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Identification of criteria for the selection of buildings with elevated energy saving potentials from hydraulic balancing-methodology and case study

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ABSTRACT
Hydraulic balancing is key to ensure proper operation of the heating system. When the heating system is not hydraulically balanced, heat is unevenly distributed across dwellings resulting in a wide temperature spread, overheating, and consequently, wastage of energy. In this paper, we study to which extent hydraulic imbalance affects the thermal energy demand of buildings. Furthermore, key variables and interactions that influence the thermal performance of buildings are identified. In the first part, a dataset, including building features, boiler capacity and energy consumption of 49 multifamily buildings in Geneva (Switzerland), is analysed. Applying regularization regression, we find that higher variation in indoor temperature leads to larger energy consumption. Buildings constructed before 1980, having large boiler capacity and large heated floor area, are more likely to be hydraulically imbalanced and to consume more energy, indicating higher energy saving potential from hydraulic balancing. The second part consists of a case study of four multifamily buildings in Geneva where hydraulic balancing was implemented. We monitor data associated with temperature levels and energy consumption and find that hydraulic balancing significantly reduces the temperature spread avoiding overheating. The yearly energy savings by hydraulic balancing at an outdoor temperature of 0°C are estimated at 9% in Geneva.

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Thermal energy savings; hydraulic balancing; regularization method; heat distribution; field monitoring

1. Introduction

Buildings in Europe consume 41% (residential accounts for 27% and tertiary accounts for 14%) of total final energy (Santamouris, 2015). Aiming to reduce the energy demand of buildings in Europe, the European Union (EU) has set targets and introduced the Energy Performance of Buildings Directive (EPBD) in which ‘nearly zero energy buildings’ concept was adopted as a requirement for all new buildings. While new buildings have to

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comply with increasingly strict building energy standards, old existing buildings representing more than 90% of the building stock in Europe are the main challenge. EU member states have committed under the EPBD to improve the energy efficiency of old existing buildings through renovation strategies since 2010 (European Commission, 2018).

Space heating that accounts for around 70% of the final energy use is the predominant driver of energy consumption in residential buildings (Mazzarella, 2015). The thermal performance of buildings can be improved by (1) improving insulation system of the building envelope, (2) replacing the old inefficient heating system by a more efficient one or (3) optimizing the heat distribution system.

The first two options can be implemented in different ways and can significantly reduce heat loss. Nowadays the degree of thermal retrofitting varies significantly, ranging from single measures delivering small overall improvements to deep comprehensive retrofits that may enhance the buildings' energy efficiency performance by 50% or more (Olson, 2011; Park et al., 2013). However, the latter implies relatively high investment costs and is characterized by long payback periods (Lefter & Popescu, 2015; Streicher et al., 2020), e.g. compared to new buildings (Rulff, 2011). Frequently, building owners lack the financial means to cover the large up-front investment, regardless of whether they have access to subsidies or not (Afonso et al., 2015). Compared to thermal insulation of the building envelope and installation of a new heating system, the third option of optimizing the existing heat distribution system represents a cost-effective and relatively simple way to save energy, albeit typically resulting in limited energy savings (del Hoyo Arce et al., 2018).

The thermal performance of buildings is partly determined by the state of the hydronic system which is characterized by hydraulic (e.g. flow rates, pressure drops, etc.) and thermal (e.g. fluid temperatures, room air temperatures, etc.) operational conditions. By optimization of the hydronic system an improved thermal and hydraulic equilibrium is aimed for which allows the heat to be more evenly distributed across the flats and consequently leading to higher energy efficiency (Olson, 2011). Buildings, whose hydronic system is not balanced, fail to effectively transfer heat to all households, subsequently resulting in heat wastage.

The process to balance the hydronic system, the so-called hydraulic balancing includes re-adjustment of hydraulic components, such as pipes, balancing valves, pumps and radiators that influence flow rates and heat transfer rates, followed by more precise temperature control. Given the complexity of operation of a thermal system, computer simulation models have been developed and applied to identify the optimal set-point value for temperature and flow rates (Park et al., 2013; Rulff, 2011). As recommended by EN 12975, quasi steady-state methods are frequently used (Afonso et al., 2015). Since they ignore the dynamic impacts of hydraulic and temperature changes, they have the advantage of being relatively simple (del Hoyo Arce et al., 2018; Gabrielaitien et al., 2002; Gabrielaitiene, 2011; Stevanovic et al., 2007). However, time-dependent variables that describe transient behaviour of individual components, such as pipe or pump equipment, are not well addressed and, therefore, average values are used (Gabrielaitiene, 2011). Hence, substantial deviations between simulated and optimal were found (Corrado et al., 2007; Ho et al., 1995; Pernigotto, 2013). To consider both temporal and spatial performance of the system, dynamic models have been developed (Alessio et al., 2018). Since dynamic models include each component such as boiler, heat exchanger and piping systems, the model results are used to evaluate various operating conditions and develop control strategies (Yiteng, 2013). Some types of simulation are developed based on quasi-dynamic models in which the thermal operation is modelled dynamically, while hydraulic operation is calculated based on a static flow model (Bøhm et al., 2002; del Hoyo Arce et al., 2018; Larsen et al., 2002). In other words, the temperature is calculated by assuming flow in the network to be constant (del Hoyo Arce et al., 2018). Thereby, interactions between thermal and hydraulic conditions are not properly addressed in the model. Lefter and Popescu analyzed different scenarios of operation by adjusting the settings of balancing valves and differential pressure controllers (Lefter & Popescu, 2015). Field experiments also have been conducted to validate simulated values or to study interaction effects among variables that are not reflected in the equations due to their co-occurrence. Previous studies implied the installation of equipment and evaluated its impact on heat distribution, as well as on energy savings. Cholewa et al. estimated the energy savings that can be achieved by implementing diverse valves, such as TRVs (Thermostatic Radiator Valves), DPCVs (Differential Pressure Control Valves) and PIBRVs (Pressure Independent Balancing Radiator Valves) under different hydraulic operation conditions (Cholewa et al., 2017). Previous studies that carried out field experiments and computer simulations conclude that energy saving potentials, which can be achieved through hydraulic balancing, are estimated to be in the range of 2–23% (Ahern & Norton, 2015; Cholewa et al., 2017; Cholewa et al., 2018; Dieter & Kati, 2004; Ghahramani et al., 2016; Henze & Floss, 2011).

The wide range of energy saving potentials is explained by variations in scenario assumptions, scope of modelling and/or quality of the buildings in which hydraulic balancing was implemented. However, building qualities that potentially affect thermal operational performance of the buildings are frequently neglected. The outcomes from such modelling do not always guarantee achieving even distribution of flow and heat, and they sometimes rather further exacerbate variations of indoor temperature among flats increasing heat losses.

To our knowledge, there is no study in Europe that explored the correlation between building characteristics and hydronic performance in terms of heat distribution. We aim to investigate if there is any correlation between physical characteristics of buildings and the imbalance of their hydraulic system by focusing on multifamily buildings in Geneva, Switzerland. Our main goal is to determine a simple correlation using a readily available dataset, thereby allowing practitioners to quickly and easily identify potentially unbalanced systems. Currently, hydraulic balancing is sometimes conducted in buildings following tenants’ complaints about too high or low indoor temperature or after monitoring indoor temperature to determine the degree of variation in the temperature across flats. By identifying key variables or interactions that are related to heat distribution, this study presents a practical way to pinpoint candidate buildings and improve overall hydronic performance with reduced efforts. We also investigate to which extent hydraulic balancing improves heat distribution within buildings and energy savings. With a goal to precisely assess the impact of hydraulic balancing on hydronic performance, we use monitored data from field experiments. Unlike models or simulations, we demonstrate the actual impact of hydraulic balancing on heat distribution and energy savings based on monitored data.

2. Methodology

Aiming to pinpoint buildings in need of hydraulic balancing and assess energy savings potentials, this study has two research goals which are investigated by two separate parts. Figure 1 briefly outlines the scope and methodology applied in each part.

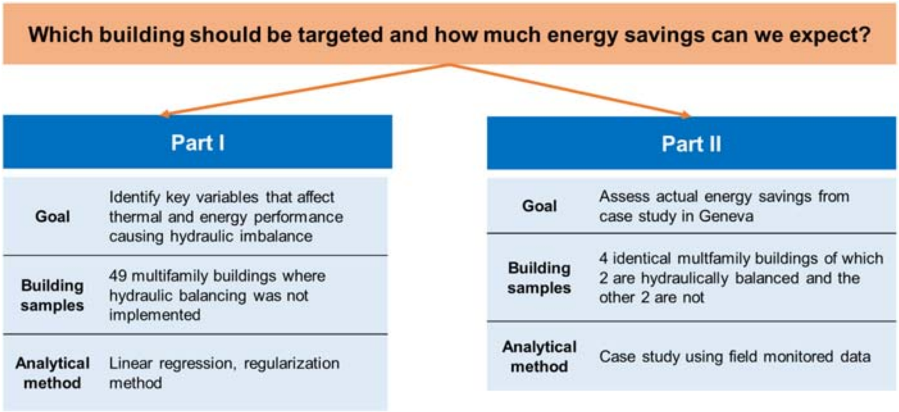
2.1. Part I-identification of key variables

2.1.1. Building samples

This study investigates 49 multifamily buildings containing 656 flats that were constructed before 2015 in Geneva. The buildings use natural gas-based or fuel-oil fired boilers for which the hydronic system has not been balanced yet. Buildings that share one central boiler are grouped which resulted in 13 groups.[1] We collect hourly indoor temperature for all flats and annual final energy consumption for heating for all buildings between 2016 and 2018 from the local database.[2] Extreme outliers are excluded by considering only the values falling between the 5th and 95th percentile. We correlate standard deviation and mean indoor temperature against annual final energy consumption for heating for each group. We then test the extent to which diverse variables explain variability of indoor temperature across flats.

2.1.2. Data collection

As illustrated in Table 1, we select diverse variables that may influence the performance of the hydronic system. The variables are related to either the buildings' physical characteristics or the heating system. All variables except age are continuous variables. As the construction year was only available in the form of a range (e.g. before 1980 or between 2000 and 2015), the variable of age is introduced as a categorical variable.



Part I	
Goal	Identify key variables that affect thermal and energy performance causing hydraulic imbalance
Building samples	49 multifamily buildings where hydraulic balancing was not implemented
Analytical method	Linear regression, regularization method

Part II	
Goal	Assess actual energy savings from case study in Geneva
Building samples	4 identical multfamily buildings of which 2 are hydraulically balanced and the other 2 are not
Analytical method	Case study using field monitored data

Figure 1. Outline of two sub-part studies in this research.

Table 1. Description of collected data.

Category	Name of variables	Additional explanation (unit)
Building	Number of floors	–
	Number of flats	–
	Average dwelling size	dwelling size (m^2)
	Height	building height (m)
	Age	building’s construction year
Heating	Total SRE (Surface de Référence Énergétique)	sum of all heated floor areas (m^2)
	Boiler capacity	boiler capacity (kW)
Energy	Average IDC (Indice de Dépense de Chaleur)	Annual final energy consumption for heating (MJ/m^2/year)

2.1.3. Analytical method

Using the linear regression, we first correlate standard deviation and mean indoor temperature against annual final energy consumption for heating for each group by applying linear regression analysis.

With a goal to select a subset of variables that explain most of the variability in indoor temperature across the flats, we apply a regularization method. The regularization method allows us to develop low-dimensional models for systems that are characterized by a large number of variables. There are two types of regularization that are commonly used: Ridge and Least Absolute Shrinkage and Selection Operator (LASSO) regression. Ridge penalizes the regression model by imposing a regularization term called ‘L2-penalty’, which is a sum of the squared coefficients, while LASSO applies a penalty term called ‘L1-penalty’, which is proportional to the sum of the absolute coefficients, in the regression model. Unlike Ridge, LASSO regression is capable of zeroing the coefficients with little explanatory power using the LI penalty. Thus, LASSO is more suitable for our study that aims to select a subset of variables with major contributions.

2.2. Part II: estimation of energy savings through case study

2.2.1. Building samples

In order to obtain a better understanding of the effects of hydraulic balancing on heat distribution and energy savings, this study presents a case study of four identical multi-family buildings in Geneva (Table 2). The studied buildings are heated with natural gas and they are equipped with an underfloor heating system.

Table 2. Description of the studied multi-family buildings.

Name of variables	Buildings in Geneva
Number of buildings	4
Number of floors (per building)	6
Number of flats (per building)	26
Ground area (per building)	234 m^2
Average flat surface	94.4 m^2 per flat
Age (construction year)	2002
Heating system	Underfloor heating
Total energy reference area (sum of all heated floor area of all buildings)	2694 m^2
Boiler capacity	150 kW (for two buildings)
Year of hydraulic balancing	Between late 2016 and early 2017
Additional control	None

Table 3. Description of collected data.

Parameters	Frequency	Unit	Source [reference]
Indoor temperature	Hourly	°C	Measured by real-time hourly monitoring system of local company
Natural gas consumption	Irregularly (every two weeks or every month)	m^3	Records maintained by local boiler technicians
Supply temperature of heating system	Hourly	°C	Measured by real-time hourly monitoring system of local company
Outdoor temperature	Hourly	°C	University of Geneva[a]

[a] University of Geneva has been collecting weather data from three stations since 2010. This study used data recorded in the station called 'Battelle'. (https://www.unige.ch/sysener/fr/activites/meteo/acces-aux-donnees/).

In Geneva, hydraulic balancing was implemented in two buildings between late 2016 and early 2017, while the other two were not balanced. We refer to the two buildings that underwent hydraulic balancing as the treatment group and the other as the control group. Since the buildings in the control group and in the treatment group are identical (same building materials, same shape, same orientation and located right next to each other) there is no need to correct for variation in internal environment due to external factors such as solar heat gains or seasonal variations. We collected hourly indoor temperature data[3] of all flats in the two groups of buildings for the past two heating seasons (January–April,2016 and January–April, 2017).

2.2.2. Data collection

As Table 3 shows, the following parameters are chosen and data are collected through monitoring with the following intervals. Natural gas consumption for space heating and hot water are metered separately in the studied building. We monitored and collected the amount of natural gas consumed for the space heating.

2.2.3. Analytical method

We applied energy signature to estimate energy savings. An energy signature is a plot that shows the relationship between energy consumption of a building and mean outdoor air temperature. Since there are day-to-day variations due to the difference in solar heat gains or wind velocity and due to inaccuracies in monitored data, the real values do not form a straight line. However, we practically apply a linear fit between energy consumption and temperature (Hitchin & Knight, 2016).

3. Results and discussions

3.1. Part I

3.1.1. Linear regression

Investigating the correlation between indoor temperature and energy consumption, we find a distinctive cluster formed by each age group (Figure 2). Based on the comparison of the relationship between mean and standard deviation of indoor temperature on the one hand with annual final energy consumption for heating on the other, we observe an opposite pattern between old and new buildings. The old buildings show low mean indoor temperature and high standard deviation of indoor temperature, whereas the new buildings show high indoor temperature and low standard deviation. Buildings of medium age take an intermediate position. The old and new buildings indicate that

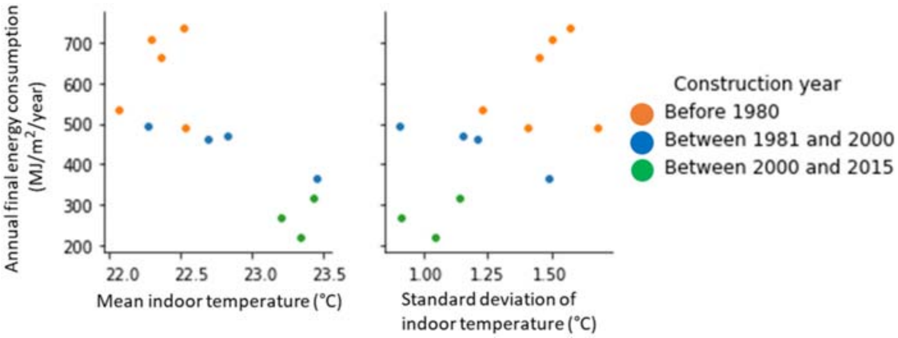


Figure 2. Scatter plot of annual final energy consumption of buildings in Geneva as a function of mean and standard deviation (indicated as 'sd indoor temp') of indoor temperature between 2016 and 2018.

the buildings with high mean and standard deviation of indoor temperature might consume more energy.

3.1.2. Regularization

We select the variables that have the highest explanatory power. In order to determine the presence of multicollinearity, we examine the variance-inflation factors (VIF)[4] that measure the level of multicollinearity among variables (Ho et al., 1995). A VIF value of 3.3 is applied as threshold beyond which we carry out LASSO regression, as an earlier study (Huebner et al., 2016). The LASSO regression effectively selects a subset of variables that produces the best fit by setting the coefficients of irrelevant variables to zero. To meet the requirement that the LASSO regression runs on the basis of linear regression model, we chose continuous variables excluding categorical variables. While other variable selection approaches, such as stepwise selection, are prone to result in overfitting the data (Kumar et al., 2019), this is avoided by applying LASSO regression with 3-fold cross-validation (He, 2020; Li, 2017). Tables 4 and 5 show the coefficients of the LASSO regression and the subsequent OLS regression when the standard deviation and average of indoor temperature are taken as a dependent variable, respectively.

Two variables, i.e. boiler capacity and total SRE (total heated floor area) that have a non-zero coefficient (β_L) in both cases (Tables 4 and 5) after LASSO regression, are selected as key variables. The final models developed using the key variables result in a coefficient of determination $R^2$of: (i) 11.3% for standard deviation of indoor temperature as a

Table 4. LASSO regression results for standard deviation of indoor temperature as a dependent variable, for buildings in Geneva β_L represents the coefficients of the Lasso regression, B_{OLS} stands for the unstandardized coefficients of the reduced OLS regression, SE_{OLS} is the standard error.

Name of variables	β_L	B_{OLS}	SE_{OLS}
Number of floors	0.000000	NA	NA
Number of flats	0.000000	NA	NA
Average dwelling size	0.000000	NA	NA
Boiler capacity	0.0002831	0.001	0.001
Total heated floor area	-4.79e-05	7.59e-05	0
Height	0.000000	NA	NA
Age	0.000000	NA	NA

Table 5. LASSO regression results for average of indoor temperature as a dependent variable, for buildings in Geneva (see Table 4 for abbreviations).

Name of variables	β_L	B_{OLS}	SE_{OLS}
Number of floors	0.000000	NA	NA
Number of flats	0.000000	NA	NA
Average dwelling size	0.000000	NA	NA
Boiler capacity	-1.58e-03	−0.0009	0.001
Total heated floor area	3.99e-05	-2.00e-04	0
Height	0.000000	NA	NA
Age	0.000000	NA	NA

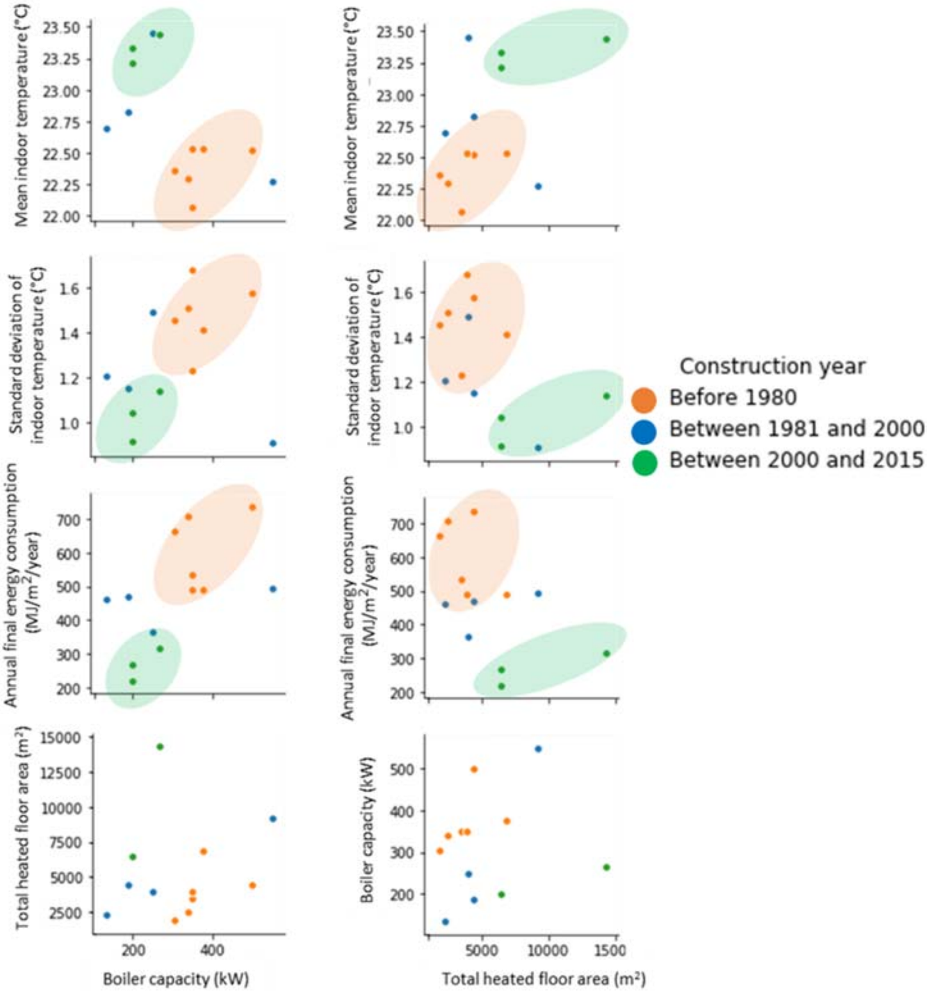


Figure 3. Scatter plot matrix representing the relationship between the level (mean) and deviation (standard deviation) of indoor temperature and the explanatory variables, for buildings in Geneva.

dependent variable and of (ii) 49.6% for the average of indoor temperature as a dependent variable. Standard errors reaching close to 0 indicate that collinearity between boiler capacity and total heated floor area is not high.

Figure 3 is a scatter plot matrix that shows all possible pairwise scatter plots of the selected variables. We observe that boiler capacity and total heated area are related to the extent to which the building is hydraulically imbalanced and to the amount of final energy consumed for heating purposes. As the coloured zones (orange and green) indicate old buildings (orange) and new buildings (green) are placed in different zones. The new buildings are characterized by a small boiler capacity and a large total heated area, while the opposite features are found in old buildings. The buildings in each group (old and new) indicate that the higher boiler capacity and total heated area, the higher mean and standard deviation of indoor temperature, leading to higher annual final energy consumption for heating. The buildings of the medium age group are spread out rather than showing a distinctive pattern. Hydraulic balancing is most likely to achieve higher energy savings from buildings, which were constructed before 1980, have a larger boiler capacity than 300kW and a larger total heated area than 1900 m^2.

3.2. Part II

3.2.1. Indoor temperature profile

The variability in indoor temperature of control and treatment groups is illustrated in Figure 4. Before hydraulic balancing was implemented (i.e. in the period between January and April in 2016), the standard deviation of the treatment group was rather high (2016 heating season). It was never below 0.6 for the treatment group and was mostly higher than that of control group. This indicates the presence of thermal discomfort in the treatment group prior to hydraulic balancing throughout the entire period. After the heating system was hydraulically balanced (i.e. between January and April in 2017, which we call 2017 heating season), the standard deviation of the treatment group became lower than that of the control group. Comparing mean indoor temperature for each day before balancing (2016 heating season), it was found that the treatment group shows higher mean indoor temperatures than the control group for most of the days during the 2016 heating season, although the difference was small. After hydraulic balancing was conducted, the mean indoor temperature of the treatment group decreased and became smaller than the respective temperature of the control group.

As Figure 5 shows, both standard deviation and mean value decreased for the treatment group in the 2017 heating season compared to the 2016 heating season, while both values increased for the control group. This means that heat is more evenly distributed due to hydraulic balancing and that the radiator temperature was at a lower level in 2017 than in 2016. On the other hand, the control group experienced a larger temperature difference among flats in 2017 than in 2016. In the control group, the number of flats with an indoor temperature above 23°C significantly increased in 2017 leading to an increase in the mean indoor temperature. As displayed in Table 6, the median of standard deviation is increased by 8.5% for the control group, while it decreases by 6.4% for the treatment group.

3.2.2. Other multifamily buildings

As the previous figures show, the control group shows an increase in standard deviation and in mean indoor temperature from 2016 to 2017. To investigate whether

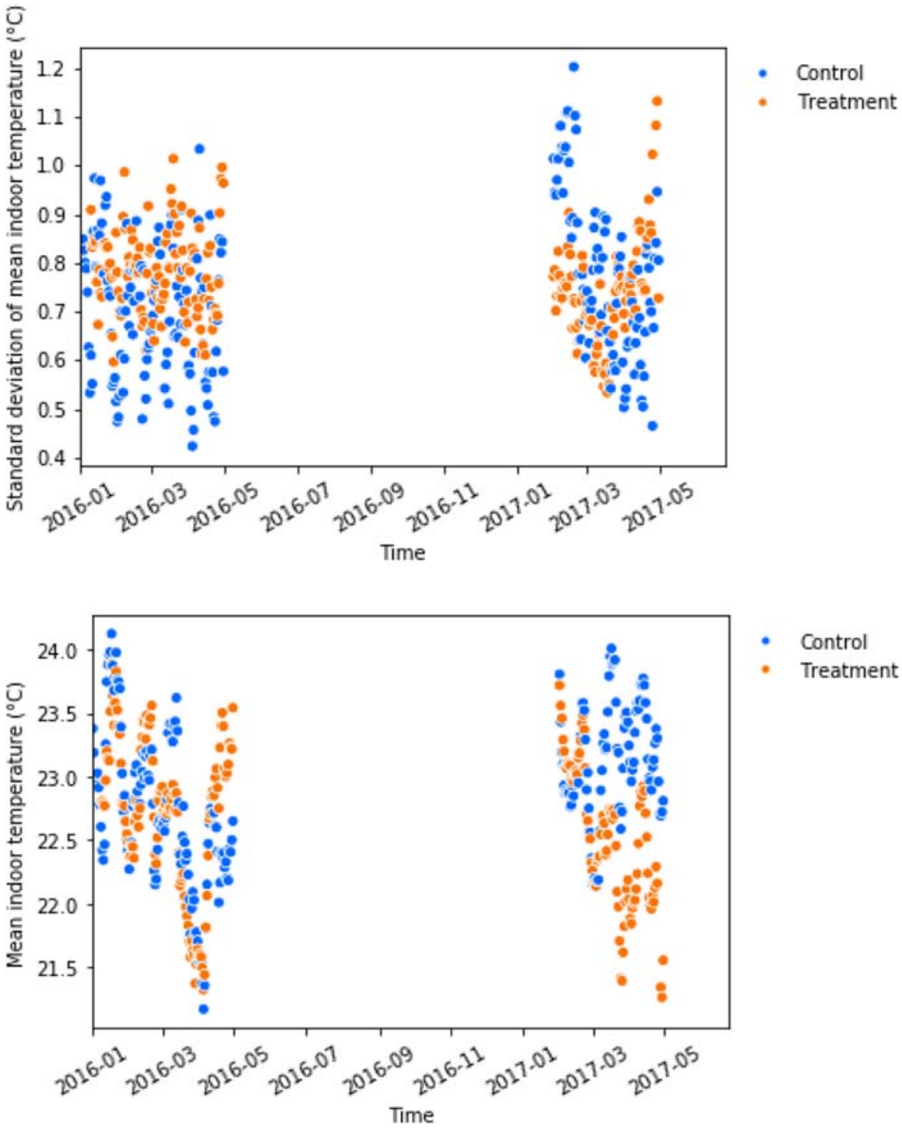


Figure 4. Scatter plot of standard deviation and mean daily of indoor temperature across time during two heating periods (Jan–April 2016 and Jan–April 2017).

the same pattern is found in other existing multifamily buildings, we carried out the same analysis for other buildings in Geneva. We selected other 43 multifamily buildings (443 flats) that have similar characteristics as the control group in terms of construction age, type of fuel, total heated area and boiler capacity. As illustrated in Figure 6, the selected multifamily buildings are also showing the same pattern. Standard deviation increased from 0.80 to 1.20, while mean temperature increased from 22.02°C to 22.42°C. This indicates that the heating season 2017 was colder than 2016, which we discuss next.

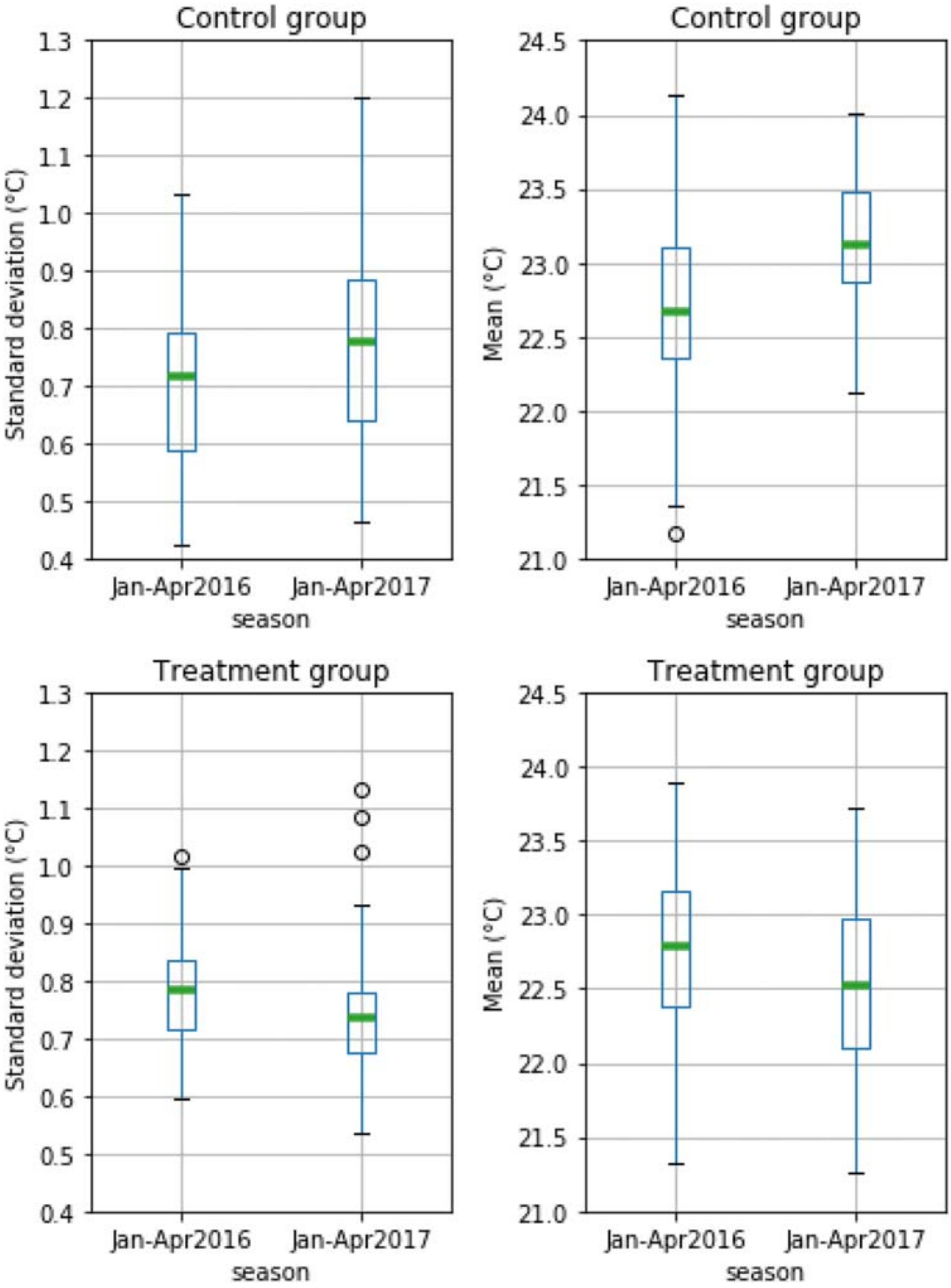


Figure 5. Multiple box plots of mean and standard deviation of control and treatment group.

3.2.3. Compared to outdoor air temperature

As confirmed by previous studies, indoor temperature is affected by outdoor temperature. As displayed in Figure 7, the curves exhibit an increase of indoor temperature as outdoor temperature decreases, and it also shows an exponential increase in standard deviation (yellow line) as outdoor air temperature drops below 0°C. Figure 8 shows

Table 6. Median values of standard deviation and mean of control and treatment groups.

		2016	2017	Difference between 2016 and 2017 (%)
Control	Standard deviation	0.71	0.77	8.5
	Mean	22.67	23.11	2.0
Treatment	Standard deviation	0.78	0.73	−6.4
	Mean	22.79	22.52	−1.2

that the 2017 heating season had more days of lower temperature. It is plausible that this is the main reason for the higher indoor temperature in the 2017 heating season compared to the 2016 heating season. This is confirmed by the number of heating degree days which were also higher in the period January–April 2017 compared to the respective period in 2016. Cold outdoor temperature leads to increase in indoor temperature. Large temperature spread at low outdoor temperature indicates that temperature might have been regulated but heat may have not been evenly distributed due to imbalanced hydraulic system.

3.2.4. Energy savings in Geneva

The impact of hydraulic balancing on natural gas consumption is assessed by comparing two heating seasons based on the energy signature. We compared the data of the treatment and the control group during the 2016 heating season, i.e. prior to hydraulic balancing. We found that the supply temperature of the treatment group is higher than that of

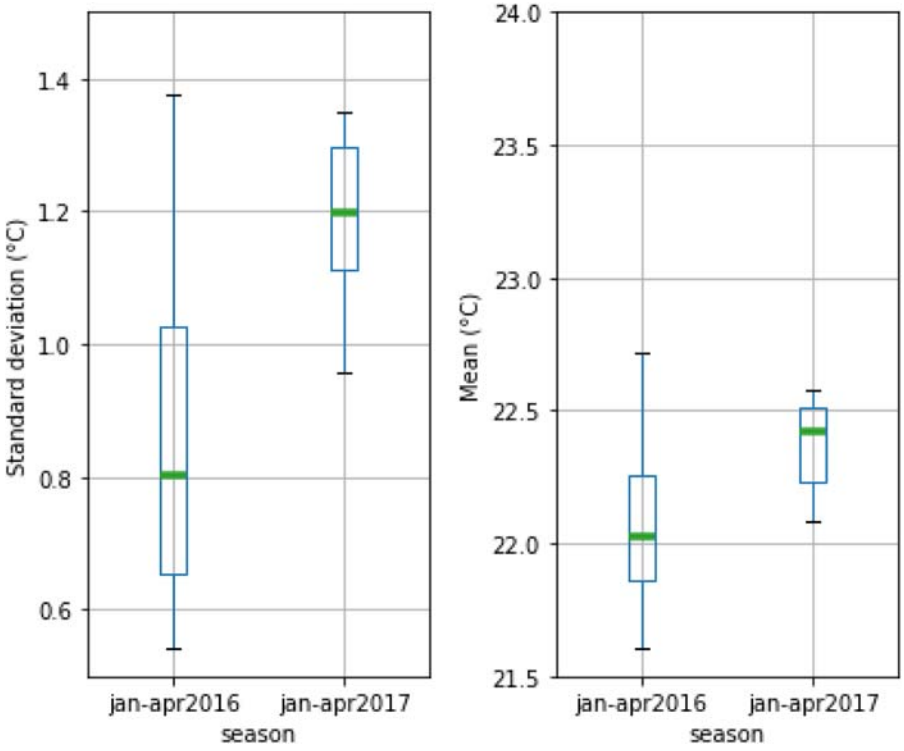


Figure 6. Boxplot of standard deviation and mean of other multifamily buildings in Geneva.

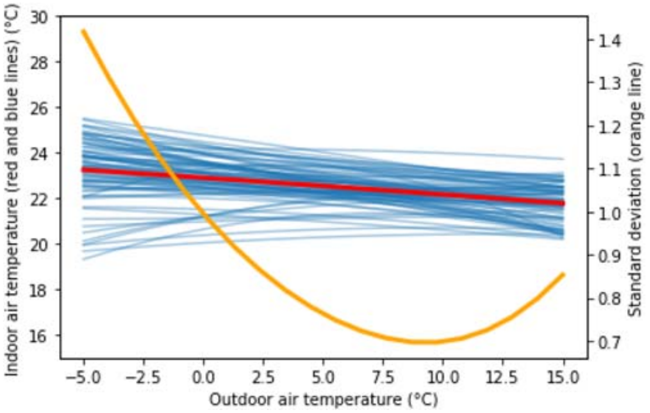


Figure 7. OLS regression prediction of average hourly mean indoor air temperature and outdoor air temperature, for multifamily buildings in Geneva (Cho et al., 2020).

the control group, resulting in more energy consumption (orange and red lines in Figures 9 and 10) although the four buildings are all identical. This implies the need for hydraulic balancing and a potential to save energy especially in the treatment group. As the energy signature of the control group in Figure 10 shows, gas consumption does not show any difference between two heating seasons. On the other hand, the treatment group shows lower gas consumption during the 2017 heating season compared to the 2016 heating season. This is in line with the lower supply temperature due to hydraulic balancing, as displayed in Figure 10. For example, at the outdoor temperature of 0°C (Table 7)[5], the control group keeps almost the same level of supply temperature in the 2016 and

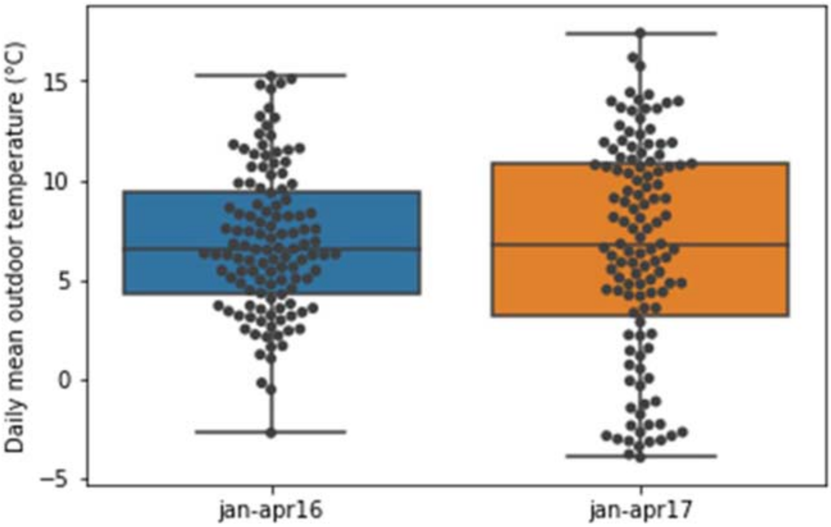


Figure 8. Boxplot and swarm plot that show distribution and all observation of daily mean outdoor temperature during two heating seasons, for multifamily buildings in Geneva.

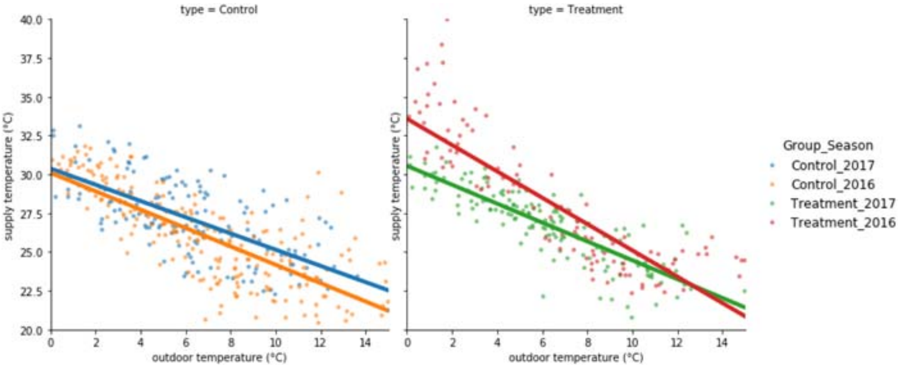


Figure 9. Supply temperature of the heating system of control and treatment groups during two heating seasons.

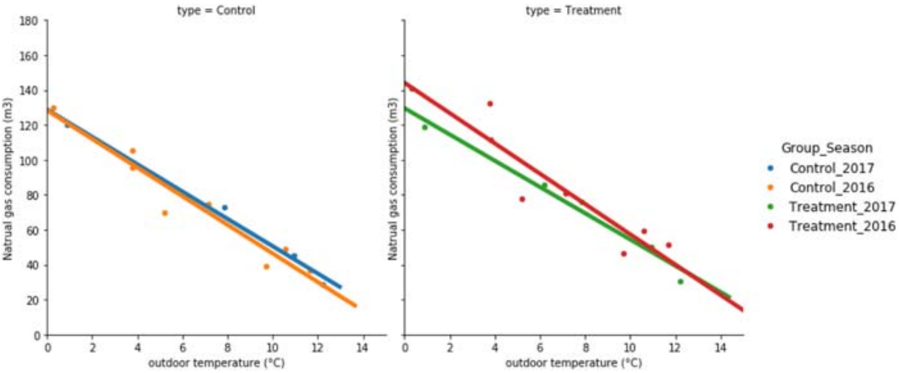


Figure 10. Natural gas consumption of control and experimental groups during two heating seasons.

2017 heating seasons (30.1°C in 2016 and 30.4°C in 2017). However, the treatment group experiences a decrease in supply temperature in 2017 compared to 2016 by 3°C. Outdoor temperature during the heating season stayed between −1 and 13°C on average. When the outdoor temperature was at the upper end of the range (between 8°C and 13°C), the supply temperature and natural gas consumption increased for control group heating season, while the opposite was found for the treatment group (values for 2017 in both cases). To calculate energy savings due to hydraulic balancing, the difference in natural gas consumption between the two heating seasons was calculated at the outdoor

Table 7. Supply temperature and natural gas consumption at 0°C of outdoor temperature in control and treatment group in Geneva in the 2016 and 2017 heating seasons.

	At 0°C of outdoor temperature	2016	2017	Difference between 2016 and 2017 (C for temperature, % for natural gas consumption)
Control	Supply temperature	30.1	30.4	0.3°C
	Energy consumption	128.4	128.8	0.3%
Treatment	Supply temperature	33.6	30.6	−3.0°C
	Energy consumption	142.4	129.6	−9.0%

temperature of 0°C for which the control group shows practically no change in natural gas consumption between 2016 and 2017. As illustrated in Table 7, both groups show very similar changes for both supply temperature and natural gas consumption.

4. Limitations and future research

The limitation of the present study is the small sample size of each age group for the first part of the study, raising the question whether the findings can be generalized. This calls for future studies with larger sample sizes per age group, leading to more representative findings. Moreover, as found in previous studies (Cho et al., 2020), occupant behaviour, occupancy level and personal thermal preferences significantly influence the amount of energy savings. This highlights the needs for future studies that incorporate behavioural aspects. Future case studies analysing for more buildings energy savings in both relative and absolute terms would provide practical insights into the relationship between temperature spread and actual energy savings from hydraulic balancing.

5. Conclusions

Apart from onerous measurement campaigns there is so far no other accurate way to identify buildings whose heating systems are hydraulically unbalanced, and there is so far only very limited understanding of actual energy savings through hydraulic balancing. Therefore, this study applied a regularization method (LASSO regression) in order to establish the most important subset of variables allowing predicting the potential need of hydraulic balancing. In addition, we conducted a case study in order to quantify the amount of energy saved as a result of hydraulic balancing.

Among the variables analysed, boiler capacity and total heated area are identified as the variables with highest explanatory power to identify the presence of hydraulic imbalance in buildings constructed before 1980. The buildings with higher boiler capacity and larger total heated area are found to offer relatively high energy saving potentials by hydraulic balancing. This insight is expected to make the selection of buildings in need of hydraulic balancing more reliable.

The buildings we investigated in this case study were constructed in 2002 and 2016 and they consume less thermal energy compared to old ones due to the better level of insulation. The yearly energy savings by hydraulic balancing at an outdoor temperature of 0°C were estimated at 9% in Geneva. By conducting further case studies for new and old buildings with different boiler capacity and total heated area, it should be possible to reach a good understanding of typical energy savings that are achievable by hydraulic balancing and to devise better strategies for implementing hydraulic balancing.

Notes

1. Three groups of two buildings served by one boiler, one group of three buildings sharing one boiler, six groups of four buildings sharing one boiler, one group of six buildings sharing one boiler and one group of eight buildings sharing one boiler.
2. A local company has been monitoring indoor temperature and relative humidity in some residential buildings in Geneva since 2016. In each flat, one sensor was installed on the wall of the

living room at the height of 1.5m by the company in order to ensure that the measurement is as representative as possible for the entire flat. Temperature data were calibrated.

3. The indoor temperature was monitored in real time by a company in Geneva.
4. A VIF value of 1 means that there is no multicollinearity whereas a VIF value higher than 1 indicates multicollinearity.
5. For degree-day correction, we use the 'energy signature' where we plot energy consumption against outdoor temperature. We then measure the energy savings for an outdoor temperature of 0°C.

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No potential conflict of interest was reported by the author(s).

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