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A sensitivity analysis on the heating and cooling energy flexibility of residential buildings

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ABSTRACT

The present paper evaluates the potential of the buildings thermal inertia to modify their heat load pattern using two energy flexibility indicators: the available heat storage capacity and the efficiency of active demand response events. The study analyses the effects of building envelope, user behaviour and weather conditions on the flexibility indicators for three reference apartments. The results show that during the heating season the available storage capacity increases from new to old buildings. Part of the thermal energy shifted is lost through the envelope after the events, resulting in lower efficiencies for old buildings. In general, upwards and downwards modulation events are preferable just before and just after the peak load periods, respectively. The paper shows that severe weather conditions and intermittent set-point schedules lead to exceptions to this general rule. In the heating season, forced modulation events do not bring to significant variation of thermal comfort in well-insulated buildings, whereas they do in old ones. During the cooling season, the choice of the best event is more difficult due to the high variability of diurnal heat gains and the indoor thermal conditions depend on the start time of events rather than on the type of building envelope.

Available capacity for ADR (kWh)
Average thermal power shifted (kW)
Efficiency of ADR events (%)
Average efficiency of ADR events (%)
G Global solar radiation (kWh/m2)
L Duration (h)
N Number of ADR events (-)
Heat load (kW)
T Dry-bulb air temperature [°C]
U Thermal Trasmittance [W/(m2 K)]
V Net heated air volume [m3]
ADR Simulation with ADR event
hor Horizontal
i Indoor air
lim Limit (minimum/maximum)
max Maximum
m Mean
min Minimum
occ Occupancy hours
op Operative
REF Reference simulation
ADR Active Demand Response
B70 Building built according to L. 373/76
B90 Building built according to L. 10/91
BN Building built post 2005
DOWN Downwards modulation events
DSM Demand Side Management
FAM Young families occupancy schedule
FF Flexibility function
HVAC Heating, ventilation and air-conditioning
IHG Internal heat gains
KPI Key performance indicator
MILP Mixed integer linear programming
OC Old couples occupancy schedule
PMV Predicted Mean Vote
RC Resistance-Capacitance
TDDH Thermal discomfort degree-hours
TDI Thermal discomfort index
TES Thermal energy storage
UP Upwards modulation events

1. Introduction

Nowadays buildings are responsible of 36% of CO_2 emissions and space heating and cooling alone accounts for 40% of the final energy consumption at European level (European Union, 2018). The 2015

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Nomenclature

Subscripts

ADR	Simulation with ADR event
hor	Horizontal
i	Indoor air
lim	Limit (minimum/maximum)
max	Maximum
m	Mean
min	Minimum
occ	Occupancy hours
op	Operative
REF	Reference simulation

Abbreviations

ADR	Active Demand Response
B70	Building built according to L. 373/76
B90	Building built according to L. 10/91
BN	Building built post 2005
DOWN	Downwards modulation events
DSM	Demand Side Management
FAM	Young families occupancy schedule
FF	Flexibility function
HVAC	Heating, ventilation and air-conditioning
IHG	Internal heat gains
KPI	Key performance indicator
MILP	Mixed integer linear programming
OC	Old couples occupancy schedule
PMV	Predicted Mean Vote
RC	Resistance-Capacitance
TDDH	Thermal discomfort degree-hours
TDI	Thermal discomfort index
TES	Thermal energy storage
UP	Upwards modulation events

Paris Agreement on Climate Change following the COP21 Conference boosted the European Union's efforts to decarbonise its building stock. As a result, the European Commission presented in November 2016 the Clean Energy Package (European Union: European Commission, 2016), i.e. a set of measures aimed at regulating the transition towards a sustainable energy system. The first document to be approved was the new Directive 2018/844 on the energy performance of buildings (European Union, 2018). Among other novelties, the Directive introduces a framework to calculate the smart readiness of buildings, which assesses their ability in (i) adapting to user needs and energy environment; (ii) operating more efficiently and (iii) interacting with the energy system and with the district infrastructure in the context of demand response programs. This capability is strongly related to the so-called energy flexibility of the building, i.e. to its "… *ability to manage its demand and generation according to local climate conditions, user needs and grid requirements*", as defined by the research group of the IEA EBC Annex 67 (Jensen et al., 2017).

The concept of energy flexibility goes well with the widely discussed concept of Demand Side Management (DSM). The meaning of DSM can be described as reported in (Gellings, 1985): "…*the planning and implementation of those electric utility activities designed to influence customer uses of electricity in ways that will produce desired changes in the utility's load shape.*"

Among the possible DSM activity, active demand response (ADR) programs are defined as the changes in electric energy use implemented directly or indirectly by end users from their normal consumption patterns as function of certain signals (Arteconi et al., 2016). One of the most promising applications of ADR consists of using the thermal capacitance of buildings and thermal energy storage (TES) systems to shift the load of electrically driven HVAC devices -such as heat pumps (Arteconi et al., 2016). Using the building structures alone or combined with existing heat storage systems is potentially disruptive, as no additional investment costs are needed but those for the "intelligence" and "connectivity" of existing HVAC control devices.

A higher energy flexibility of buildings will favour their participation to ADR programs based on the requirements of the system operator (SO) or of an external third-party actor, often named "aggregator" (Hurtado, Rhodes, Nguyen, Kamphuis, & Webber, 2017). The control in ADR programs can be either direct or indirect. In the direct control, the SO (or the aggregator) can directly change the consumption pattern, whereas indirect control implies that the user has full control over its appliances, and can freely choose whether to participate or not to the ADR program (Shen et al., 2014).

The quantification of the energy flexibility is a complex process that must consider the requirements of both the grid operators and the customers (Hurtado et al., 2017).

The growing interest towards energy flexibility of buildings and Demand Response has generated a broad scientific literature around this topic. Indeed, there is a huge number of publications focused on Demand Response, where the authors evaluated directly the performance of specific control strategies in terms of cost or energy savings, reduction of CO_2 emissions or peak shaving just to name some of the most common Key Performance Indicators (KPIs). These metrics can be evaluated on different scales: on a single building level (Arteconi, Hewitt, & Polonara, 2013; Rodríguez, Ramosa, Domínguez, & Eicker, 2018), on a limited set of building units (Hedegaard, Heidmann Pedersen, & Petersen, 2017), on a neighbourhood or district scale (Pau, Cunsolo, Vivian, Ponci, & Monti, 2018) or even at national level (Arteconi et al., 2016) to report a few examples.

Differently from these works, where the energy flexibility of buildings was evaluated for specific case studies, in other papers researchers have tried to evaluate such property by using specific indicators. This approach allows to predict the energy flexibility beforehand and at the same time to compare different buildings.

In a recent paper, Reynders et al. (2018) summarized six methodologies to quantify the energy flexibility of buildings. Among them, Nuytten, Claessens, Paredis, Van Bael, and Six (2013) defined the energy flexibility as the amount of hours the energy supply system of the building can be delayed or forced to operate. They applied this concept to a heat network with CHP and either centralized or decentralized buffers. They found that the central TES offers the highest amount of maximal available flexibility, especially in the delayed operation mode. D'Hulst et al. (2015) proposed to assess the energy flexibility as the possible power increase/decrease that can be realized at a certain time of day, combined with how long this power increase or decrease can be sustained without affecting thermal comfort conditions inside the building. They classified the electrical loads into two groups according to the type of flexibility they can provide: buffered – i.e. having an inherent buffer/inertia and postponable loads –operation can be delayed or anticipated. Stinner, Huchtemann, and Müller (2016) suggested similar indicators, i.e. temporal and power – or energy – flexibility, but using a different process to calculate them. Two simulations are carried out, starting with the hot water storage tank at maximum and minimum "state of charge". They concluded that the available flexibility varies over time. De Coninck and Helsen (2016) evaluated the flexibility in their research using cost functions. They used a reference scenario in order to obtain the optimal system operation with respect to the operational costs. The methodology returns as output the amount of energy that can be shifted to or from a specified flexibility interval and the costs associated with this load shifting. Oldewurtel, Sturzenegger, Andersson, Morari, and Smith (2013) extended the use of traditional performance indicators for storage systems – such as the energy capacity, the maximum charge/discharge power and the autonomy – to demand response technologies. A similar approach was adopted by Reynders, Diriken, and Saelens (2017): they suggested to evaluate the energy flexibility by the use of three indicators: the available storage capacity, the storage efficiency and the power shifting potential. The methodology based on these indicators has been used in this paper and will be therefore thoroughly described in the methodological section. Le Dréau and Heiselberg (2016) compared the energy flexibility of a house built in the 1980s with that of a recently built passive house and found that the modulation potential of the thermal mass depends on many factors (level of insulation, type of emitter, etc.) and varies over time (cold vs. transition season). This article was the first to clearly state that, due to these factors, different buildings need different control strategies to find a good balance between flexibility, energy demand and indoor thermal comfort. Similar results were obtained by Foteinaki, Li, Heller, and Rode (2018) and by Balint and Kazmi (2019), who considered the additional flexibility supplied by 200 L hot water tanks. As most of the literature, these works were focused on the heating season. Yin et al. (2016) presented a novel demand response estimation framework for residential and commercial buildings in the cooling season. They used regression models to predict the ADR potential based on the main inputs (i.e. hour of day, set-point change and outside air temperature). Their new approach proved very useful for predicting hourly ADR potential along with the weather prediction. They also found some conditions to decrease the ADR potential in the cooling season: an aggressive change of thermostat set-point when the outside air temperature is lower than 24 °C and when the HVAC system exceeds its capacity. Hurtado et al. (2017) simulated 15 office buildings in two different climate zones and concluded that buildings located in hot climates offer higher flexibility potential during shorter time ranges, while buildings in cold climates offer lower flexibility potential but during longer time ranges. Johra, Heiselberg, and Le Dréau (2019) studied the role of the building envelope and they concluded that thermal insulation and thermal capacitance are the dominant parameters. Differently from previous research works, they considered the effects of indoor items and furniture present in the built environment. They concluded that their effect can increase the energy flexibility potential up to 42% in the case of dwellings with low structural thermal capacitance.

Junker et al. (2018) proposed a novel methodology to evaluate the energy flexibility of buildings and districts using a dynamic function, called Flexibility Function (FF). The authors criticized approaches that consider the flexibility as a static function due to the typical transient behaviour of the buildings. The FF describes the reaction of a specific smart building, or cluster of smart buildings, to a penalty signal based, for instance, on economic or environmental objectives. As such, the FF is suitable for control purposes and can be, at the same time, used for labelling, once standardized penalty signals and comfort intervals are defined. This approach brings new possibilities for enabling the grid operators or other operators to manage the energy demand through the use of dedicated penalty signals as price, CO_2, etc. Vigna, Pernetti, Pasut, and Lollini (2018) proposed an original review of concepts related to the energy flexibility of building clusters. According to the authors, evaluating the flexibility of the buildings on a district scale represents an effective strategy for providing local and low-carbon energy supply, through the enhancement of district energy systems and decentralized energy production.

Liu and Heiselberg (2019) studied the performance of energy flexibility of a nearly zero-energy building. They found that this strategy, compared to the reference case, allows a maximum peak shaving of around 0.005 kW/m^2 during high-price periods only by changing the set-points of heating and cooling according to the energy price. Around

Table 1
Overview on building energy flexibility evaluation criteria.

Reference	Use of measured data	Impact of ADR on		Source of flexibility (general if not specified)					Heating and/or cooling season	ADR strategy (if any)		Scale of the evaluation	
		Thermal comfort	Energy demand or cost	Building structure	HVAC system	Hot/cold water tank	DHW tank	Other (PCM, EV, WM..)		Optimization-based	Rule-based	Ref. building(s) or profiles	Multi-unit to district
(Nuytten et al., 2013)						x			H		x		x
(D'Hulst et al., 2015)	x						x	x	H	x			x
(Stinner et al., 2016)						x			H		x	x	
(De Coninck & Helsen, 2016)			x	x	x	x			H	x	x	x	
(Oldewurtel et al., 2013)	x			x	x				HC	x		x	
(Reynders et al., 2017)			x	x					H		x	x	
(Le Dréau & Heiselberg, 2016)		x	x	x	x				H		x	x	
(Foteinaki et al., 2018)			x	x					H		x	x	
(Balint & Kazmi, 2019)			x	x		x			H		x	x	
(Yin et al., 2016)				x					C		x	x	
(Hurtado et al., 2017)				x	x				HC		x	x	
(Johra et al., 2019)		x	x	x				x	H		x	x	
(Junker et al., 2018)			x						H		x		x
(Liu & Heiselberg, 2019)		x	x	x					HC		x	x	
(Li et al., 2019)	x			x	x				C		x	x	
(Hu et al., 2019)		x	x	x	x				H	x		x	

80% of the energy consumption during high-price periods can be removed by the control strategies. Moreover, by adding weather predictive control on the previous strategy, the energy cost is 26% lower but slightly higher than the case that is without flexibility control. Recently Li, Yang, Ji, and Xu (2019) showed that the thermal inertia of an air-conditioning system is non-negligible in the ADR potential of a building. Hu, Fu Xiao, Jørgensen, and Li (2019) developed a stochastic grey-box model of a single room with floor heating system and used it in a MPC framework. Simulations showed that compared to the conventional on-off control, the MPC control for floor heating systems improves the thermal comfort and reduces the daily electricity costs for residential end-users at the price of a higher energy consumption during the one-week test period. This result confirms the claim by De Coninck and Helsen: flexibility is not for free (De Coninck & Helsen, 2016). Any ADR action influences either the energy demand, the cost or the thermal comfort in the indoor environment. Moreover, the literature review showed that the flexibility can be provided not only by the building structure but also by TES and HVAC systems, furniture, electric vehicles and household appliances such as washing machines, fridges etc. The ADR potential is usually evaluated by modifications of the internal air temperature set-point or by ad-hoc control optimizations, usually based on mixed integer linear programming (MILP). Table 1 resumes the main characteristics of the commented research works that perform a general and reproducible evaluation of the energy flexibility of buildings or building clusters.

The literature reported above demonstrates the growing interest of the engineering community in the use of the thermal mass of buildings to improve the flexibility of the energy system. However, to the authors knowledge, there is still no study that considers all the factors that contribute to the energy flexibility of buildings for both space heating and cooling. The present work aims to fill this gap and therefore considers the effect of ADR events on the indoor thermal comfort and on the energy demand of the building in both heating and cooling season for a reference flat with different levels of thermal insulation. To this end, the paper investigates how different boundary conditions –time of ADR event, weather conditions and user behavior – affect the energy flexibility and thermal comfort indicators. The final objective of the article is to find general trends with which to estimate the energy flexibility of residential buildings. These trends can then be used by the scientific community to interpret the results of specific Demand Response cases.

2. Methods

The literature review showed that several methods for assessing the energy flexibility of building structures have already been proposed in recent years. Among them, the method proposed by Reynders et al. (2017) was chosen due to its reduced computational effort and the easy interpretation of the related KPIs.

The method relies on two simulations: a reference simulation and a so-called ADR simulation, i.e. a simulation where an ADR event occurs. An ADR event is a time-limited change in the boundary conditions that affects both the indoor conditions and the energy consumption pattern of the building. This change can be a reduction or an increment in the schedule of the temperature (and eventually also humidity) set-point at certain hour of the day.

For example, a reference simulation calculates the heating energy demand of a building with a predefined schedule of set-point temperature and occupancy patterns, and the ADR simulation determines the energy demand of the same building with an increase or a decrease of the set point temperatures for two hours every three days at four o'clock in the morning, as shown in Fig. 1.

The thermal load profiles obtained with the simulations are then used to calculate two flexibility indicators. The first one, shown in Eq. (1), is based on the so-called *available capacity for active demand response*, defined by Reynders et al. (2017) as:

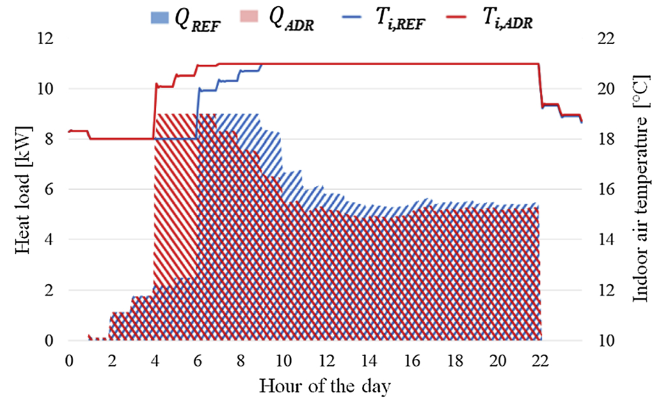

Fig. 1. Thermal load profile of a building in the reference (blue) and ADR (red) simulation scenarios.

$$C_{ADR} = \int_0^{L_{ADR}} (Q_{ADR} - Q_{REF})\, dt \tag{1}$$

where Q_{REF} is the heat load profile of the building in the reference simulation, Q_{ADR} is the energy demand in the ADR simulation and L_{ADR} is the duration of the event. C_{ADR} indicator measures the surplus/deficit of energy stored in the building structure during the ADR event, which can be considered as the capacitance of a virtual thermal storage. In the present work, this index was processed to obtain average values of thermal power shifted on a monthly/seasonal basis as reported in Eq. (2):

$$\bar{C}_{ADR} = \frac{\sum_i^N C_{ADR,i}}{N\, L_{ADR}} \tag{2}$$

where N is the number of ADR events during the considered period (month/season). In case the temperature set-point is increased during heating mode (*upwards modulation*), only part of the energy surplus will be used after the event to reduce the energy consumption of the building. A similar argument holds true for *downwards modulation* events such as the decrease of the temperature set-point in winter: the energy spent after the ADR event is higher than the energy saved due to the forced shutdown during the ADR event. Therefore, the second indicator in Eq. (3), measures the "efficiency" of the virtual thermal storage, defined as follows:

$$\eta_{ADR} = 1 - \frac{\int_0^{\infty} (Q_{ADR} - Q_{REF})\, dt}{\left|\int_0^{L_{ADR}} (Q_{ADR} - Q_{REF})\, dt\right|} \tag{3}$$

As discussed in Pan, Torres, Salom, and Ortiz (2018), the ADR efficiency of the virtual storage η_{ADR} can be interpreted as the ratio between the "rebound effect" and the "ADR event", i.e. the difference between the energy needs of the building after and during the ADR event. As a corollary of this definition, it can be concluded that any ADR event involves a certain loss of energy. Coherently with the first index ($\bar{C}_{ADR}$), also the ADR efficiency was averaged on monthly/seasonal basis. However, since in this case the unit of measure does not change, the symbol was not changed for sake of simplicity.

The duration of the ADR events L_{ADR} is set to 2 h, as this value was found to be a good compromise between low energy losses and high available storage capacity (Reynders et al., 2017). Secondly, three days were chosen for the calculations of the numerator of η_{ADR} in Eq. (3). In fact, a post-processing analysis revealed that for all the considered buildings the rebound effect after 72 h has almost stopped. This is important to ensure that consecutive events do not influence each other. Three different building structures were considered, differing by the type of both external walls and windows, as described in the next paragraph. Lastly, for each type of building two different schedules of indoor air set-point temperature and internal heat gains were used to simulate different behaviour of the users –see Fig. 2. The schedules are

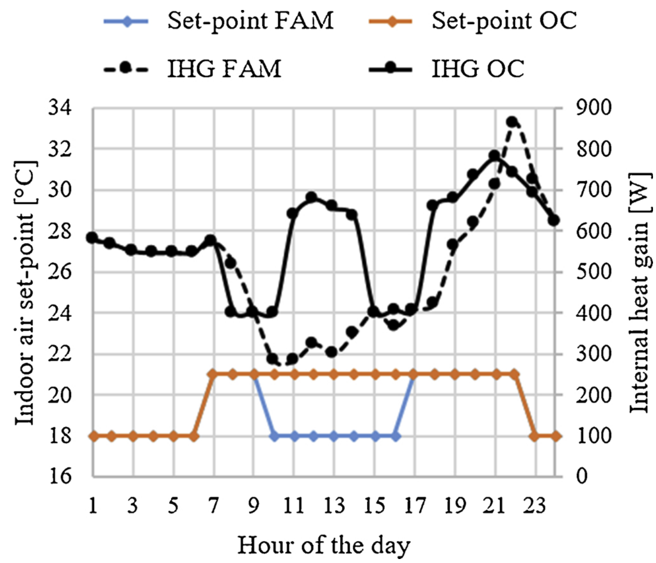

Fig. 2. Boundary conditions for the simulations of the heating season: temperature set-points and internal heat gains for two occupancy patterns (FAM and OC).

intended to represent two different patterns of occupancy of the building units: the continuous occupancy of old couples (OC) and the discontinuous occupancy of young families (FAM). The schedules, resumed in Fig. 2, are deterministic and were built using the work of Barthelmes, Becchio and Corgnati (2016) and the Standard EN 16798 (European Committee for Standardization, 2019) as starting points. In summer, the reference cooling load profile was calculated using a constant set-point temperature of 26 °C and the internal heat gains of the schedule FAM. The other assumptions are the following:

- The energy needs were calculated fixed indoor air temperature (according to the set-point schedules) and the maximum limit on the thermal power was calculated according to the EN 12831 Standard (European Committee for Standardization, 2017) (20% being set as radiative and 80% convective) including the heating-up power for intermittent operation;
- The heating-up power in the heating season was set, according to the EN 12831 Standard (European Committee for Standardization, 2017), using 2 h for recovery duration and the inactivity temperature drops are 2 K for buildings of recent construction and 3 K for older buildings;
- The cooling power was set to 7.5 kW for all cases, corresponding to the typical size of a split system with three internal units (100% convective);
- The weather data is taken from the Test Reference Year of Venice (U.S. Department of Energy (DOE) 2003). The climatic mean monthly values are summarized in Table 2.
- The internal gains are divided in 30% radiative and 70% convective contributions;
- In summer an internal generation of 9 kg/day of water vapour was set as an average medium value for residential buildings;
- Summer and winter simulations were carried out separately to avoid variations in the boundary conditions.

The participation of the buildings to Active Demand Response programs brings benefits to the energy system as a whole and to the user in economic terms. However, forced start-ups and shut-downs of HVAC plants unavoidably change the indoors thermal comfort conditions. Therefore, it is important to assess the thermal discomfort eventually caused by different ADR events. The number of degree-hours of thermal discomfort was calculated according to Eq. (4):

$$TDDH = \int_0^{t_{occ}} |T_{op} - T_{op,lim}| \; dt \tag{4}$$

where T_{op} is the operative temperature of the indoor environment and $T_{op,lim}$ indicates the minimum and maximum operative temperatures suggested by Annex A of Standard EN 15251 (European Committee for Standardization, 2007), i.e. 20 °C and 25 °C respectively. Note that the degree-hours are summed up only during occupancy periods and that, in all the considered cases, the operating temperature never reaches the upper comfort limit. Then, the thermal discomfort index TDI_{ADR} of any ADR events was calculated as the variation of degree-hours of thermal

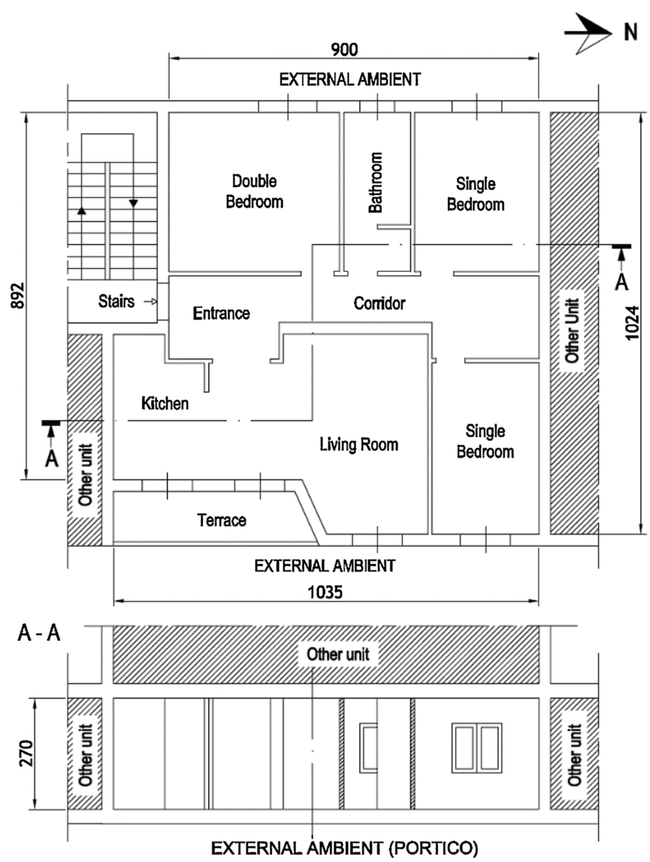

Fig. 3. Plan and prospectus of the building with main dimensions (cm).

Table 2
Monthly climate data of Venice.

Venice - Italy - (N 45° 30' - E 12° 19')												
Month	J	F	M	A	M	J	J	A	S	O	N	D
T_m [°C]	2.6	3.9	7.7	12	17.2	20.8	23.8	22.7	19.6	13.9	8.7	4
T_{min} [°C]	11.1	13.4	18.2	22.5	25.6	30.8	33.6	31	26.6	22.6	17.4	10.7
T_{max} [°C]	11.1	13.4	18.2	22.5	25.6	30.8	33.6	31	26.6	22.6	17.4	10.7
G_{hor} [kWh]	27	32	79	111	156	164	176	145	101	61	27	23

discomfort compared to the reference simulation as shown in Eq. (5):

$$TDI_{ADR} = TDDH_{ADR} - TDDH_{REF} \quad (5)$$

The operative temperature range corresponds to Category II for residential buildings, i.e. from 20 °C to 25 °C for heating and from 23 °C to 26 °C for cooling. Note that while TDDH is an absolute index for the long term evaluation of general thermal comfort conditions, TDI_{ADR} measures the variation of thermal comfort with respect to a baseline, i.e. the corresponding reference simulation without event. By way of example, during the heating season the thermal discomfort index is expected to be negative in case of upwards modulation events as a consequence of a reduced number of degree-hours of thermal discomfort.

3. Description of the case studies

3.1. Building types

The main dimensional properties of the reference building, which are the same for all the three building types, are summarized in Fig. 3 and Table 3. The three case studies have typical thermal insulation characteristics of houses built in the 70 s (B70), 90 s (B90) and recent years (BN) respectively, according to the corresponding national Laws and Standards in force at time of construction. The thermal properties of windows and structures used in the simulations are summarized in Table 4.

Table 3
Main properties of the building.

General data	
V: Air-conditioned volume [m^3]	202.5
S : Thermal loss area [m^2]	151.1
Ratio S/V [m^{-1}]	0.746
Main dimensions of the building [m^2]	
External walls	20.6 (West) / 19.6 (East)
Floor	94.4
Windows	4.5 (West) / 12.4 (East)
Internal Walls	106.2
Dividing walls	57.9
Ceiling	94.4

Table 4
Thermal properties of the building envelope elements.

Opaque Building Elements.

	Heat Capacity [kJ/(m^2 K)]	U - Thermal Trasmittance [a] [W/(m^2 K)]
B70 - External Wall	426	1.099
B70 - External Floor	570	1.534
B90 - External Wall	428	0.661
B90 - External Floor	566	0.658
BN - External Wall	486	0.314
BN - External Floor	586	0.376
ALL - Upper Floor	515	1.660
ALL - Internal Wall	129	2.226
ALL - Dividing Wall	472	1.455

Windows

	U - Thermal Trasmittance [a] [W/(m^2 K)]
B70	2.75
B90	2.75
BN	1.53

[a] The U values of the opaque elements have been calculated considering 7.7 W/(m^2 K) and 25 W/(m^2 K) as surface heat exchange coefficients for inside and outside side of the walls.

The building has an internal net floor area of 94.4 m^2 with two external walls West and East oriented (Fig. 3). The apartment lays on a portico, which makes the pavement an additional external surface as well as the walls between the apartment and the common stairs. The other surfaces are adjacent to other neighbors lodgings. They have been considered at the same indoor temperature of the investigated building unit. Thus, these surfaces accumulate and release heat but don't transfer it to the outdoor environment. The air change rate due to the infiltration was considered constant and equal to 0.5 V^{-1} for buildings B70 and B90 and to 0.3 V^{-1} for new buildings.

3.2. Types of ADR events

During the heating season, all of the events consist in an increase/drop in the indoor air temperature set point of ± 3 K compared to the reference schedule. Moreover, the upward flexibility events take place when the temperature in the reference schedule is 18 °C. Similarly, downward flexibility event during the heating season take place only when the set point temperature in the reference schedule is 21 °C. Table 5 summarizes the events chosen for the simulations. Note that most events were located at the end or at the beginning of the periods with presumed presence of the occupants, i.e. when the set-point changes, and that at least one event was chosen in the middle of the "occupied" period.

In summer six ADR events (one every six hours, starting from midnight) were selected to thoroughly picture the flexibility of the buildings under different conditions. In fact, the cooling load changes significantly during the day due to presence of the solar radiation. The relative humidity set-point during the events has been increased to 60% during the upward flexibility events (24 °C) and reduced to 45% during downward flexibility events (27 °C) in order to reduce the latent heat load during the events and at the same time to operate within the limits of the thermal comfort. Indeed, with these values, a

Table 5
Summary of ADR events during heating season.

Type of ADR events during the heating season	Hours of the day	
	FAM	OC
UP (upwards modulation): increments of the set point temperature	4-6	0-2
	9-11	4-6
	12-14	22-24
	14-16	–
DOWN (downwards modulation): increments of the set point temperature	17-19	8-10
	19-21	13-15
	–	18-20

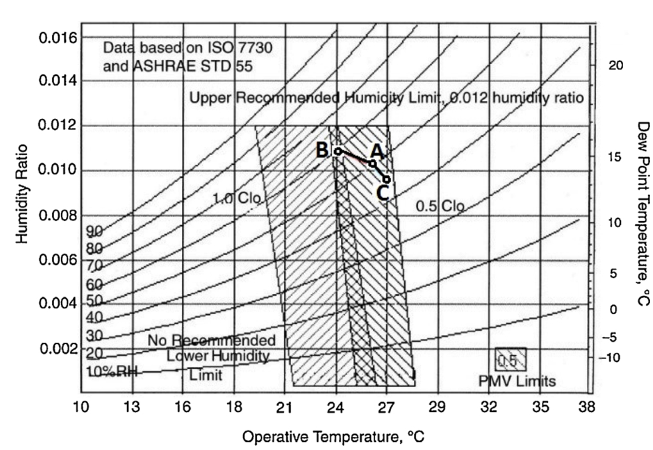

Fig. 4. Indoor air boundary conditions in summer (modified from American Society of Heating, Refrigerating & Air-Conditioning Engineers, Inc., 2017).

Table 6
Summary of ADR events during cooling season.

Type of ADR events during the cooling season	Hours of the day when the single event occurs
UP (upwards modulation): reduction of the set point temperature	0–2
	4–6
	8–10
	12–14
	16–18
	20–22
DOWN (downwards modulation): increments of the set point temperature	0–2
	4–6
	8–10
	12–14
	16–18
	20–22

$-0.5 < \text{PMV} < +0.5$ can be achieved with a clothing thermal resistance equal to 0.5 clo according to the diagram of ASHRAE Standard 55 (American Society of Heating, Refrigerating & Air-Conditioning Engineers, Inc., 2017) and ISO 7730 (International Organization for Standardization, 2005) – see Fig. 4. The events are summarized in Table 6.

From all these considerations, 42 transient simulations (6 reference simulations and 36 with ADR events) were performed to characterize the energy flexibility of the considered buildings in the heating season and 39 simulations (3 reference simulations and 36 with ADR events) in the cooling season. The detailed simulations have been carried out using TRNSYS (Klein et al., 2010).

4. Results

The energy simulations of the buildings described above show a heating-dominated thermal load profile in the climate of Venice (Italy). The following paragraphs describe how the energy flexibility of the reference buildings varies with changing boundary conditions and how the flexibility events affect the comfort within the building.

4.1. Effect of building type

Fig. 5(a) shows, for instance, the average thermal power shifted $\bar{C}_{ADR}$for the events UP_4-6 (i.e., forced start-ups from 4 to 6 a.m.) and DOWN_13-15 (i.e., forced shut-downs between 1 and 3 p.m.) in the winter season with an OC schedule. The results show that the average power shifted decreases from the winter season (from December to February) to the mid-season (March, April, October and November) as a consequence of a lower heat demand, in particular for the new building that has almost no energy needs during mild months.

Fig. 5(b) shows, differently from the previous one, the average monthly $\bar{C}_{ADR}$in the cooling season for upward (UP_4-6) and downward (DOWN_8-10) modulation events. The peaks in all upward cases are reached in the warmest month (July), with an average power shifted of almost 5 kW. In milder months (June and August) the values tend to decrease, especially for buildings B90 and B70, due to the low thermal insulation and the free cooling occurring during the night hours. The downward modulation events (i.e., increase of the set-point temperature) have a lower heat storage capacity compared to upward events, with an average power shifted of around 2 kW in July. As far as the efficiency of the events is concerned, Fig. 6 shows that the trend is the same for both the heating (a) and cooling (b) season: the annual average efficiency grows with increasing thermal insulation level of the building envelope.

4.2. Effect of start time of ADR event

This section shows that the available storage capacity and the efficiency of the ADR events depend on the temporal distance from high energy demand hours and on the maximum power of the heating or cooling system. Fig. 7 shows, for instance, an example of the first effect on an upward modulation event occurring in February in the B90 building. In Fig. 7(a), the event occurs before the peak load hours (4–6) and in Fig. 7(b) the forced start-up occurs at the beginning of the night, when the set-point is decreased and there is no heat demand. In the first case, the heating system is switched on when the indoor air temperature has reached a low value (close to 18 °C), i.e. when all the heat stored in the building during the previous day has been discharged. Therefore, in this event the building structure can be used to store the heat for the following hours, thus leading to a high value of $\bar{C}_{ADR}$. Then, the stored heat is quickly used after the event for flattening the morning peak load and the heating demand in the next hours, thus leading to an efficient ADR event with η_{ADR} reaching 90.2%. The UP_22-24 case, instead, is one of the worst cases among the upward modulation events. In fact, the surplus of thermal energy supplied to the building is low due to the high state of charge of the building during the event. This small amount of heat is also highly wasted during the night, i.e. it is not efficiently used to shift the heat load. Consequently, η_{ADR} drops to 81.8%. The same trend can be observed in the other two buildings, as confirmed by Fig. 6.

In the cooling season, a distinction must be made between upward and downward modulation events. An increased set-point temperature (downward modulation) during nighttime does not necessarily involve a start-up of the cooling system. Therefore, $\bar{C}_{ADR}$ of events DOWN_0-2 and DOWN_4-6 is very low (from 0.1 to 0.4 kW) compared to that of diurnal events (from 1.1 to 1.7 kW). ADR efficiencies, instead, do not show significant variations among ADR events occurring in the same building. The values have already been discussed in the previous Section. For upward modulation events, the opposite holds true: η_{ADR} depends on the start time of event while $\bar{C}_{ADR}$ does not change significantly. This is because a 2 K reduction of the set-point temperature

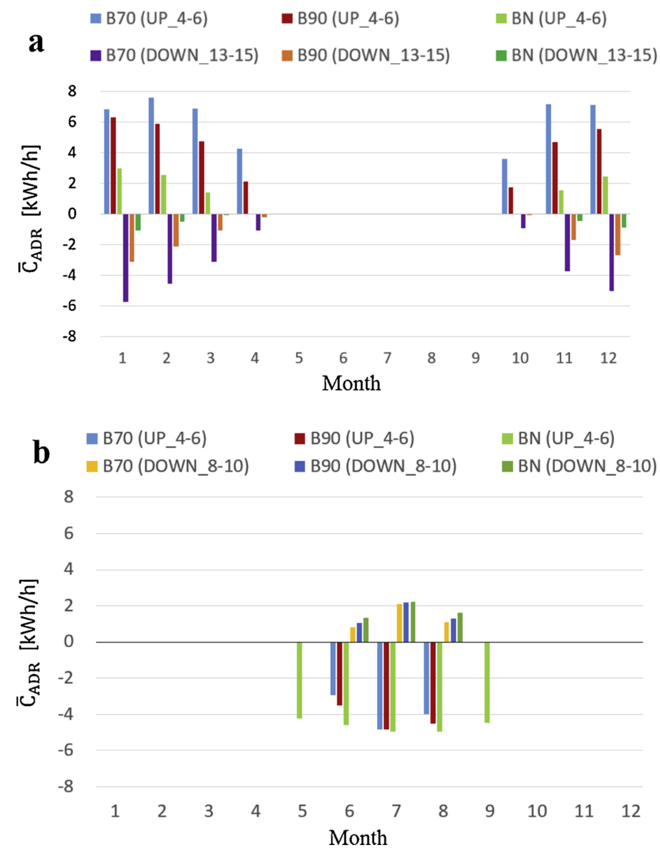

Fig. 5. Average hourly $\bar{C}_{ADR}$ per month in (a) heating and (b) cooling season.

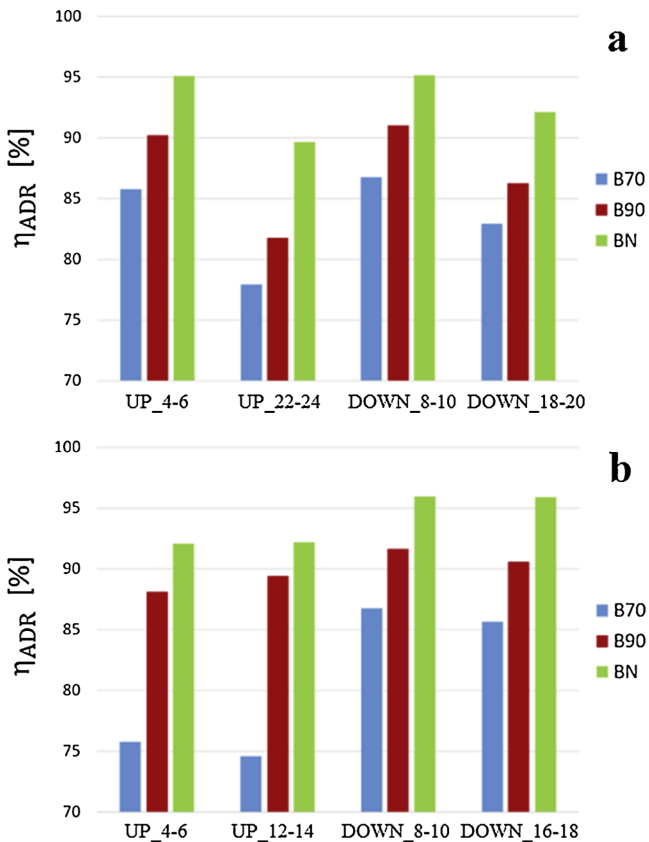

Fig. 6. Average η_{ADR} in (a) heating and (b) cooling season.

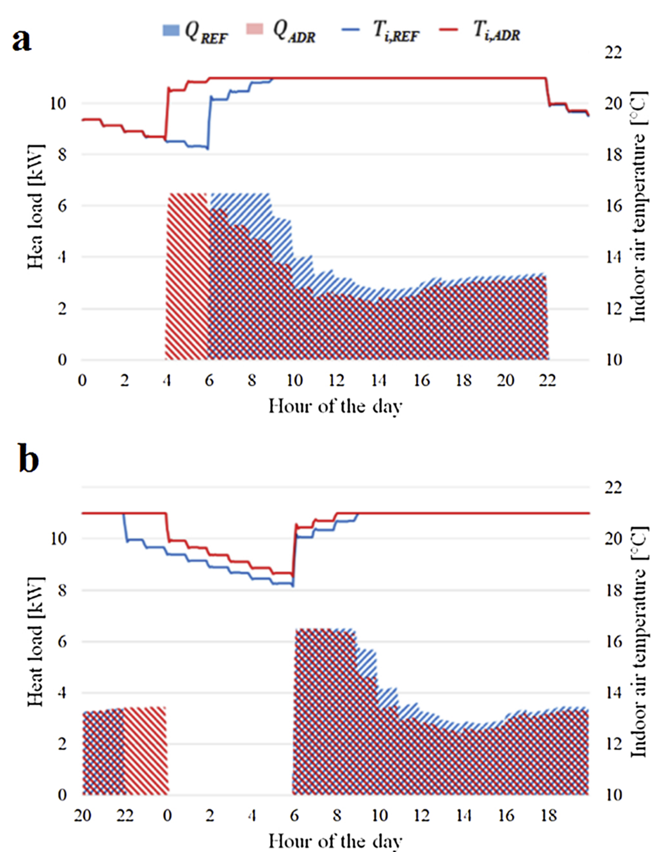

Fig. 7. Heat load profiles of the ADR events for (a) UP_4-6 and (b) UP_22-24 for building B90 with OC occupancy schedule.

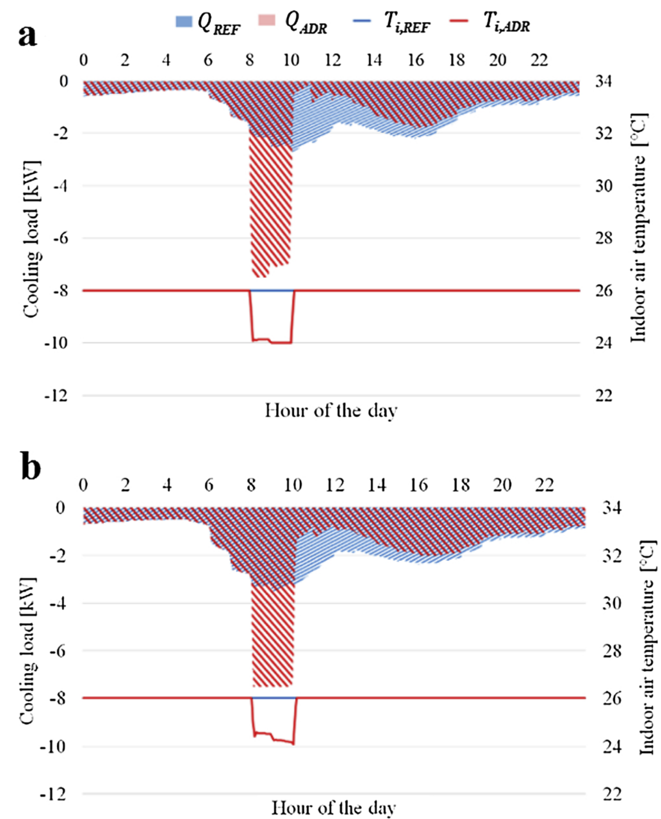

Fig. 8. Upwards modulation events in the cooling season: a day of (a) June and (b) July.

always implies starting up the cooling system or increasing its load factor. The UP_8-10 event shows the highest ADR efficiency for all buildings (87% for B70, 92% for B90 and 96% for BN) because the heat removed from the building at this time contributes to reduce the cooling load in the following hours. However, in summer the peak load hour varies day by day depending primarily on the amount of solar radiation entering the building, that in turn depends on the orientation of the glazed surfaces. For instance, Fig. 8 shows the cooling load profiles of building BN in a day of June and in a day of July with and without ADR event (UP_8-10). In the day of June, the cooling peak load is lower than 3 kW and occurs at 10 a.m., whereas in July it occurs one hour earlier and is higher than 3 kW. As a consequence, the best ADR events may change depending on the characteristics of the envelope and on the weather conditions, making it difficult to establish a general rule.

4.3. Effect of user behaviour

When discontinuous occupancy of young families (i.e., FAM schedule) is considered, two peak load periods appear during the day: one in the morning, between 6 and 9 a.m., and one in the afternoon, between 4 and 7 pm. The upward modulation events with the highest available storage capacity are UP_4-6 and UP_14-16. Thus, the aforementioned rules on the most favorable events hold true. However, the intermittent behaviour imposed by the user reduces the efficiency of event UP_4-6 due to the diurnal temperature set back. Fig. 9 shows, for example, that most of the thermal energy stored in the building B90 during an event UP_4-6 in February is lost between 9 a.m. and 4 pm. Moreover, the intermittent operation during the day imposed by schedule FAM increases the energy consumption during night hours even for buildings B90 and BN during the coldest months of the year. This change in the reference heat load pattern improves the performance of events occurring later, such as UP_9-11 and DOWN_19-21. With the OC schedule

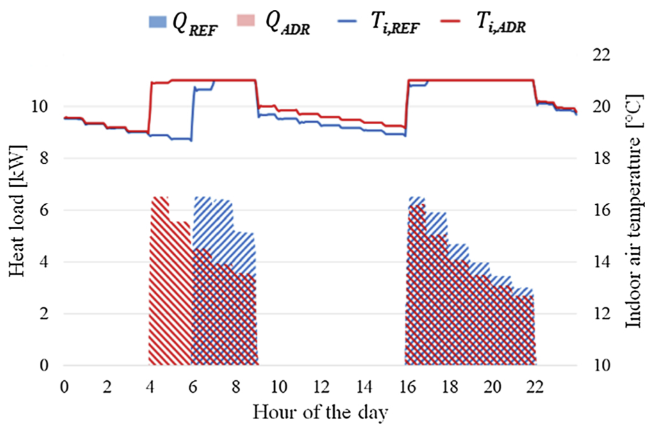

Fig. 9. ADR event with FAM occupancy schedule.

this happened only to uninsulated buildings in the coldest months of the year as shown in the previous paragraph. The FAM schedule extends this change to refurbished and new buildings.

The investigation was carried out for the heating season only. In the cooling season, downward modulation events are expected to rapidly bring the indoor environment outside the boundaries of thermal comfort, especially during diurnal ADR events with high incident solar radiation.

4.4. Energy flexibility and thermal comfort

Fig. 10(a) shows the annual average performance indicators of the considered events: the ADR efficiency η_{ADR} is always above 75% and new buildings have lower $\bar{C}_{ADR}$ and higher η_{ADR} compared to older ones as discussed in Section 4.1. However, two ADR events with similar flexibility parameters may differ significantly in terms of indoor thermal comfort. The relationship between $\bar{C}_{ADR}$ and η_{ADR} and the thermal discomfort index TDI_{ADR} is shown in Fig. 10(b) and (c), respectively. Every dot in the graphs represents a certain event occurring in a building once every three days. The colour indicates the type of building (red for B70, blue for B90 and green for BN) and the shape corresponds to different user habits (circle for OC schedule, squared for FAM schedule). From Fig. 10(b), it is clear that ADR events significantly affect the indoor thermal comfort conditions of both upward and downward modulation events in old buildings with low thermal insulation, whereas they have a negligible effect in new buildings. It should be noted that in this study a fixed event duration of two hours was considered for all events. The most significant variations in terms of degree-hours of thermal discomfort occur for buildings with intermittent operations. This situation may occur, for instance, in buildings where the HVAC system was designed for continuous operation and is instead operated with an intermittent schedule. In such a case, the ADR efficiency may drop below 70% even in new and partially refurbished buildings and the thermal discomfort increases significantly. These observations suggest that both $\bar{C}_{ADR}$ and η_{ADR} parameters provide an incomplete evaluation of the thermal energy flexibility of the buildings, unless they are calculated for equal indoor thermal comfort conditions. As far as the first index is concerned, it is clear that setting an upper limit to the degree-hours of thermal discomfort will necessarily reduce either the thermal load or the duration of the event compared to that of new buildings, thus leading to lower available thermal capacities. This is particularly important for downward modulation events occurring in the heating season in order to avoid conflicts between the aggregator and the people engaged in the DSM program. As far as the ADR efficiency is concerned, it must be noted that η_{ADR} = 100% in downward modulation events means that all the energy not supplied during the event will be supplied afterwards. Thus, one would expect higher efficiencies for old low-insulated buildings that are not able to maintain a

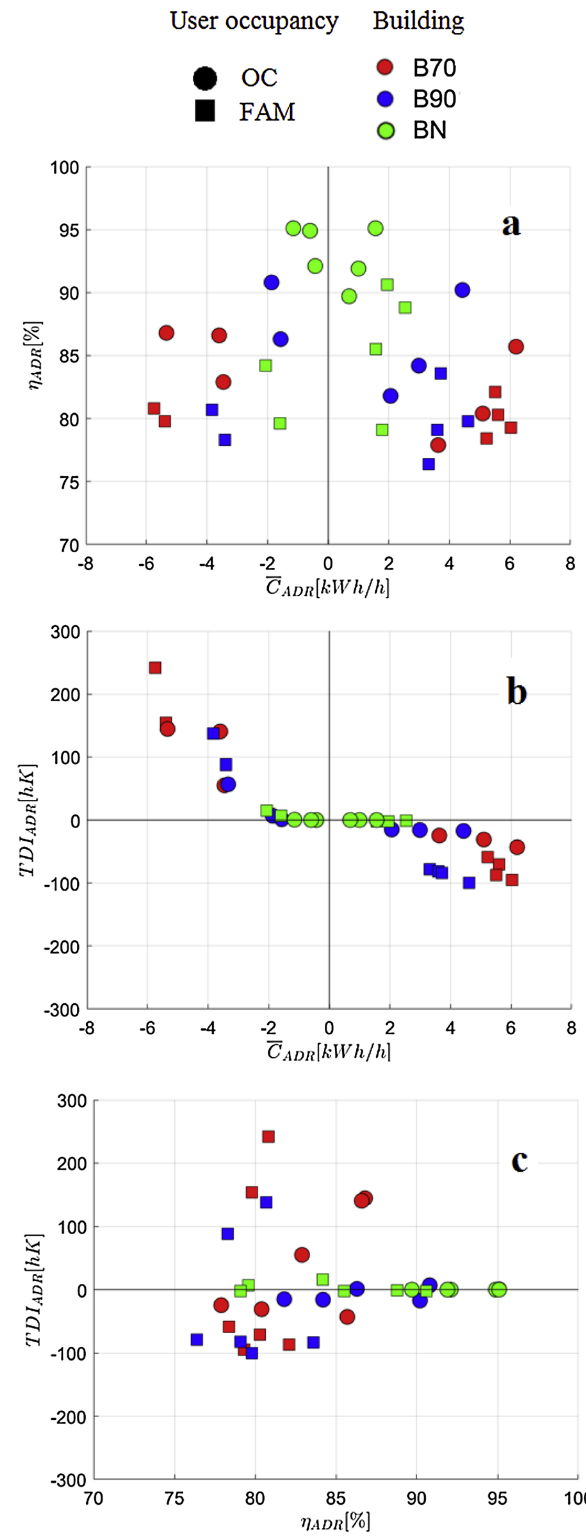

Fig. 10. Relationship between (a) energy flexibility indicators; (b) thermal discomfort index and C_{ADR}; (c) thermal discomfort index and η_{ADR} during the heating season.

high indoor air temperature during forced shut-downs. Instead, as it can be seen in the left-hand side of Fig. 10(a), old buildings have lower efficiencies. In the authors' opinion, this counterintuitive behaviour is due to the fact that the efficiency of the building in shifting its own heat demand is strictly related to the thermal comfort conditions allowed in the indoors. However, a clear correlation between the thermal

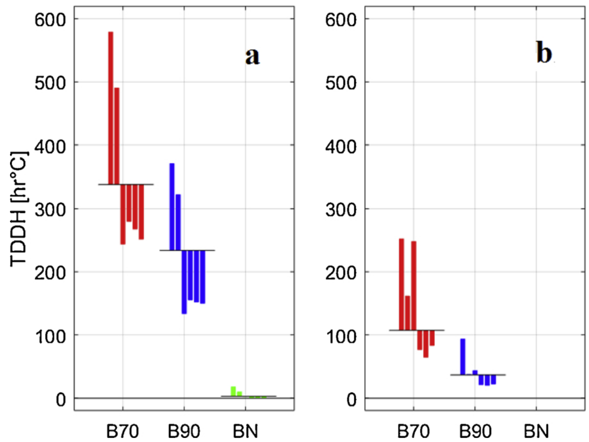

Fig. 11. Degree-hours of thermal discomfort during the heating season with schedule (a) FAM and (b) OC.

discomfort index and the ADR efficiency does not appear for the considered cases, as Fig. 10(c) shows.

Fig. 11 shows the degree-hours of thermal discomfort of both the reference simulations and the simulations including the ADR events. The first is represented, for each of the buildings considered, by the black horizontal baseline of the bar charts. The bars increase the TDDH for downward modulation events and reduce them for upward ones. It can be seen that buildings of class B70 start from a situation of thermal discomfort (338 h °C for FAM schedule and 107 h °C for OC schedule) and at the same time show the most significant variation in case of downward modulation events. Buildings of class B90 have lower discomfort in the reference simulations (234 h °C for FAM schedule and 37 h °C for OC schedule) and show a significant improvement with upward modulation events. Finally, buildings of class BN have a negligible TDDH in both reference and ADR simulations.

With the summer events, two main assumptions were made: (i) the design cooling load is quite the same for the considered buildings and roughly corresponds to the cooling capacity of three internal split units; (ii) the operation is continuous, i.e. the intermittent behaviour assumed in the heating simulations is not considered here. The right-hand side of Fig. 12(a) shows that upward modulation events in the cooling season have a rather low available storage capacity (below 2 kW). This is partly caused by assumption (ii), since all the buildings have a significant energy needs for space cooling also without the reduction of the temperature set-point, i.e. in the reference simulations. All downward modulation events have similar $\bar{C}_{ADR}$ (slightly higher than 4 kW), regardless of the building envelope considered. The ADR efficiency, instead, shows a clear increasing trend towards buildings with higher thermal insulation. Fig. 12(b) and (c) suggest that this result does not depend on the indoor thermal comfort as it seems for the heating events, because the relationship between the thermal flexibility indicators and those related to thermal comfort is different in the cooling season. This can be partly explained by assumptions reported above. In fact, in the simulations of the heating season the intermittent operation of the FAM schedule affected the heat load profiles with and without ADR events, with a clear effect on the degree-hours of thermal discomfort. As a result, both flexibility indicators seemed to be related to the indoor thermal comfort conditions – Fig. 10(b) and (c). On the contrary, in the simulations of the summer season, the "efficiency" in shifting the cooling load (η_{ADR}) does not show any dependency on the thermal discomfort index TDI_{ADR} – see Fig. 12(c). In other words, the TDI_{ADR} depends on the start time of the event but not on the building envelope.

The same behaviour can be observed in Fig. 13. The degree-hours of thermal discomfort of the different buildings is similar in reference conditions. The growing trend of $TDDH_{REF}$ towards buildings with

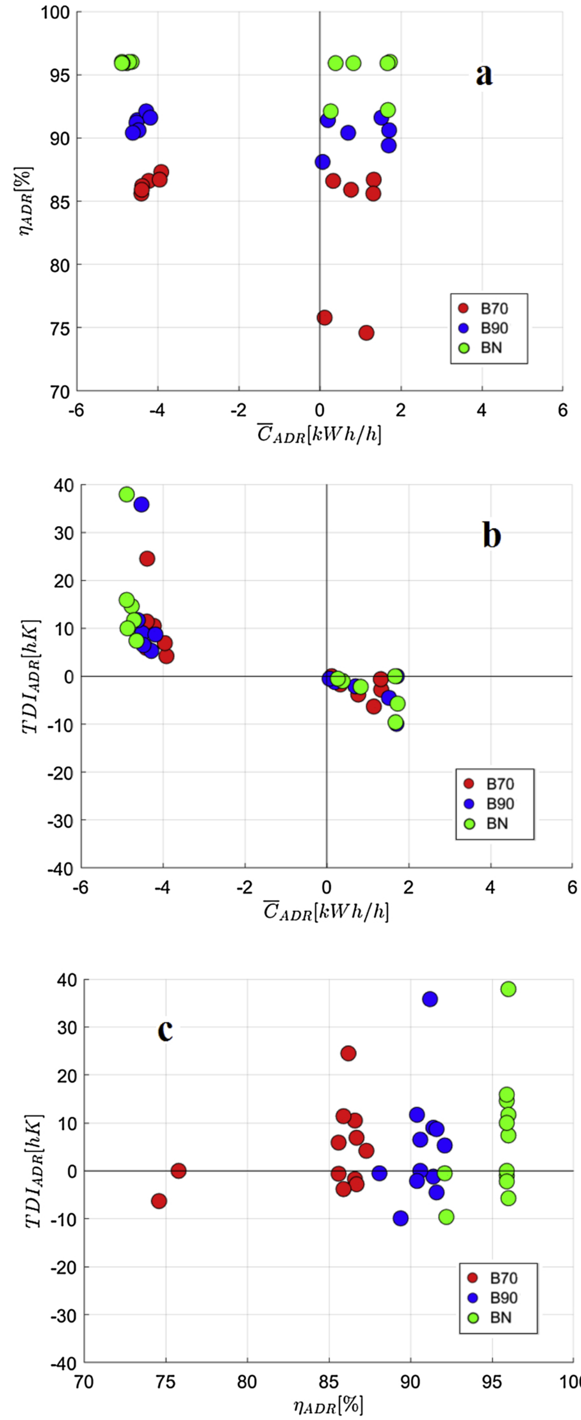

Fig. 12. Relationship between (a) energy flexibility indicators; (b) thermal discomfort index and $\bar{C}_{ADR}$; (c) thermal discomfort index and η_{ADR} during the cooling season.

higher thermal insulation seems to be related to the difficulty of free-cooling during night hours, that is amplified by the assumption of having a lower air change rate in new buildings compared to buildings B70 and B90 as specified in Section 3.1. The variation of the TDDH compared to the baseline clearly depends on the start time of ADR event.

5. Concluding discussion

The energy shifting potential of three residential buildings with

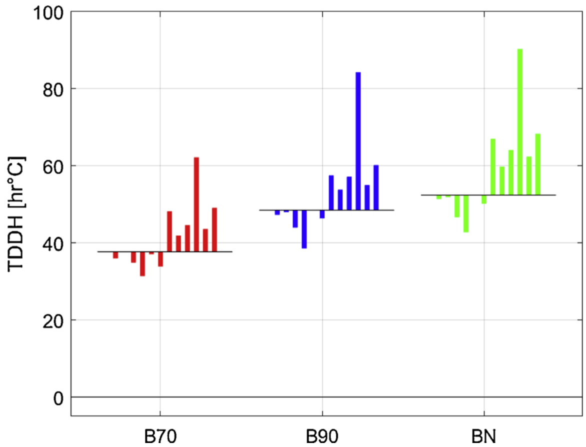

Fig. 13. Degree-hours of thermal discomfort during the cooling season.

different thermal performance of the envelope was assessed using the energy flexibility indicators $\bar{C}_{ADR}$ and η_{ADR}. These parameters outline the potential energy stored or saved during the considered ADR events and how such amount of energy is effectively shifted to the following hours. Moreover, the paper links these flexibility indicators with a thermal discomfort index and draws some general conclusions about the energy flexibility of residential buildings.

5.1. Summary of the main results

The results have shown that $\bar{C}_{ADR}$ decreases from old to new buildings during the heating season, while it slightly increases in the cooling season – except in the month of July, when it is similar for all buildings. In both seasons, the better the thermal insulation of the buildings, the higher the value of ADR efficiency. This means that, for upward modulation events, the surplus of thermal energy stored in the building structure allows reducing the heat demand after the event in a more significant way for new buildings than for those with a poor thermal insulation. Conversely, for downward modulation events, the definition of η_{adr} can be misleading, as higher thermal losses – and therefore higher energy consumption after the events – results in higher efficiency. Table 7 shows the results aggregated by start time and season of the ADR events.

Furthermore, the study has shown that for upward modulation events the highest η_{ADR} values occur when the events take place immediately before the high-consumption hours of a day, while $\bar{C}_{ADR}$ tends to be higher at the end of low-consumption periods. A similar rule was found for downward modulation events: η_{ADR} tends to be higher if the event is located immediately after the end of the peak load hours of energy demand during the day and $\bar{C}_{ADR}$ value increases if the event is located at the beginning of the occupation hours.

The previous conclusion did not hold true in the coldest months for low-insulation buildings, due to nocturnal start-ups of the HVAC devices. As a result, the best starting hours of the events were distant from the high-consumption hours. When the occupancy schedule was changed from the continuous to the intermittent one, these exceptions occurred also in more insulated buildings and during milder months.

Table 7
Effect of building envelope on flexibility indicators.

	Heating				Cooling			
	$\bar{C}_{ADR}$ [kW]		η_{ADR} [%]		$\bar{C}_{ADR}$ [kW]		η_{ADR} [%]	
	UP	DOWN	UP	DOWN	UP	DOWN	UP	DOWN
B70	5.3	−4.9	80	82	4.2	0.8	72	82
B90	3.5	−2.9	83	85	4.4	1.0	86	85
BN	1.7	−1.4	91	89	4.8	1.1	93	89

In the cooling season, the general rule still applies but the choice of the best ADR events is more difficult due to the high fluctuation of diurnal heat gains, especially for buildings with low thermal insulation. In fact, the charge and discharge cycles are highly affected by the amount of solar radiation entering the building, which changes depending on weather conditions and on the size and orientation of the glazed surfaces. In the downward modulation events during the cooling season, the value of $\bar{C}_{ADR}$ of all events was very low compared to the upwards modulation cases.

The above considerations are valid under the assumption of a constant duration of the ADR events. However, the duration of the events must be such that they do not exceed the comfort limits tolerated by the users. Therefore, the second step of the work aimed at evaluating the effects of the forced modulation of the heating and cooling system on the indoor environmental conditions. The results showed that, in the heating season, forced switch-offs or start-ups of the HVAC system do not bring to significant variation of thermal comfort in well-insulated buildings, whereas they do in those with low thermal insulation. During the cooling season, the indoor thermal conditions depend on the start time of ADR events rather than on the type of building envelope.

5.2. General conclusions

In conclusion, the article shows that the potential for energy flexibility of a building is mainly related to the level of insulation of the envelope during the heating season, and to the time of the event during the cooling season. The combination of these variables and the climatic conditions during the event determine the amount of energy that can be shifted over time. Some recurring trends and exceptions due to different user habits have been highlighted. In addition, the results show that the cost associated with flexibility is an increase in consumption for upward modulation events and a reduction in thermal comfort conditions for downward modulation events. The greater the flexibility potential of the buildings, the higher the costs, both in heating and cooling modes. The benefit of ADR actions should not be intended as energy savings for single participants, but rather as the possibility to shift the energy consumptions of the whole set of participants towards time windows with cheaper and/or cleaner energy production. The results obtained in this article will be used in future research activities to evaluate the thermal behaviour of buildings within Active Demand Response policies at the level of both single building unit and district.

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