AN EVALUATION OF ENERGY EFFICIENCY MEASURES IN A TURKISH CAMPUS BUILDING FOR THERMAL COMFORT AND ECONOMIC RISK

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ABSTRACT

As new and retrofitted Turkish buildings adopt state-of-the-art energy efficiency measures, hidden risks associated with compromised thermal comfort and disappointing returns on investment could go unnoticed unless a building is subjected to an uncertainty and risk analysis. Standard deterministic predictions are not sufficient, as they do not capture the effects of uncertainty and variability with regard to local microclimate conditions, physical parameters, and discrepancies in the model formulations, also known as "model form uncertainties". In this paper, we analyze the impact of uncertainty on the performance of a Turkish campus building. We examine the risk that an energy efficient design that is accepted because of the positive results of a conventional energy simulation, causes unacceptable discomfort and unsatisfactory returns on investment. The results of a comprehensive uncertainty analysis shows that these risks exist in certain areas and not in others. The predicted annual output of PV panels is relatively stable with only minor variability, which justifies the investment in Istanbul. Same with shading devices, which lead to a satisfactory internal rate of return under uncertainty. However, with regard to comfort we find that risks could be substantial. We find that relying completely on occupants opening and closing windows for fresh air with fan coil units maintaining the indoor temperature may lead to an insufficient supply of outdoor air for occupants and a substantial risk of overheating. Overall, the results of the analysis demonstrate that understanding risks is in some cases crucial to make an informed design decision regarding various energy saving design strategies.

INTRODUCTION

The building sector and its energy demand has grown rapidly in the last ten years in Turkey. According to the Turkish State Institute of Statistics (TSIS) (2000), in 1984 and 2000, the number of buildings increased from 4.3 million to 7.8 million, which amounts to a 79% increase rate. In addition, the Ministry of Energy and Natural Sources of Turkey (MENR) (2013) finds that the number of buildings reached 8.35 million and the energy consumption in the building sector increased by 39% between 2001 and 2011 and accounted for 26 percent of the total energy consumption in Turkey. MENR also projects that by 2020, energy consumption of the building sector will be 47 Mtoe (million of tonnes of oil equivalent) (Ministry of Energy and Natural Sources of Turkey (MENR), 2012a). To mitigate the increasing demand of energy from the building sector, Ministry of Energy and Natural Sources of Turkey (MENR) (2012b) has specified that reducing buildings' energy demand and promoting sustainable environment-friendly buildings are strategic goals to be achieved. It is targeted that by 2023, at least one fourth of the building stock in the year 2010 should consist of sustainable buildings. Additionally, in order to increase energy efficiency in buildings, National Climate Change Plan 2011-2023 by the Ministry of Environment and Urbanization (MEU) (2012) indicated to, a) establish heat insulation and energy-efficient systems meeting standards in commercial and public buildings with usable areas larger than 10,000 m^2 and in at least one million residential buildings by 2023, b) issue "Energy Performance Certificates" for all buildings before 2017, and c) reduce annual energy consumption in buildings and premises of public institutions by 10% in 2015 and by 20% in 2023. As there is a growing demand for new buildings and almost half of the current building stock is more than 30 years old and in need of retrofits, the above goals seem aggressive. In an effort to meet these goals, innovative energy technologies and conservation measures for buildings are being extensively promoted in Turkey.

As new and retrofitted Turkish buildings push the envelope in energy performance, design decisions have to well founded and typically based on the results of energy simulation studies. However, as energy modelers rely solely on simulation software to predict building performance in a deterministic way, such results may not always tell the whole story and therefore be less reliable. Despite the maturity of current energy simulation tools, their power of prediction remains imprecise with regard to local conditions, physical parameters, and usage scenarios. Consequently, energy efficiency measures and passive strategies may fail to achieve the expected benefits in real life. The models may be misleading by predicting outcomes that deviate from what we would observe in the realized building. The primary cause of such deviation is uncertainties mostly from the following two sources. The first source is uncertainty associated with the physical properties of building components, system parameters, and operational scenarios. For example, the actual efficiency of building HVAC systems generally deviates from their nameplate efficiency obtained from industrial compliance tests under nominal boundary conditions. Instead, their on-site performance may vary, depending on the local environments and construction and installation circumstances such as the effect of deficient workmanship. In addition, the modeler has to make assumptions resulting from a lack of information or expertise, which can lead to an inaccurate prediction of performance. Another source of uncertainty is discrepancies in the model itself. Most state-of-the-art energy simulation tools represent complex physical processes through certain levels of abstraction and simplification. Bearing these in mind, we postulate that new and retrofitted Turkish buildings that appear to have proved effective with the results of conventional simulation studies may potentially carry the risk of compromised thermal comfort and disappointing returns on investment. The need to identify such hidden risks calls for a type of uncertainty analysis that quantifies the impact of physical parameter uncertainties, modeler assumptions, and model simplifications on the outcomes.

A growing body of work responds to the need for uncertainty analysis that extends beyond the conventional boundary of deterministic building simulations. Macdonald and Strachan (2001) implemented uncertainty analysis into the building simulation tool ESP-r and analysed the effect of uncertainty over building design process. de Wit and Augenbroe (2002) introduced a general procedure for uncertainty analysis of building thermal performance and initiated the integration of uncertainty analysis with risk analysis in a decision-making context. Similarly, Hopfe and Hensen (2011) quantified uncertainties in physical properties and scenario conditions and used them to support decision making due to differences in climate change. More recent work by Heo, Choudhary, and Augenbroe (2012) extended the application of uncertainty analysis to the support of risk-conscious decision-making in building design and retrofit, such as in the context of an energy performance contract. Wang, Zhang, Ahuja, and Augenbroe (2014) proposed a methodology to evaluate the effectiveness of passive design strategies under uncertainty and concluded that an uncertainty analysis is able to predict extreme conditions inside buildings such as overheating while the conventional simulation approach cannot.

This paper presents an uncertainty analysis for an academic building in Turkey at the design stage with respect to investment risk and thermal comfort risk. Our study shows the importance of such an analysis for identifying strategies that can be proven applicable and potentially scale up the building energy efficiency market in Turkey without downside risks.

BUILDING DESCRIPTION

Building

Özyeğin University Campus is located on the Anatolian side of Istanbul. The School of Languages (ScOLa) building in Özyeğin University, which we evaluate within the scope of this paper, was constructed in 2013 as a part of European Union 7th Frame Program NEED4B project. The ScOLa building, depicted in Figure 1, has an area of about 17,715 square meters, divided into four above-grade floors and two below-grade floors. The building hosts more than 1,450 students and 135 staff, and mainly consists of classrooms, lecture rooms, meeting rooms, study rooms and offices. The energy efficient design measures applied in the building mainly comprises the following four features, as schematically shown in Figure 2:

- Earth air heat exchangers, also known as earth tubes. They are underground horizontal ducts or pipes buried at moderate depths. Outside fresh air or re-circulated air is conditioned by the thermal mass of the earth and channeled into the building. In this case, the earth tube is a horizontally installed system on the eastern side of the building with 72 m in length, 10 m in width, and 2 m in depth. The systemd covers an area of approximately 1,200 m^2. These tubes pre-condition the fresh air to be supplied to the two underground floors.
- Cross ventilation with mechanical exhaust. Openings are carefully placed around the building, facilitating optimal use of cross natural ventilation and free cooling in the summer. Therefore, in the four floors above grade, no mechanically driven fresh air system is installed but a mechanical exhuast system is present. The building relies on occupants' opening and closing windows for fresh air with fan coil units maintaining the indoor temperature.
- Double skin façade with fixed perforated aluminium sunshade elements, and double glazed, low-e type glazing for western, eastern and southern facades. Such designs intend to reduce solar heat gain during cooling seasons.
- Roof mounted photovoltaic (PV) panels. The roof of the building hosts around a 126 kWp photovoltaic system based on multi-crystalline silicon technology. The peak power wattage for each module is 250 W and in total 504 modules are installed. Surplus generation will be used for neighboring buildings.

In terms of construction methods, the ScOLa building adopted the conventional reinforced concrete frame construction method with expanded polystyrene (EPS) insulation and lightweight pumice concrete walls for separation between classrooms. The U value of the exterior walls and the window system that consists of insulated aluminium frame and double glazed low-e type glass is 0.3 W/m^{2}K and 1.3 W/m^{2}K, respectively.

Figure 1 ScOLa building in Özyeğin University

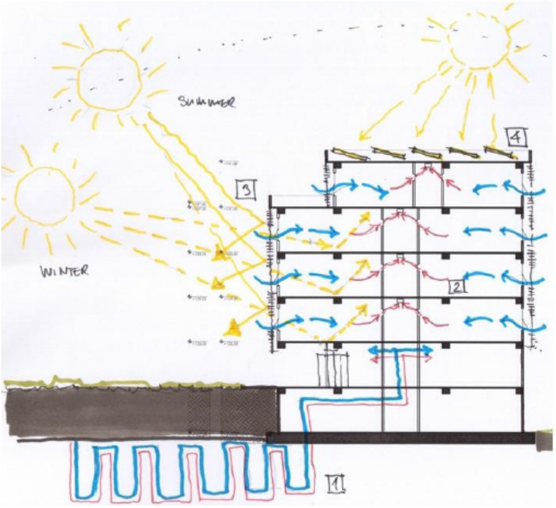

Figure 2 A schematic of the energy efficient measures in the ScOLa building

The pre-conditioned air by the earth tube is connected with the primary variable air volume air handling unit, which serves the two below-grade floors. Four-pipe fan coil units with two-way control valves throttling hot or chilled water and a central mechanical exhaust system maintain the indoor thermal comfort of the four floors above grade. Chilled water and hot water are provided centrally by the energy distribution center located on campus. Information about occupancy schedules, and lighting/appliance usage is collected from the building operational policy.

Uncertainty quantification

In the quantification of uncertainties associated with the performance of the ScOLa building, we borrow quantified generic uncertainties contained in the XML repository from GURA-W (Georgia Tech Uncertainty and Risk Anlaysis Workbench) (Lee, Sun, Augenbroe, & Paredis, 2013). We need to point out that the model form uncertainties are specific to the simulation engine EnergyPlus Version 7.0, with which a model of the ScOLa building is created. Furthermore, we have to define some project specific uncertainties that are not provided by the generic GURA-W repository. This relates in particular to the additional variability of electricity production by the PV panels on the ScOLa building. The predicted performance of PV systems typically deviates from that under operational conditions because of the following aspects:

- Inaccuracy of the radiation model
- Dirt accumulation (or soiling) and aging
- Post module loss by maximum power point tracker (MPPT) and inverter
- PV model simplification

These factors will be explained in greater detail below.

A radiation model translates the solar radiation values from weather data into energy incident that falls upon the PV panels. The discrepancy from the Perez model implemented in EnergyPlus Version 7.0 has been taken into account with the model from uncertainty quantified in Y. M. Sun, Su, Wu, and Augenbroe (2015).

The performance of PV panels may be adversely impacted by dirt accumulation on the surface of arrays as well as deterioration of PV efficiency from aging. Several studies have approached the soiling issue by comparing the energy throughput of clean and dirty modules and attributing the loss to soiling. A review of such experiments conducted at various locations in the United States and other countries suggests a range of performance loss between 1.4% to 5%. Considering that the Ozyegin University campus is located on the migration path of birds, the above range for the annual loss from the impact of soiling seems reasonable. It is safe to assume that loss due to deterioration can be ignored in the first a few years after the installation.

Figure 3 presents a typical I-V curve of a PV module. At about the knee of the curve, there is a point that corresponds to the maximum electricity generation power. It is thus desirable to operate the PV module at this point for the highest efficiency and the maximum power output. However, this maximum power point varies with the insolation level and module temperature, so we have to rely on maximum power point tracking to insure that the PV module operates at the maximum power point at any instant of any given load. A typical maximum power point tracker (MPPT) operates with efficiency between 97% and 99% (Eckstein, 1990). In addition, the power generated by a PV module needs to be converted from direct current (DC) into alternative current (AC) in order to be used by builidng appliances. The efficiency of the inverters in the ScOLa builidng ranges between 95.6% and 98.2% according to the data sheet provided by the manufacturer.

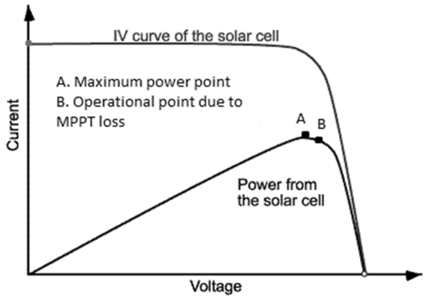

Figure 3 A typical I-V curve of a PV module

EnergyPlus implements the well-known five-parameter equivalent circuit model (Figure 4) for the prediction of PV output. This model takes into account operational conditions that deviate from standard test conditions (STC) and efficiency loss from increased panel temperature. For crystalline modules, it is often safe to assume that the module shunt resistance $R_{sh} \to \infty$, so the five parameters reduce to the four parameters $I_{L,ref}$, $I_{o,ref}$, a_{ref} and R_s, which are assumed to be constant for a particular PV module.

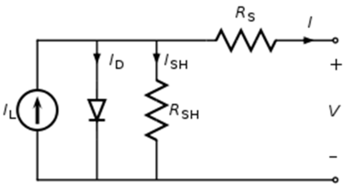

Figure 4 An equivalent circuit for PV module

By applying the Kirchoff's current law, the following current flow balance stands:

$$I = I_L - I_D - I_{sh}, \tag{1}$$

Since we assume that $R_{sh} \to \infty$, $I_{sh} \to 0$. Equation 1 reduces to

$$I = I_L - I_D = I_L - I_o[\exp\left(\frac{V+IR_s}{a}\right) - 1], \tag{2}$$

The photocurrent I_L depends linearly on incident radiation:

$$I_L = I_{L,ref}\frac{G_T}{G_{T,ref}}, \tag{3}$$

The diode reverse saturation current I_o is a temperature dependent quantity:

$$I_o = I_{o,ref}(\frac{T_c}{T_{c,ref}})^3, \tag{4}$$

where $T_{c,ref}$ is 298.15 K.

The ideality factor a is a linear function of the cell temperature:

$$a = a_{ref}\frac{T_c}{T_{c,ref}}, \tag{5}$$

The reference parameters can be calculated from the following information from the manufacturer: the short circuit current, the open circuit voltage, and the current and voltage at the maximum power point. Once we calculate I_L, I_o and a from Equations 3 through 5, Newton's method is applied to Equation 2 to obtain the I-V curve of the PV module. In order to quantify the accuracy of the five-parameter model, Cameron, Boyson, and Riley (2008) described a detailed comparison of model predictions to actual measured PV system performance. In their study, authors particularly isolated the effect of model simplification by removing the effect of radiation models and physical factors such as soiling and system mismatch loss. They found that the five-parameter model almost always over-predicts the DC output by a factor of 3.5% to 5.3%.

In summary, assuming that the efficiency loss from the four aspects are sequential and multiplicative, we find the actual PV system efficiency should be:

$$\eta = \eta_{dirt} * \eta_{\text{MPPT}} * \eta_{\text{inverter}} * (1 - \varepsilon_{model}) \tag{6}$$

Since all these efficiency factors are uncertain as characterized above, we perform a crude Monte Carlo analysis for an empirical distribution for the overall system efficiency η. The curve fitting suggests η follows a normal distribution N(0.88, 0.014), as shown in Figure 5.

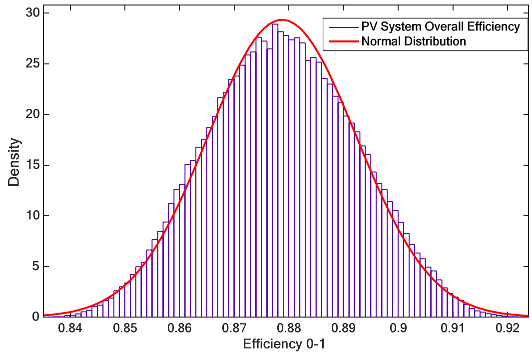

Figure 5 Curve fitting of the PV system efficiency

Uncertainty propagation

The uncertainty propagation is performed in a non-intrusive Monte-Carlo fashion. Following the quantified distributions of all uncertain parameters, we first generate a Latin hypercube design that partitions each input distribution into N intervals of equal probability so that it can explore the parameter uncertainty space more evenly than conventional brutal force random sampling. We then feed these uncertain parameters into the EnergyPlus simulation engine to obtain an empirical distribution of the output variable of interest. Such a process is facilitated and automated with GURA-W, enabling the quantification of the risks that energy saving strategies to be invested forfeit their expected performance.

The variables of interest in this case study are the annual amount of energy saved by introducing the shading devices on the western, eastern and southern facades, the annual electricity generation of PV panels, and the indoor comfort in a demonstration classroom in July measured by the thermal discomfort (occupied) hours and indoor "stuffiness" hours measured by CO₂ concentration. Our emphasis in the results discussion will be on the last variable of interest, because of a general concern about the effectiveness of relying on occupants' operation of windows for fresh air supply and the consequent risk of overheating.

RESULTS AND DISCUSSION

Energy saving by shading devices

The determination of energy savings from an energy efficiency measure under uncertainty is essentially a comparative analysis of the empirical distributions of pre and post retrofit energy consumption. We divide the uncertain parameters in the pre retrofit building model into two groups ($X_i s$, $X_j s$), in which $X_i s$ are common to both the pre and post-retrofit building but $X_j s$ are unique to the pre-retrofit building. Similarly, we denote the post-retrofit uncertain parameters as ($X_i s$, $X_k s$), where $X_k s$ are specific to the shading devices. Now we need to ensure in our comparative analysis that the samples in the pre and post retrofit case remain the same for $X_i s$, and the savings have to be calculated as the difference between pair-wise pre and post-retrofit samples. The implementation of such a comparative analysis is also embedded in GURA-W with a parser that sweeps the values of post-retrofit Latin hypercube samples for $X_i s$ with those of the pre-retrofit samples.

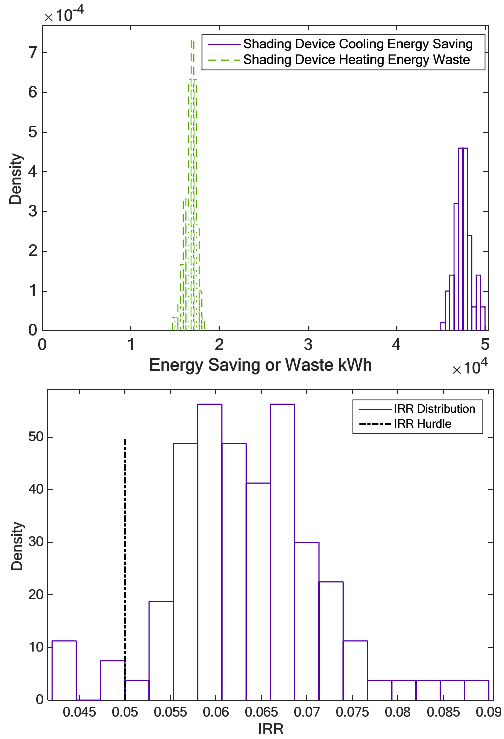

Figure 6 Distributions for reduced energy consumption for cooling and increased consumption for heating (top) and the IRR distribution for shading device investment (bottom)

Figure 6 shows the empirical distributions for the reduced energy consumption for cooling and increased consumption for heating that result from the installation of shading devices. As expected, these fixed perforated aluminium sunshade elements block the sun and help reduce cooling demand in cooling seasons but also reject useful solar heat in heating seasons, which increases the need for space heating. The trade-off between gain and loss leads to a ten-year internal rate of return (IRR) of 4.5% to 9%, taking into account the cost of the shading devices at € 8,000. The benefit of such an uncertainty analysis is that it clearly indicates to the decision maker that the confidence that the IRR for shading devices is higher than the hurdle rate of 5% is 95%, which may help justify the investment given a particular risk preference of the decision maker. On another note, we find that the instalment of shades at the northern facades does not justify the extra investment, which will .

PV electricity generation

Having considered four sources of uncertainty associated with the PV power generation prediction, we derive the distribution for the annual output of the 126 kWp photovoltaic system based on multi-crystalline silicon technology as shown in Figure 7.

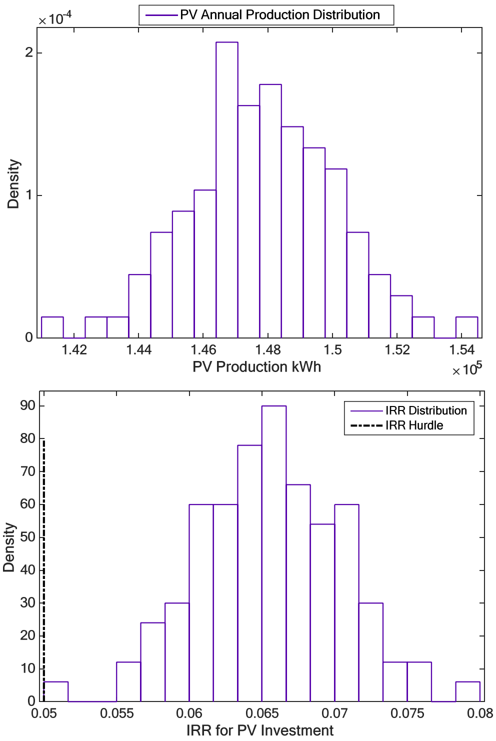

Figure 7 Distribution for annual PV system output (top) and the IRR distribution for PV system investment (bottom)

The above results suggest that the predicted annual output of the PV system is quite stable with only a little variability around the mean value of 148 MWh. The cost of the whole system is €115,000. The predicted range for the six-year IRR is between 5% and 8% with 100% confidence. This result infuses confidence in the decision maker that investing in PV systems in Istanbul is indeed worthwhile.

Indoor comfort

There is a potential concern for indoor air quality and thermal comfort in the ScOLa building since there is no mechanical ventilation on the upper four floors. Instead, fresh air supply relies on the window opening behavior of occupants. However, when students feel stuffy in the classrooms, the outside air temperature may not be appropriate for ventilation. This implies a trade-off between indoor air quality and thermal comfort during occupied hours of the classrooms.

The indoor "stuffiness" is measured by the CO_2 concentrations. Researchers at the Lawrence Berkely National Laboratory (LBNL) have found that moderately high indoor concentrations of CO_2 can significantly impair the decision-making capability of test subjects in the study (Satish et al., 2012). In the experiment, researchers came up with nine scales of decision-making performance, and the test subjects showed dramatic decline in performance on seven of them at a CO_2 concentration of 2,500 ppm. Contrary to previous research that focuses on concentrations higher than 10,000 ppm, the LBNL study has shown that in occupied classrooms where concentrations frequently exceed 1,000 ppm and sometimes exceed 2,500 ppm, CO_2 at these levels not only indicates poor ventilation with increased exposure to other indoor pollutants, but also presents itself as a source of adverse impact on some students' activities. In summary, the indoor air quality with CO_2 concentrations as an indicator clearly warrants a detailed simulation study for the new energy efficient campus building.

A deterministic model was first built for simulating the (occupied) thermal discomfort hours and indoor "stuffiness" hours measured by CO_2 concentration in a demonstration classroom in July. The thermal comfort standard in Istanbul follows ISO 7730:2005 (2005), suggesting the indoor operative temperatureshould not exceed 25.5 °C. The CO_2 concentration threshold is 2,500 ppm. The deterministic results show that out of the 133 occupied hours in July (7 hours per day, excluding the religious holidays starting July 26th), there are 26 hours when the classroom lacks sufficient ventilation and 29 hours when the classroom suffers from overheating. This finding points to potential problems as the exceedance is around 20%, which can be considered as relatively high. Nevertheless, with presumed occupant intervention, the current design may be able to maintain reasonably good indoor air quality and thermal comfort. However, we argue that the above result is insufficient for establishing the required confidence to make the right decision due to the impreciseness and incompleteness of the deterministic prediction. Following the methodology proposed in this paper, we re-evaluate the building under uncertainty and quantify the risk that the building under-performs the expected performance indicated by the deterministic prediction. We present the uncertainty analysis result in Figure 8. The Two-dimensional contour plot shows pairwise discomfort hours on the horizontal axis and CO_2 overshoot hours on the vertical axis. The isolines on the graph represent the level sets in which the data density is constant, and areas with warmer colors denote higher data density. Analyzing the data more closely reveals that the risk that the building under-performs the deterministic prediction is 89%, which corresponds to the percentage of data points outside the highlighted rectangle in Figure 8. Such risk cannot be captured at design stage without an uncertainty analysis as conducted in this paper.

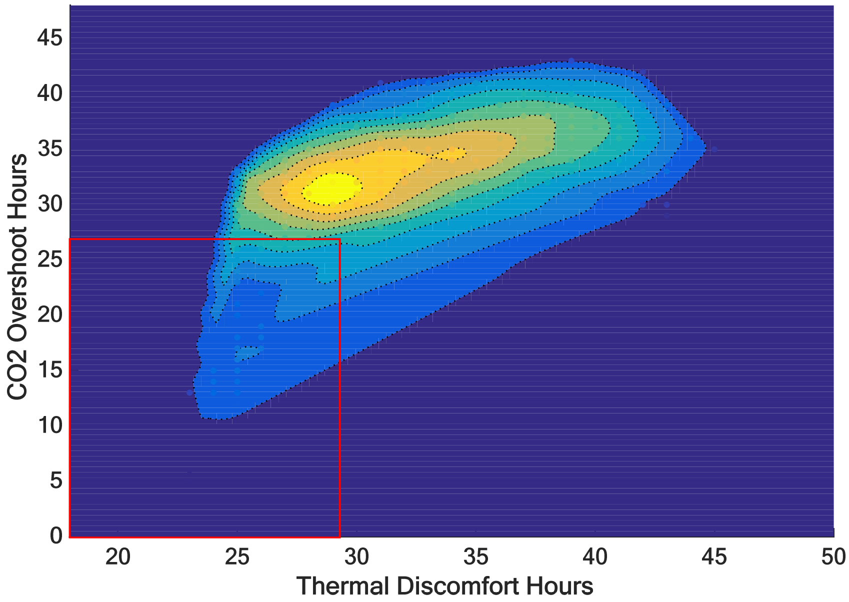

Figure 8 Two-dimensional contour plot of the thermal discomfort hours against CO_2 overshoot hours

An imminent step following the risk analysis is to identify influential parameters and mitigate the risk by controlling the uncertainty of them. In this case study, we perform a sensitivity analysis to find the sources of uncertainty that contribute most to the overall uncertainty of the outcome, that is, indoor air quality measured by CO_2 overshoot hours. Because of the high dimensionality of the model, the sensitivity analysis includes two steps: (i) parameter screening to remove insignificant parameters; (ii) computing the sensitivity measures of the remaining parameters based on a decomposition of the output variance (Y. Sun, Gu, Wu, & Augenbroe, 2014). We find that the uncertainty of envelope leakage accounts for 76% of the overall uncertainty of indoor air quality, which suggests that it may be necessary to invest in on-site inspections and ensuring the envelope air tightness meets the design intention at the construction stage. Whether further investments on a mechanical ventilation system is necessary warrants a second-round uncertainty analysis with reduced uncertainty on infiltration and more detailed information on occupant behavior.

CONCLUSION

We proposed a methodology for evaluating building performance under uncertainty that meets the need of innovative energy efficient building development in Turkey. It is found that energy saving design measures that push the envelope in energy performance in a Turkish campus building warrant an uncertainty analysis, which led to the following conclusions:

(1) The proposed method is able to predict the occurrence of extreme conditions inside buildings such as overheating and poor ventilation, while the conventional approach cannot. The explicitly quantified risk information will enable more informed decision making. It can also warn against too much confidence in deterministic predictions.

(2) A further analysis of the renewable energy system in the case building reveals that the predicted annual output of PV panels is relatively stable with minor variability, which suggests this type of PV investment in Istanbul is warranted. The same conclusion is true for the chosen shading devices. However, we find that relying completely on occupants opening windows for fresh air supply with fan coil units to maintain indoor temperature, leads to a substantial risk of insufficient fresh air supply for occupants and overheating. We show that a risk mitigation plan based on a variance based sensitivity analysis can put a sensible guarantee in place. The trade-off between investing in a mechanical ventilation system and the risk of poor indoor air quality certainly calls for a second-round uncertainty analysis to inform the decision maker.

NOMENCLATURE

R_{sh} = model shunt resistance [Ω]
I_L = module photocurrent
I_o = diode reverse saturation current
a = ideality factor
R_s = module series resistence [Ω]
I_D = diode current
I = output current
I_{sh} = shunt current
V = output voltage
G_T = incident radiation
T_c = module temperature [K]
η = module overall efficiency
ε_{model} = model discrepancy adjustment factor

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