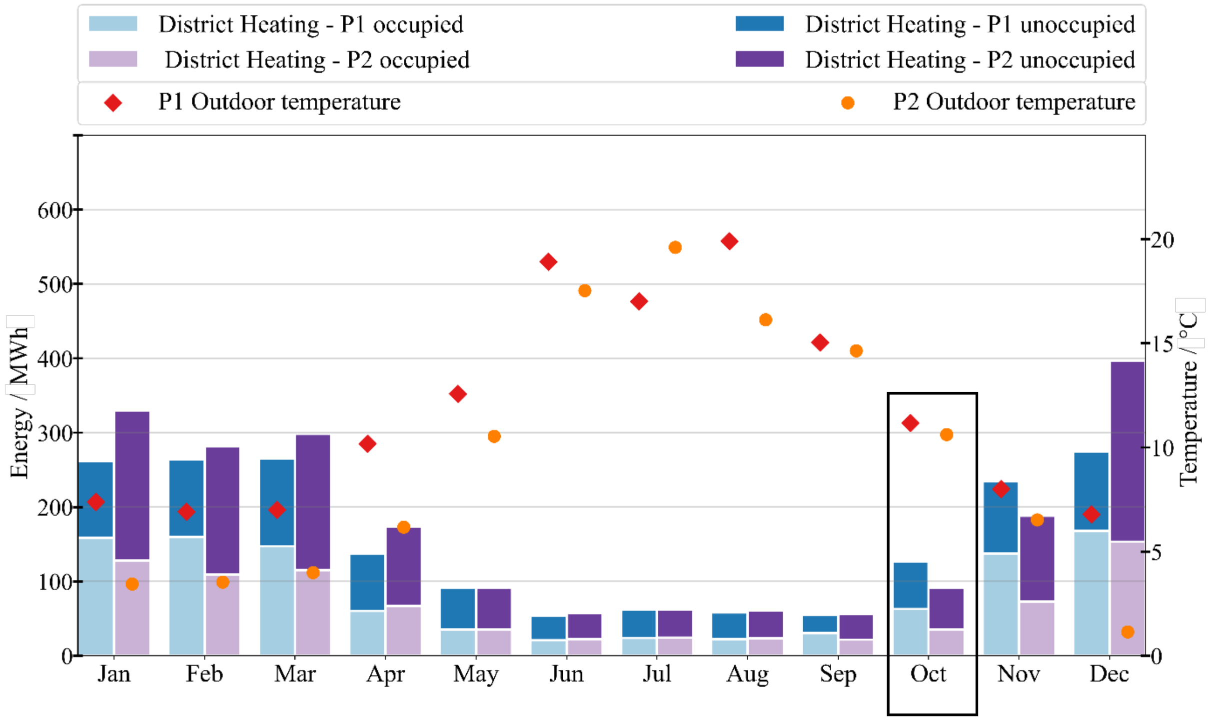


Figure 15 Monthly District heating use (heating and domestic hot water)

3.2.2 Cooling electricity

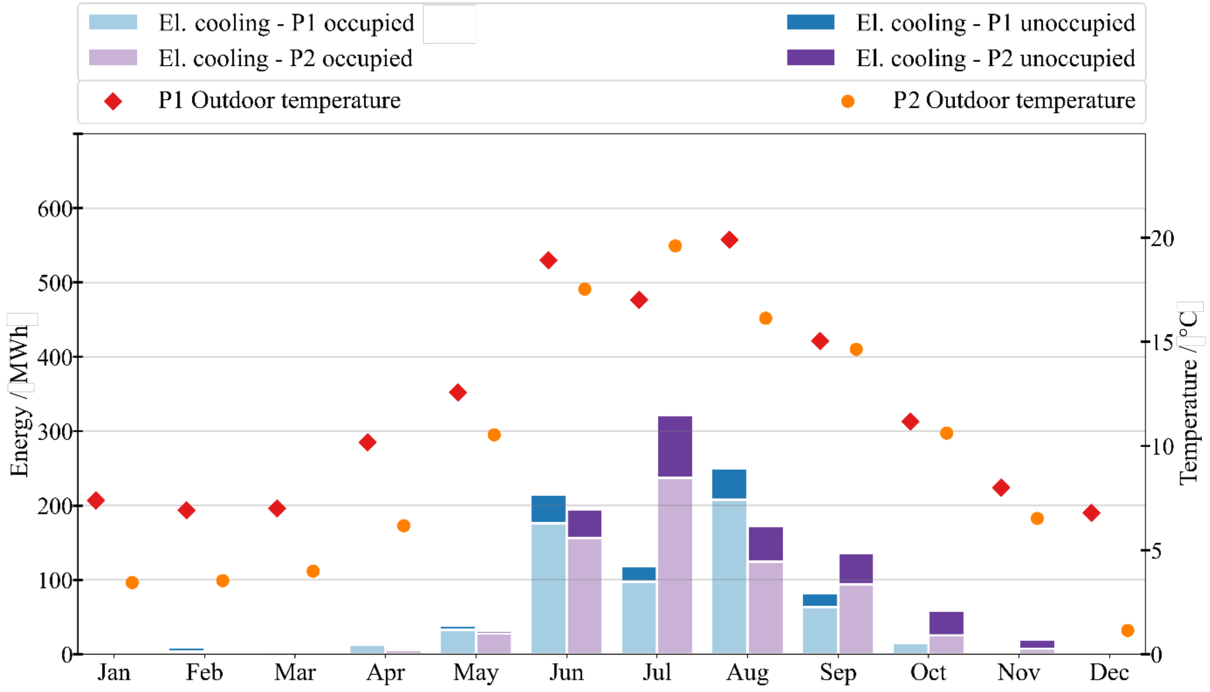
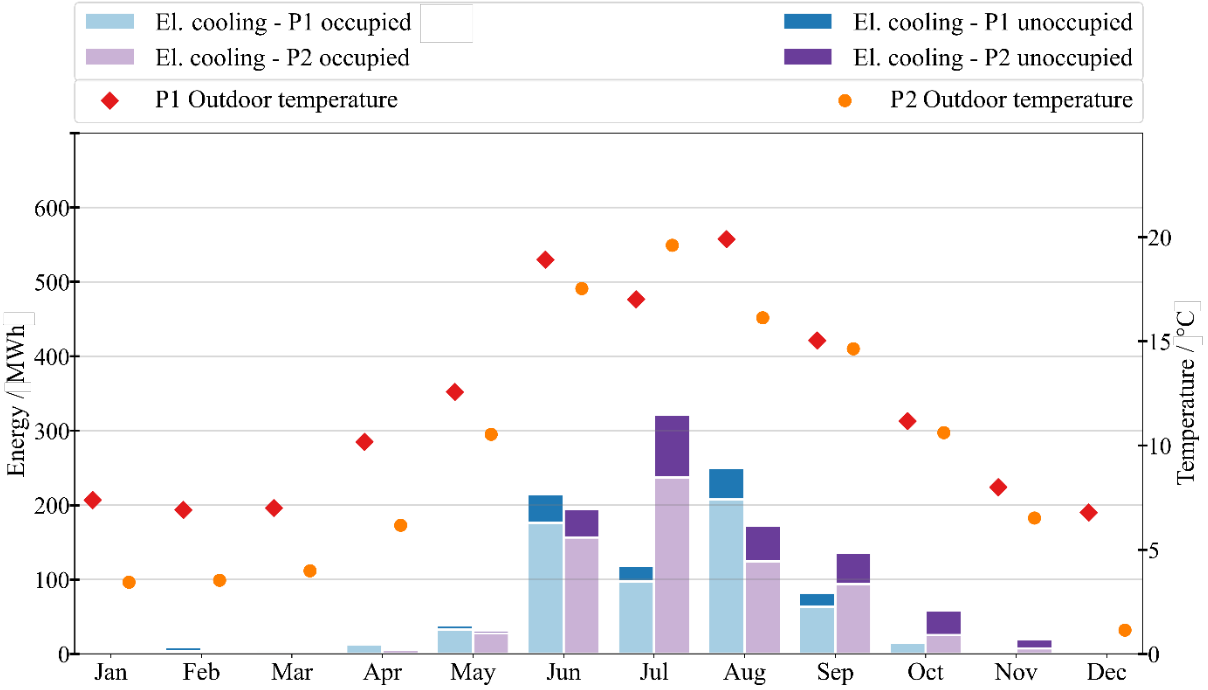


Figure 16 illustrates the direct relation between outdoor temperature and cooling demand from May to September. A comparison shows that cooling demand is correlated to the outdoor temperature during the warm months in both periods. However, cooling electricity use is quite negligible in colder months. Cooling demand is not related to outdoor temperature in the colder months. An example, a comparison between two periods shows that, although the mean outdoor temperature of November is lower in the second period, cooling demand is remarkably higher. Other reasons, such as required cooling to balance extra heat from internal gain, are predominant during cold months. Moreover, in October, cooling energy over unoccupied hours is comparable to occupied hours, whereas, for the rest of the year, most energy is consumed during occupied hours (Figure 16). Below, all provided data and discussion are according to a comparison between period one and period two.



June to August - CDH of the occupied hours is 450 degree hours lower than the first period. Thus, cooling demand is 11 000 kWh lower than in the first period. However, during unoccupied hours, even with a lower CDH in the second period, electricity needed for cooling increased by approximately 68 000 kWh.

December to March - on cold months, approximately 50% to 60% of cooling demand is needed over occupied hours.

Entire year – on the second period, cooling degree hour in 440 degree hour less during the occupied hour, while Cooling electricity use increased 129 000 kWh. In the same way, in the second period, CDH on unoccupied hours is lower than in the first period, but required energy is 85% higher.

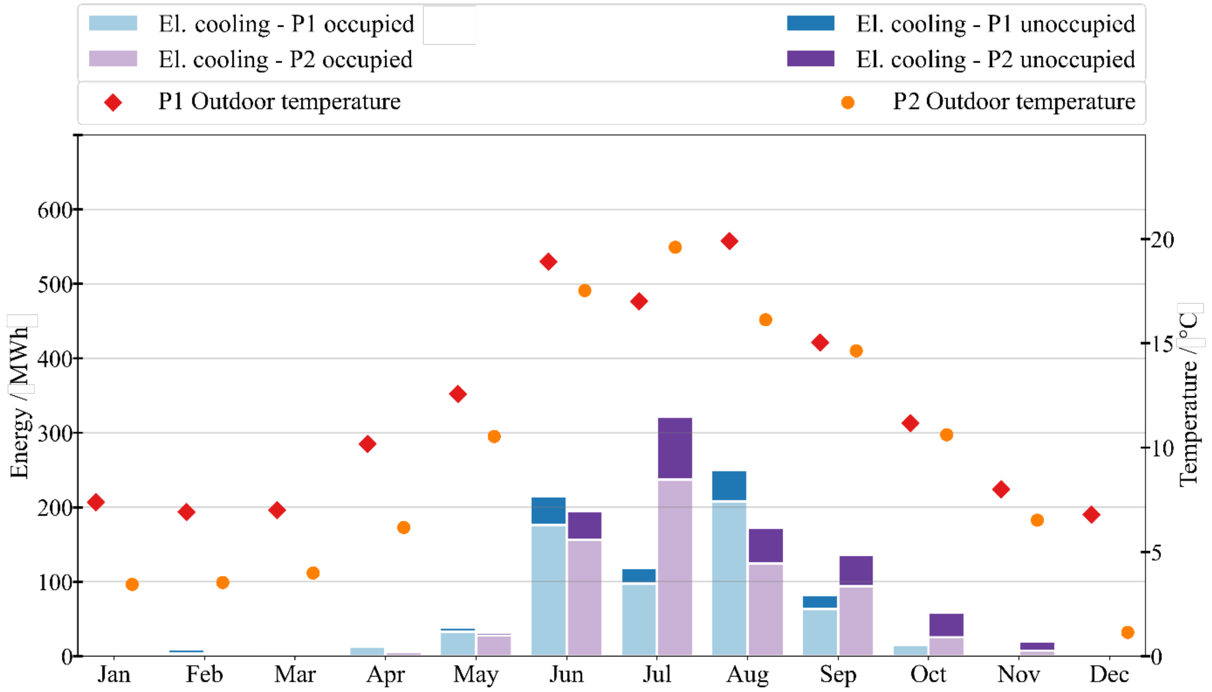


Figure 16 Monthly electricity demand for cooling of two studied periods

3.2.3 Property electricity

Figure 17 provides the monthly electricity use on occupied and unoccupied hours. As different levels of restrictions applied during pandemics, the electricity demand of tenants decreased compared to 2019 and 2022. Again, it should be noticed that months are sorted out to make the periods comparable. The second period covers March to December of 2021, January and February of 2022. Also, the first period includes January to August 2020 and September to December 2019. The effect of restriction decreases the number of occupants and higher requirements regarding hygienic airflow. These reasons raise uncertainty in the interpretation of the property electricity patterns. A comparison of the two periods shows that in May, June, and August (2020 versus 2021), the monthly property electricity demand of the second period is higher than period one, regardless of the lower mean outdoor temperature.

Overall calculation of electricity demand during occupied and unoccupied hours revealed that about 30 to 35 percent of property electricity demand is consumed over unoccupied hours. The three months of January, July, and October have the highest Property electricity use. In the first period, 4500 MWh and 2100 MWh electricity are used over occupied and unoccupied hours.

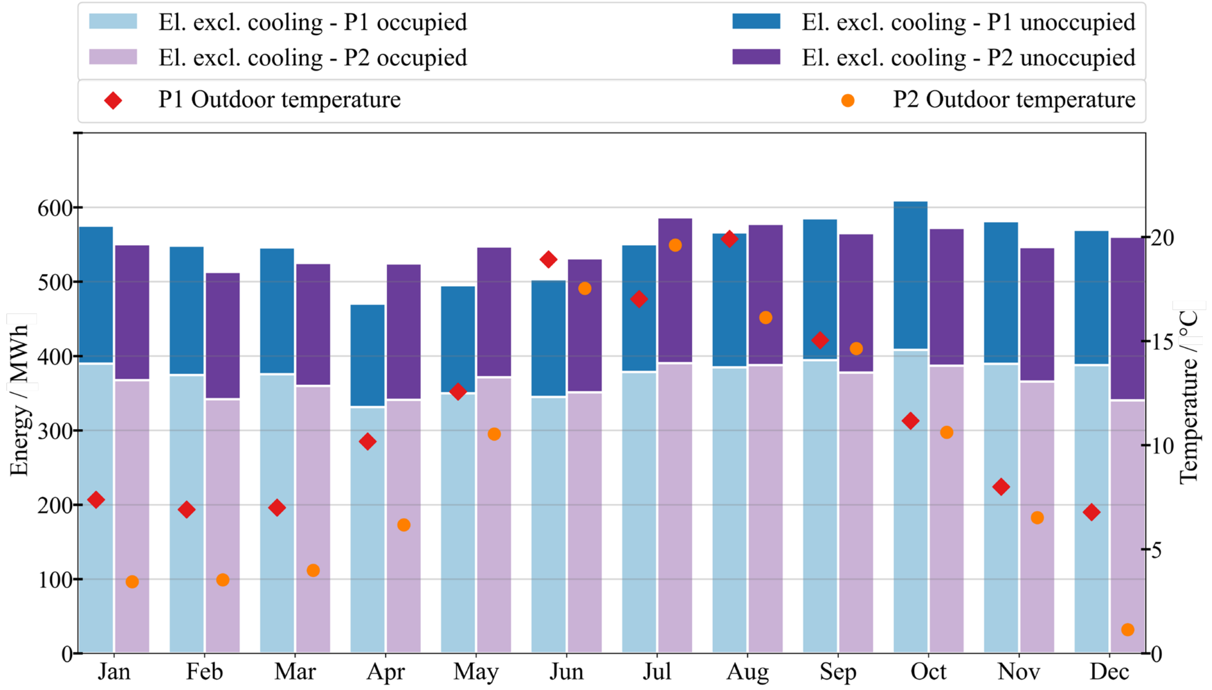


Figure 17 Monthly electricity demand for property

3.2.4 Supply Airflow

A comparison between data from the two periods mentioned above reveals a significant difference in overall monthly supply airflow, as shown in Figure 18. Therefore, it is impossible to have dramatically increased airflows from 2020 to 2021 if no significant replacement in equipment has been implemented. Thus, the dataset has been explored to find an error in AHUs.

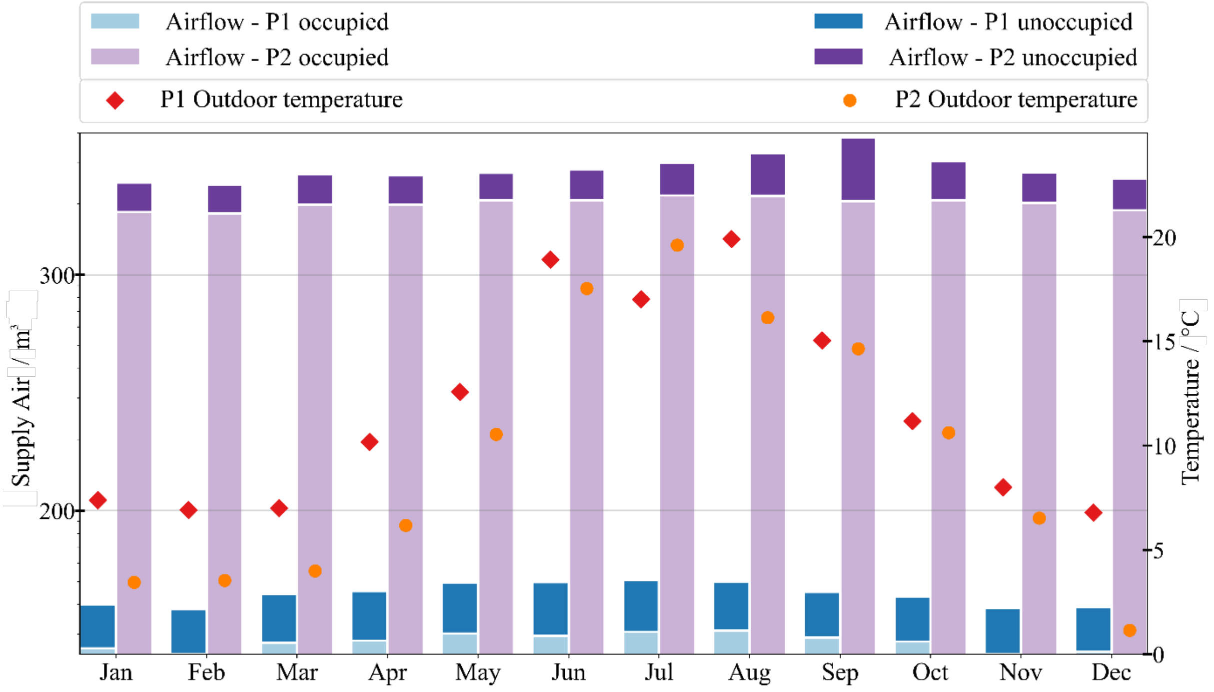


Figure 18 Monthly supply airflow

One of the AHUs recorded abnormal values about 32 000 times higher than its total airflow in the first period (Figure 19)[2]. As a result, FTX34 has been eliminated from the calculation as recorded airflow is thirty thousand times higher over the second period than the corresponding airflow in the first period. To eliminate the impact of this error on assessments, FTX34 has been excluded from further assessments. As a result, 23 over 31 AHUs are included in airflow measurements, covering 78836 m^2, approximately 91% of the AHU service area.

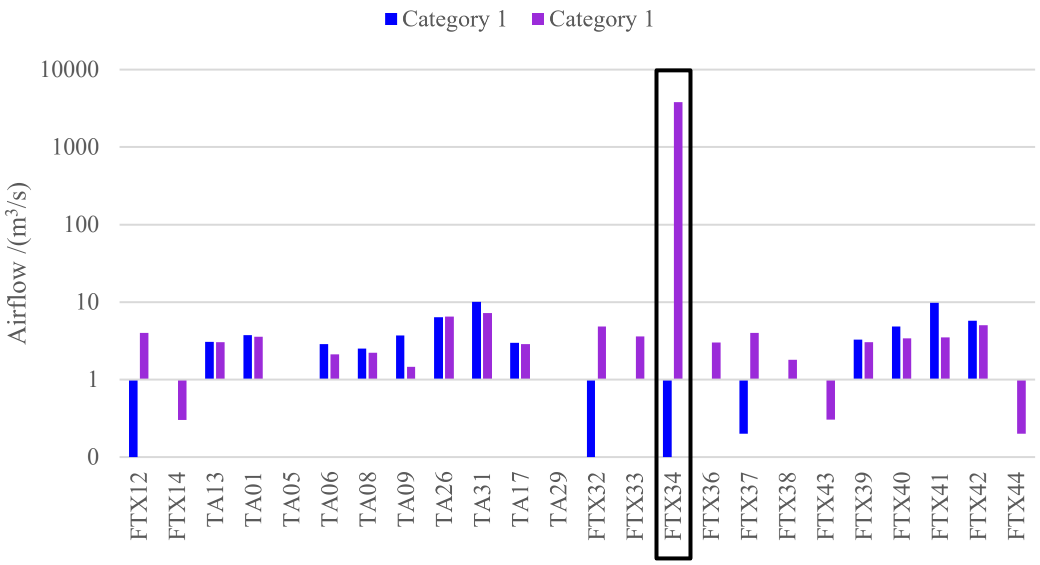


Figure 19 annual airflow demand of each AHU

Adjusted monthly airflow shows that about a third of required airflow is needed over unoccupied hours (Figure 20). In the first period, supplied airflow from May to August 2020 are the peaks which are almost constant. From September, supply airflow decreased gradually until November. From December the trend is increasing except in February a reduction is observed. In addition, over the cold months, airflows vary regardless of the constant mean outdoor temperature. Overall, in warmer months, airflow is higher than in cold months, but it is not varied according to temperature within the cold or warm period. The proportion of supplied airflow during an unoccupied hour gradually increases from 35% to 40% From January to July. It can be interpreted as the majority of required airflow during warm months supplied at the unoccupied hour, which is unexpected due to the higher cooling demand over occupied hours.

In the second period, the airflow occurred in May, while the highest mean temperature was in August. A gradual decrease starts from May to November. Then an increase started from December to May, again except November. Similarly, the proportion of provided airflow during an unoccupied hour increases gradually from 29% to 36%, the peak being in May. A comparison between required airflow and outdoor temperature indicates that the trend is not following the outdoor temperature. A possible reason could be higher airflow due to the pandemic. A population meter in the center could be advantageous for interpreting the observation.

A comparison between the two periods shows that lower temperature results in higher airflow as it should convey more heat to the space in colder months. From October to June, the lower the mean temperature caused higher the supplied airflow, except in December, when the mean outdoor temperature is notably lower, supply airflow did not decline significantly. A reverse relation between outdoor temperature and supply airflow can

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[2] Axis Y is presented on a logarithmic scale

be observed during a year except for July to September. In addition, during warm months, supply airflow increased to more than one-third over the occupied hours. However, unoccupied hours airflow did not vary markedly, which means supply air demand is higher during working hours whereas the major increase in colder months was during unoccupied hours. Increases in occupied and unoccupied hours were 5% and 15%, respectively.

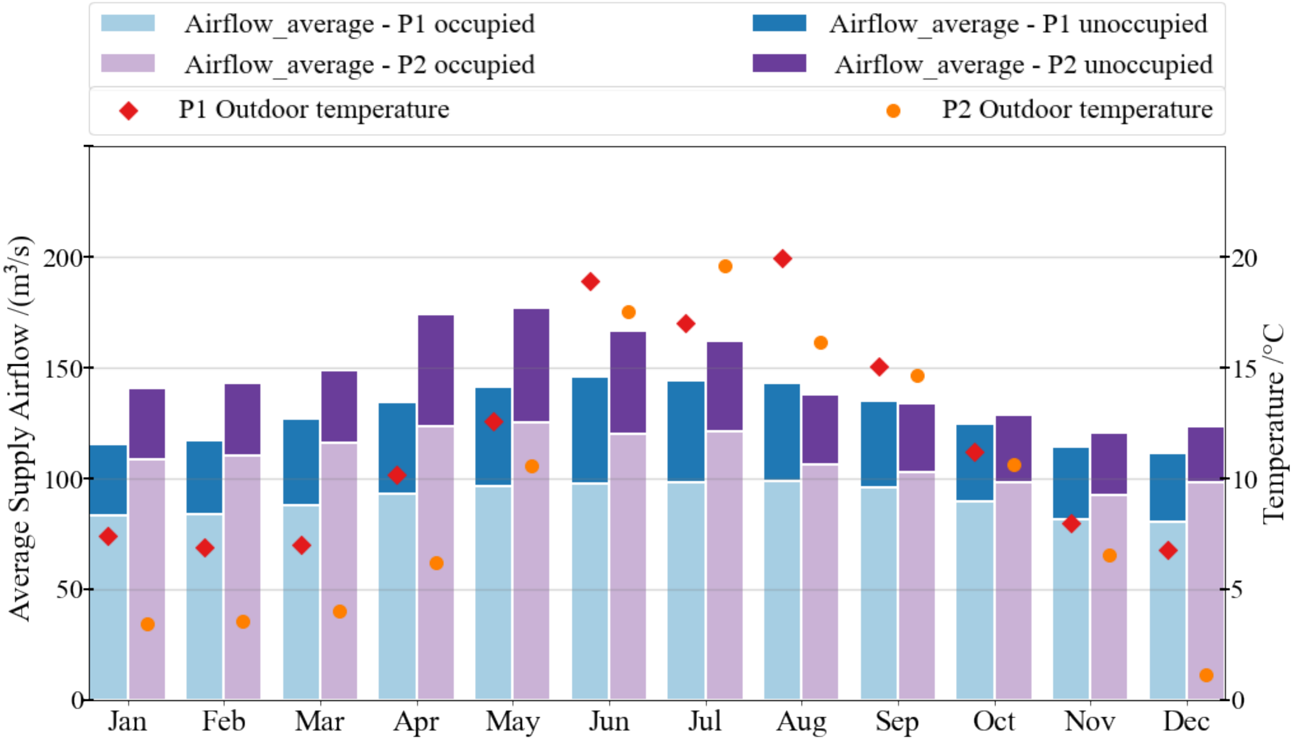

Figure 20 adjusted monthly supply airflow

3.2.5 Summary of occupied and unoccupied demands

Figure 21 provides information on the proportion of each variable during the whole year, cold months, and warm months.

Entire year - An observation of the entire year showed that, in period one, almost half of the district heating demand was consumed over unoccupied hours while the majority of cooling electricity was required during working hours. Proportions of tenant electricity and property electricity during working hours over unoccupied hours are almost identical. The overall pattern of the second period is similar to the first period. Although the percentage of aggregated heating degree hours during the unoccupied hour to overall heating degree hours are similar to the first period, a higher proportion of district heating flow is consumed during unoccupied hours. This means another parameter affected the proportion of required energy. It also could be observed that the proportion of provided supply airflow decreased regardless of the increase in energy demands over unoccupied hours (Figure 21 – Entire year).

Warm month (June to August) - The proportion of occupied-unoccupied hour variables over warm months is identical in the two periods.

Cold months (December – March) - Contrary to warm months, the pattern of occupied to unoccupied hours of the parameters is utterly distinguishable between the two periods. In the first period proportion of HDH and heating over an occupied-unoccupied hour are analogous, whereas the proportion of HDH and district heating flow are not relatable. A higher part of the energy is consumed during the occupied hour in the second period.

Considering cold months, the only airflow pattern remains constant while other parameters' patterns altered notably.

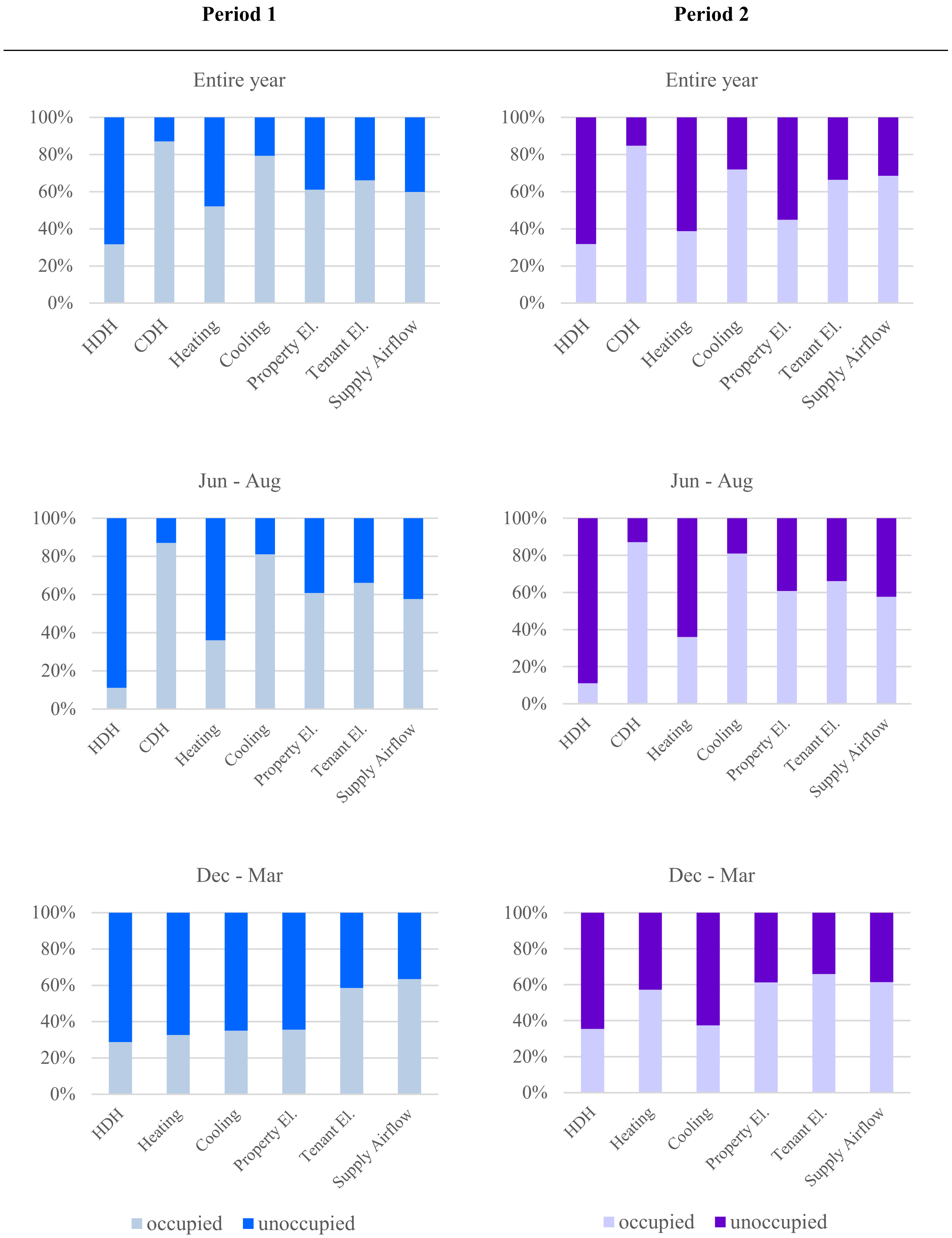

Figure 21 Aggregated proportion of variables over occupied and unoccupied hours.

Pearson Correlation Coefficients

Pearson Correlation Coefficient investigations on three scales of the entire year (annually correlations), warm/cold months, and warmest/coldest week based on an hourly interval are presented in this section. Only coefficients that indicate a relationship between dependent and independent variables in all the tables are desired to be discussed. It should be mentioned that district heating flow is constant during a month over warm months of the first period and throughout the entire second period. The most important parameter respecting to comfort heating is district heating flow, which is provided in hourly interval during cold months, the misleading impact of monthly interval measures of district heating flow during warm months could be overlooked. In each section, correlation between district heating, cooling electricity and property electricity. Since in second period district heating flow measured monthly while other variables are in hourly interval, correlation coefficients are not reliable. Then, the relation between tenant electricity and heating or cooling is evaluated in different time frames that those cooling and heating uses are predominant, and variation of the outdoor temperature is more extreme on those periods. Due to this, assessments are conducted over warm/cold months and weeks. The used terms of strength in bellow are identified in section 2.4.2.4.

3.2.6 Annually correlations

The Pearson Correlation matrix is presented in Table 15. All the mentioned relationships are in comparison to the assigned section's dependent variable.

Table 15 Pearson correlation coefficients over a year on each period

	Working Hour	**Time of day**	**Outdoor Temperature**	**HDH**	**CDH**	**District Heating**	**Cooling El.**	**Property El.**	**Tenant El.**	**Supply Airflow**
Working Hour	1	0.89	0.15	-0.13	0.11	0	0.31	**0.79**	**0.83**	**0.69**
Time of day	0.98	1	0.15	-0.12	0.11	0	0.30	**0.72**	**0.77**	**0.67**
Outdoor Temperature	0.17	0.17	1	-0.99	0.3	**-0.82**	**0.66**	0.07	0.20	0.31
HDH	-0.13	-0.13	-0.96	1	-0.17	**0.84**	-0.57	-0.05	-0.17	-0.29
CDH	0.15	0.16	0.45	-0.24	1	-0.11	0.52	0.09	0.14	0.15
District Heating	0.34	0.31	**-0.61**	**0.66**	-0.11	1	-0.41	0.08	-0.02	-0.12
Cooling El.	0.32	0.32	**0.69**	-0.52	**0.68**	-0.24	1	0.26	0.39	0.41
Property El.	0.63	0.62	0.03	**0**	0.08	0.44	0.23	1	0.89	**0.70**
Tenant El.	**0.80**	**0.79**	0.16	-0.11	0.16	0.43	0.36	0.84	1	**0.85**
Supply Airflow	**0.76**	**0.75**	0.3	-0.27	0.19	0.27	0.45	0.77	**0.92**	1

District heating (period 1) – The district heating, working hours, and time of day are moderately correlated. Although the corporation between district heating and outdoor temperature or HDH is strong, the correlation with HDH is stronger at about 0.05. In addition, district heating demand has a reverse relation with outdoor temperature. The correlation between district heating and cooling is negligible. Property electricity and tenant electricity have a strong positive relationship with district heating.

District heating (period 2) – District heating is not correlated to working hours, time of day, property, and tenant electricity, while it has a very strong correlation with outdoor temperature and HDH. Furthermore, its relationship with cooling electricity and supply airflow is strong. It should be considered that the relationship with outdoor temperature and cooling electricity are a reverse relation. A comparison between period one and two indicates that the correlation coefficient between district heating and outdoor temperature is 0.2 higher in quantity.

District heating (P1 versus P2) - The moderate correlation coefficient on working hour and time of day is interpreted as a significant part of district heating consumed over the unoccupied hour; therefore, a study regarding district heating demand corporations on occupied hours would provide further information. The impact of tenant electricity and property electricity on heating demand is positive, which needs a precaution in interpretation. A probability is that it can be arisen accidentally due to the synchrony in use.

Cooling El. (Period 1) - working hour and time of day are moderately related to cooling electricity, which is similar to district heating. Outdoor temperature and CDH are very strongly correlated to cooling electricity. In this case, cooling electricity has a reverse relationship with HDH, categorized as strong. However, there is a strong correlation between HDH and cooling, and the correlation with district heating is weak. Property electricity has a weak association where tenant electricity has a moderate relationship with cooling electricity. As property electricity includes required energy for AHUs, that makes the parts of the relation. It was expected that tenant electricity to have a highly positive association since excess heat from internal loads is compensated by cooling. Supply airflow has a strong relationship with cooling due to the fact that airflow is a means to distribute cooling to the indoor environment.

Cooling El. (Period 2) - relationships of all the factors can be interpreted equally to period one. The difference is on quantity which correlated weakly to outdoor temperature and CDH in period 2. Compared to CDH, the correlation coefficient between cooling electricity and outdoor temperature is marginally higher in both periods. Moreover, the correlation of CDH is lower than HDD. More investigation on cold months would be advantageous to explain the results.

Property El. (Period 1) – The correlation coefficient with working hour and time of day are very strong. There is no correlation between property electricity and outdoor temperature, HDH, or CDH. District heating has a strong relationship with property electricity while cooling electricity has a low correlation (weak). The correlation between tenant electricity and property electricity is high. Although a part of property electricity is dependent on the other factors, it is generally assumed as an independent variable; a high correlation between two independent variables can be interpreted as a similar pattern in demand of them. Supply airflow also has a very strong relationship, the strongest among the abovementioned relations.

Property El. (Period 2) – All the independent variables show the same relation in terms of interpretation except for district heating which, based on previous discussions on district heating and cooling, electricity was expected**.**

Tenant electricity – The only association of tenant electricity that has not been discussed is how tenant electricity is related supply airflow**.** Pearson's correlation coefficient is 0.92, the highest correlation studied for the entire year.

Below are comparisons made between the dependent variables and their influential parameters:

- Considering the quantity, the impact of HDH and CDH on electricity for cooling and district heating demand is higher in the second period.

- In terms of quantity, cooling electricity is more dependent on outdoor temperature than district heating demand. It could be explained that the building's domestic hot water demand is almost constant.
- Comparing the relation of outdoor temperature to cooling electricity or district heating, the correlation of cooling is higher. However, the high negative correlation with cooling and HDH is highly dependent on the fluctuation of temperature in the studied period; therefore, it cannot be generalized.
- In the first period, tenant electricity is stronger in district heating flow than cooling electricity. However, in the second period, tenant electricity is not related to district heating; The reason could be that tenant electricity over the second period is constant over each month while tenant electricity is varied hourly.

3.2.6.1 Annually correlation on occupied hours

Table 16 gives data on the relationship between dependent and independent variables over occupied hours. The aim is to compare occupied hours to 24-hours calculation.

Table 16 Occupied hours' Pearson correlation coefficients over a year on each period

	Time of day	**Outdoor Temperature**	**HDH**	**CDH**	**District Heating**	**Cooling El.**	**Property El.**	**Tenant El.**	**Supply Airflow**
Time of day	1	0.69	0.69	0.14	0.67	0.41	0.87	0.89	0.87
Outdoor Temperature	0.85	1	0.08	0.32	0.22	0.81	0.72	0.77	0.79
HDH	0.69	0.27	1	-0.05	**0.87**	-0.14	0.66	0.62	0.52
CDH	0.2	0.44	-0.07	1	-0.01	**0.49**	0.12	0.14	0.16
District Heating	0.66	0.3	**0.94**	-0.02	1	0	0.75	0.71	0.63
Cooling El.	0.44	0.77	-0.12	**0.71**	-0.02	1	0.41	0.47	0.51
Property El.	0.92	0.75	0.74	0.14	0.73	0.36	1	0.97	0.91
Tenant El.	0.96	0.83	0.71	0.19	0.70	0.43	0.96	1	0.95
Supply Airflow	**0.96**	**0.89**	**0.64**	0.21	**0.64**	0.49	**0.93**	**0.98**	1

District heating (Period 1) – The correlation coefficient of the time of day in an occupied hour is almost twice the 24-hours study, which is interpreted as very strong. The coefficient of the outdoor temperature is half of the correlation calculated for 24-hours. Moderate correlation results from higher district heating use at night due to the lower temperature and lower internal gain. On the other hand, HDH is very strongly related since it indicates building heating demand. CDH and cooling demand are not relatable. Property and tenant electricity have a very strong correlation. Supply airflow has a strong correlation. Except for the outdoor temperature, correlations of other variables of occupied hours are one level stronger than the 24-hours assessment (i.e., from moderate to strong).

District heating (Period 2) – All the calculated correlation coefficients are almost equal to period 1.

Cooling El. (Period 1) – Correlation coefficient of Time of day on occupied hours does not change significantly. The correlation of outdoor temperature to cooling is higher than the 24-hours calculation. Although HDH has a strongly negative correlation with cooling electricity for 24 hours, considering the occupied hour, the correlation is negligible. CDH has a stronger correlation. Property and tenant electricity have a strong relationship to cooling electricity which is substantially higher than the 24-hours calculation. Supply airflow remained strong.

Cooling El. (Period 2) – Correlations differ slightly from period one except CDH, which related strongly instead of very strong correlation. The reason could be the wrong base temperature in the calculation of CDH since the impact is more intense when the correlation is expected to be more robust due to the higher proportion of cooling demand during occupied hours.

Property El. (Period 1) – As major property electricity demand is during occupied hours, all the relations are more robust than 24-hours correlations.

Property El. (Period 2) – the difference between periods one and two are negligible.

In this case, temperature fluctuations are lower during the occupied hours, which means the impact of constant measured district heating is less severe. Thus, HDH is correlated more strongly with district heating.

3.2.7 Cold extreme week correlations

Table 17 gives information regarding the most extreme cold week. As observed in 4.1, cooling demand is a small fraction of total demand with a uniform pattern. Hence, electricity for cooling and CDH are disregarded from the table. District heating use in the second period is constant during the week, resulting in a correlation of 0.

Table 17 Pearson correlation coefficients over the coldest week on each period

	Day of week	**Working Hour**	**Time of day**	**Outdoor Temperature**	**HDH**	**District Heating**	**Property El.**	**Tenant El.**	**Supply Airflow**
Day of week	1	0.04	0.05	-0.25	0.25	0	-0.25	-0.26	-0.06
Working Hour	0.04	1	0.89	-0.04	0.04	0	0.66	0.65	0.66
Time of day	0.05	0.98	1	-0.04	0.04	0	0.61	0.61	0.64
Outdoor Temperature	0.02	0.19	0.19	1	-1	0	0.17	0.18	0.1
HDH	0	-0.14	-0.14	-0.96	1	0	-0.17	-0.18	-0.1
District Heating	-0.09	0.74	0.68	-0.24	0.24	1	0	0	0
Property El.	-0.06	0.66	0.65	0.05	-0.01	0.76	1	0.99	0.75
Tenant El.	-0.06	0.80	0.78	0.19	-0.13	0.87	0.87	1	0.71
Supply Airflow	-0.04	0.79	0.77	0.33	-0.29	0.86	0.86	0.98	1

District Heating (Period 1) - Day of the week is unrelated to district heating flow. The working hour and time of day are very strongly related. Outdoor temperature and HDH are identically correlated to district heating and have a moderate correlation. The reason is in extremely cold conditions, when the weather is too cold, due to the lack of occupancy, less energy is needed to reach the setpoints, while during the day, when the temperature is higher, more energy is needed for heating. The property energy coefficient is also very strong because a higher proportion of property electricity is dedicated to AHU electricity use. Therefore, change in property electricity is associated more with district heating. Tenant electricity and supply airflow are also strongly correlated to district heating.

In conclusion, as more energy is consumed during a day, it is more correlated to property electricity and tenant electricity which is highly consumed during the day.

District Heating (Period 2) – all the coefficients are zero since, on a weekly time frame, the measured district heating flow remains constant.

Property El. (Period 1) - working hour and time of day with a correlation coefficient of 0.66 and 0.65 are at the threshold of strong/very strong correlation. Relation of district heating flow, tenant electricity and supply airflow are completely equal to those of district heating. Outdoor temperature and HDH are not related to property electricity. Tenant electricity was the most impactful factor on district heating demand during the first period.

Property El. (Period 2) – in general, relations are stronger in the second period except for supply airflow and time of day.

A comparison of Extreme cold week with annual correlations shows that the only weaker relation is HDH to district heating. In more extreme conditions, HDH over nights will increase while a major proportion of district heating is used during the days.

3.2.8 Warm extreme week correlations

Coolin El. (Period 1) – the relation with working hour, and time of day to cooling are strong but not as strong as the outdoor temperature. The highest correlation coefficient of 0.84 is between cooling electricity and outdoor temperature. CDH is related significantly weaker than the outdoor temperature. Tenant electricity and supply airflow are also very strongly related to cooling electricity. Moreover, a positive relationship was anticipated with tenant electricity and property electricity, as tenant electricity and property electricity aggravate a high internal load to the building; therefore, cooling demand will change aligned with them.

Coolin El. (Period 2) – correlation of working hour in the second period is 0.1 higher than in the first period. In the second period, CDH and airflow are less related to cooling electricity than they were in the first period, but the other variables are more strongly related. The more extreme warm temperature causes the more critical difference between the correlation of outdoor temperature and the correlation of CHD.

Property El. (Period 1) – working hour, time of day, tenant electricity and supply airflow are very strongly correlated to the property electricity. The weakest relation is between property electricity and CDH while outdoor temperature is strongly correlated.

Property El. (Period 2) – All the parameters are more related to the property electricity in the second period except for outdoor temperature, which converted from strong to a moderate relationship. Despite a decline in outdoor temperature coefficients, CDH correlations increased.

The most powerful relationship is between supply airflow and tenants' electricity in both study periods.

In the first period, supply airflow also has a strong relationship with property electricity, while in the second period, it is not as strong as in the first period. The most robust relation between cooling electricity and outdoor temperature is supply airflow, tenants' electricity, and cooling degree hours. Notably, the impact of the outdoor temperature is stronger than CDH.

In the second period, cooling electricity mostly depends on outdoor temperature and time of day. Similar to the first period, Cooling demand is less dependent on CDH than on outdoor temperature (Table 18).

Table 18 Pearson correlation coefficients over the warmest week on each period

	Day of week	Working Hour	Time of day	Outdoor Temperature	CDH	Cooling El.	Property El.	Tenant El.	Supply Airflow
Day of week	1	0.04	0.05	0.19	-0.08	-0.05	-0.06	-0.06	-0.08
Working Hour	0.04	1	0.89	0.54	0.36	0.65	0.78	0.85	0.70
Time of day	0.05	0.98	1	0.51	0.37	0.61	0.71	0.78	0.68
Outdoor Temperature	0.23	0.45	0.46	1	0.58	0.77	0.32	0.56	0.51
CDH	0.23	0.19	0.21	0.65	1	0.55	0.21	0.34	0.31
Cooling El.	0.13	0.54	0.55	0.84	0.62	1	0.50	0.75	0.65
Property El.	-0.14	0.66	0.67	0.40	0.10	0.49	1	0.82	0.60
Tenant El.	-0.08	0.82	0.81	0.56	0.21	0.68	0.82	1	**0.87**
Supply Airflow	-0.11	0.77	0.75	0.53	0.2	0.67	0.79	**0.94**	1

3.2.9 Cold months correlations

District heating (Period 1) – working hour and property electricity correlation coefficients are just above the very strong correlation threshold. Time of day's relationship is strong. Outdoor temperature and HDH are strongly related to district heating. Tenant electricity and supply airflow are strongly related to district heating. The relationship between district heating and tenant electricity is stronger than HDH, working hours, and working time in the first period.

All the monthly correlation values are all between weekly and annual values. All correlations except HDH and outdoor temperature in cold months are more potent than in the annual assessment.

District Heating (Period 2) – Only correlation with HDH and outdoor temperature have been calculated. The result is lower than the first period but still interpreted as strong correlation.

Property Electricity (Period 1) - the strength of outdoor temperature's correlation and HDH are significantly higher than an extremely cold week and the entire year, those are considered strong relations. Other correlations are comparable. The reason for this is required to be studied more. One hypothesis can be the impact of the cold cycle's length on property electricity. Results of the second period could accept or reject the statement.

Property Electricity (period 2) – Results show that the strength of correlations is significantly higher than in the first period. However, both periods are in the range of very strong correlation. Outdoor temperature and HDH are aligned with weekly and annual patterns in quantity.

The highest correlation is 0.94 between supply airflow and tenant electricity.

Property electricity and working time/working hours with a correlation coefficient of 0.80 and 0.74 versus 0.66 and 0.67 outlines a stronger relation in the second period than in the first period. However, the lack of proper data on district heating makes it challenging to conclude that relations are more intense in the second period.

Table 19 Pearson correlation coefficients over cold months on each period

	Day of week	**Working Hour**	**Time of day**	**Outdoor Temperature**	**HDH**	**District Heating**	**Property El.**	**Tenant El.**	**Supply Airflow**
Day of week	1	0.04	0.05	0.04	-0.04	0	-0.10	-0.10	-0.06
Working Hour	0.04	1	0.89	0.12	-0.12	0	**0.80**	0.80	**0.68**
Time of day	0.05	0.98	1	0.12	-0.12	0	**0.74**	0.74	**0.66**
Outdoor Temperature	0.23	0.45	0.46	1	-1	-0.37	0.08	0.15	0.14
HDH	-0.12	-0.49	-0.50	-0.85	1	0.37	-0.08	-0.15	-0.14
District Heating	0.02	**0.66**	**0.61**	-0.44	0.44	1	0.02	0	0.02
Property El.	-0.14	**0.66**	**0.67**	0.40	-0.51	**0.66**	1	0.95	**0.85**
Tenant El.	-0.08	0.82	0.81	0.56	-0.64	**0.76**	0.82	1	**0.82**
Supply Airflow	-0.11	0.77	0.75	0.53	**-0.62**	**0.73**	**0.79**	**0.94**	1

3.2.9.1 Cold months occupied hours coefficients

Since the working hour of the shopping mall is varied during weekdays and weekends, to investigate the correlation between time of the day and energy demands in detail, a study of Pearson Correlation was implemented on only occupied hours. Study of correlation coefficient during occupied hours, working hours which represents occupied-unoccupied hours are excluded from the study (Table 20).

District heating has a correlation of 0.96 to heating degree hours which is higher by about 0.2 than the correlation of outdoor temperature. Therefore, time of day and district heating is not as related as other factors like district heating and HDH, which are strongly related.

Although supply airflow is strongly related to tenant and property electricity, higher coefficients are calculated in the first period.

Table 20 Pearson correlation coefficients over cold months on occupied hours

	Time of day	**Outdoor Temperature**	**HDH**	**District Heating**	**Property El.**	**Tenant El.**	**Supply Airflow**
Time of day	1	0.59	0.95	-	0.89	0.87	0.85
Outdoor Temperature	0.94	1	0.42	-	0.57	0.68	0.62
HDH	0.95	0.87	1	-	0.88	0.85	0.79
District Heating	0.86	**0.76**	**0.96**	1	-	-	-
Property El.	0.93	0.90	0.93	0.88	1	0.99	0.93
Tenant El.	0.96	0.93	0.96	0.91	0.97	1	0.92
Supply Airflow	0.96	0.94	0.96	0.91	0.96	0.99	1

3.2.10 Warm months Coefficients

Coolin El. (Period 1) – working hour, time of day property electricity are strongly correlated. No weak or moderated correlation has been detected during the warm cycle. Outdoor temperature and CDH correlations are interpreted as very strong correlations, despite the substantial variance between the two coefficients (Table 21).

Coolin El. (Period 2) – All the coefficients are strongly and very strongly related to the cooling electricity. A comparison of the correlation between cooling electricity and the other variables on weekly and monthly bases revealed that any changes in the correlation of outdoor temperature have a direct impact on the correlation of CHD and supply airflow.

Property El. (Period 1) - the strong relationships have been detected with working hours and time of day. The coefficient of cooling electricity and working hours is interpreted as high cooling demand during unoccupied hours. Outdoor temperature is moderately related to the outdoor temperature, whereas CDH is associated weakly. Supply airflow correlated very strongly to property electricity. One reason is that when supply airflow increases, property electricity increases because the required energy for AHUs is a part of property electricity.

property El. (Period 2) – in the second period, the relation of CDH and supply airflow are smaller in quantity. The difference in the strength of the relationship of working hour and time of day is substantially higher in the second period. Correlation with outdoor temperature, cooling, and tenant electricity are almost comparable to the first period.

Table 21 Pearson correlation coefficients over warm months on each period

	Working Hour	**Time of day**	**Outdoor Temperature**	**CDH**	**Cooling El.**	**Property El.**	**Tenant El.**	**Supply Airflow**
Working Hour	1	0.89	0.47	0.23	0.64	0.78	0.84	0.71
Time of day	0.98	1	0.44	0.21	0.60	0.70	0.77	0.68
Outdoor Temperature	0.46	0.47	1	0.60	0.80	0.40	0.54	0.52
CDH	0.31	0.33	0.72	1	0.55	0.19	0.26	0.25
Cooling El.	0.60	0.61	0.82	0.69	1	0.58	0.77	0.68
Property El.	0.62	0.61	0.39	0.24	0.57	1	0.83	0.61
Tenant El.	0.81	0.80	0.54	0.35	0.73	0.81	1	0.87
Supply Airflow	0.77	0.75	0.49	0.32	0.72	0.78	0.93	1

3.3 Discussion

On the coldest week, district heating and property electricity are fully aligned with working hours and time of the day. Also, tenant electricity and supply airflow are strongly related to district heating demand. Heating degree hour does not correlate linearly to district heating use. In the period from June to August cooling electricity is highly correlated to all the independent factors in addition to property electricity. As the quantity of correlation factors is comparable, the extreme week could be a representative of a warm period.

Cooling electricity is highly dependent on working hour, time of day, tenant electricity, and supply airflow. However, it should be noted that supply airflow is not an independent factor. In contrast, the relationship between cooling demand and property electricity is weak. The pattern of the relations is similar to the coldest week. The only acceptance is HDH and OT, which have been estimated to be more influential over four months. Thus, an extremely cold week cannot be assessed as an indicator of a cold period.

Table 22 summarizes the strongest correlation coefficients calculated on annual evaluation. All mentioned influential factors are independent variables with a correlation coefficient higher than 0.50. Although the outdoor temperature is highly correlated, heating degree hour is a more powerful coefficient. Although cooling degree hours are related less to the cooling electricity than the outdoor temperature, finding a new base temperature to calculate cooling degree hour will amend the results. Working hour, tenant electricity, and supply airflow are the pragmatic factors that can be used in a shopping mall's performance assessment. Availability of data from tenant electricity use is a concern that should be considered. Although Time of day is one of the crucial variables, it is impractical to use in overall performance assessment. Considering the time of day in building performance assessment would reveal how modification of starting and ending time, without any changes in working time, would influence building energy performance.

Table 22 Crucial Pearson's correlation coefficient based on annual assessments

	Period 1		**Period 2**	
District heating	Outdoor temperature	-0.61	Outdoor temperature	-0.82
	HDH	0.66	**HDH**	0.84
Cooling El.	Outdoor temperature	0.69	Outdoor Temperature	0.66
	HDH	-0.52	HDH	-0.57
	CDH	0.68	**CDH**	0.52
Property El.	**Working hour**	0.63	**Working hour**	0.79
	Time of day	0.62	Time of day	0.72
	Tenant El.	0.84	**Tenant El.**	0.89
	Supply airflow	0.77	**Supply airflow**	0.70

In a cold cycle of a year, since cooling demand is negligible compared to district heating flow and electricity use, it is ignored from investigations. Cold condition analysis can represent a climate with colder outdoor temperatures and less fluctuation in temperature. Results presented in Table 23 show that contrary to the whole year assessment, working hour, time of day, property El., tenant El., and supply airflow are highly related to district heating. Property electricity is ignored as it comprises electricity required for district heating equipment to run. Thus, the reason for the relationship might be accidentally high by a mutual effect on the need for heating. As an increase in Tenant electricity should decrease the heating demand, the positive relation is due to the relevant factors.

Table 23 Crucial Pearson's correlation coefficient based on cold cycle assessments

Cold	**Period 1**			**Period 2**		
Condition	**Variable**	**Week**	**Months**	**Variable**	**Week**	**Months**
District heating	**Working Hour**	0.74	0.66	-	-	-
	Time of Day	0.68	0.61	-	-	-
	Property El.	0.76	0.66	-	-	-
	Tenant El.	0.87	0.76	-	-	-
	Supply airflow	0.86	0.73	-	-	-
Property El.	**Working hour**	0.66	0.66	**Working hour**	0.66	0.80
	Time of day	0.65	0.67	Time of day	0.61	0.74
	District Heating	0.76	0.66		-	
	Tenant El.	0.87	0.82	Tenant El.	0.99	0.95
	Supply Airflow	0.86	0.79	**Supply Airflow**	0.75	0.85

Warm condition analysis can represent a climate with warmer outdoor temperatures and lower fluctuation in temperature. Table 24 shows that in warmer conditions, number influential factors are higher than cold conditions or annual assessments. Contrary to district heating in cold conditions, CDH is positively correlated to cooling demand. Tenant electricity is highly correlated, and the reliability of the high correlation coefficient between cooling and tenant electricity is needed more studies to be approved.

Table 24 Crucial Pearson's correlation coefficient based on warm cycle assessments

Warm condition	**Period 1**			**Period 2**		
	Variable	Week	Months	Variable	Week	Months
Cooling El.	**Working hour**	0.54	0.60	**Working hour**	0.65	0.64
	Time of day	0.55	0.61	Time of day	0.67	0.60
	Outdoor temperature	0.84	0.82	Outdoor temperature	0.77	0.80
	CDH	0.62	0.69	**CDH**	0.55	0.55
	Property El.	0.49	0.57	Property El.	0.50	0.58
	Tenant El.	0.68	0.73	**Tenant El.**	0.75	0.77
	Supply airflow	0.67	0.72	**Supply airflow**	0.65	0.63
Property El.	**Working hour**	0.66	0.62	**Working hour**	0.78	0.78
	Time of day	0.67	0.61	Time of day	0.71	0.70
	Cooling El.	0.49	0.57	Cooling El.	0.5850	0.58
	Tenant El.	0.82	0.81	Tenant El.	0.82	0.83
	Supply Airflow	0.79	0.78	**Supply Airflow**	0.60	0.61

The analysis revealed that the shopping mall's load profile exhibits significant and repeatable daily, weekly and annual load profiles depicted in section 3.2 and Appendix C. The energy demand is positively correlated with time of day, occupancy, tenants' electricity loads, and outdoor temperature. As it has been mentioned in Data gathering method 2.2), due to the lack of energy meters on system and component level, assessment of building zones was not applicable in this case. Hence, correlations have been investigated yearly, seasonally, and weekly to simulate different cases by considering varied weather conditions. Two cases of annual assessment of period one and two, two cases of cold months of P1 and P2, two cases of warm months of P1 and P2, two cases of coldest week of P1 and P2, and two cases of the warmest week of P1 and P2; in total 10 conditions are investigated as different cases to distinguish between typical years, warm/ cold conditions. Over a year, the number of influential factors is lower than in cold conditions, and cold condition is lower than in warm conditions. On annual assessment, district heating is mainly related to heating degree hour, whereas it is highly correlated to working hour, time of day, and supply airflow in cold conditions. The reason is during cold conditions, heating is predominant energy use, but annually assessment includes cooling and property electricity over warm conditions in addition to cooling energy use; heating energy use is almost constant during warm conditions. Cooling electricity is positively related to cooling degree hour, supply airflow, and negatively related to heating degree hour. In warm conditions, cooling is correlated to working hours, cooling degree hours, property electricity, tenant electricity, and supply airflow. The same logic could explain higher correlation to working hour during warm months. Moreover, tenant electricity, which is an internal load increases needs for extracting of extra heat; thus, when tenant electricity is increased, energy use of two cooling units is also grown.

Although about 30 % of property electricity is used during unoccupied hours, it is still highly related to working hours, tenant electricity, and supply airflow. In addition, in cold conditions, it is correlated to district heating flow, while in warm conditions, it is related to electricity for cooling.

A limitation of the research was using Pearson correlation coefficient, which was unable to capture the non-linear relationships between variables or the assumption that independent and dependent variables had linear relationships. To perceive the pattern between variables, scatter graphs are analyzed and presented in Appendix B. The depicted graph will show which relation is strong but non-linear. Also, the of weaker correlation between CDH and cooling electricity in comparison to outdoor temperature and cooling electricity can be seen in the scatter graphs, where it is indicates cooling electricity use while calculated CDH based on 23.3℃ is zero.

However, the study deals with only one building; therefore, it is imperative to conduct further analysis on a larger sample to draw more general conclusions. Although, the results are likely only representative of a building with identical characteristics, applied methodology which was based on typical and established statistical methods/tools can be applied to other buildings. The requirement for energy can be affected by other factors which are not taken into consideration in this research, and do not depend on envelope materials and constructions. For instance, energy load may also be driven by the fact that those set points could be varied from case to case or time to time as it was seen in monthly demand pattern showed energy demand for unoccupied hours had increased during the second period, where overall building characteristics were not changed.

As it was discussed in Sorting and categorization2.3), lack of energy meters on system and components level was one of the crucial limitations of the study. Installation of energy meters on the component level will give information to implement detailed evaluation of building on zones level. Adding meters to each AHU will facilitate study of property electricity use and its operational and functional settings. Then district heating can be assessed on each section, considering district heating flow, aggregated measured AHUs settings and floor area as it is varied in each section. Number of occupants could be one the influential factor which are not investigated in this study due to the limitation in archived data on the control system, that were filed just over few weeks. Recording and archiving number of visitors is one the scopes which can be investigated in future study to identify the relation between occupancy and energy use, specifically cooling and heating.

Quantitative analysis of influential factors on the energy demand of shopping malls provides essential information for decision-makers at both the design and maintenance stages. A facility manager can reduce the energy use by taking preventive actions based on the results showing that tenant electricity usage leads to higher energy demand. The observed energy demand patterns show that the highest energy demand is highly correlated with the time of day when the temperature and irradiation are also high in summer. Useful information regarding Occupied and unoccupied energy use are studied in demand pattern shows both impact of temperature and operational settings can be utilized by facility managers. Nevertheless, conducted analysis in this study does not provide ready-to-use KPIs, it should be considered a preliminary study of factors influencing the energy use of shopping malls. This research can be used as a basis for further analysis to define a new performance indicator or make a statistical model to estimate shopping malls' energy use in regression studies.

4 Conclusion

Since it is an established fact that outdoor temperature influences the building's energy demands, additional energy is needed to maintain a thermal comfort in the indoor environment by, for example, removing excessive heat (cooling) or providing fresh air. This research aimed to analyze the energy use of a shopping center in Sweden and find the most influential factors in building energy demand. The selected building is a well-visited center with 71800 m^2 and about 12 million visitors per year. Outcome of the implemented analysis can be used in building demand-side management. This study measured the relationship between the independent variables such as outdoor temperature, working hours, time of day, tenant electricity demand, and energy demands and aimed at distinguishing typical annual energy patterns based on statistical tools including the Pearson coefficient of correlation and linear regression analysis. As initial data, three-year time series of hourly energy use, HVAC systems operational data, and weather data were obtained from the building control system. Influential factors were selected due to the availability of data, and the available literature on the relationship between weather data, operational parameters, and energy performance is missed from commercial buildings, including shopping malls. Furthermore, shopping malls have specific characteristics which cannot be assessed with the same method as offices.

Quantitative analysis of influential factors on the energy demand of shopping malls provides essential information for decision-makers at both the design and maintenance stages. A facility manager can reduce the energy use by taking preventive actions based on the results showing that tenant electricity usage leads to higher energy demand. The observed energy demand patterns show that the highest energy demand is highly correlated with the time of day when the irradiation is also high in summer. Understanding the relationships between several variables or demand patterns does not necessarily lead to energy savings or other benefits. The analysis conducted in this study does not provide ready-to-use KPIs and should be considered a preliminary study of factors influencing the energy use of shopping malls. This research can be used as a basis for further analysis to define a new performance indicator or make a statistical model to estimate shopping malls' energy use.

The conducted analysis revealed that the shopping mall’s load profile exhibits significant and repeatable daily and weekly load profiles, and that energy demand is positively correlated with time of day, occupancy, tenants’ electricity loads, and outdoor temperature. Correlations have been investigated on a yearly, seasonally, and weekly basis investigations aim to distinguish between typical year, warm/ cold conditions, and extreme conditions. The number of influential factors over a year is less than in cold condition, and the cold condition is less than in warm conditions. On annual assessment, district heating is mainly related to heating degree hour while in the cold condition, it is highly correlated to working hour, time of day and supply airflow. Cooling electricity is positively related to cooling degree hour, supply airflow, and negatively related to heating degree hour. In warm conditions, cooling is correlated to working hour, cooling degree hour, property electricity, tenant electricity, and supply airflow. Property electricity is correlated working hour, tenant electricity, and supply airflow. In addition, in cold conditions, it is correlated to district heating flow, and in warm conditions, it is correlated to electricity for cooling.

As cooling demand is less related to outdoor temperature than cooling degree hour, a precaution is needed in the selection of base temperature for cooling degree hour. However, heating degree hour is strongly correlated to district heating demand; worth to mention that part of district heating flow is domestic hot water use which is not entirely dependent on the outdoor temperature.

Supply airflow has a low correlation with outdoor temperature, cooling degree hour, and heating degree hours. On the other hand, it is highly related to tenant electricity use in all the studied periods. As tenant electricity use is one of the most influential variables. In addition, a demand pattern study showed that a considerable part of the tenant electricity uses occur during unoccupied hours. Although tenant electricity use is not under the authority of the building owner or manager, making guidelines and rules to reduce it would be beneficial for both tenants and owners.

The strong relationship between airflow and property electricity could be interpreted as increasing in airflow would cause in rising in property electricity due to growth in AHU’s energy demand. In annual calculation, property electricity is more reliant on working hours than heating and cooling. Therefore, it could be used as a factor in primary energy calculations. However, more regression analysis is required to calculate a factor.

This study was constrained by tools, such as the Pearson correlation coefficient, which was unable to capture the non-linear relationships between variables or the assumption that independent and dependent variables had linear relationships. In addition, the study deals with only one building; therefore, it is imperative to conduct further analysis on a larger sample to draw more general conclusions. The applied methodology was based on typical and established statistical methods/tools. Therefore, this approach can be applied to other buildings. However, the results are likely only representative of a building with identical characteristics. Moreover, the requirement for energy can be affected by other factors that are not taken into consideration and those do not depend on envelope materials and constructions; energy load may also be driven by the fact that those set points could be varied from case to case or time to time. For example, the presented monthly demand pattern showed energy demand for unoccupied hours had increased during the second period, although overall building characteristics were not changed.

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Appendix A

Table A 1 Categorized meters and time frames

Category		Meter	Unit	Start	End
Chillers	Multiple parameters	VKA1 , VKA2, VKA3, VKA4, VKA5	Multiple	8/9/19	3/10/22
AHUs	Multiple parameters	FTX 10 , FTX12, FTX15 , FTX25, FTX32 , FTX33, FTX34, FTX35, FTX36, FTX37, FTX38, FTX39, FTX40, FTX41, FTX42, FTX43, FTX44 , FTX43, TA01, TA02, TA03, TA04, TA05, TA06, TA08, TA09, TA26, TA31, TA17, TA29	Multiple	3/14/19	9/23/20
	Multiple parameters	FTX10-M, FTX12 M, FTX14 M, FTX25 M, FTX32 M,FTX33 M, FTX34 M,FTX35 M,FTX36 M, FTX37 M,FTX38 M,FTX39 M, FTX40 M,FTX41 M,FTX42 M, FTX44 M, FTX43 M,TA01 M, TA03 M, TA02, TA04, TA05, TA06, TA08, TA09, TA17,TA26, TA13, TA29, TA31, FTX15	Multiple	2/12/21	3/14/22
DH Plants	Multiple parameters	VVX1, VVX4, VVX5	Multiple	3/14/19	3/14/22
		VVX3	Multiple	5/23/19	3/14/22
Cooling Energy	Energy	Cooling	MWh	1/1/19	3/14/22
		Cooling	kWh	1/1/19	3/14/22
	Property meters	EL. Unit1	MWh	1/1/19	3/14/22
		El. Unit2	MWh	1/1/19	3/14/22
		EL. Unit 1,2	kWh	1/1/19	3/14/22
Property energy	El. Incl. Cooling	Electricity No Tariff	MWh	1/1/19	3/14/22
	El. Excl. Cooling	Electricity No Tariff	kWh	1/1/19	3/14/22
	Electricity property (F)	Electricity	kWh	1/1/19	3/14/22
	Electricity property (H)	Electricity	kWh	1/1/19	3/14/22
	Energy meters	Heating demand flow	kWh	1/1/19	3/14/22
		District heating	MWh	1/1/19	3/14/22
Heating Energy	Property meters	District heating flow (A)	m^3	1/1/19	3/14/22
		District Heating(F)	kWh	1/1/19	3/14/22
		District Heating(F) Volume	m^3	1/1/19	3/14/22
		District Heating(A) Heat	MWh	1/1/19	3/14/22
Tenant electricity	Billing meter	Tenant Electricity	kWh	1/1/19	3/14/22
Weather		Temperature	˚C	6/8/20	3/14/22

Table A 2 Summary of dependent and independent variables from June to August

	Period 1	**Period 1**	Period 1	**Period 2**		
	occupied	unoccupied	occupied	unoccupied	occupied	unoccupied
HDH	335	2681	1797	3142	536%	117%
CDH	762	113	310	58	41%	52%
Heating	60055	106763	81743	110561	136%	104%
Cooling	432470	101290	421476	169386	97%	167%
Property El.	1365530	878710	1519413	1864294	111%	212%
Tenant El.	1001478	512459	1113175	565884	111%	110%
Supply Airflow	81235380	59557490	111650200	63290420	137%	106%

Table A 3 Summary of dependent and independent variables from December to March

	Period 1	**Period 1**	Period **1**	**Period 2**		
	occupied	unoccupied	occupied	unoccupied	occupied	unoccupied
HDH	11207	27827	10988	20069	98%	72%
CDH	0	0	0	0		
Heating	386420	795595	565988	422296	146%	53%
Cooling	2499	4624	7670	12850	307%	278%
Property El.	1241069	2241210	2193330	1388150	177%	62%
Tenant El.	1037589	733591	1359385	701752	131%	96%
Supply Airflow	85715250	49362660	90326870	56768410	105%	115%

Table A 4 Summary of dependent and independent variables over period 1 and period 2 (whole year calculation)

	Period 1	Period 1	Period 1	Period 2		
	occupied	unoccupied	occupied	unoccupied	occupied	unoccupied
HDH	18639	40191	24395	52270	131%	130%
CDH	763	113	323	58	42%	52%
Heating	927060	852681	807641	1280990	87%	150%
Cooling	554280	145010	683195	266823	123%	184%
Property El.	6063720	3856990	6056598	7462847	100%	193%
Tenant El.	4065062	2087656	4381837	2219072	108%	106%
Supply Airflow	296632300	199332600	402112900	184774700	136%	93%

Table A 5 Pearson correlation coefficients using hourly intervals

entire year-hourly data	**Day of week**	**Working Hour**	**OT**	**HDH**	**CDH**	**District Heating**	**Cooling El.**	**Property El.**	**Tenant El.**	**Supply Airflow**
Day of week	1	0.04	0.02	-0.02	0.01	-0.01	-0.01	-0.09	-0.08	-0.08
Working Hour	0.04	1	0.15	-0.13	0.11	0	0.31	0.79	0.83	0.69
OT	0.04	0.17	1	-0.99	0.3	-0.82	0.66	0.07	0.20	0.31
HDH	-0.02	-0.13	-0.96	1	-0.17	**0.84**	-0.57	-0.05	-0.17	-0.29
CDH	0.05	0.15	0.45	-0.24	1	-0.11	**0.52**	0.09	0.14	0.15
District Heating	-0.01	0.34	-0.61	**0.66**	-0.11	1	-0.41	0.08	-0.02	-0.12
Cooling El.	0.01	0.32	0.69	-0.52	**0.68**	-0.24	1	0.26	0.39	0.41
Tenant El.	-0.06	0.63	0.03	0	0.08	0.44	0.23	1	0.89	0.70
Property El.	-0.07	0.80	0.16	-0.11	0.16	0.43	0.36	0.84	1	0.85
Supply Airflow	-0.06	0.76	0.30	-0.27	0.19	0.27	0.45	0.77	0.92	1

Table A 6 Pearson correlation coefficients using daily intervals

	Day of week	**OT**	**HDH**	**CDH**	**Cooling EL.**	**District Heating**	**Property El.**	**Tenant El.**	**Supply Airflow**
Day of week	1	0.02	-0.02	NaN	-0.01	-0.02	-0.44	-0.53	-0.26
Working Hour	0.62	0	0.01	NaN	-0.01	-0.03	-0.29	-0.37	-0.21
OT	0.04	1	-0.97	NaN	-0.85	0.85	-0.33	0.17	0.63
HDH	-0.02	-0.95	1	NaN	0.84	-0.78	0.29	-0.18	-0.62
CDH	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
Cooling EL.	0.02	0.87	-0.79	NaN	1	-0.63	0.38	-0.14	-0.51
District Heating	-0.02	-0.85	0.84	NaN	-0.55	1	-0.23	0.21	0.63
Property El.	-0.28	-0.43	0.33	NaN	-0.33	0.49	1	0.7	0.01
Tenant El.	-0.39	-0.11	0.04	NaN	-0.06	0.21	0.86	1	0.32
Supply Airflow	-0.28	0.6	-0.59	NaN	0.48	-0.53	-0.16	0.2	1

Table A 7 Pearson correlation coefficients using monthly intervals

	OT	**HDH**	**CDH**	**District Heating**	**Cooling El.**	**Property El.**	**Tenant El.**	**Supply Airflow**
OT	1.00	-0.78	0.78	-0.91	0.92	0.13	0.54	0.93
HDH	-0.92	1.00	-1.00	**0.62**	-0.75	-0.22	-0.42	-0.89
CDH	0.92	-1.00	1.00	-0.62	**0.75**	0.22	0.42	0.89
District Heating	-0.93	**0.87**	-0.87	1.00	-0.71	-0.08	-0.42	-0.78
Cooling	0.93	-0.83	**0.83**	-0.74	1.00	0.11	0.59	0.91
Property El.	-0.58	0.53	-0.53	0.66	-0.48	1.00	0.57	0.27
Tenant El.	-0.15	0.18	-0.18	0.22	-0.13	0.86	1.00	0.52
Supply Airflow	0.86	-0.78	0.78	-0.87	0.74	-0.81	-0.44	1.00

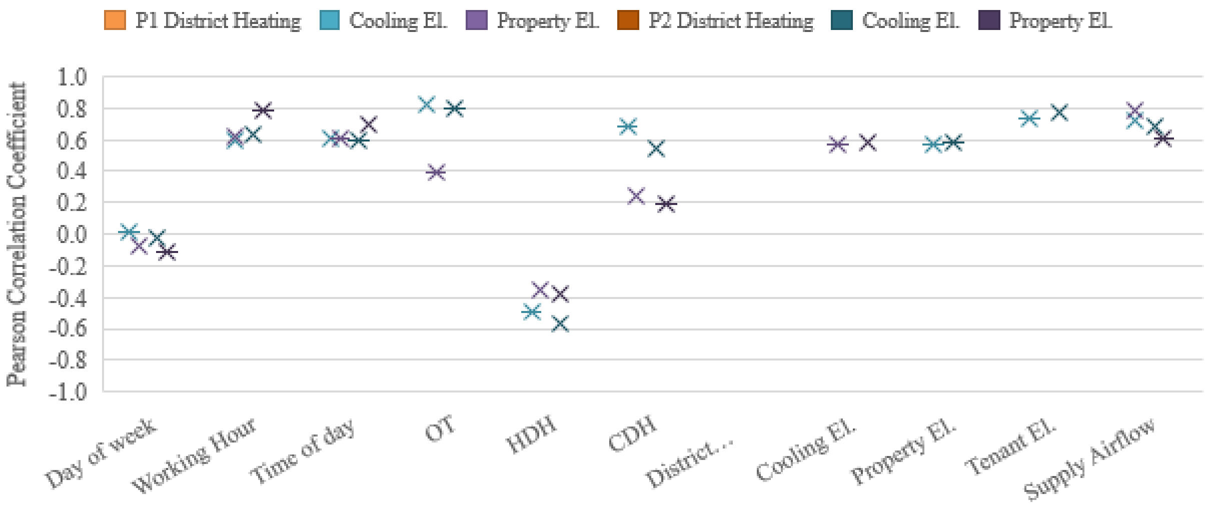


Figure A- 1 Distribution of Pearson correlation studied from June to August.

Figure A- 2 Distribution of Pearson correlation studied on warmest week.

Figure A- 3 Distribution of Pearson correlation studied from December to March

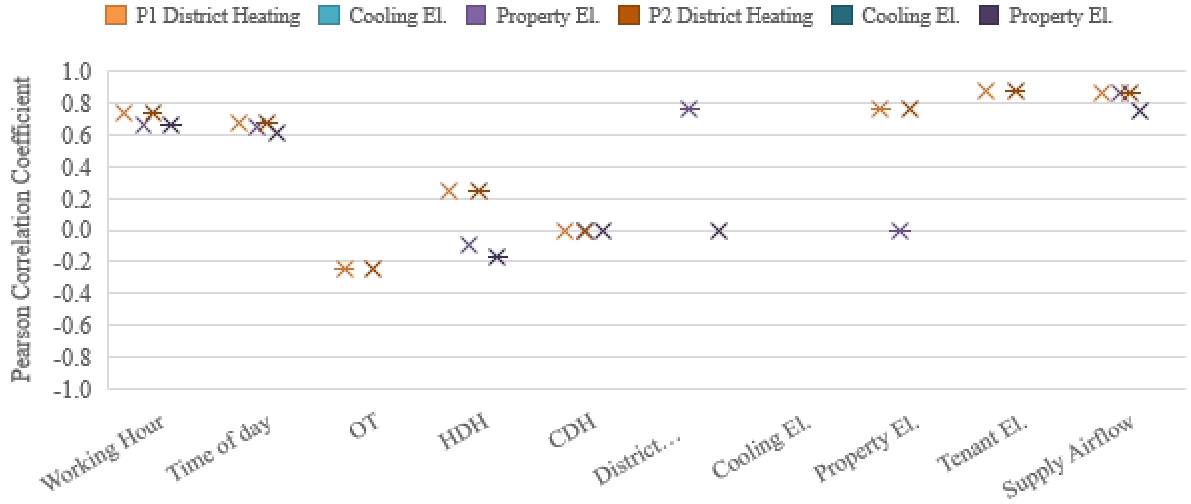


Figure A- 4 Distribution of Pearson correlation studied on coldest week.

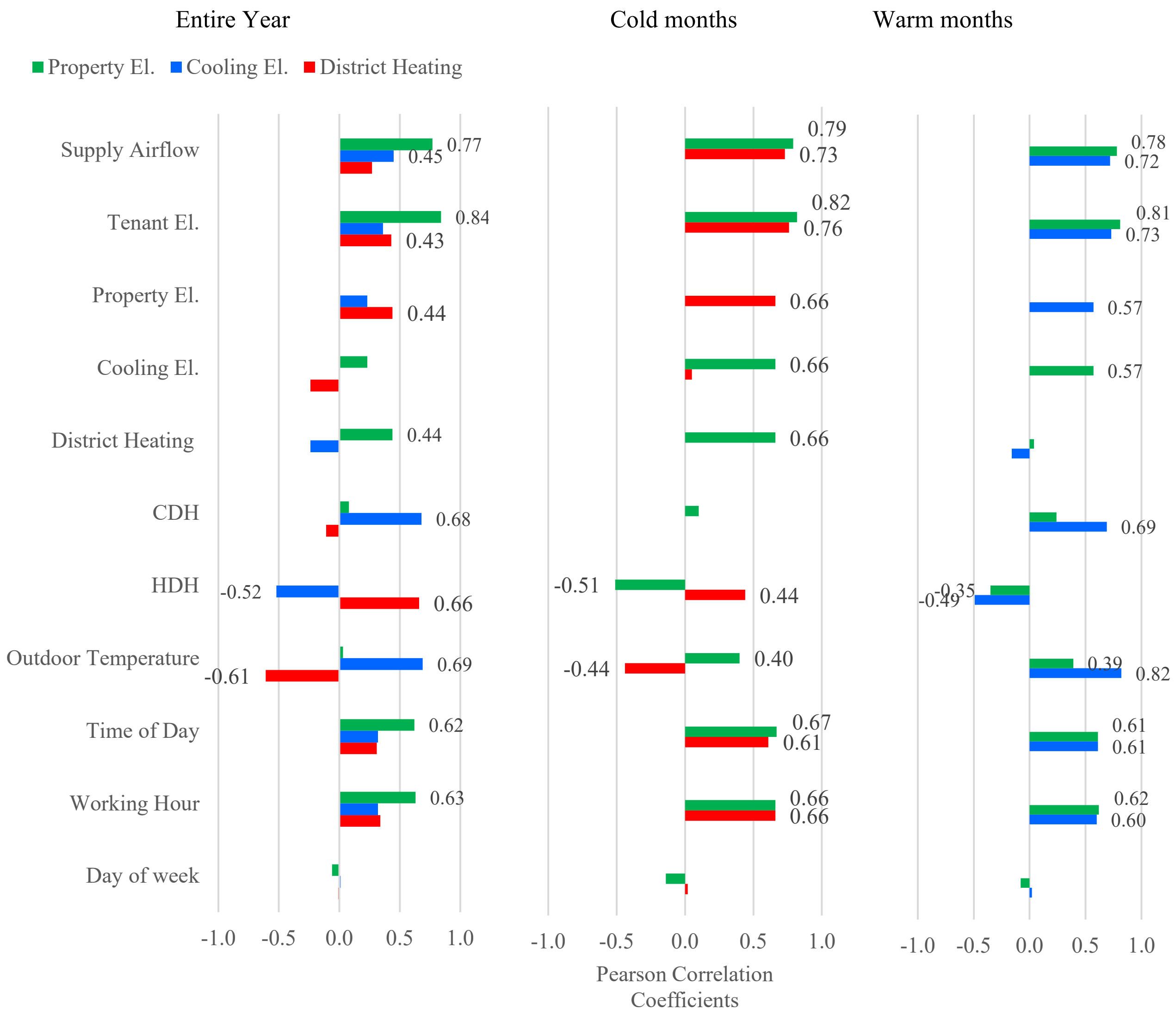
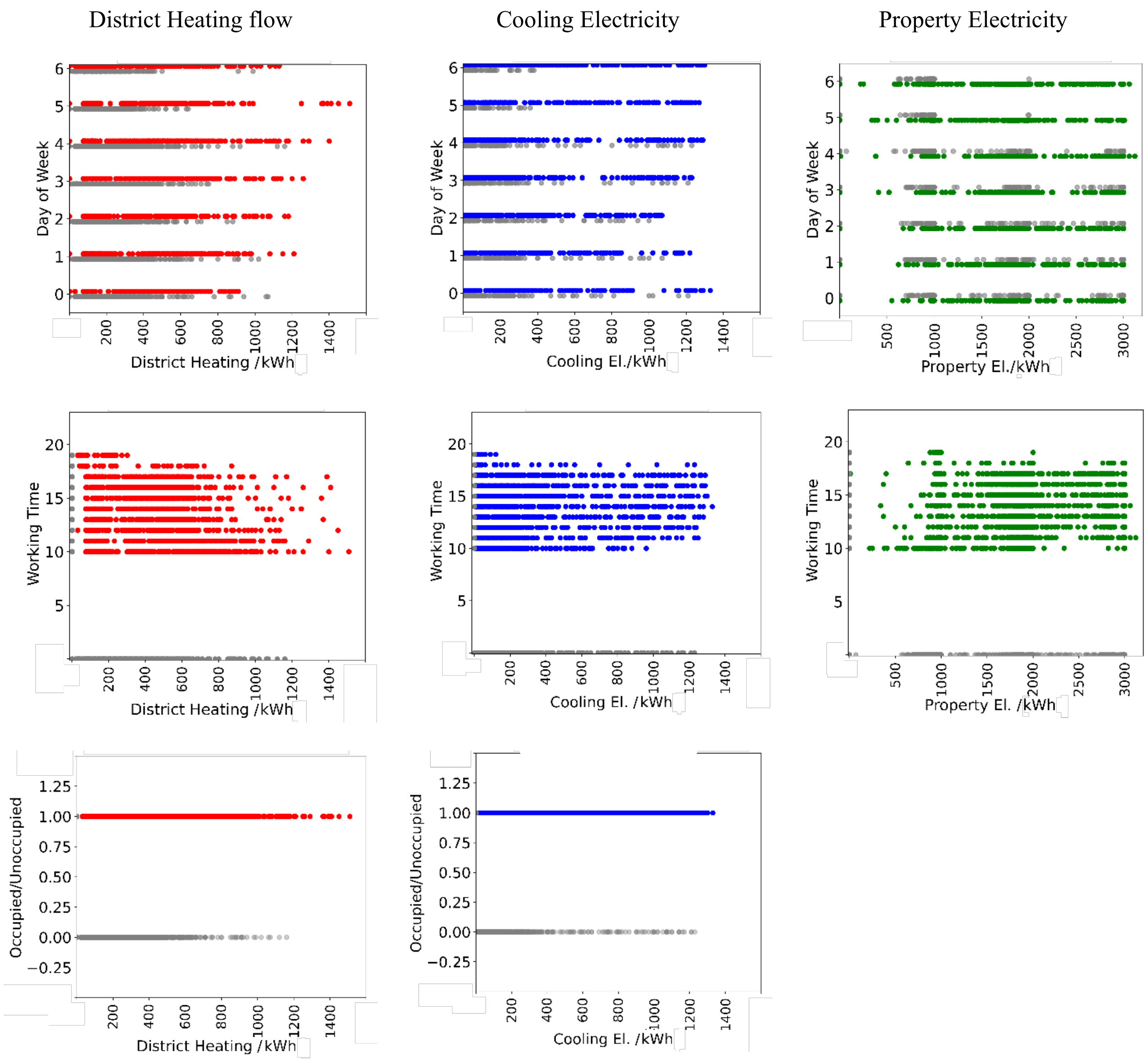
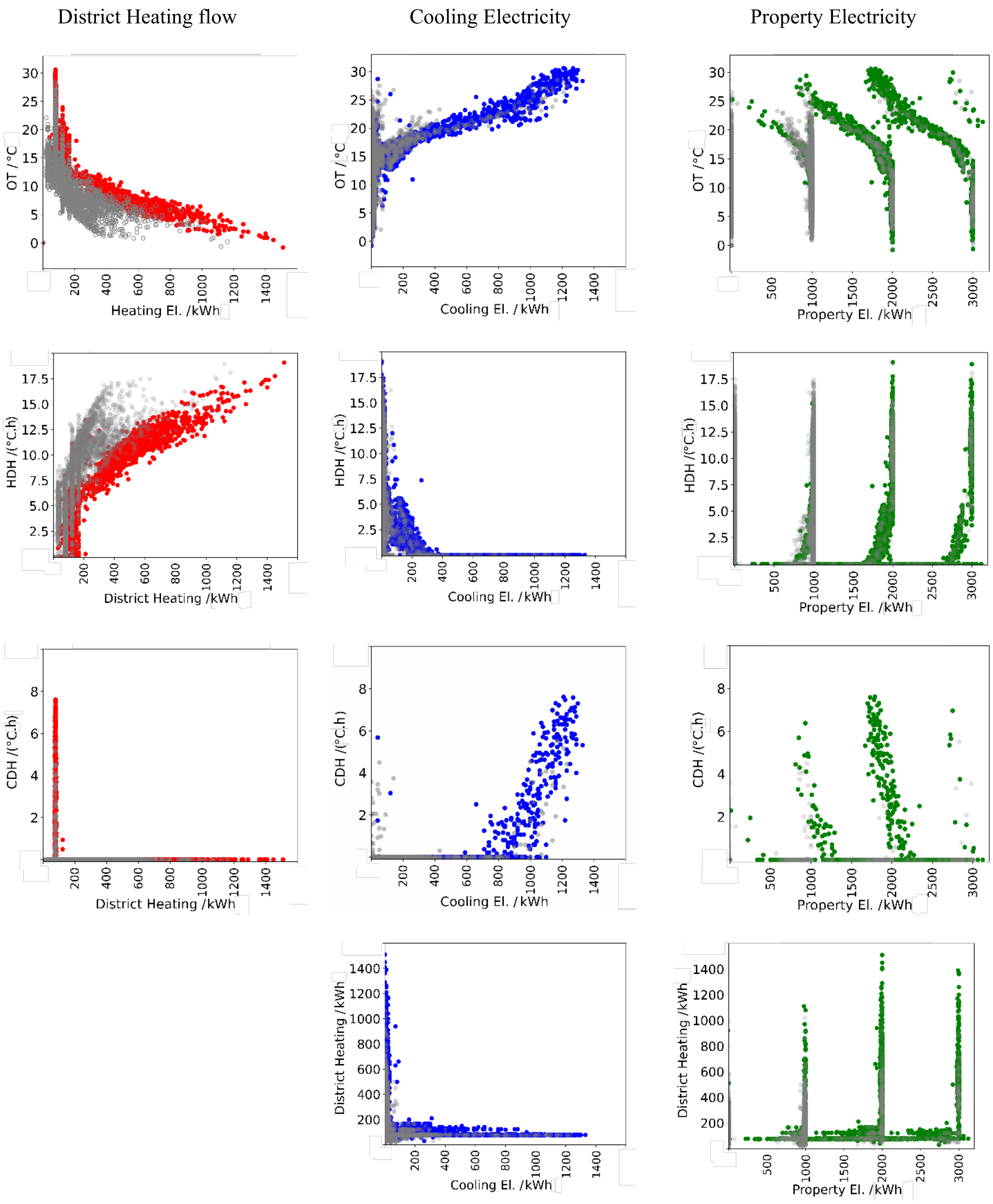
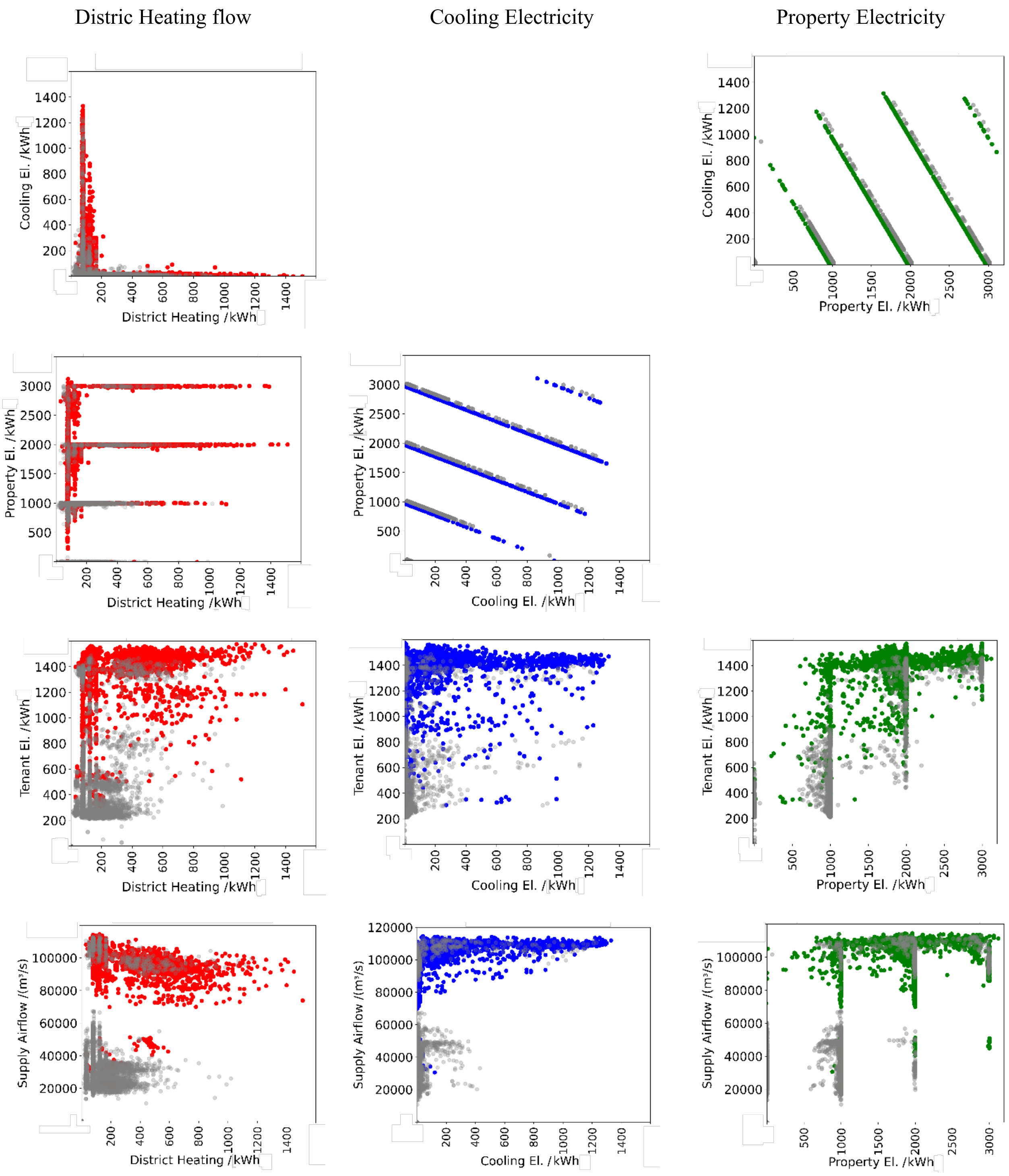


Figure A- 5 Parson correlation coefficients of property El. cooling El. and District heating flow of P1

Appendix B


District Heating flow
Cooling Electricity
Property Electricity
Day of Week
0
1
2
3
4
5
6
200
400
600
800
1000
1200
1400
District Heating /kWh
Cooling El./kWh
500
1000
1500
2000
2500
3000
Property El./kWh
Working Time
5
10
15
20
District Heating /kWh
Cooling El. /kWh
Property El. /kWh
Occupied/Unoccupied
−0.25
0.00
0.25
0.50
0.75
1.00
1.25
District Heating /kWh
Cooling El. /kWh


District Heating flow
Cooling Electricity
Property Electricity
OT /°C
Heating El. /kWh
Cooling El. / kWh
Property El. /kWh
HDH /(°C.h)
District Heating /kWh
Cooling El. / kWh
Property El. /kWh
CDH /(°C.h)
District Heating /kWh
Cooling El. / kWh
Property El. /kWh
District Heating / kWh
Cooling El. / kWh
Property El. /kWh
0
5
10
15
20
25
30
2.5
5.0
7.5
10.0
12.5
15.0
17.5
2
4
6
8
200
400
600
800
1000
1200
1400
500
1500
2000
2500
3000


Distric Heating flow
Cooling Electricity
Property Electricity
Cooling El. /kWh
District Heating /kWh
Cooling El. /kWh
Property El. /kWh
Property El. /kWh
District Heating /kWh
Property El. /kWh
Cooling El. /kWh
Tenant El. /kWh
District Heating /kWh
Tenant El. /kWh
Cooling El. /kWh
Tenant El. /kWh
Property El. /kWh
Supply Airflow /(m³/s)
District Heating /kWh
Supply Airflow /(m³/s)
Cooling El. /kWh
Supply Airflow /(m³/s)
Property El. /kWh
200
400
600
800
1000
1200
1400
500
1500
2000
2500
3000
20000
40000
60000
80000
100000
120000

Appendix C

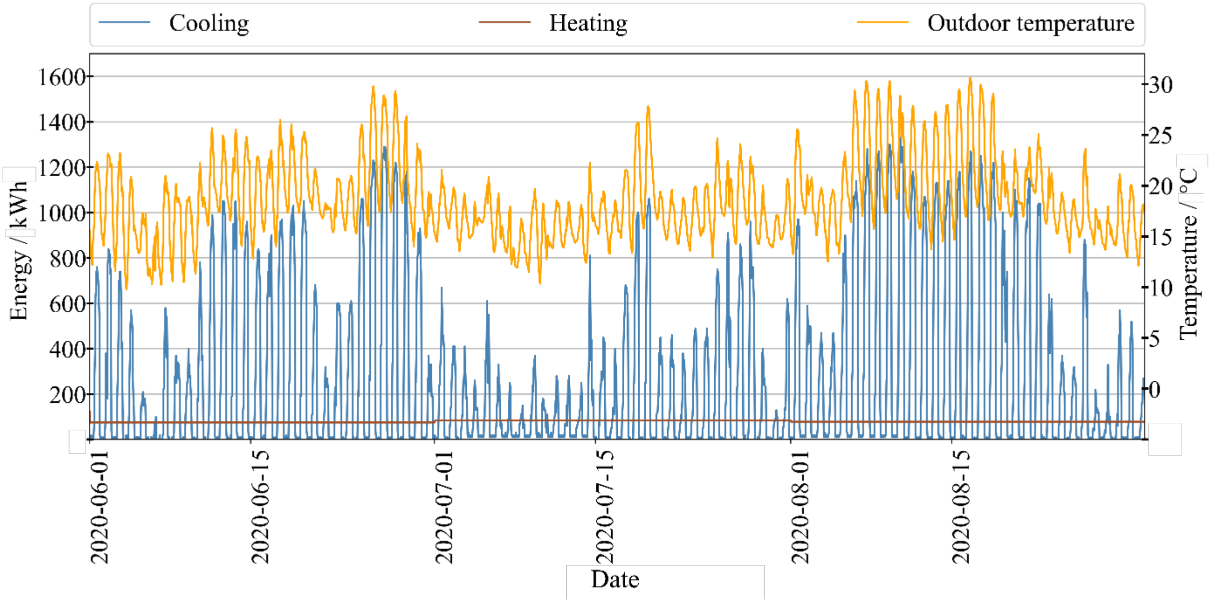


Figure C 1 cooling electricity use from June to August in the first period

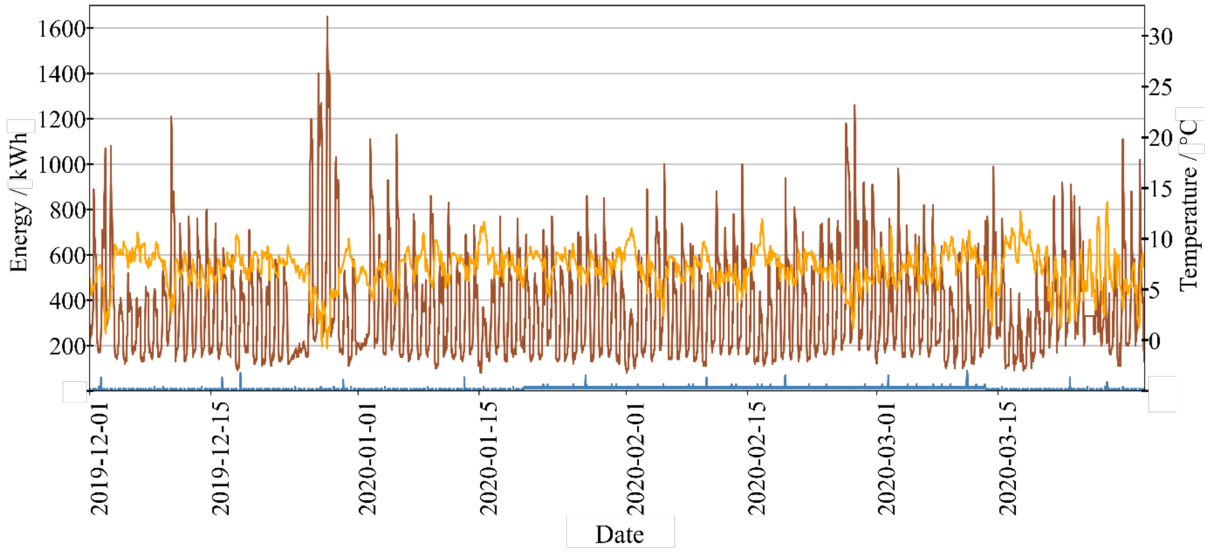


Figure C 2 District heating use from December to March in the first period

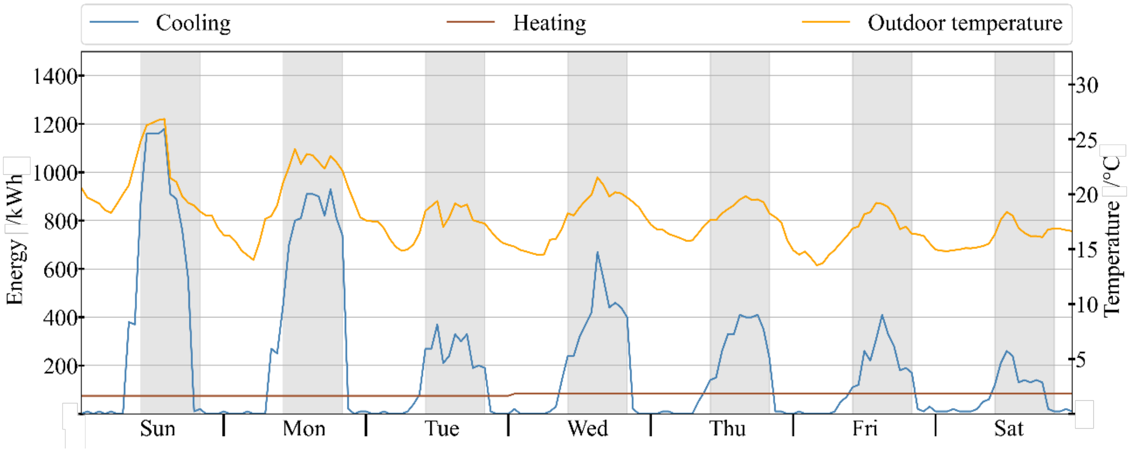


Figure C 3 cooling electricity use and outdoor temperature during the warmest week of in first period

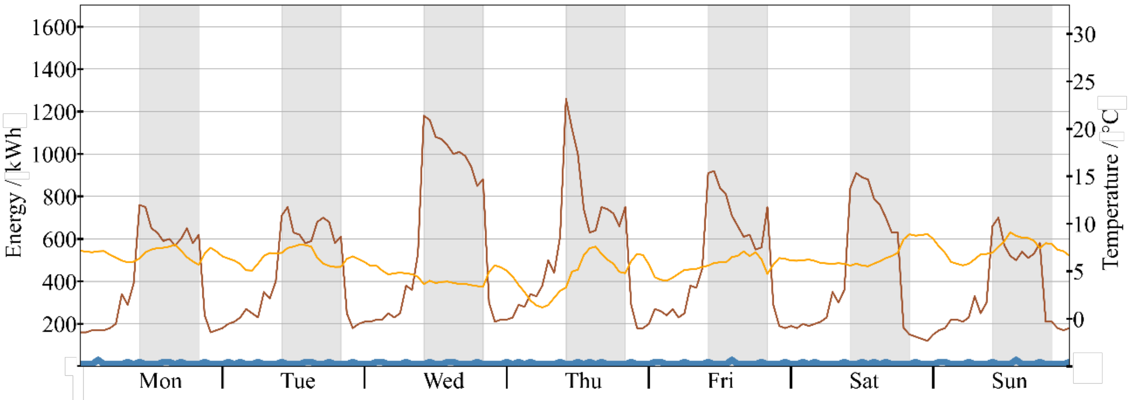


Figure C 4 District heating use and outdoor temperature during the coldest week of in first period

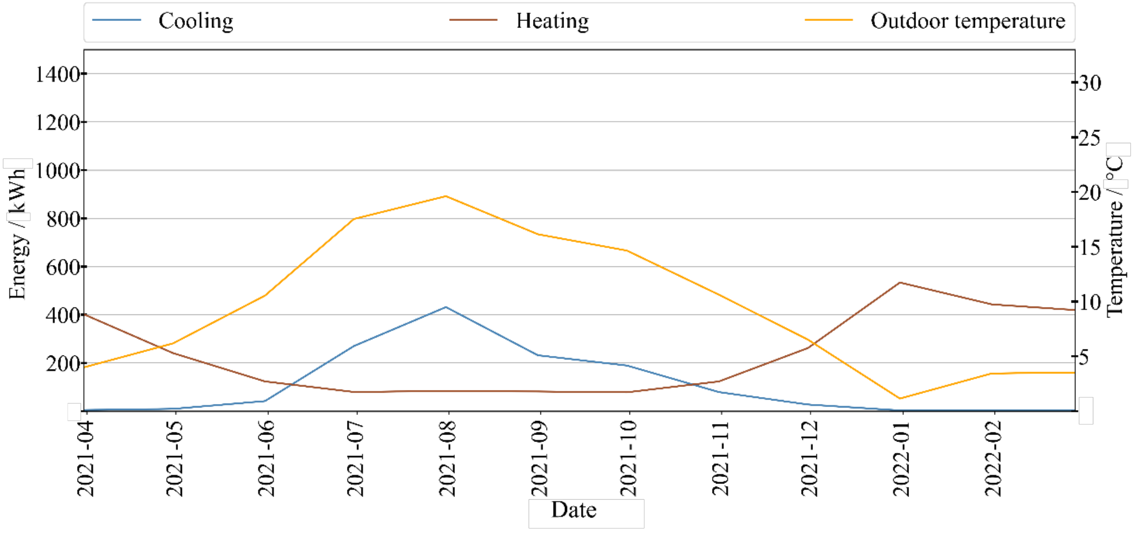


Figure C 5 monthly energy use and mean outdoor temperature in second period

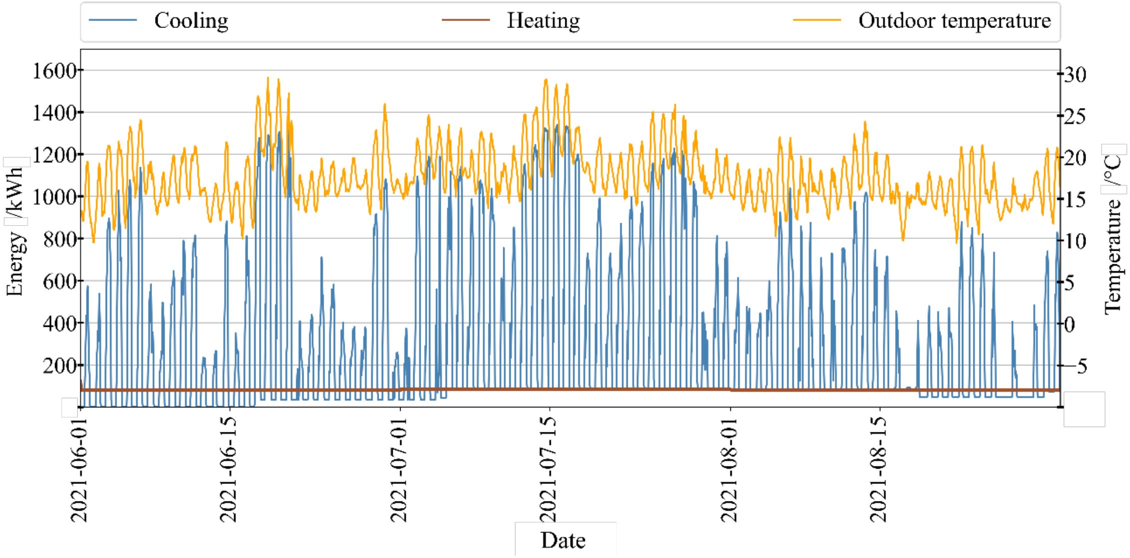


Figure C 6 cooling electricity use from June to August in the second period

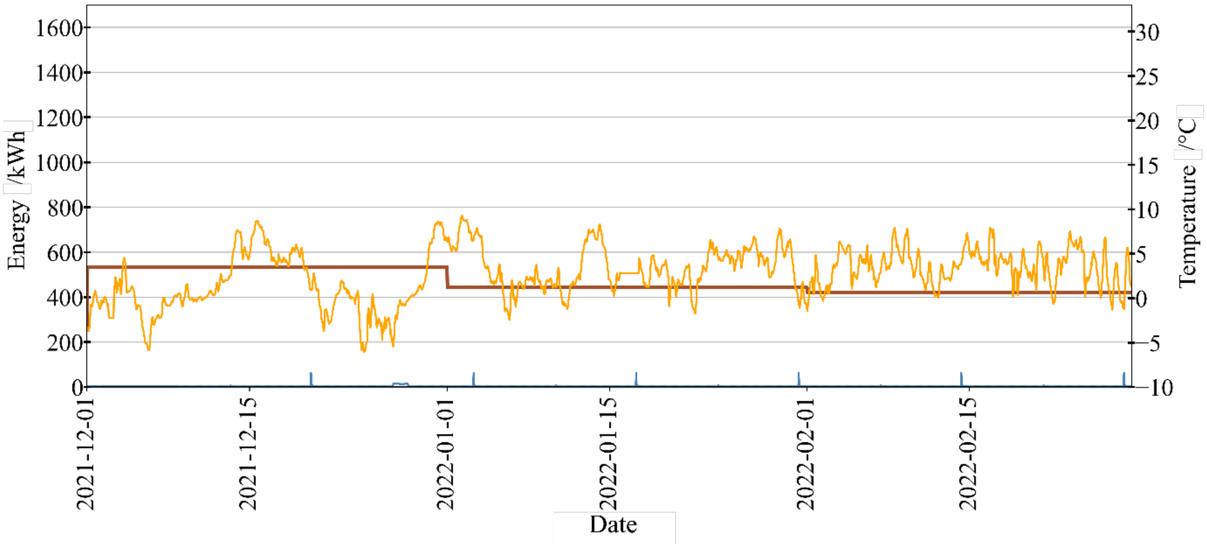


Figure C 7 District heating use from December to March in the second period

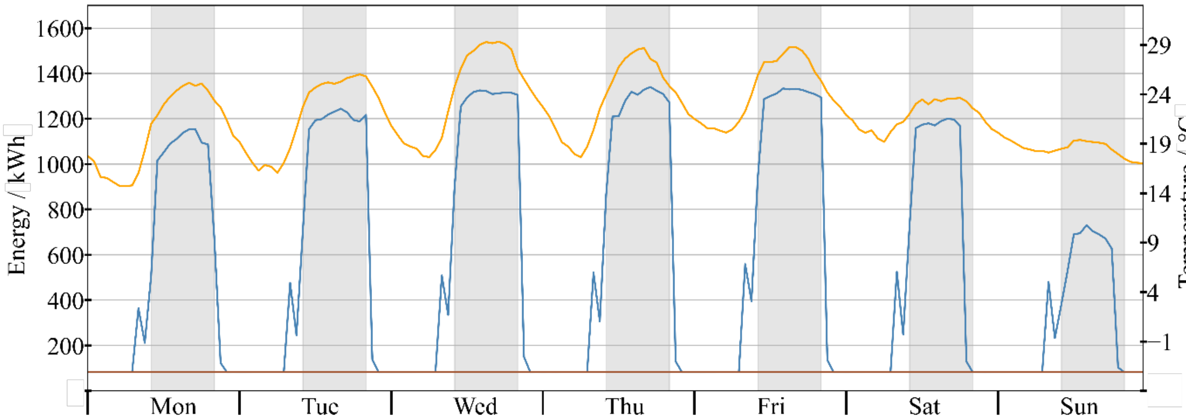


Figure C 8 cooling electricity use and outdoor temperature during the warmest week of in second period

LUND UNIVERSITY

Divisions of Energy and Building Design, Building Physics and Building Services

Department of Building and Environmental Technology