ROBUSTNESS ASSESSMENT METHODOLOGY FOR THE EVALUATION OF BUILDING PERFORMANCE WITH A VIEW TO CLIMATE UNCERTAINTIES

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ABSTRACT

This paper describes a new methodology to assess the robustness of building performance in the long term with a probabilistic approach. The aim is to include uncertainties related to climate change predictions as well as the intrinsic uncertainties in weather files describing them.
A case study focussing on refurbishment strategies of a realistic building in Turin is presented to demonstrate the methodological steps.
The main outcome is that it is advisable to have outcomes in terms of ranges of energy consumption instead of single output values to evaluate energy efficient design solutions in both present and future years.

INTRODUCTION

The complex relationship that tightly binds climate conditions and buildings makes it necessary to use building simulation techniques coupled with weather data to calculate energy performance and make design decisions. Conventionally, building energy performance is evaluated with a deterministic approach by using a single input weather file referring only to historical weather conditions (characterized by a TMY file). Hence, the choice of a particular design strategy is based on a single energy usage referring to current weather conditions. However, since buildings have a life span of 50 to 100 years, they must perform satisfactorily under both current and future climate (Ascione et al., 2014; Kaklauskas et al., 2005; Wilde et al., 2008), which according to the IPCC report is going to be warmer mostly due to man-made emissions of greenhouse gases (GHGs) (IPCC, 2007). For this reason, the assessment of different design strategies must take into account weather files referring to both present and projected climate conditions in future years. Climate change adaptation of buildings has been investigated in some studies, which have calculated the impact of climatic changes on energy performance (Camilleri et al., 2001; Frank, 2005; Gaterell and McEvoy, 2005; Guan, 2009; Zmeureanu and Renaud, 2008). However, all of this previous work is deterministic and uses just one input weather file (Tian and de Wilde, 2011). In other words, they underestimate the uncertainties related to climate change projections and the intrinsic uncertainties of weather files describing both present and future climate, due to different years of record, morphing method and weather variables recorded. Using a single weather file in building simulations, regardless of its source or generative algorithm, could lead to inaccurate energy consumption forecasts, and therefore wrong design decisions.

Building on the work of Tian and de Wilde (2011) on sensitivity analysis in the prediction of the thermal performance of buildings under climate change, this study illustrates a new methodology for the evaluation of building robustness using probabilistic energy performance results. The impact of using multiple input weather files and the methodological steps to interpret the results are explored. The methodology is demonstrated by means of a case study simulated with eighteen weather files coming from different sources, referring to many future years and IPCC scenarios (Solomon et al., 2007). The case study selected is an existing dwelling with twenty-two refurbishments in Turin, Italy. The retrofit solutions focus on the thermal properties of the envelope by varying U-value, solar heat gains, thermal mass and air tightness of the envelope. The methodology is divided into two steps: first the energy usage ranges of different refurbishments are calculated and represented by an index (RI), then the energy saving due to refurbishments in each year (in comparison with the non-refurbished building) are evaluated and compared using a second index (ESI).

It is important to note that the proposed work-flow is built so as to be able to accommodate changing climate predictions and new findings from the IPCC, updating the results as more information becomes available or models improve. The methodology could also be used to modify or at least revisit building energy codes to better evaluate energy savings for new constructions or refurbishments.

The structure of this paper is as following. First, the intrinsic uncertainties of weather files are briefly presented by means of two preliminary studies. Then the methodology steps of the robustness assessment evaluation are explained, and the case study is described. Finally, the results of the simulations and the methodology are explored.

WEATHER FILE UNCERTAINTIES

This paper does not address climate change projection uncertainties, because they are mainly related to climate models and future scenarios (Nakicenovic and Swart, 2000), but it focus on weather file uncertainties. The latter can be illustrated by means of two preliminary studies, referring respectively to present and future years. In general, future weather files are associated with temporal uncertainty, and present weather files with spatial uncertainty.

In previous work (Chinazzo et al., 2015), we illustrate the first preliminary study, which demonstrates that spatial uncertainties of present weather files are related to intrinsic variability that can neither be predicted nor avoided. To prove that, we simulate a building model with weather files referring to present climate conditions coming from two weather file sources in six different weather stations in the north of Italy. The main outcome of that study is that energy usage results are quite different even if the model is the same and it is situated in the same climatic area. The main differences can be observed between the results calculated with files coming from the two sources. These ones are the U.S. Department of Energy's website (E+) and the METEONORM software (MN).

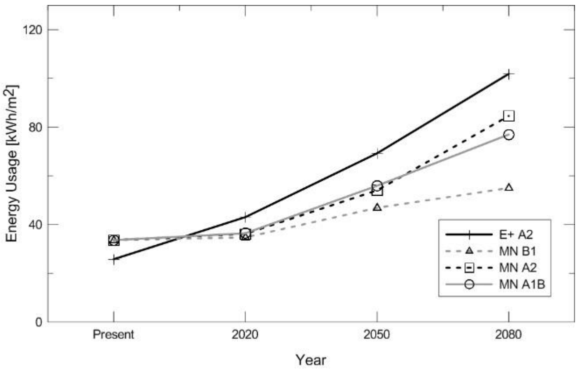

Figure 1: Comparison between the influence of weather files from different sources and referring to different years and future scenarios, in terms of energy usage for cooling

In the following, we describe the second preliminary study, which refers to future weather files and the associated temporal uncertainties. Future weather files are generated from the present ones by means of two different software. The first one is the software 'CC WorldWeatherGen Climate change world weather file generator', a Microsoft Excel based tool which generates climate change weather files for any location (Jentsch et al., 2013). It transforms 'present-day' .epw weather files into future .epw weather files by using a model from the IPCC 2013 report (HadCM3 A2 experiment ensemble) for three future time slices, the 2020's, 2050's and 2080's. The second software used to generate climate change weather files is Meteonorm, for different scenarios (B1, A1B and A2), and for any year between 2010 and 2200 (Remund, 2014). In the second preliminary study, the two present weather files (from the two sources E+ and MN) refer to Milan. Figure 1 displays the four years on the x-axis and the energy usage in kWh/m^2 on the y-axis for cooling. The energy usage for cooling has an increasing trend through the years for both sources and the different scenarios, due to the predicted warming of the earth. The worst projection is made by the E+ weather files, because the energy usage is always higher compared to the three MN data sets. In each scenario of the MN sets, the difference between the three results is higher the further the projection is in the future. One way to interpret this is to say that, the further a projection is in the future, the less precise the predictions of energy usage are. In general, the differences between the energy usage predicted by the two sources is due to different extrapolation algorithms and to different input data, which we demonstrated to vary even in the present. Due to the fact that the weather files refer to the future, we cannot assess which one is wrong and which one is correct. For this reason, all the weather files can be considered as probable future projections.

The main conclusion of these two preliminary simulations is that two different weather files cannot be considered as 'duplicates' of the same point, even if they refer to the same climatic area. Instead, they can be counted as random inputs, or 'replicates' in a simulation of building performance where all other factors remain the same. In other words, our methodology is a sensitivity analysis (Lomas and Eppel, 1992; Saltelli et al., 2004) where the uncertainties are represented by the input weather files.

METHODOLOGY

The objective of this paper is to describe a methodology to assess the robustness of building performance to uncertainties in weather file, which we illustrated in the two preliminary studies before. The methodology starts with the simulation of a building model with different weather files, coming from different sources and stations and representing many future years and scenarios. These weather files create a large ensemble of plausible future climates, where each member of the ensemble represents one equally probable guess about how the climate could be. In this way it is possible to analyse the behaviour of different design strategies under many plausible future climates and assess their robustness over climatic uncertainties. In general, the robustness is defined as the sensitivity of particular performance indicators of a building to errors in the design assumptions (Hoes et al., 2009). In our case the errors are represented by the weather files used as inputs, and a robust solution is insensitive to climate change uncertainties. The methodology can be divided into two main parts: the energy usage robustness evaluation and the energy saving evaluation. Each of them is characterised by a graphical part and by an index. In general, the methodology helps to compare various design strategies in terms of ranges of energy usage. This approach could ultimately help architects and engineers to make more informed energy efficient choice at an early design phase.

Energy usage evaluation

The first part of the methodology is focused on the total energy usage of different design solutions. The final goal is to assess the strategies in terms of robustness to a changing climate that could potentially happen in the future. This fact means that, in this part of the analysis, it is not important if a weather file refers to a particular year or a particular scenario. The climate changes that the weather files predict are considered possible to the same degree. For this reason, the weather files referring to the present are considered in the robustness evaluation as well because they describe a possible stable climate. By considering all the weather files we have, a particular solution is robust if the range of variation of energy usage is small. In other words, thanks to particular properties of the building, the energy usage will be the same or will have little variations in many possible future climates.

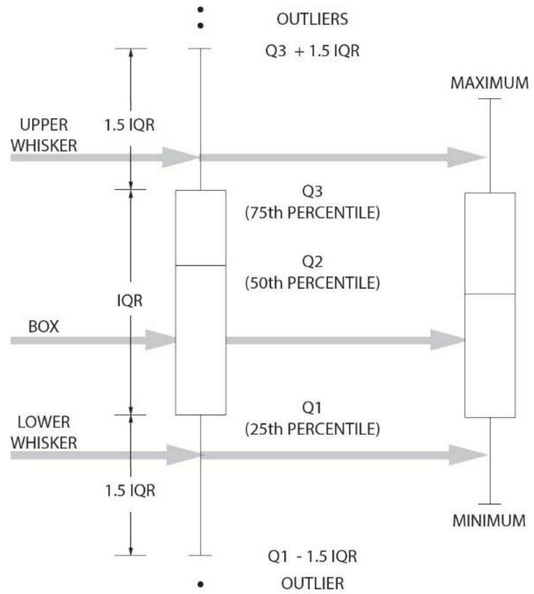

Figure 2: Box-whiskers plot

The box whisker plot (Figure 2) is the graphical tool which is used in this part of the methodology. It provides a useful way to compare distributions between several groups or sets of data without making any assumptions of the underlying statistical distribution. It uses the quartiles of a group of data to analyse the distribution of the response to particular variations, which in our case are the weather files and the related energy usages. In our analysis, each design strategy has a box-whiskers, which represents all the energy usage outputs from the different weather files. The robustness of a particular building model can be assessed with the dimension of the box and the length of the whiskers. If the box is tall and/or the whiskers are long, the response of the building in terms of energy usage to climatic changes varies substantially and, therefore, the particular solution is sensitive (or not robust) to climate variations. On the other hand, if the box and/or the whiskers are short, the properties of the building make it insensitive (or robust) to changes in the climate, no matter which scenario turns out to have been correct. The box whiskers plot is a good graphical representation that helps to compare various strategies only if there are big differences between the dimensions of whiskers and boxes, but not if the differences are small. For this reason we introduce the Robustness Index (RI). The RI permits the comparison of design strategies in terms of robustness. Before evaluating the RI, it is necessary to calculate a *comparison number* (1) for each design strategy (S_i) and for the base case (BC). The *comparison number* is composed by a weighted sum of the interquartile (IQR) and the standard deviation of the set of data (σ).

$$\omega_i = 0.3 \cdot IQR_i + 0.7 \cdot \sigma \qquad (1)$$

The RI is expressed in Equation (2).

$$RI_i = 1 - \left(\frac{\omega_{S_i}}{\omega_{BC}}\right) \qquad (2)$$

The RI permits the comparison of many strategies (comparing their different RIs), but also the comparison between a strategy and the base case (i.e. if $\omega_{Si} > \omega_{BC}$ then the design solution is less robust than the base case). However, it does not convey a sense of the magnitude of energy usage. That is, a design strategy could have a high RI value, and so be robust to climate change, but at the same time could have very high energy usage.

Energy saving evaluation

The second part of the methodology consists of the comparison of design solutions in terms of energy saving. The final goal is to understand how much energy each strategy could save in comparison with the base case and in each year. Many weather files must be used to calculate the ranges of energy saving in each year in this part as well.

The histogram is the graphical tool that is used in this part of the methodology. In particular, we use floating bars to show the ranges of energy differences in the present and future years. Figure 3 shows that for each case (base case and strategy$_i$) four floating bars illustrate the maximum and the minimum energy saving in comparison with the base case at present, for different years. Therefore the bar referring to the base case at present will always be zero. The bars indicate only the maximum and the minimum difference, without taking into account the distribution of data. Like in the previous part of the methodology, a smaller bar represents a better strategy due to little uncertainties.

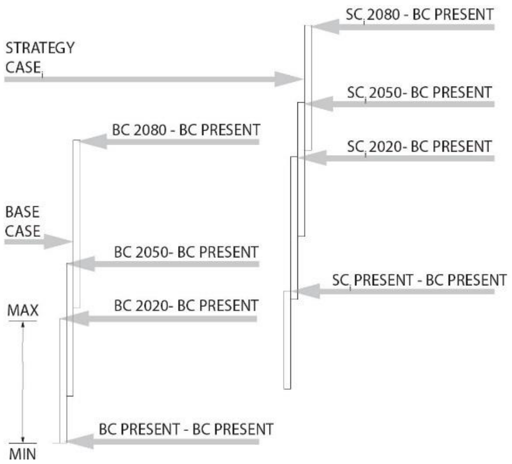

Figure 3: Floating bar chart

The floating bar chart is a useful graphical tool to understand at first sight the ranges of energy variation in different years and for various strategies. However, if the differences between the ranges are small, it is not possible to distinguish one solution from another, making it difficult to compare them. For this reason we decided to calculate a second index able to classify the different design measures in terms of energy saving in comparison with the base case, the Energy Saving Index (ESI). The ESI is used to rank the overall energy saving, due to climate change and to different strategies. With this number, therefore, we want to rank in a positive way the strategies that save more energy, whether due to climate change or to the improvement of the building properties.

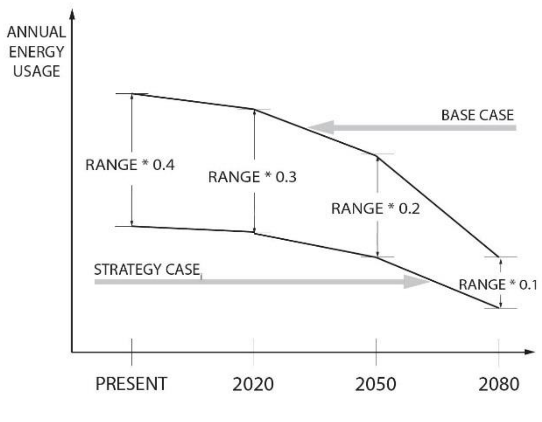

Figure 4: Energy saving index calculation

The process for the calculation of the ESI begins with the evaluation of a value for each case, a second comparison number. It represents the weighted sum of energy usage differences in each year between a particular strategy and the base case. In this way, each year of a strategy case is compared with the same year of the base case. The weighted sum gives less importance to the differences between energy usage in future years, assuming that weather projections referring to the future years are less and less precise the further they are from the present. Figure 4 shows a schematic which illustrating the principle behind the calculation of this comparison number, for just the base case and one strategy case referring to one set of data (same station and source). The real calculation for the comparison number is more complex since it takes into account many energy usage estimates for each case, referring to different stations and sources. Therefore the comparison number (υ_i) for each case is the average of all the results (3).

$$\vartheta_i = \left(\sum_{j=1}^{n}\left(\left(x_{BC} - x_{SC_i}\right)_p \cdot 0.4 + \left(x_{BC} - x_{SC_i}\right)_{20} \cdot 0.3 + \left(x_{BC} - x_{SC_i}\right)_{50} \cdot 0.2 + \left(x_{BC} - x_{SC_i}\right)_{80} \cdot 0.1\right)\right) \cdot \frac{1}{n} \quad (3)$$

The Energy Saving Index for each strategy is the normalization of the comparison number of a strategy with respect to the comparison number of the base case. Consequently, to normalize each result, υ_i must be divided by the same number referring to the base case, where all the x_{SCi} terms are zero. The final ESI for each design strategy is expressed by the Equation (4).

$$ESI_{SC_i} = \frac{\upsilon_{SC_k}}{\upsilon_{BC}} \quad (4)$$

The higher ESI a strategy case has, the better it is in terms of energy saving in comparison with the base case.

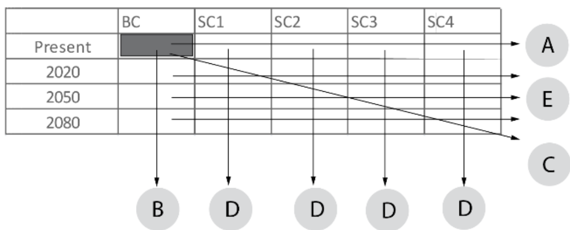

Figure 5: Different comparisons between energy usage results

It is important to note that the floating bar chart and the ESI illustrate two different comparisons. Figure 5 shows the possible comparisons that can be done between the energy usage results. The floating bar chart displays comparison C (between all the cases in all years and the base case at present), while the ESI illustrates comparisons A and E (between the strategy case in a particular year and the base case in the same year).

SIMULATION

To validate the methodological steps presented previously, we ran energy simulations using EnergyPlus (version 8.1) with a case study in Torino, Italy. The two input files of the software are the IDF (file generated with DesignBuilder software), which describes the building model, and the EPW files containing hourly weather data. In the following subsections, the building models and the weather files used are described. Further information about these can be found in previous work (Chinazzo, 2014; Chinazzo et al., 2015).

Case study

Figure 6: The base case model

The case study we analysed is divided into a base case (BC) and twenty-two refurbishment strategies (RC). The base case is a detached single family house built before the 70's, hence before any energy regulations (Figure 6). The walls are of masonry block and brickwork with internal cavities, the ground floor is only concrete and the roof is made of rafters and clay tiles. All envelope components, therefore, lack insulation. The windows are single glazed with aluminium frames. Table 1 illustrates the thermal properties of the base case envelope.

Table 1: Envelope's U-values in W/(m^{2}K)

WALL	ROOF	GR. FLOOR	WINDOW
1.4	1.0	1.0	5.8

The refurbishment strategies can be classified into four categories: use of insulation (RC1-RC18), use of shading systems (RC19-RC20), use of thermal mass (RC21) and increased airtightness (RC22). In the first group, there are two important variables that are taken into account and that distinguish one solution from another: the total U-value of the structure considered and the location of the insulation layer (internal or external). The material used is not important, nor its thickness.

The model of the base case is modified with just one passive measure at a time, which does not take into account the combination of more than one solution.

Weather files

We run the base case and the refurbishment cases with eighteen weather files. They are similar to the ones used in the preliminary studies in terms of sources (E+ and MN), years (present, 2020, 2050 and 2080) and future scenarios (A2, B1 and A1B), but this time they refer to Torino weather stations. Figure 7 illustrates that Torino has two weather stations (city centre and Caselle airport respectively). The source of the typical weather file for the first weather station is the U.S Department of Energy's website (E+), whereas the second weather station has two sources, the same website and Meteonorm. The three present weather files are then converted to future .EPW with the CCWorldWeatherGen (.EPW from E+) and with METEONORM software (.EPW from MN). The weather files are considered in two different ways in the two parts of the methodology. First, they are considered equally probable in a 'general future' during the robustness evaluation. Then, they are divided into years for the energy saving evaluation. In this last part, the range of results is due to different sources and scenarios.

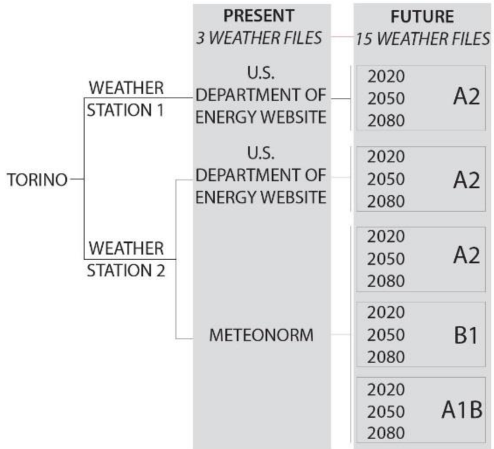

Figure 7: Weather files, sources, years and scenarios

DISCUSSION AND ANALYSIS

In the following analysis, we will divide the simulations results of the case study and the eighteen weather files according to the methodological steps. We will first analyse the graphical results and the indices for the robustness evaluation of energy usage. Then, we will explain the results for the energy saving part. In each part we analysed the energy usage for cooling, heating and their sum.

Energy usage results

Figure 8 shows the annual energy usage for heating. The results highlight the sensitivity of different measures to alternative climate scenarios. All the cases have two outliers, which represent the Caselle E+ set of data at present and in 2020. In general, almost all refurbishments lead to a lower energy usage with respect to the base case. In terms of the height of the boxes and the length of the whiskers, the reduction of infiltration (RC22) seems to be the least sensitive refurbishment under future scenarios, hence the most robust.

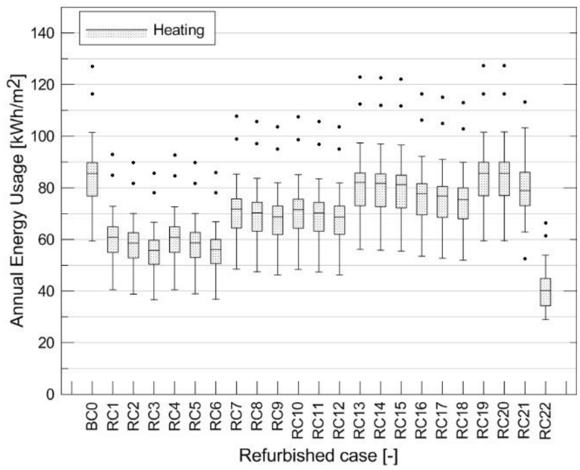

Figure 8: Annual energy usage for heating

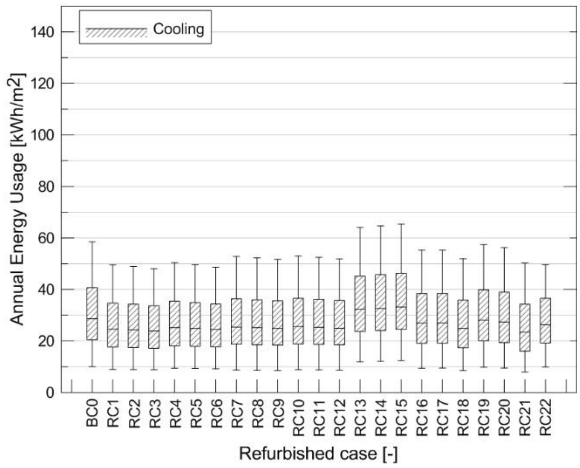

Figure 9: Annual energy usage for cooling

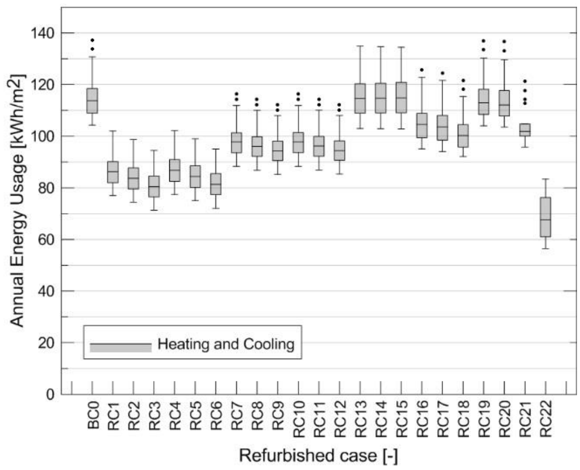

Figure 10: Annual energy usage for the sum of heating and cooling

Figure 9 shows the annual energy usage for cooling. The first thing that can be noticed is that the cooling final energy is lower compared to the heating one. The differences between different refurbishments is really small and it seems that almost all the solutions behave the same way. There are no outliers, which means that the uncertainty for cooling is higher compared with the one for heating (in terms of height of the boxes).

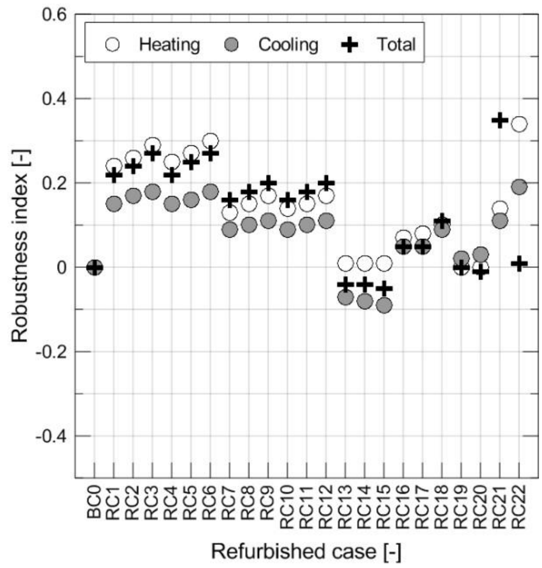

Figure 11: Refurbishment Index for cooling, heating and the total energy usage

Figure 10 shows the sum of energy usage for heating and cooling. Due to the fact that the heating loads are higher than the cooling ones, the sum of the two energy figures is more influenced by the heating results. The box of the RC22 is larger compared to the heating box due to the fact that there are no more outliers. In terms of robustness, the use of PCM (RC21) seems to be the least sensitive to climate change due to the small size of the box. It is also the only solution with four outliers. Looking at the results more closely, these four higher values refer to all years of the Caselle E+ data set. Hence, choosing weather files from different stations could not lead to correct results.

After the graphical analysis it is necessary to quantify the spread of data by means of the RI, due to the fact that the dimensions of the boxes are quite similar. Figure 11 compares the RIs for cooling and heating and their sum. The rankings are different according to the three sets of data. For example the use of PCM (RC21) is one of the worst in terms of cooling energy, but it is the best for the total energy usage.

Energy saving results

Also in the energy saving evaluation, the floating bar charts for heating and cooling display different rankings. We show only the graph that illustrates the sum of them, which is mostly influenced by the heating energy usage (figure 12). The figure shows that the ranges of energy saving are different in the four years. In particular, the further a time snap is from the present, the more uncertain is the climate prediction, which in turn implies a wider range of energy saving possibilities. For this reason, in general, the present ranges are smaller than the ranges for 2020, 2050 and 2080. The energy saving in 2080s are higher due to general warming of the planet (hence, less heating demand).

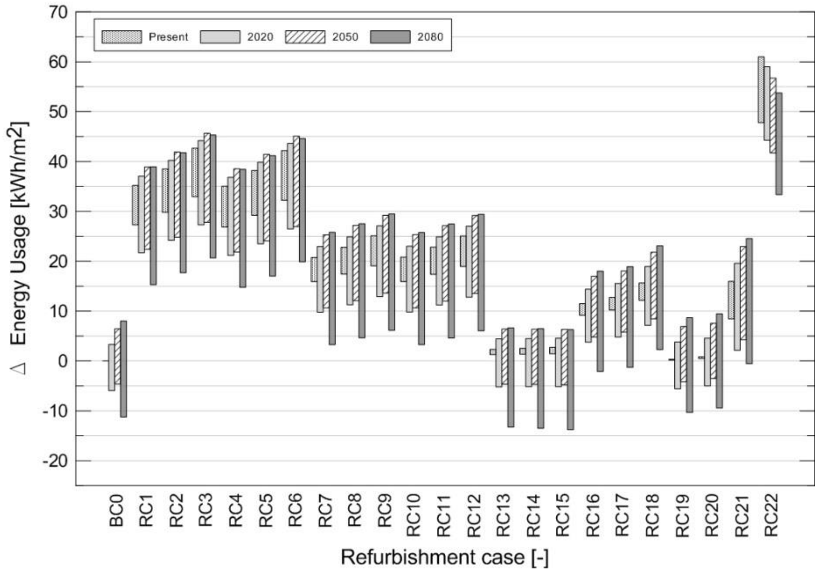

Figure 12: Energy difference ranges for the sum of heating and cooling between base case and refurbishment cases in different years.

It is interesting to notice that also the base case will face energy usage changes in future years, which could generate negative or positive energy difference from the present consumption. In the evaluation of different solutions, all weather files must be considered probable future scenarios, hence we have to compare the ranges of energy variation. In our case study, the majority of the refurbishments overlap with each other. Only the improvement of the airtightness (RC22) presents very high energy savings in all the years and has almost no overlap with any others, but the ranges are comparable with the ones of the other solutions. The ranges calculated using present weather data have more variations among the different refurbishments. The difference between the other ranges is difficult to see, especially in the same refurbishment group (e.g. wall insulation RC1-RC6).

For this reason it is necessary to use the Energy Saving Index to assess the refurbishments more precisely. Figure 13 compares the Energy Saving Index for heating, cooling and their sum. In comparison with the energy usage analysis, the ESIs for cooling and heating are more different. It is interesting to notice how the ESI and RI are not related. For example the increase of airtightness (RC22) is one of the less robust refurbishment in terms of energy usage, but it is the best one in terms of energy saving (for the total final energy). In both RI and ESI the internal and external insulation of the walls (RC1-RC6) are among the best performing solutions.

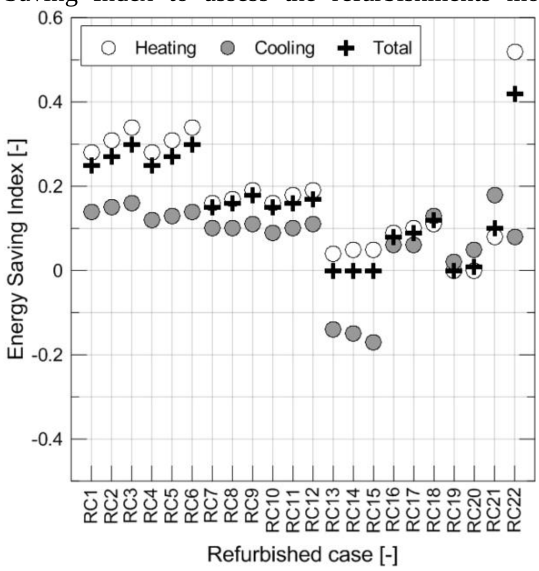

Figure 13: Energy Saving Index for heating and cooling and the sum of them

CONCLUSION

The purpose of this study is not to evaluate the best type of refurbishment for a particular construction and climate, but rather to develop a methodology that engineers and architects could apply in the evaluation of different design strategies. The innovation is the inclusion on many weather files in energy simulations and the methodological steps to analyse the results by means of graphical tools and indices. In particular, we show how design choices based on just one weather file may differ from those based on a wider range of input weather data. The results of the simulations show that the box-whiskers plots and the floating bar charts are a valuable tool to express performance uncertainties, but an index is needed to be able to compare the results with the base case in a more detailed way. Moreover, the comparison between different strategies must be conducted with the sum of heating and cooling energy usage, since the evaluation with just one of the two parameters could lead to misleading results. In fact, energy performance rankings tend to differ for heating and cooling.

It is important to note that our validation was conducted with only eighteen weather files. Results would be more accurate, or representative of the full range of expected performance, with a larger sample of weather files. As a matter of fact, the whole process is based on statistical approaches that are, strictly speaking, only valid as sample sizes approach infinity. For example, using non-parametric estimates of data range like quartiles/percentiles could give absurd results for extremely small sample sizes. In future work, we propose to examine our methodology with larger sample sizes. Moreover, it will be necessary to develop a single index to assess different strategies in terms of robustness and energy saving. Ongoing work aims to solve these problems.

NOMENCLATURE

E+ = Energy Plus
MN = Meteonorm
ω = comparison number for RI
RI = Robustness Index
BC = Base Case
SC = Strategy Case
RC = Refurbishment Case
υ = comparison number for ESI
ESI = Energy Saving Index

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