THE EFFECT OF THE INTERACTION BETWEEN SUBOPTIMAL INPUT DATA AND BUILDING FEATURES ON THE SIMULATION RESULTS

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ABSTRACT

Dynamic energy simulation has the potential to provide relevant information about building energy behavior. However detailed models require an increased number of input data, which sometimes can undermine the accuracy of the simulation outcomes.

Among the terms of the building energy balance, one of the greatest contributions is provided by the heat transfer through the envelope. This is mainly affected by the uncertainty of the thermo-physical properties such as conductivity, specific heat and specific mass. Furthermore, buildings are not equally sensitive to uncertain material properties, the effects of which are strictly connected with building characteristics.

For this reason, the research aims to investigate the interaction between building features and uncertainties in thermal conductivity and specific heat. Several building configurations are examined by changing the aspect ratio, the percentage of glazing surface, the envelope and the glazing features.

INTRODUCTION

Dynamic energy simulation allows better modeling of the dynamic interactions between building, occupants and energy systems. However one of the problems in the application of enhanced simulation models, that sometimes can undermine the accuracy of their results, is the difficulty to gather reliable input data. In fact, the reliability of simulation outcomes hinges upon the accuracy and coherence of input data, simulation model and energy modeler choices all together. Each of these characteristics is required to limit the deviations between the actual and the simulated energy performances. Therefore, an estimation of the sensitivity and of the degree of uncertainty introduced by each factor can help to increase the awareness of the result reliability and of the actual robustness of the whole simulation process.

In the last few years, increasing attention has been paid to the uncertainty and sensitivity analyses on building energy simulations. In one of the earliest work (Lomas and Eppel, 1992), the authors compared three different techniques for sensitivity analysis. Following on from this work, Macdonald (Macdonald, 2002) integrated some uncertainty procedures in the software Esp-r. Another research dealing with uncertainty is reported in (Holm and Kuenzel, 2002), where the authors investigated the impacts of materials properties and surface coefficients on hygro-thermal building simulation through a Monte Carlo technique. More recently, in (Corrado and Mechri, 2009) a sensitivity analysis of the quasi steady state approach defined in EN ISO 13790 (CEN, 2008) is proposed. Similarly, in (Tian and de Wilde, 2011) the authors explored the uncertainties of climate, material properties, infiltration rate, internal loads and equipment efficiency for the energy simulation of an office building in the UK.

Hopfe and Hensen (2007, 2011) analyzed the influence of uncertainty in the early stage of design process, while, in Domínguez-Muñoz et al. (2010a) the impacts of suboptimal design parameters on the simulated peak-cooling loads is presented.

The problem is approached from another point of view by Pietrzyk and Hagentoft (2008), who analyzed the risk of exceeding the critical value of energy demand due to the variability of all together climate, material properties and serviceability parameters.

Although the literature is extensive, it is not yet addressed the interaction between the characteristics of the building and the analyzed uncertain variables. Moreover the simultaneous influence of several parameters on the simulation outcomes is generally analyzed without attempting to isolate each contribution and to evaluate the effects of their interactions. Due to their different nature, it is dangerous to combine different sorts of uncertainties (Hopfe and Hensen, 2011).

The paper aims in particular to deeply investigate the effects of uncertainties in material thermal conductivity and specific heat on heating and cooling energy needs. For several building configurations the uncertainties of model predictions are analyzed when suboptimal thermo-physical material properties are used in dynamic energy simulations. These building configurations are obtained by changing the aspect ratio, the percentage of glazing surface, the climate conditions, the envelope and the glazing features of a reference building module.

The approach is based on a factorial plan of comparison aimed to consider the main variables related to the envelope of the building and its effect on the uncertainty propagation.

A Gaussian distribution of material properties is generated through a custom–written Fortran code and dynamic energy simulations are performed. Following on from this point, the Probability Density Function (PDF) that best fit the model output distribution is investigated. Finally, the interaction between the building features and the uncertainty of simulation outcomes is thoroughly analyzed.

CALCULATION PROCEDURE

Test Cases

The distributions of the annual heating and cooling needs caused by uncertain thermo-physical properties are investigated. A sample of 96 simplified thermal zones is developed in order to analyze the interactions between the uncertain conductivity and heat capacity of the massive layers with the envelope characteristics. The base module consists of a single thermal zone with a 100 m^2 squared floor, 3 m of internal height and façades oriented towards the main cardinal directions. The thermal bridges are neglected and, when non-adiabatic, the floor is modeled as a suspended floor on a ventilated underfloor space while the ceiling is directly exposed to the external environment. All opaque components are modeled considering a massive layer with a thermal resistance around 0.8 m^2 K W^{-1} and, in the insulated configurations, an external polystyrene layer of 0.1 m thickness is added. The solar absorptance is equal to 0.3 for both sides of the vertical walls and for the internal side of the ceiling, equal to 0.6 for the external side of the ceiling and the internal side of the floor and equal to 0 for the external side of the floor. The reference values of the thermo-physical properties are reported in Table 1.

The windows are positioned all on the same façade and consist of a double-pane glazing (U_{gl} = 1.1 W m^{-2} K^{-1}) and a timber frame (U_f = 1.2 W m^{-2} K^{-1}), whose area is the 20% of the whole window area. The internal gains are 4 W m^{-2}, half radiative and half convective, as indicated by the EN ISO 13790 (CEN 2008) for residential dwellings. As suggested by the Italian technical specification UNI/TS 11300-1 (UNI 2008) the ventilation rate is set to a constant value equal to 0.3 ACH.

Table 1
Properties of the opaque components

Property	Timber	Concrete	Insulation
λ [W m^{-1} K^{-1}]	0.13	0.37	0.04
c [J kg^{-1} K^{-1}]	1880	840	1470
ρ [kg m^{-3}]	399	1190	40
α [m^2 s^{-1}]	$1.733\cdot10^{-7}$	$3.701\cdot10^{-7}$	$6.803\cdot10^{-7}$
s [m]	0.10	0.30	0.10
R [m^2 K W^{-1}]	0.77	0.81	2.50

The variables considered in the factorial plane are the most relevant parameters of the building envelope. Except for the window orientation, each parameter presents a high and a low level:

- the thermal capacitance of the opaque elements (area specific heat capacitance of the internal layer: 75 kJ m^{-2} K^{-1} for the timber structure or to 300 kJ m^{-2} K^{-1} for the concrete);
- the solar heat gain coefficient of the glazing (low or high: 0.352 or 0.608 respectively);
- the size of the windows (low level: 14.56 m^2, high level: 29.12 m^2);
- the insulation level of the envelope components (low level with 0 cm and high level with 10 cm of polystyrene) in order to have two thermal transmittance values (e.g., for the vertical walls, U ≈ 1.03 W m^{-2} K^{-1} and U ≈ 0.29 W m^{-2} K^{-1});
- the ratio of the dispersing envelope over the conditioned volume of the thermal zone (low level: S/V = 0.3 m^{-1} with floor, ceiling and one vertical wall set as adiabatic; high level: S/V = 0.97 m^{-1} with just one vertical adiabatic wall);
- the orientation of the windows (East, South or West).

Statistical approach

In this paper, the interaction between the uncertainty of material properties with building features is investigated using the Monte Carlo method. According to the Monte Carlo approach, by randomly selecting a set of data from a population characterized by a particular distribution, it can be used as a deterministic input in the energy balance and, subsequently, a distribution of the model expectation can be generated (Figure 1)

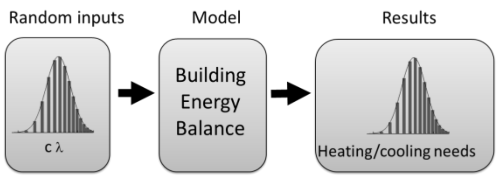

Figure 1 Scheme of the simulation process

A Monte Carlo method entails full random selection, out of all possible values of the inputs in a correct statistical combination. By means of variance reduction techniques, the sampling efficiency can be increased (Janssen, 2013). However, with enhanced sampling methods unbiased results cannot be taken for granted and, consequently, this assumption should be verified with additional computational costs (Macdonald, 2009). Therefore, a simple random sampling method is adopted in this work.

Firstly, a set of uniform pseudo-random numbers is generated by means of the Marsenne-Twister method (Matsumoto and Nishimura, 1998). Starting from these data, the Box-Muller transformation (Box and Muller, 1958) is adopted for the generation of the Gaussian pseudo-random numbers.

In order to quantify the probability distribution of the simulation outcomes, a large sequence of simulation runs is required. The higher the number of runs, the lower the variance of mean and standard deviation.

Although in the literature several authors suggested a threshold of 100 runs after which negligible improvements of accuracy are noted, Janssen (Janssen, 2013) demonstrates that this limit is closely related to the problem characteristics. Besides, also for high number of runs noticeable reductions in variations are registered. According to this consideration, with the purpose of ensuring a reasonable level of outcomes accuracy, in this work 1000 simulation runs are performed for each test case.

Variability of material properties

As concerns the two properties considered in this paper, the thermal conductivity is primary related to the transmission through the envelope while the specific heat and the specific mass are involved both in the heat flux damping and in the storage of internal and solar heat gains. Since the specific mass and the specific heat perturbations have the same effect on the heat transfer (Prada, 2012), only the latter is analyzed.

Focusing on the effect of suboptimal material properties, one of the key aspects in order to get meaningful results from the stochastic simulation, is the quantification of the input variability.

In the literature only a limited number of works has formally dealt with the issue of uncertainty quantification. For instance, Domínguez-Muñoz (2010b) obtained the distribution parameters from a large set of thermal conductivity measurements. Similarly, Macdonald (2002) processed the measured material properties used in (Clarke et al. 1990). Macdonald stated that a variability of thermal conductivity up to 30% could be noted in samples of the same material, and quantified the random errors in the specific heat measurements around 12%.

Starting from these references, mean and variance are defined for each material property as summarized in Table 2, as well as their 1 % and 99 % fractiles.

Table 2 Parameters of properties distribution

LAYER	$E_{\{x\}}$	$S.Dev_{\{x\}}$	$f_{1\%}$	$f_{99\%}$
Concrete Block				
λ (W m^{-1} K^{-1})	0.37	0.074	0.208	0.558
c (J kg^{-1} K^{-1})	840	102.9	610	1100
Timber				
λ (W m^{-1} K^{-1})	0.13	0.026	0.072	0.194
c (J kg^{-1} K^{-1})	1880	230.3	1370	2470

Result post-processing and analysis

The last step of the analysis involves the investigation of the output distributions. In order to perform it, a post-processing code has been implemented using Matlab.

Starting from the heating and cooling energy needs, the terms are firstly classified in one of the bins in which the output variability range is divided. The authors observed that a number of 60 bins is high enough to clearly identify the shape of the probability distribution.

Then the code fits one of three implemented probability distributions (i.e. Normal, Log-normal and Weibull) to those of the output data. In order to perform the comparison, the point by point sum of square differences between output and cumulative distribution functions is calculated. The lowest squared 2-norm of residual is assumed as the distribution of the output data.

In order to compare the different cases and to correlate the envelope characteristics with the resulting distributions, for each configuration, the maximum, the minimum, the median, the first and third quartiles (Q_1 and Q_3) of the output produced by the considered uncertain thermo-physical property are calculated and normalized with respect to the median. Since it is less sensitive to extreme results and outliers, the normalized interquartile range *IQR* (i.e., the difference between the normalized Q_3 and the normalized Q_1 values) is selected as dispersion indicator to compare the different cases.

Moreover, in order to describe the effect of the interactions between the uncertainties of λ and c of the massive materials and the other properties of the envelope, the different *IQR* are grouped separately for concrete and timber cases according to the SHGC, the windows size, the insulation of the opaque envelope, the S/V aspect ratio of the thermal zone and the windows orientation.

RESULTS AND DISCUSSIONS

Results

The first results of the post-processing analysis are the PDF shapes of the annual heating and cooling needs.

This investigation firstly highlights, as it happens for the heat transfer through the envelope (Prada et al. 2013), that the Gaussian random inputs do not directly imply a Gaussian structure of the distributions of simulation outcomes.

Therefore, the effects of the building energy model are both a propagation of the uncertainty and a distortion of the corresponding probability distribution. Both effects are strictly connected to the uncertain parameter and to the interactions with building characteristics. The shape of PDF changes also from heating to cooling needs distributions. In fact, while the heating needs are always normally distributed, the distribution of cooling needs varies depending on the analyzed cases (Figure 2 and Figure 3).

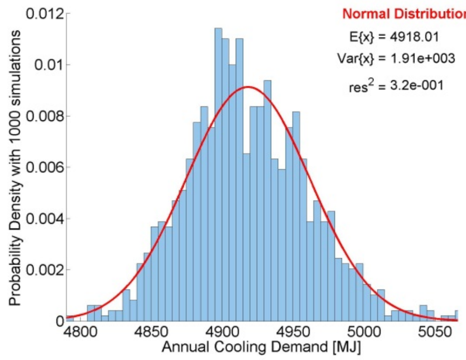

Figure 2 PDF for concrete insulated construction with S/V=0.97 m^{-1},West oriented windows with high SHGC and glazed surface.

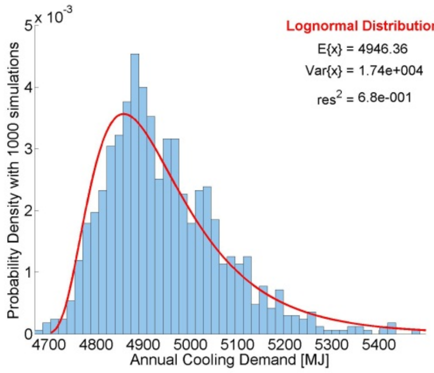

Figure 3 PDF for concrete construction with S/V=0.97 m^{-1}, South oriented windows with high SHGC and glazed surface.

A preponderance of Weibull PDF is noted for the cooling needs and only in some cases a greater distortion through the model causes a log-normal distribution. In particular it is observed that, when the uncertain parameter is the specific heat, the distribution shape becomes a log-normal for poorly insulated walls with high glazed surfaces.

Also for the uncertain conductivity the skewed distributions are, to a considerable extent, connected to well insulated wall and they usually present a lesser data dispersion.

In this regard, the measure of data spread around the median value is given by the normalized *IQR*. As regards the study about the thermal conductivity of the massive layers, in Figure 4 the normalized *IQR* distributions of the studied building sample are reported. Both timber and concrete structures have similar behaviors, even if the *IQR* presents larger values for the massive ones. In percentage terms, the effect of the uncertainty of the thermal conductivity on the energy performances is more relevant on the cooling needs with respect to the heating needs. About the interactions between the envelope characteristics and the variability of the *IQR* of the simulated energy results, the following observations can be done:

- for the SHGC, a direct interaction with the uncertain conductivity is registered on the evaluation of the cooling needs while it is almost null for the heating needs. In the cooling needs distributions, passing from the low to the high value of this parameter, the *IQR* median changes from 7% to 4% and from 6% to 10%, respectively for the lightweight and the massive configurations. For all cases, the *IQR* medians are around 12% for the heating needs distributions.
- About the window size, results are similar but with an opposite trend with respect to SHGC analysis. For the heating needs, an increasing in the windows area induces slightly decrease in *IQR* variations but the medians still remain around 12%. As concerns the cooling analysis, the results of the considered materials are the similar: the *IQR* medians pass from 7% to 4% for the timber envelopes and from 6% to 10% for the concrete one when the windows are doubled. Despite of this, the general trend is the same.
- Both for heating and cooling needs, the interaction between the uncertainty of the thermal conductivity and the insulation level of the opaque envelope is the most relevant. As regards the cooling needs, with the addition of an external layer of polystyrene the *IQR* medians pass from 12% to 3% for the timber structures and from 18% to 3% for the concrete walls. Similar trends are noted tor the heating needs, the medians are reduced from values of 19% to 4% and to 5%, respectively for lightweight and massive envelopes.
- Analyzing the relationship between the S/V ratio and the uncertainty of the conductivity, it can be observed that the interaction is direct for the heating needs and opposite for the cooling ones. The interaction is weak and it is more relevant for the cooling energy needs (*IQR* medians from 7% and from 9% to 5% and 6%, respectively for lightweight and massive cases).
- Finally, about the interaction between the window orientations and the uncertainty of the conductivity, it can be noticed that the largest effects are registered for the configurations with South-oriented glazings, both for the heating needs and for the cooling ones.

In Figure 5 the *IQR* of the normalized distributions are reported for the study about uncertain specific heat capacity. Compared to the thermal conductivity results, the variability is more limited due to lower error encountered in this parameter.

The effects on the heating needs are almost null and, with the exception of the windows orientation, the *IQR* are generally around 1%. For that variable, the higher interaction is registered for South-oriented windows and an almost null variation for the other ones.

About the interactions between the envelope characteristics and the variability of the *IQR* of the cooling energy results, the concrete structures are less sensitive with respect to the timber constructions. Distinguishing the results according to the different variables:

- Both for the SHGC and for the window size, the interactions are very limited and the *IQR* median is around 3% for the timber structures and between 2% and 1% for the concrete walls. Increasing the SHGC or the size of windows makes the *IQR* slightly decreased.
- As regards the insulation level, a relevant interaction is registered, especially considering the timber envelopes. For this kind of structures, the *IQR* medians pass from 8% to 1% when the insulation level is increased while for the massive walls the *IQR* decreases from 2% to 1%.
- Differently from the other variables, by increasing the S/V ratios also the *IQR* assume larger values. For the timber walls, the medians grow from 2% up to 6% and for the concrete, from 1% to 2%.
- About the windows orientation, the most relevant is the South, with *IQR* medians equal to 4% and 2%, respectively for timber and concrete envelopes.

Discussion

As observed in the result description, the trends with uncertain thermal conductivity are similar in both materials, even if different uncertainty levels are present. By changing the thermal conductivity also the thermal diffusivity and so the dynamic response of the opaque component are varied. The range of variation is more relevant for the concrete (from $2.961 \cdot 10^{-7}$ to $4.441 \cdot 10^{-7}$ m^2 s^{-1}, considering the standard deviations) with respect to the timber (from $1.386 \cdot 10^{-7}$ to $2.079 \cdot 10^{-7}$ m^2 s^{-1}). Therefore, some effects of the uncertain thermal conductivity are related to the dynamic response of the envelope and they are more evident for the massive structures.

As expected, when the insulation is null, the effect of the uncertainty on both heating and cooling needs is higher. For instance, considering one standard deviation, for uninsulated timber wall the thermal resistance varies from 0.96 to 0.64 m^2 K W^{-1} (i.e., 16.88% respect to the nominal value), while with 10 cm of insulation it changes from 3.46 to 3.14 m^2 K W^{-1} (i.e., 3.97% respect to the nominal value). For what concerns the interactions with the other variables describing the envelope characteristics, they are less relevant. For the cooling needs, the configurations with high SHGC, small windows, smaller dispersing surface and South-oriented windows are the most sensitive to the uncertainty of the thermal conductivity. This suggests also a correlation with the absorption and the transmission of the solar heat gains and, consequently, their role in the zone heat balance to counterbalance the thermal losses in the cooling needs calculation. For the heating needs, there is a strong interaction only with the insulation level and with the window orientation. The uninsulated configurations with South-oriented windows are the most sensitive.

As regards the analysis of the specific heat capacity of the massive layer, the behavior of the two materials is similar but this time larger variations in the results are for the lightweight envelopes. This could be explained considering that the area specific heat capacitance of the concrete structures is 4 times the one of the timber walls (300 kJ m^{-2} K^{-1} respect to 75 kJ m^{-2} K^{-1}, according to the EN ISO 13786 (CEN, 2007) procedure). Therefore uncertainties about the specific heat are less critical on massive envelope with respect to the lightweight cases. Considering again the thermal diffusivity and one standard deviation, the values are within $3.297 \cdot 10^{-7}$ and $4.218 \cdot 10^{-7}$ m^2 s^{-1} for the concrete and between $1.544 \cdot 10^{-7}$ and $1.975 \cdot 10^{-7}$ m^2 s^{-1} for the timber. The ranges are similar to those seen for the analysis of the thermal conductivity but smaller.

About the annual cooling needs, for the chosen location the variations of the dynamic properties of the envelope are not particularly relevant but analyzing a single month with large daily variations of the external air temperature around the internal set-point the influence of uncertain specific heat increases as observed by (Prada, 2012). As concerns the heating needs, the configurations with uninsulated envelope, larger dispersing surfaces and South-oriented windows are the most sensitive to the uncertainty of the specific heat capacity. In those cases, characterized by larger heat losses, the heat capacitance is more important to exploit the solar gains available to reduce the heating needs. Thus, an uncertainty on the specific heat affects the heating needs more than in other configurations.

CONCLUSION

In this work we investigated the extent to which uncertain thermo-physical properties interact with building features.

Firstly, the research highlighted that the heating and cooling needs are not always normally distributed when Gaussian distributions of input data are used. In particular, the asymmetrical distribution of cooling needs can lead to different output uncertainties in terms of overestimations or underestimations with respect to nominal results.

With respect to the interaction between material uncertainties and building features, the results show two different behaviors. While uncertainties about the specific heat significantly interact only with the insulation level, the aspect ratio and the window orientation, the uncertain conductivity depends on the analyzed building features all together. However, for both cases the highest interactions are noted with the insulation level. Therefore, in this research the role of insulation in smoothing over the uncertainties of other wall materials has been emphasized.

Nonetheless, in further developments, other climates as well as the combined effect of uncertainties in all wall materials will be studied in order to broaden the results validity.

NOMENCLATURE

α	*thermal diffusivity ($m^2\ s^{-1}$)*
λ	*thermal conductivity ($W\ m^{-1}\ K^{-1}$)*
ρ	*density ($kg\ m^{-3}$)*
c	*specific heat ($J\ kg^{-1}\ K^{-1}$)*
$E_{\{x\}}$	*expected value of the variable x*
$f_{1\%/99\%}$	*1% or 99% fractile*
IQR	*interquartile range (-)*
$Q_{1/3}$	*first or third quartile (-)*
R	*thermal resistance ($m^2\ K\ W^{-1}$)*
s	*thickness (m)*
S	*dispersing surface (m^2)*
$S.Dev_{\{x\}}$	*standard deviation of the variable x*
$SHGC$	*solar heat gain coefficient (-)*
U	*thermal transmittance ($W\ m^{-2}\ K^{-1}$)*
U_f	*frame thermal transmittance ($W\ m^{-2}\ K^{-1}$)*
U_{gl}	*glazing thermal transmittance ($W\ m^{-2}K^{-1}$)*
V	*conditioned volume (m^3)*

REFERENCES

Box, G., and Muller, M. (1958). A note on the generation of random normal deviates. Annals of Mathematical Statistics, 29, 610-611.

CEN. (2007). EN ISO 13786 - Thermal performance of building components Dynamic thermal characteristics - Calculation method. European Committee for Standardization.

CEN. (2008). EN ISO 13790 - Energy performance of buildings - Calculation of energy use for space heating and cooling. European Committee for Standardization.

Clarke, J. A., Yaneske, P. P., and Pinney, A. A. (1990). The Harmonisation of Thermal Properties of Building Materials. BEPAC Research Report.

Corrado, V., and Mechri, H. (2009). Uncertainty and sensitivity analysis for building energy rating. Journal of building physics, 33(2), 125-156.

Domínguez-Muñoz, F., Anderson, B., Cejudo-López, J., and Carrillo-Andrés, A. (2010a). Uncertainty in the thermal conductivity of insulation materials. Energy and Buildings, 42(11), 2159-2168.

Domínguez-Muñoz, F., Cejudo-López, J., and Carrilo-Andrés, A. (2010b). Uncertainty in peak cooling load calculations. Energy and Buildings, 42(7), 2798-2805.

Holm, A., and Kuenzel, H. (2002). Practical application of an uncertainty approach for hygrothermal building simulations - drying of an AAC flat roof. Building and Environment, 37(8-9), 883-889.

Hopfe, C., and Hensen, J. (2007). Uncertainty analysis for building performance simulation - a comparison of four tools. Building Simulation, (pp. 1383-1388). Beijing (China).

Hopfe, C., and Hensen, J. (2011). Uncertainty analysis in building performance simulation. Energy and Buildings, 43(10), 2798-2805.

Janssen, H. (2013). Monte-Carlo based uncertainty analysis: sampling efficiency and sampling convergence. Reliability Engineering and System Safety, 109, 123-132.

Lomas, K., and Eppel, H. (1992). Sensitivity analysis techniques for building thermal simulation programs. Energy and Buildings, 19(1), 21-44.

Macdonald, I. (2002). Uncertainty in building simulations. Glasgow UK: University of Strathclyde.

Macdonald, I. (2009). Comparison of sampling techniques on the performance of Monte-Carlo based sensitivity analysis. Building Simulation 2009, (pp. 992-999). Glasgow.

Matsumoto, M., and Nishimura, T. (1998). Mersenne twister: a 623-dimensionally equidistributed uniform pseudo-random number generator. ACM Transactions on Modeling and Computer Simulation, 8(1), 3-30.

Pietrzyk, K., and Hagentoft, C. (2008). Reliability analysis in building physics design. Building and Environment, 43(4), 558-568.

Prada, A. (2012). Energy performance of buildings: modeling of dynamic summer behavior. Ph.D. Thesis, University of Trento, Civil and Environmental Engineering, Trento.

Prada, A., Baggio, P., Baratieri, M., and Gasparella, A. (2013). The effect of material uncertainties on envelope heat transfer simulations. Building Simulation Application - 1st IBPSA-Italy conference. Bolzano - Italy.

Tian, W., and de Wilde, P. (2011). Uncertainty, sensitivity analysis of building performance probabilistic climate projections: a UK case study. Automation in construction, 20(8), 1096-1109.

UNI - Ente Nazionale Italiano di Normazione. (2008). UNI/TS 11300-1:2008 - Energy performance of buildings Part 1: Evaluation of energy need for space heating and cooling. Milan, Italy.

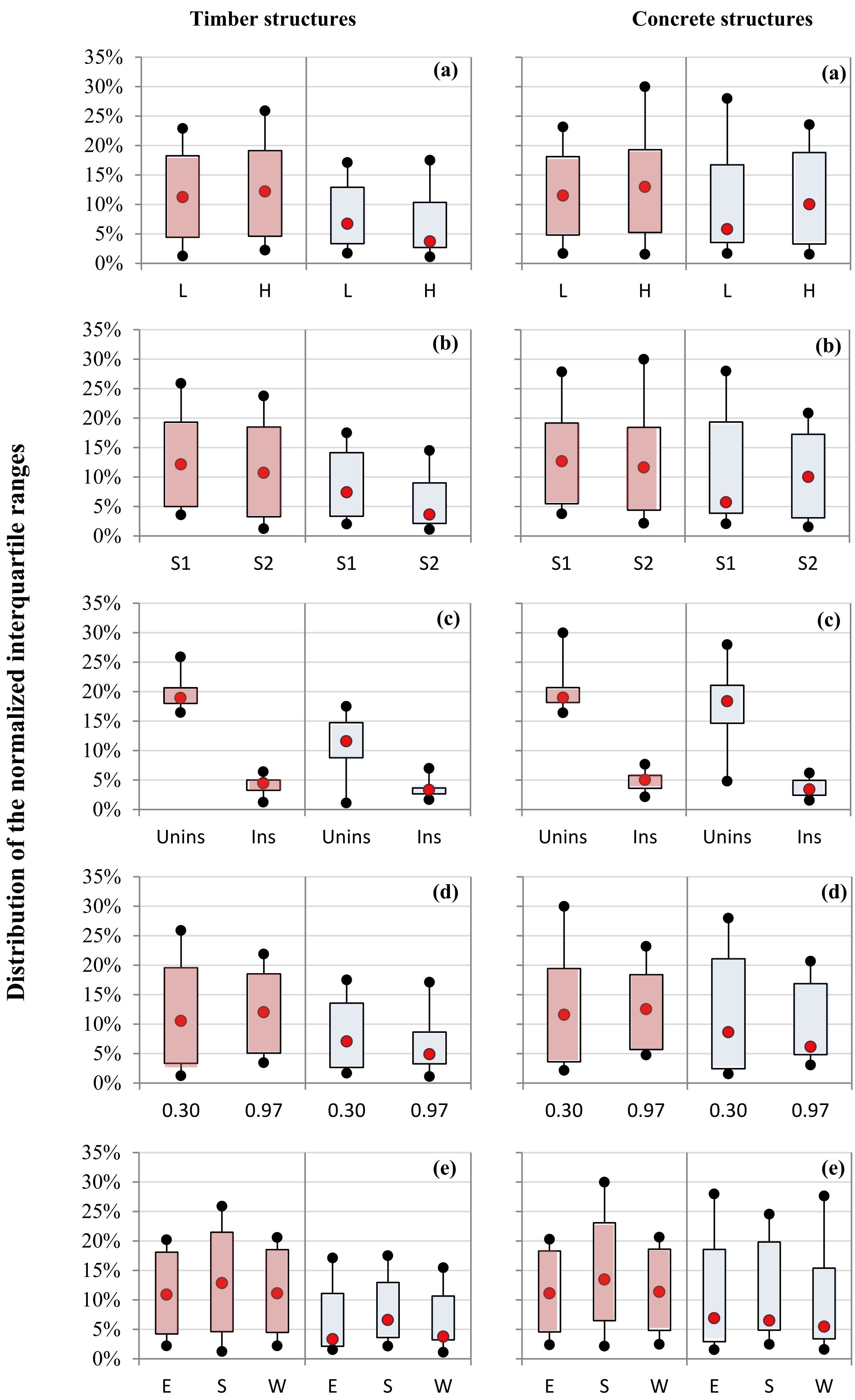

Figure 4 Analysis of the thermal conductivity uncertainty: distribution of the interquartile ranges (IQR) for the considered sample of cases for timber and concrete structures. Heating needs IQR in red and cooling needs IQR in blue grouped by SHGC (a), windows size (b), insulation (c), aspect ratio (d) and windows orientation (e).

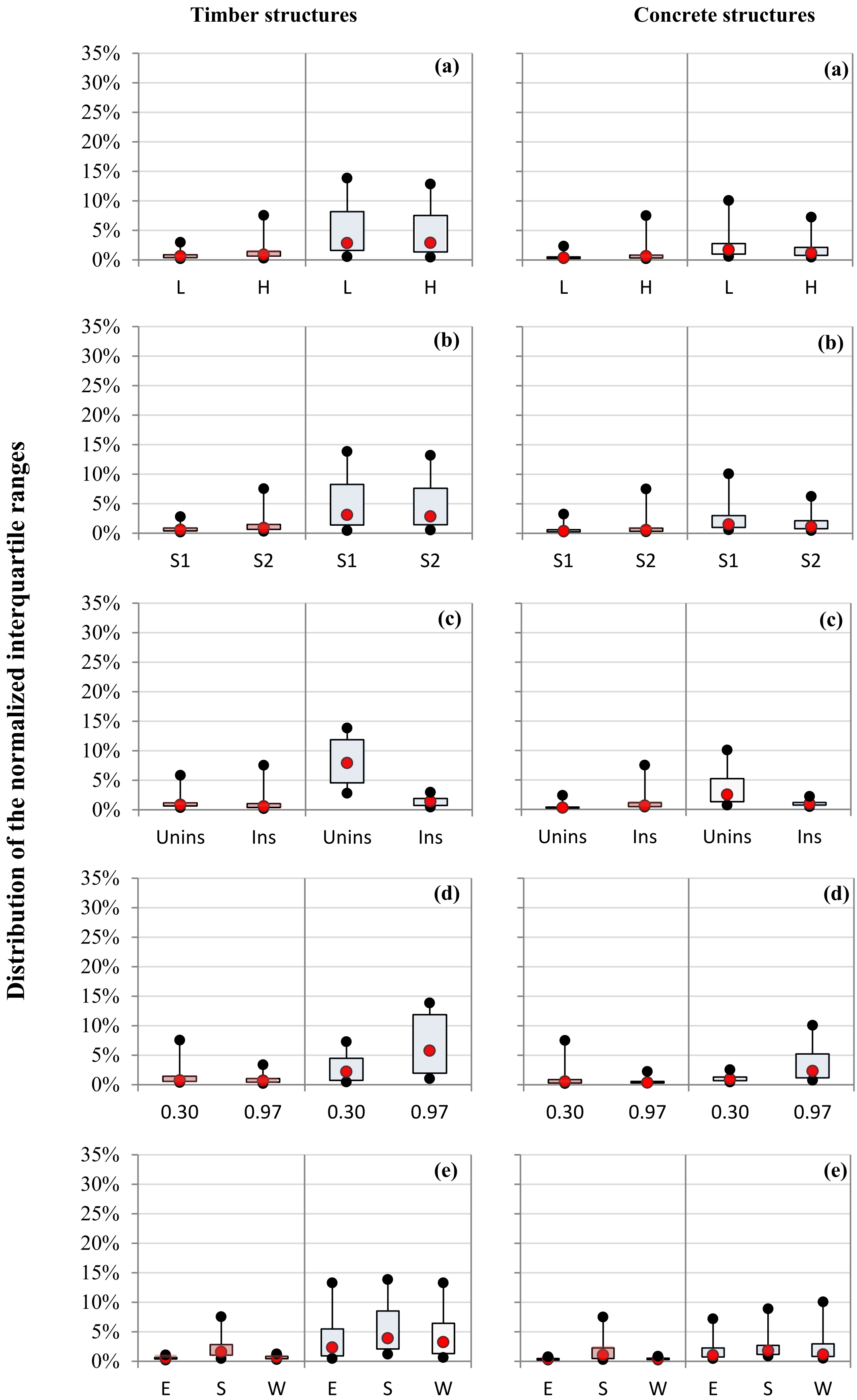

Figure 5 Analysis of the specific heat uncertainty: distribution of the interquartile ranges (IQR) for the considered sample of cases for timber and concrete structures. Heating needs IQR in red and cooling needs IQR in blue grouped by SHGC (a), windows size (b), insulation (c), aspect ratio (d) and windows orientation (e).