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A novel measurement method for accurate heat accounting in historical buildings

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ABSTRACT

Nowadays, two different heat accounting methods are available: the direct method, based on heat meters, and the indirect one, based on heat cost allocators. Unfortunately, in existing buildings, due to the plant configuration, heat meters are often technically unfeasible or not cost efficient, whereas heat cost allocators can be easily installed in almost all conditions. At the same time, the indirect method relies on a high number of interconnected devices with installation and operative conditions often variable within the same building and influencing the on-field metrological performances. In this paper, the authors propose a novel "hybrid" method for accurate heat accounting combining the advantages of indirect method with the higher accuracy typical of direct methods. The proposed method has been experimented at INRIM, the primary metrology institute in Italy, assessing the on-field performance in a virtual eight-apartments building. The experimental results show that the proposed method always presents improved accuracy.

1. Introduction

The Energy Efficiency Directive (EED) 2012/27/EU [1] and its subsequent recast 2018/844/EU [2] identified individual heat accounting as an essential tool for improving energy efficiency in buildings. To this aim, EED has set the obligation to install heat accounting systems for individual measurement of energy consumption of space heating in condominium buildings supplied by district heating or by a common centralized system, when technically feasible and economically convenient. Heat accounting methods can be classified into two main categories: i) direct methods, which provide through heat meters (HM) [3] an accurate measurement of the thermal energy consumed by each apartment within a building through an energy balance on the flow and return pipes of the heating/cooling circuit; ii) indirect methods, which provide estimates proportional to the heat exchanged between single heating elements and ambient of each apartment through dimensionless allocation units (*AU*). To this last category belong the heat cost allocators (HCA) [4] and the insertion time counters compensated with the heating fluid temperature [5] or with the degree days [6]. HMs are the most accurate devices currently available on the market for thermal energy measurement presenting also the peculiarity of being regulated by legal metrology MID directive [7] thus providing specific guarantees and consumer protection in terms of type approval, production, installation, initial and periodic verifications [8]. HMs are among the most used in new buildings, generally provided with central heating system and horizontal distribution configuration with manifolds for single apartments [9]. HCAs, on the other hand, are the most popular and widely used indirect accounting systems in northern and central European countries (such as Germany, Austria, Denmark). Besides, there is a huge theoretical potential for installation in existing buildings also in other European countries (estimated at around 20 million) such as Spain, France and Italy. In particular, in Italy the estimated multi-family buildings stock where individual measurement systems are not yet installed, is approximately 4.5 million [10].

The EED directive allows indirect heat accounting methods to be used when the direct one is not technically feasible and/or economically efficient. As a matter of fact, in many historical buildings, due to architectural constraints and/or to the configuration of the heating system (generally with vertical raising mains), direct HMs are not always technically feasible or cost efficient. In this case, in fact, it would be necessary to install one HM for each heating element, with consequent metrological issues due to low flow-rates and measured temperature differences in addition with

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Nomenclature

Acronyms and Symbols

EED Energy Efficiency Directive
HCA Heat cost allocator
HM Heat Meter
MID Measuring Instrument Directive
PLC Progammable logic computer
St.dev Standard deviation
AU_b Allocation units of the whole building for the indirect method, dimensionless
$AU_b^{'}$ Allocation units of the whole building for the hybrid method, dimensionless
$AU_{i,j}$ Allocation unit of each *j-th* radiator in the *i-th* apartment (indirect), dimensionless
$AU_{i,j}^{'}$ Allocation unit of each *j-th* radiator in the *i-th* apartment (hybrid), dimensionless
AU_i Allocation unit of the *i-th* apartment of the building for the indirect method, dimensionless
$AU_i^{'}$ Allocation unit of the *i-th* apartment of the building for the hybrid method, dimensionless
$AU_{k,j}$ Allocation unit of the single raising main, dimensionless.
AU_k Allocation units of the single raising main, dimensionless
$E\%_{max}$ maximum relative display deviation, dimensionless
E_i errors of the shares for hybrid and indirect methods
K_C rating factor for thermal contact between HCA and radiator
K_Q rating factor for the nominal thermal power of the radiator
Q_b Total thermal energy consumed in the building, kWh
Q_i Thermal energy consumed by the single *i-th* apartment, kWh
$Q_{k,j}$ energy consumed in the single raising main, kWh
Q_k Thermal energy supplied along each *k-th* vertical raising main, kWh
Q_k thermal energy supplied along each vertical *k-th*, kWh
R_{AU} heat cost allocator display resolution, dimensionless
S_{HM} Individual share of each *i-th* apartment (reference direct), dimensionless
S_i Individual share of each *i-th* apartment (indirect), dimensionless
$S_i^{'}$ Individual share of each *i-th* apartment (hybrid), dimensionless
$\dot{V}$ radiator volumetric flow rate, $m^3\ s^{-1}$
c_p specific heat capacity of the heat conveying fluid, kJ $kg^{-1}\ K^{-1}$
n_i Number of apartments in the building, dimensionless
n_j^i Number of radiators in each *i-th* apartment, dimensionless
n_j^k Number of j-th radiators installed on the same *k-th* vertical raising main, dimensionless
n_k Number of vertical raising mains in the distribution plant, dimensionless
H Radiator height, m
K resulting rating factor of the heat cost allocator
L Radiator length, m
$U(E_i)$ expanded uncertainty of errors, dimensionless
W Radiator width, m
t time period, s.
$u(K_Q)$ standard uncertainty of rating factor K_Q, kWh
$u(Q_i)$ standard uncertainty of individual apartments heat consumption, dimensionless
$u(S_{HM,i})$ standard uncertainty of the share ref. thermal energy measurements, dimensionless
$u(Q)$ standard uncertainty of thermal energy measurement, kWh
$wRMSE$ weighted Root-Mean-Square-Error, dimensionless
ΔT_{io} temperature difference between the inlet and outlet flow section of the radiator, °C
ΔT_r Temperature difference between heating fluid and indoor ambient temperature, °C
ρ density of the heat conveying fluid, kg m^{-3}

unavoidable higher costs. In Europe, this is a typical situation in almost all historical buildings and in buildings built before the 1980s [9,11]. Unfortunately, not all heat accounting systems show the same reliability. Besides, indirect accounting systems show lower measurement accuracy which is extremely dependent on installation and programming features. A specific methodology for estimating the accuracy and reliability of indirect heat accounting systems is still lacking in the scientific literature and technical standards. Moreover, due to the specific architecture of such systems (that is to say a sort of complex distributed system consisting of a large number of similar devices installed on radiators together with data gathering/storage/processing devices), the accuracy of heat allocation will depend on both the accuracy of the individual devices and on the different installation and operation characteristics of the plant. From a field analysis on the different heat metering and accounting methods [12] in fact, different accuracy levels have been found, ranging from about 4.4% for HMs to 21.6% for insertion time counters compensated with degree-days. Intermediate accuracy, on the other hand, were estimated for HCAs (about 9.2%) and for the insertion time counters compensated with the heating fluid temperature (about 13.4%). In reality, the accuracy of indirect accounting systems in different operating conditions may vary from about 2.7% (i.e. in a large multi-family building in optimal conditions) to about 11.7% (i.e. in a two-family building in critical conditions). Furthermore, the allocation accuracy can be estimated through a model allowing to assess the influence of the installation conditions with particular reference to the number and type of radiators and of the related installation, also in relation to the installation issues and use of single apartments. This model can be adopted both to design appropriate heat accounting systems in new buildings and to evaluate their reliability in existing ones. [13].

In this work, aiming at addressing the above mentioned issues of accounting methods in existing buildings with a centralized heating system, especially for large buildings and occasionally lived, the authors propose a novel accounting method, namely the "hybrid heat accounting" method. The proposed method relies on indirect systems on single radiators and on direct heat meters on the existing raising mains of the heating plant, merging the advantages of direct and indirect allocation methods. In particular, in respect to the actual available heat accounting methods such as proportional methods based on floor area or installed heat power or indirect HCAs, it allows knowing the consumption of each room in the apartment typical of indirect methods and it is expected to show an increasing accuracy and reliability of the share typical of direct methods. The metrological performance of the proposed method was analysed at the experimental mockup of INRIM, the National Metrological Research Institute of Turin, specifically configured to simulate field operation of an eight apartments building. Through a specific design of the experiments, it was possible to assess the influence of some operating parameters such as: i) the usage mode (occasional or continuous) by excluding some apartments; ii) the different consumption due to changes in the external climatic conditions through the variation of the heating fluid flow and temperatures.

2. Theory and methods

The direct heat accounting method allows accurate measurement of the energy supplied to each apartment, at the same time showing generally high commissioning costs and above all an intrinsic limitation of use in buildings with vertical distribution. On the other hand, the heat accounting method does not directly measure the energy consumed but estimates dimensionless allocation units proportional to it, presenting a lower accuracy together with simpler installation and basically lower costs. Furthermore, indirect methods allow to discriminate the consumption of each emission element and therefore of each room within the apartment. Fig. 1 shows the two typical operational schemes of distributed heating plants in existing condominium buildings supplied by a common centralized system. In ring distribution plants direct heat accounting with HMs is in principle technically feasible, whereas in vertical mains distribution ones only indirect accounting systems combine technical feasibility and economic convenience.

2.1. Direct and indirect heat accounting methods

When a direct heat accounting method is applied, the "individual" share of single apartments, S_i (%), is estimated by calculating the ratio between the energy consumed by the single apartment (measured through HMs used as sub-meters), Q_i (kWh), and the total energy consumed in the building, Q_b (kWh), and measured by a supply thermal energy meter (e.g. through a HM in the heat exchange substation in the case of supply from district heating, or the energy measured by a gas meter if the boiler is supplied by natural gas network), as per equation (1).

$$S_i = \frac{Q_i}{Q_b} \tag{1}$$

On the other hand, for indirect heat accounting methods, the allocation unit of the *i-th* apartment of the building (AU_i), is obtained by summing the allocation unit of each *j-th* radiator in the apartment ($AU_{i,j}$), as per eq.(2). Then, the share S_i of each *i-th* apartment (i.e. the so-called "voluntary" heat consumptions) is given by the following equation (3).

$$AU_i = \sum_{j=1}^{n_j^i} AU_{i,j} \tag{2}$$

$$S_i = \frac{AU_i}{AU_b} = \frac{\sum_{j=1}^{n_j^i} AU_{i,j}}{\sum_{i=1}^{n_i} \sum_{j=1}^{n_j^i} AU_{i,j}} \tag{3}$$

where n_j^i is the number of radiators (which is usually equal to the number of columns in the heating plant) in each *i-th* apartment and n_i is the number of apartments in the building, respectively.

2.2. The novel "hybrid heat allocation" method

The novel hybrid allocation method has been developed at the LAMI, the industrial measurement laboratory of the University of Cassino and Southern Lazio, and consists of indirect heat accounting devices (e.g. HCAs) installed on each radiator and direct HMs installed at the base of each raising main of the heating distribution plant in addition to the supply HM, as shown in Fig. 2.

The possibility of improving the metrological performance of indirect accounting devices in buildings supplied by centralized heating plant with vertical raising mains was first proposed by Celenza et al. [9]. In this case, heat allocation is carried out selectively on each column and not on the entire building, also allowing in this way:

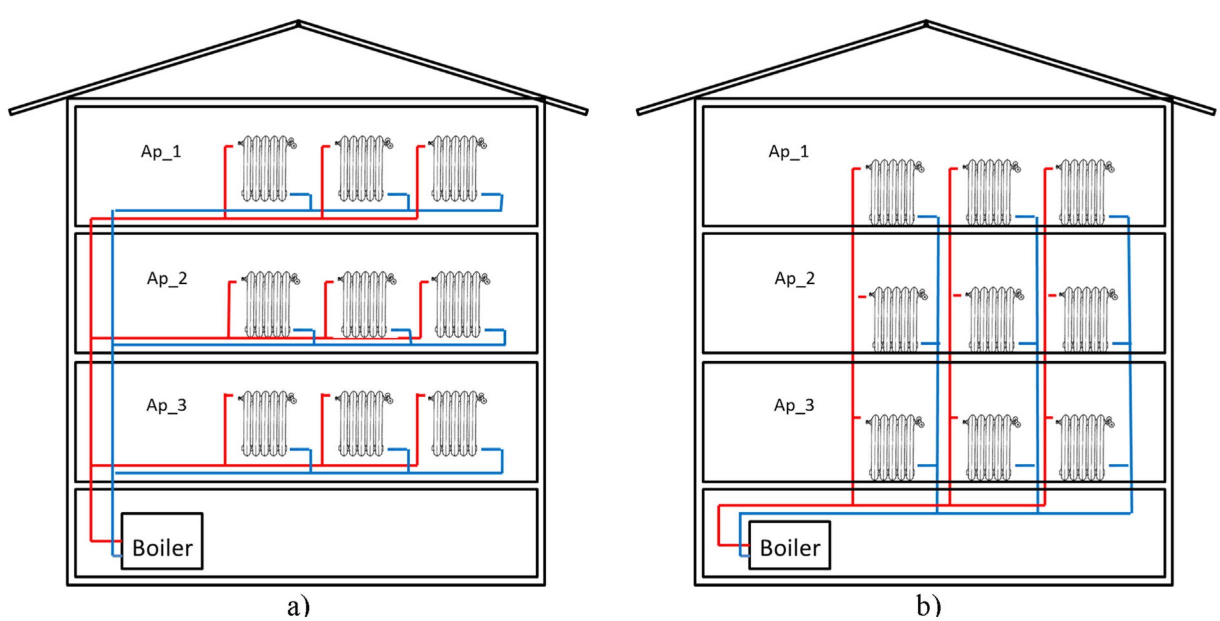

Fig. 1. Heating plant configurations of distributed heating plants: a) Ring distribution, b) Vertical mains distribution.

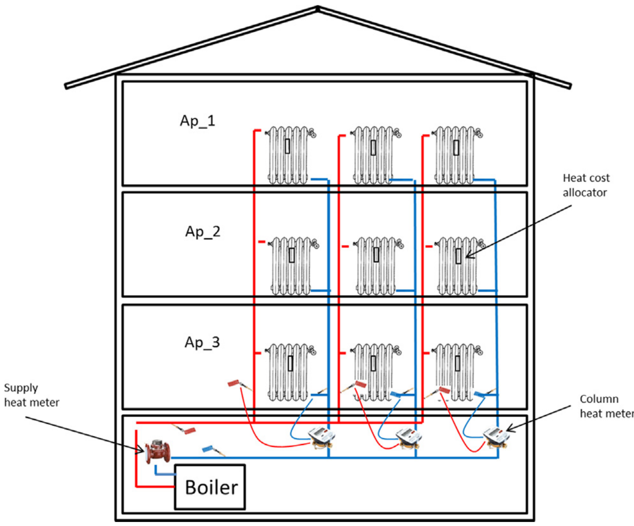

Fig. 2. Hybrid heat allocation method scheme.

- to verify the thermal energy produced by the boiler and, therefore, to monitor its efficiency and promptly schedule eventual maintenance interventions;
- to evaluate the individual share of heat consumption, considering groups of radiators with similar installation conditions and nominal heat output, like the radiators on each vertical raising main; indeed, the apartment typology and the rooms distribution is typically repetitive for the overlapping floors, thus, higher accuracy of the accounting is expected as a positive effect of the compensation of the similar systematic errors affecting the indirect heat accounting devices;
- to monitor the energy consumption of single rooms, maintaining at the same time the energy measurement on each column;
- to show the economy and simplicity of installation of indirect devices with a slight additional cost depending on the number of vertical raising mains. For example, in a ten-story building with 20 apartments and 100 heating elements with a heating distribution system with 5 columns (i.e. needing the installation of 5 HMs additional to the indirect system) the increase of fixed cost for commissioning would be about 15–20%.

The direct measurement on the vertical raising mains returns the values of the thermal energy Q_k (kWh) supplied along each vertical *k-th* and therefore the total one of the building as per eq. (5). Allocation unit $AU'_{i,j}$ of each radiator in the hybrid method is then given by eq. (6).

$$Q_b = \sum_{k=1}^{n_k} Q_k \tag{5}$$

$$AU'_{i,j} = AU_{i,j}\frac{AU_b}{AU_k}\frac{Q_k}{Q_b} = AU_{i,j}\frac{\sum_{i=1}^{n_i}\sum_{j=1}^{n_j^i} AU_{i,j}}{\sum_{j=1}^{n_j^k} AU_{i,j}}\frac{Q_k}{Q_b} \tag{6}$$

where n_k is the number of the vertical raising mains in the distribution plant, n_j^i is the number of radiators in each *i-th* apartment and n_j^k is the number of radiators installed on each raising main.

For the sake of simplicity, it can be argued that a correction factor is introduced which depends on both the ratio between the energy consumed in the single raising main ($Q_{k,j}$) and the total in the building (Q_b) and between the total AU_b in the building and the $AU_{k,j}$ in the single raising main.

Therefore, the share S'_i, of each *i-th* apartment (i.e. the so-called "voluntary" heat consumptions) is given by the following equation:

$$S'_i = \frac{AU'_i}{AU'_b} = \frac{\sum_{j=1}^{n_j^i} AU'_{i,j}}{\sum_{i=1}^{n_i}\sum_{j=1}^{n_j^i} AU'_{i,j}} = \frac{\sum_{j=1}^{n_j^i}\left(\frac{AU_{i,j}}{\sum_{j=1}^{n_j^k} AU_{i,j}}\frac{Q_k}{Q_b}\right)}{\sum_{i=1}^{n_i}\sum_{j=1}^{n_j^i}\left(\frac{AU_{i,j}}{\sum_{j=1}^{n_j^k} AU_{i,j}}\frac{Q_k}{Q_b}\right)} \tag{7}$$

2.3. Design of experiments

The authors designed an experimental campaign at the Energy Measurement Laboratory of INRIM, the National Metrology Institute of Turin, aimed at evaluating the performance of the novel hybrid accounting method. The test facility (Fig. 3) consists of a full-scale central heating system with 40 radiators characterized by different shapes, hydraulic connections, dimensions and materials, installed on four levels and connected through a hydraulic circuit which can be automatically set in order to simulate alternatively raising mains or single pipe horizontal distribution plant configuration.

The test facility allows testing both conventional and innovative heat accounting systems and methods in experimental conditions similar to the operational ones [14,15]. The experimental mockup has been configured with vertical raising main distribution, which is the typical application case of the indirect heat accounting through HCAs in historical buildings. Fig. 4 shows the layout of the experimental mockup with the identification of the individual heating elements and vertical mains.

In Table 1 a summary of the technical characteristics of the radiators installed in the experimental mockup is reported.

To compare the performance of the novel hybrid method against a conventional indirect heat accounting method, 40 two-sensors electronic HCAs (EN 834 approved) have been installed on the mockup radiators and programmed according to the manufacturer's instructions. Reference data are provided by combined HMs made up of an electromagnetic flow meter, a pair of Pt100 resistance thermometers and a thermal energy calculation unit directly implemented on the central control PC, which receives the converted measurement signals from a Programmable Logic Controller (PLC).

The sub-assemblies of HMs are periodically calibrated at the INRIM laboratories, guaranteeing the necessary metrological traceability to the national standards. In particular:

- electromagnetic flow meters are calibrated by comparison with a reference electromagnetic flow meter (which is in turn calibrated against the national standard of liquid flow rate), on at least five flow rate values, automatically configuring the hydraulic circuit so that the flow meters of single radiators are in series with the reference meter;
- temperature sensors are calibrated by comparison with a reference Pt100 resistance thermometer in a thermostatic bath.

The entire system is monitored and controlled by means of a SCADA-HMI software, through which it is possible to vary the working points of the centralized generator, the circulation pump and the opening and closing states of the valves of each heating body, intervening both manually and automatically according to a predetermined program. Thus, it is possible to adjust the flow temperature and the flow rate of the heat transfer fluid in each radiator. Furthermore, through the automatic system, the output signals of the reference direct heat meters (power, thermal energy,

Fig. 3. Heat accounting experimental mockup at INRIM.

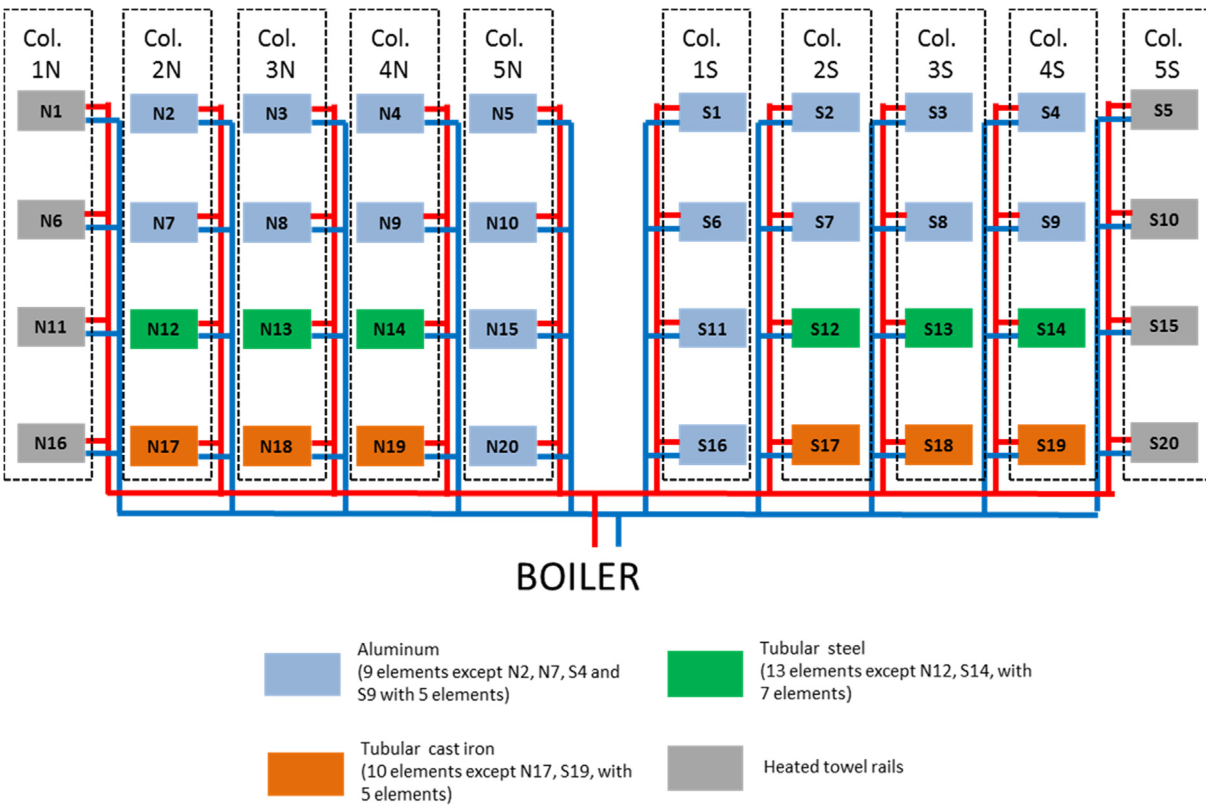

Fig. 4. INRIM mockup for heat accounting measurements with vertical raising main configuration.

Table 1
Technical characteristics of the radiators of the experimental mockup.

Radiator type and id.		Number of radiator elements	Radiator Dimensions (H, L, W), mm	Nominal Heat output EN 442 [16,17] $\Delta T_r = 50°C$, W	Radiator exponent (EN 442)
Aluminum	N3, N4, N5, N8, N9, N10, N15, N20, S1, S2, S3, S6, S7, S8, S11, S16	9	720, 870, 80	1.36	1716
	N2, N7, S9, S4	5	400, 870, 80		973
Cast iron	N18, N19, S17, S18	10	600, 880, 140	1.37	2044
	S19, N17	5	300, 880, 140		1060
Steel	N13, N14, S12, S13	13	590, 900, 150	1.28	1908
	S14, N12	7	320, 900, 150		1073
Heated towel rail	N1, N6, N11, N16, S5, S10, S15, S20	–	535, 713, 30	1.25	496

flow rate, inlet and outlet temperatures) can be logged with a sampling interval of at least 15 s.

With the aim to reproduce as far as possible the typical installation and operational conditions on the field, the experimental

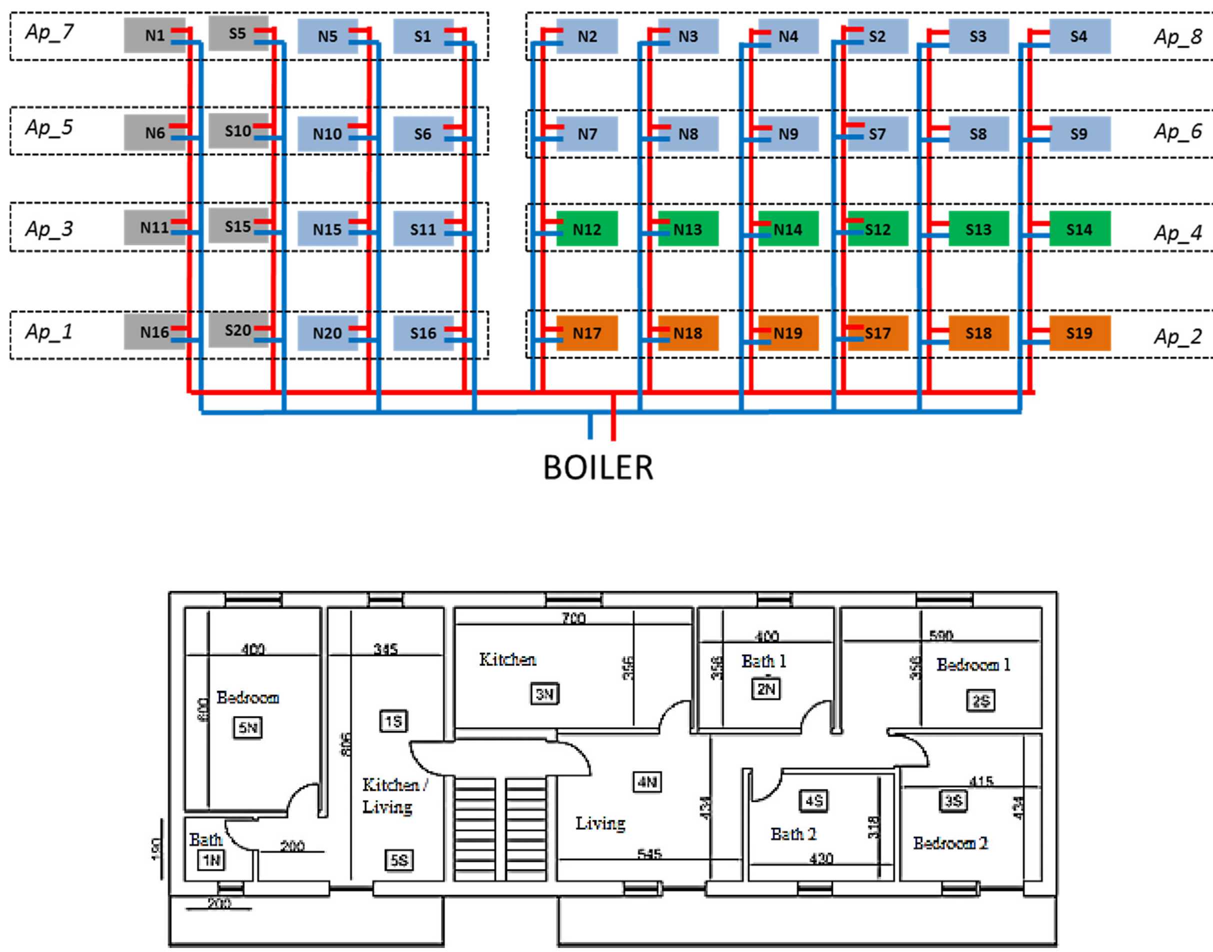

Fig. 5. Experimental set-up and corresponding virtual building.

mockup has been configured as a virtual four-storeys / eight-apartments building (Fig. 5). Each virtual floor consists of two apartments: a two-room apartment with four radiators (apartments 1, 3, 5 and 7) and a four-room apartment with six radiators (apartments 2, 4, 6 and 8). Therefore, the centralized heating plant presents ten vertical raising mains. The four vertical raising mains of the two-room apartments are characterized by identical radiators with the same heat output, whereas the six vertical raising mains of the four-room apartments consist of radiators of different type, but similar nominal heat output.

The authors also performed the calculation of the thermal energy need and the related radiators nominal heat output of the virtual building, considering the requirements of the climatic zone "*E*" where the INRIM experimental mockup is located. For such a climatic zone, the heating period is between October 15th and April 15th for a maximum daily operation of 14 h. The indoor temperature of the heated rooms and the minimum outdoor temperature in the winter period have been conventionally set at 20 °C and −8°C, respectively. Based on such design data and on the nominal heat output of each radiator of the mockup, the virtual test rooms to which each radiator is associated have been identified. Consequently, three different climatic periods of the heating season from October 15th to April 15th were identified for which the average temperatures of Turin and the corresponding heat requirements for each room have been calculated, as well as the heat output and heating fluid flow-rates, assuming a temperature difference between supply and return of about 10 °C (see Table 3).

In order to evaluate the performance of the novel hybrid accounting method in test conditions close to the real dynamic operating conditions, the experiments were designed considering [18]:

- three different combinations of total flow rate and supply temperature of the heating plant, simulating the real operation of the system in three periods of the heating season (namely "warm", "cold" and "very cold") characterized by different average outdoor temperatures (13 °C, 6.5 °C and 0 °C, respectively);
- different time programmed heating load profiles, consisting of an initial phase of variable duration (from 30 min to 90 min) in which the heater is set at its peak load (time duration and peak heating power depend on the simulated period of the heating season), followed by a steady mode heating phase of 4 h and a final cooling phase of about 2 h for radiators surface cooling down to the indoor ambient temperature (each heating profile has been repeated four times consecutively);
- different combinations of open and closed radiators, simulating different occupational modes of the building and usage of the heating plant (tests have been carried out both with all radiators open and with the radiators of some apartments alternatively closed).

The test conditions for the evaluation of the performance of the novel hybrid accounting method are summarised in Table 2.

Table 2
Test conditions.

Period	Start	End	Av. outdoor temp.	Transient	Occupancy conditions
Warm	October 15th	November 15th	13 °C	30 min	All apartments occupied
	March 15th	April 15th	13 °C		Ap_7 and Ap_8 not occupied
Cold	November 15th	December 15th	6,5 °C	60 min	All apartments occupied
	February 15th	March 15th	6,5 °C		Ap_3 and Ap_4 not occupied
Very cold	December 15th	January 15th	0 °C	90 min	All apartments used
	January 15th	February 15th	0 °C		Ap_3, 4, 7 and 8 not occupied

3. Uncertainty estimation of heat accounting hybrid method

3.1. Uncertainty estimation of reference thermal energy measurement and of the allocation units

The uncertainty estimation of the reference thermal energy measurements is carried out considering the measurement model given by the energy conservation law [19]:

$$Q = \int \rho \dot{V} c_p \Delta T_{io} dt \tag{8}$$

where ρ and c_p are, respectively, the density and the specific heat capacity of the heat conveying fluid (water), ΔT_{io} is the temperature difference between the inlet and outlet flow section of the radiator, $\dot{V}$ is the radiator volumetric flow rate and t is the time. Thus, applying uncertainty the propagation law and considering the measurement quantities are not correlated, standard uncertainty of the reference thermal energy measurement can be evaluated approximately as:

$$u(Q) \cong Q\sqrt{\left[\frac{u(\dot{V})}{\dot{V}}\right]^2 + \left[\frac{u(\Delta T)}{\Delta T}\right]^2 + \left[\frac{u(\rho)}{\rho}\right]^2 + \left[\frac{u(c_p)}{c_p}\right]^2} \tag{9}$$

The relative uncertainties of density and specific heat capacity of the heat conveying liquid (water) have been evaluated taking into account the uncertainty contributions of water temperature and pressure measurements, the uncertainty of the equation of state for the determination of the thermodynamic properties of water [20] and, finally, the uncertainty of density and specific heat capacity measurements. The uncertainty contribution of the time integration of radiator thermal power is assumed to be negligible compared to the other contributions. In Table 3 a summary of the single uncertainty contributions of the HMs sub-assembly modules installed on each radiator has been reported together with the estimation of the reference thermal energy measurement.

Table 3
Uncertainty estimation of the reference thermal energy measurement.

HM sub-assembly	*Sensor*	*Standard uncertainty*
Flow measurement	Electromagnetic flow meter	0.1% of reading for flow-rates higher than 90 dm^3h^{-1} from 0.1% to 1.0% of reading for flow-rates in the range from 90 dm^3h^{-1} to 20 dm^3h^{-1}
Flow / return temperature difference	Pair of Pt100 resistance thermometers and PLC module for 4-wire resistance measurement	0.04 °C
Calculation of heating fluid thermodynamic properties and time integration of thermal power measurement	Calculation unit implementing approximated formulations of the fluid equation of state	1.0% (with respect to the calculated product between density and specific heat capacity of the fluid)
Standard uncertainty of reference thermal energy measurement		from 0.8 to 2.7% of reading

The uncertainty of AU counted by HCAs has been evaluated considering the following contributions: i) the display resolution (i.e. $R_{AU} = 1$), ii) the maximum relative display deviation (i.e. $E\%_{max} = \pm 5$ % in the range of $15K \leq \Delta T \leq 40K$ [4]) and iii) the uncertainty of the estimation of rating factor K_Q related to the heat output of radiators (according to EN 442 [16,17]). The uncertainty of AU' of hybrid method can be considered equal to the indirect method, since the uncertainty contribution of the direct thermal energy measurements (heat meters) is negligible with respect to the uncertainty of HCAs. Therefore, the standard uncertainty $u(AU)$ can be evaluated as follows:

$$u(AU) = u\left(AU'\right) \cong AU\sqrt{2\left(\frac{R_{AU}}{AU2\sqrt{3}}\right)^2 + \left(\frac{E\%_{max}}{\sqrt{3}}\right)^2 + u(K_Q)^2} \tag{10}$$

3.2. Uncertainty estimation of the share

The uncertainty of the share obtained through the reference thermal energy measurements at each radiator, can be evaluated approximately as:

$$u(S_{HM,i}) \cong S_{HM,i}\sqrt{\left[\frac{u(Q_i)}{Q_i}\right]^2 + \left[\frac{u\left(\sum_1^n Q_j\right)}{\sum_1^n Q_j}\right]^2 - 2\frac{cov\left(Q_i, \sum_1^n Q_j\right)}{Q_i \sum_1^n Q_j}} \tag{11}$$

where the uncertainty of the heat consumption of individual apartments $u(Q_i)$ is evaluated assuming that thermal energy measurements of radiators belonging to the same apartment (i.e. radiators on the same floor) are fully correlated. On the other hand, the uncertainty of the overall sum of heat consumptions is obtained considering a null correlation between thermal energy measurements of different apartments (null correlation between radiators on different floors):

$$u\left(\sum_1^n Q_j\right) \cong \sqrt{\sum_1^n u^2(Q_j)} \tag{12}$$

Under the same assumption of uncorrelated thermal energy measurements of single apartments, the covariance between a single apartment and the overall heat consumption can be evaluated as:

$$cov\left(Q_i, \sum_1^n Q_j\right) \cong u^2(Q_i) \tag{13}$$

Similarly, the uncertainty of the share obtained through the indirect and the hybrid method, can be evaluated as follows:

$$u(S_i) \cong S_i\sqrt{\left[\frac{u(AU_i)}{AU_i}\right]^2 + \left[\frac{u\left(\sum_1^n AU_j\right)}{\sum_1^n AU_j}\right]^2 - 2\frac{cov\left(AU_i, \sum_1^n AU_j\right)}{AU_i \sum_1^n AU_j}} \tag{14}$$

$$u\left(\sum_1^n AU_j\right) \cong \sqrt{\sum_1^n u^2(AU_j)} \quad (15)$$

$$cov\left(AU_i, \sum_1^n AU_j\right) \cong u^2(AU_i) \quad (16)$$

4. Results and discussions

Table 4 shows the experimental results for the whole investigated period in terms of heat allocation units and shares of each apartment. Heating shares are calculated from the HCAs readings by applying the conventional indirect method and the novel hybrid method and from the reference direct direct method (i.e. through thermal energy meters). The values of indirect and hybrid shares and the corresponding errors estimated over the entire test period with respect to the reference direct method are also reported.

The analysis of results in Table 4 highlighted hybrid method shows a lower maximum absolute error (i.e. 1.35% against 2.06%) and a standard deviation of accounting errors equal to 1.22% and 0.89% for the indirect and hybrid methods, respectively. In Table 4 the measured errors have been discriminated at building (i.e. the difference between the calculated share and the one of the reference direct method) and at apartment level (i.e. the ratio between this latter and the share of the reference direct method). Single errors, although they may appear small if compared to the whole accounting in the building (absolute errors), become extremely relevant when compared with the shares charged to each user (relative errors). As for example Ap_1 and Ap_4 would pay respectively 15.1% less and 10.6% more through the indirect method in respect to the reference direct one, and such difference is smoothed with the proposed hybrid method (i.e. 7.9% less and 6.4% more, respectively). The experimental results show that the proposed hybrid method leads to a significant improvement in the accuracy of heat accounting compared to the indirect one both in terms of standard deviation, weighted mean square error (*wRMSE*) and maximum errors.

Table 5 summarizes the results for the indirect and hybrid methods of the tests at different climatic (i.e. warm, cold, very cold) and occupancy conditions (i.e. full/not full occupancy) in terms of maximum error and of Root-Mean-Square-Error weighted with the estimated uncertainties of the errors (*wRMSE*), calculated as per Eq. (17):

$$wRMSE = \sqrt{\frac{\sum_i [E_i/U(E_i)]^2}{\sum_i [1/U(E_i)]^2}} \quad (17)$$

where the errors of the shares E_i for hybrid and indirect methods and the expanded uncertainty of errors, $U(E_i)$, with a coverage factor $k = 2$ which for a normal distribution corresponds to a probability of approximately 95%, have been evaluated as follows.

$$E_i = S_i - S_{HM,i} \quad (18)$$

$$U(E_i) = 2\sqrt{u^2(S_{HM,i}) + u^2(S_i)} \quad (19)$$

From data in Table 5 it can be highlighted that a reduction of both *wRMSE* and maximum error has been found when the hybrid method is applied and that in the cold period at not full occupancy error peaks of 3.69% for indirect method and 2.69% for hybrid one occur. Therefore, it is possible to state that the hybrid method shows in average an accuracy of 1.14% which is much better than the conventional indirect method one (equal to 2.06%). It is also interesting to highlight that the hybrid method is particularly effective especially when occasional occupation conditions occur. In this case, in fact, an improvement in accuracy from 2.78% to 1.63% has been found with respect to the maximum error (and from 0.55% to 0.44% in terms of *wRMSE*). In any case, the hybrid method was more effective at all the investigated climatic and occupancy conditions.

Fig. 6 and Fig. 7 show a comparison between hybrid and indirect methods in terms of *wRMSE* and of maximum error, respectively. It can be highlighted that hybrid method shows better accuracy at any climatic condition and both for full or not-full occupancy.

A tricky issue of indirect heat accounting systems, which can greatly affect their accuracy, is represented by the estimation of rated heat output of single radiators. In particular, for two sensors electronic heat cost allocators, which are nowadays the more spread indirect heat accounting systems, a resulting rating factor K must be estimated. This is given by the product of K_C and K_Q rating factors, which take into account the thermal contact between HCA and radiator surface and the nominal heat output of the radiator, respectively. Furthermore, authors investigated the sensitivity of indirect and hybrid methods when systematic errors of the estimation of rating factor K occur. In particular, the estimation of K_Q is a particularly critical issue in the indirect method, especially in existing buildings where rated heat output of heating bodies is not always known and certified [21]. To this end, systematic fictitious errors (e.g. the possible errors associated to the initial HCA configuration by the installer or consequent to a renovation of the thermal plant) were introduced in the heat output of radiators and their effects have been evaluated. Fig. 8 shows the dependence of standard deviation and maximum error of heat accounting with respect to the error of coefficient K for radiators installed in the same vertical raising main (which can be assumed equal to each other). This situation is fairly common in buildings with standard apartment types in the different storeys and, therefore, with the same configuration and installation leading to highly likely systematic errors (e.g. radiator with the same few number of elements in the bathrooms, radiators installed in a niche in the

Table 4
Experimental results for the whole investigated period.

	Direct method		Indirect method				Hybrid method			
	Q/kWh	S_{HM}	AU	S	Error (building)	Error (apartment)	AU′	S′	Error (building)	Error (apartment)
Ap_1	429.38	11.83%	299	10.04%	−1.79%	**−15.1%**	324.54	10.90%	−0.93%	**−7.9%**
Ap_2	824.92	22.73%	738	24.78%	**2.06%**	9.0%	710.58	23.86%	1.14%	5.0%
Ap_3	222.06	6.12%	178	5.98%	−0.14%	−2.3%	193.34	6.49%	0.37%	6.1%
Ap_4	502.78	13.85%	456	15.31%	1.46%	10.6%	439.02	14.74%	0.89%	6.4%
Ap_5	352.73	9.72%	273	9.17%	−0.55%	−5.7%	295.95	9.94%	0.22%	2.3%
Ap_6	665.09	18.32%	525	17.63%	−0.69%	−3.8%	505.50	16.97%	**−1.35%**	−7.4%
Ap_7	212.36	5.85%	171	5.74%	−0.11%	−1.8%	184.20	6.19%	0.34%	5.7%
Ap_8	420.63	11.59%	338	11.35%	−0.24%	−2.1%	324.87	10.91%	−0.68%	−5.9%
Total	3630.0	100.0%	2978	100.0%	0.00%	–	2978.0	100.0%	0.00%	–

Note: The maximum absolute errors have been evidenced in bold.

Table 5
wRMSE at different climatic conditions and occupancy.

Period and Occupancy conditions		wRMSE, %			Maximum error, %		
		Indirect	Hybrid	Improvement	Indirect	Hybrid	Improvement
Full occupancy	Warm	1,21	0,95	−21,8%	2.50	1.51	−39.6%
	Cold	0,93	0,82	−12.0%	2.04	1.48	−27.3%
	Very Cold	0,81	0,54	−33,6%	1.64	0.96	−41.5%
	Whole full occ. period	0,94	0,72	−23,4%	1.95	1.23	−36.9%
Occasional occupancy	Warm,	1,35	0,96	−29,1%	2.53	1.41	−44.3%
	Cold	1,30	1,02	−21,5%	3.69	2.69	−27.0%
	Very Cold,	1,83	1,31	−28,3%	2.36	1.53	−35.2%
	Whole occasional occ. period	0,55	0,44	−19,9%	2.78	1.63	−41.3%
Whole period		0,84	0,65	−23,4%	2.06	1.14	−44.7%

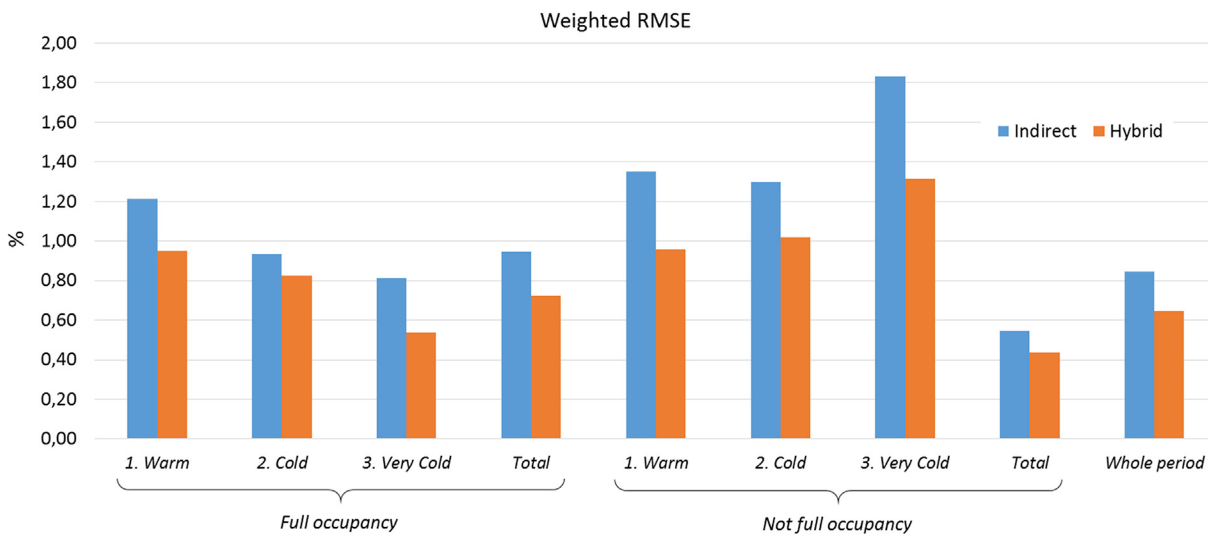

Fig. 6. *wRMSE* of indirect and hybrid methods.

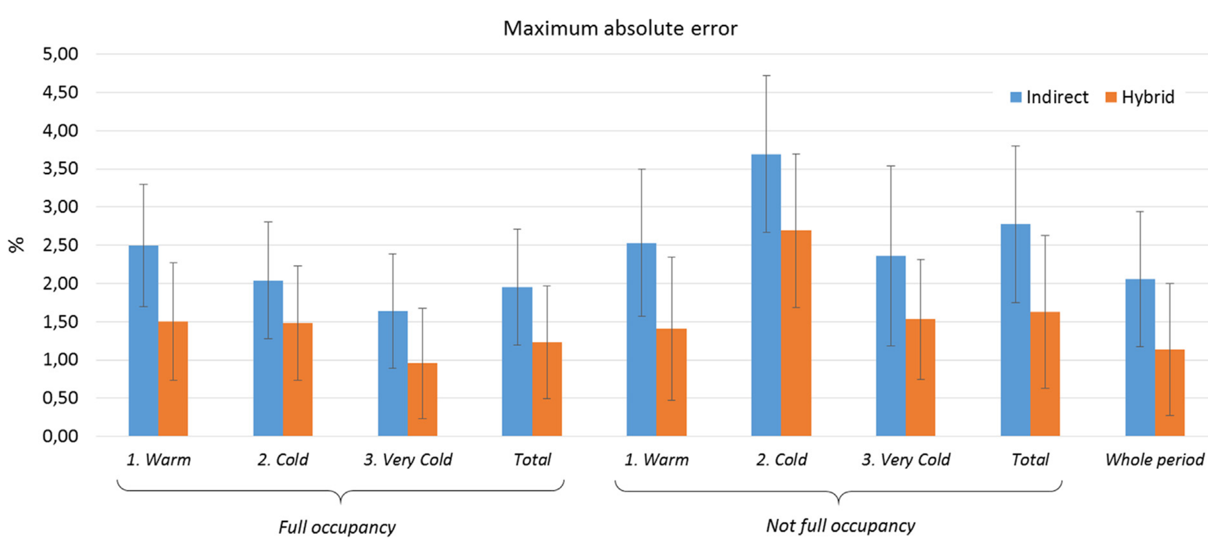

Fig. 7. Maximum error of indirect and hybrid methods.

wall, etc.). From the analysis of the results it can be pointed out, as predictable, that the hybrid method shows a constant accuracy and it is not affected in any way by the aforementioned error, whereas the indirect method accuracy shows a linear dependence with the error of K coefficient.

Authors also evaluated the influence on standard deviation and maximum error of the heat accounting due to the estimation of the coefficient K for radiators installed in a single apartment (Fig. 9a) and in two apartments (Fig. 9b). This situation occurs, as for example, when a single tenant renovates the heating system with the replacement of radiators only in few rooms.

From the analysis of the experimental results it can be pointed out that:

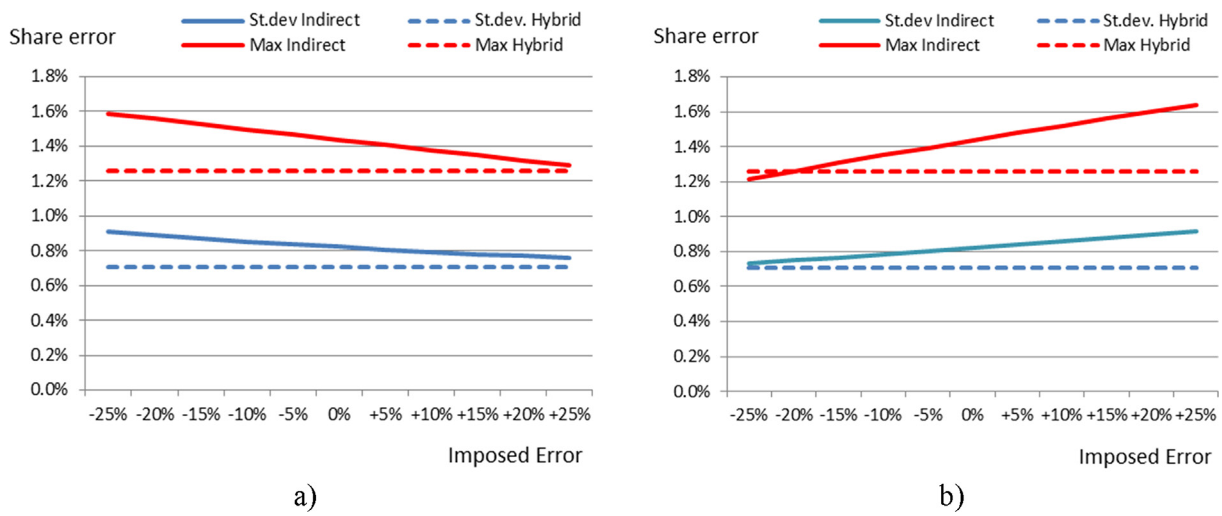

Fig. 8. Sensitivity analysis of the *K* coefficient estimation of radiators: a) error in only one raising main (1 N), b) error in two raising mains (1 N e 3S).

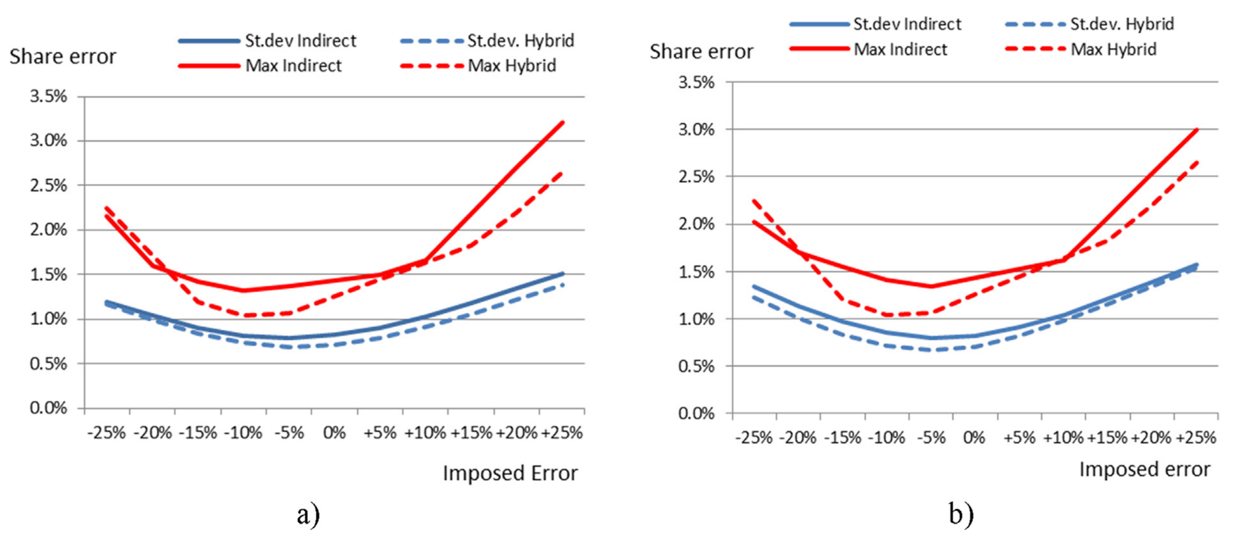

Fig. 9. Sensitivity analysis of the *K* coefficient estimation of radiators: a) error in only one apartment (Ap_8), b) error in two apartments (Ap_7 and Ap_8).

– standard deviation of Hybrid method error is slightly lower and almost similar to the Indirect method one,
– maximum error of Hybrid method is basically lower in respect to the Indirect method one, except under specific conditions (e.g. in the investigated case study, when the error of *K* is below -20% both for the case with one and two apartments).

The above described results are consistent to the fact that Hybrid method performs a correction on single raising mains (i.e. in vertical) and when the error of K is imposed on a column the effect is a generalized lower share error in respect to the Indirect method. On the other hand, such correction is not always effective in some apartments (i.e. in horizontal), in which share error could be randomly lower or higher. In fact, when the errors of K are introduced in single apartments (e.g. due to the replacement of radiators whose heat outputs are not accurately known), larger systematic share errors of Hybrid method in respect to the Indirect one may occur in a completely random way, according to the number of single accounting devices involved in the radiator replacement in the apartment.

In conclusion, the sensitivity analysis shows the hybrid method is basically less affected by the error on the estimation of coefficient *K*, except in few random conditions in which the imposed error is concentrated in single apartments.

5. Conclusions

In this paper the authors proposed a novel "hybrid" method aimed at improving accuracy of heat accounting in historical buildings supplied by centralized heating systems, by merging the advantages of indirect method with the higher accuracy typical of direct methods. The on-field accuracy of the developed method has been experimentally evaluated in comparison with the traditional direct and indirect ones at INRIM, the primary metrology institute in Italy, in a specially designed experimental mockup, simulating a virtual four-storey/eight-apartments building.

The experimental analysis shows that the proposed hybrid method always performs better than the indirect one. The advantage can be particularly relevant for buildings presenting standard apartment configurations and for occasionally occupied buildings.

In particular, the experimental results demonstrated that:

- in the whole investigated period and both for full and occasional occupancy conditions the standard deviation of accounting errors is equal to 1.22% and 0.89% for the indirect and hybrid method respectively;
- when occasional occupation conditions occur, the lowering of both maximum error (reduction of approximately 41.3%) and *wRMSE* (average reduction of about 19.9%) has been found for the hybrid method with respect to the indirect one;
- the hybrid method is not affected in any way by the error on the evaluation of the K coefficient for radiators installed on the same vertical raising main (e.g. error in the evaluation of the nominal heat output of radiators of the same type), whereas the indirect method shows a linear trend;
- the hybrid method tends to be less affected by the systematic error on the K coefficient for radiators installed in the same apartment (e.g. case of the renovation of the heating system) with respect to the indirect one.

The proposed method, therefore, despite the higher cost due to the installation of direct thermal energy meters on single vertical raising mains, could be particularly effective in old tower buildings where the accurate estimation of the K coefficients of installed radiators is particularly difficult. It is therefore the intention of the authors to perform an experimental campaign aimed at assessing on the field the accuracy of the proposed hybrid method in a real building case study.

CRediT authorship contribution statement

M. Dell'Isola: Supervision, Conceptualization, Methodology, Validation, Investigation. **G. Ficco:** Conceptualization, Methodology, Validation, Data curation, Investigation. **B. Di Pietra:** Formal analysis, Validation. **F. Saba:** Resources, Methodology, Investigation, Data curation, Software. **M.C. Masoero:** Formal analysis, Validation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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