# CLIMA 2016 - proceedings of the 12th REHVA World Congress

*volume 6*

Heiselberg, Per Kvols

*Publication date:*
2016

*Document Version*
Publisher's PDF, also known as Version of record

# Thermal Comfort in Residential Buildings by the Millions - Early Design Support from Stochastic Simulations


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**Abstract**

*In Danish building code and many design briefings, criteria regarding thermal comfort are defined for "critical" rooms in residential buildings. Identifying the critical room is both difficult and time-consuming for large, multistory buildings. To reduce costs and time, such requirement often causes other less critical rooms to be designed with the same constraints as the critical one. In this paper, we propose a method to overcome the difficulty of identifying critical rooms and exploit the design potential of other rooms. First we have defined a set of typical room variations present in most residential buildings. For each room variation, we perform 100.000 simulations while varying important design inputs such as window-floor-ratio, ventilation rates, glazing properties, and shading properties. Prior to this, the Morris method was used to identify and fixate insignificant inputs. A simulation engine based on the hourly version of ISO 13790 is used to calculate the number of hours with unacceptable operative temperature. As a result, the design team can assess a large number of room variations and input configurations by filtering millions of pre-calculated simulations accessible through a web service. An interactive parallel coordinate plot helps the design team to filter the many simulations. Such analysis reveals favorable input spans and assists the design team to quickly assess various design choices.*



***Keywords – probabilistic simulations; sensitivity analysis; interactive visualization.***


## 1. Introduction

The design and construction of low-energy buildings have received much attention in recent years. Though, emphasis on reducing energy demand has sometimes come at the expense of thermal comfort in residential buildings [1][2]. In temperate climates, passive strategies include large south-facing windows to increase solar gain and small north-facing windows to reduce heat loss. The former may lead to overheating during summer if shading and venting are insufficient. Prolonged periods with overheating arise when thermally heavy constructions, designed to keep the building cooled, cannot release the absorbed heat during nighttime due to a lack of ventilation. To address this issue of overheating, Danish building code requires documentation of thermal comfort in dwellings from July 2016 [3]. Since 2010, this requirement has been mandatory only for the voluntary low-energy class 2015. An idealized model based on ISO 13790 [4] was developed for code compliance [5]. Despite the simplicity of the model and the need to evaluate only the “critical room” this requirement becomes time-consuming and challenging in the design of multi-story buildings. We elaborate on this in the following.

Building design is an iterative, multi-collaborator process in which the design team seeks to optimize on many, conflicting objectives. When designing multi-story residential buildings, architects and building owners often want to maximize view and daylight under the constraints of thermal comfort, energy demand, and building costs. When considering thermal comfort, the notion of a “critical room” implies that other rooms are less exposed with a potential for larger windows. To demonstrate the extensive work load related to an iterative, optimizing design approach, we will look at number of possible critical rooms in two different buildings.

First, we consider a simple building with a high degree of repetition, straight lines, and a plain geometry. Fig. 1 shows a section of residential building with five floors. For this case, at least seven rooms may become “critical” due to different ventilation rates, floor areas, and window variations (note that loads and schedules are fixed due to regulations). If actions are needed to meet the requirements for the upper floors, the corresponding rooms on the lower floors with shadowing balconies must also be addressed. Additional degrees of freedom, such as variable *g*-values, ventilation rates, and window sizes, will complicate the design process even further. To highlight the challenge of optimizing on room level, we show a prestigious and complicated building project on Fig. 2. For this building the number of room variations exceeds 100. This is due to its skewed angles, terraced roofs, and irregular balconies, while *g*-values are allowed to vary on the individual facades. Finally, the total number, of rooms to evaluate, increases rapidly if we take into account the changing design proposals.

Fig. 1 Section of a multi-story residential building with rectangles indicating the possible “critical” rooms caused by different room geometries, ventilation rates, windows, and overhang. The room enclosed by a blue rectangle is used for the case study below (Illustration: AART architects).

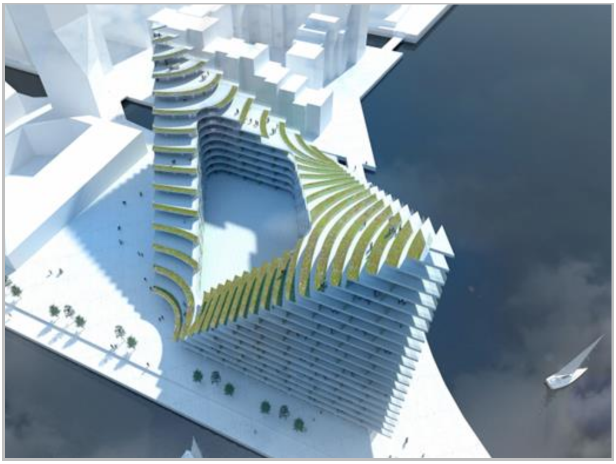

Fig. 2 Complex multi-story residential building with a trapezoidal floor plan and terraced roofs (Illustration: B.I.G architects).

In this paper, we propose a novel method in which millions of “pre-calculated” simulations provide guidance to decision-makers. Sensitivity analysis has been applied to reduce the design problem. In addition, interactive visualization facilitates “real-time” analysis with multiple stakeholders present. Hypothetically, the method helps to: a) reduce the number of design iterations, b) reduce modeling time, c) optimize on room level, and d) rapidly identify favorable input spans or actions needed to reach compliance.

The scenario described above involves various challenges related to building design: time-consuming modeling, optimization of multi-variate problems, and iterative, multi-actor decision-making. Covering these diverse topics is outside the scope of this paper. Though, this work is part of a PhD project evolving the challenges of decision-making in early building design and more information is available on *buildingdesign.moe.dk*. Here, we mention references that influenced this paper.

Attia et al. (2012) used the phrase “pre-design informative” when evaluating building performance simulation tools [6]. The logic behind is to be pro-active and to guide building design rather than evaluate individual design proposals. Stochastic modelling enables the design team to explore a large, global design space prior to decision-making. In this regard, sensitivity analysis helps identify inputs that matter the most. The application of sensitivity analysis in relation to building simulation is covered in depth by Tian [7] while the fundamental techniques are described in e.g. “Global Sensitivity Analysis: The Primer“ [8]. Since stochastic modeling often involves thousands of simulations, the results cannot be analyzed and visualized in the same way as the common comparison of a few deterministic simulations. One efficient approach is to adopt the interactive parallel coordinate plot which help narrow down the results and test different designs [9][10]. In the following, we propose to combine it all and put it to use.

## 2. Method

In this section, we describe the logic behind the proposed methodology of using millions of pre-calculated simulations to guide the early building design. First, we define a limited number of "typical" rooms that presumably will cover the vast majority of rooms in in multi-story residential buildings. The scope of the design problem is reduced further by applying sensitivity analysis to reduce the number design variables. Next, we suggest a sampling strategy to be used for the selected rooms and reduced set of variables. Finally, we present a way to analyze and visualize the millions of simulations.

### Defining Typical Rooms

For this work, we apply an idealized simulation model with few inputs which make it possible to define typical rooms and calculate (almost) all possible configurations for this model. The hourly-based model was developed by the Danish Building Research Institute to assess thermal comfort of the critical room in residential buildings [5]. The model, based on ISO 13790, evaluates the number of hours during the year in which the operative temperature exceeds 26 °C and 27 °C, respectively. Since the model is used for code compliance, some important inputs are kept fixed and cannot be changed. I.e. the combined internal loads from occupants and equipment are fixed at 5 W/m² gross floor area and the room is assumed in use all year. The room layout is defined only by floor area while solar gains depend on windows' sizes and orientation but not position and shape. Shading objects are described by the variables "horizon", "overhang", and "side fins" which are measured in degrees from windows' center points. Ventilation rates are defined from guidelines in Danish building code which only consider opening areas, opening type, and whether the room has single-sided ventilation or cross ventilation. Thus, the idealized model does not take into consideration wind pressure coefficients and thermal driving forces.

When using the idealized model for multi-story residential building, we postulate that four room types will cover the vast majority possibly critical rooms:

- Windows in one facade
- Windows in opposing facades
- Windows in two facades in a building corner
- Windows in one facade with shading side fin(s)

In the following, we consider the simplest case with windows in only one facade.

### Applying Sensitivity Analysis to Reduce the Design Problem

We wish to perform an exhaustive investigation of a global design space. First try to consider a model with 20 inputs – each discretized into 5 possible values. Evaluating all combinations would then require $5^{20} \sim 10^{14}$ simulations! Fortunately, for many models, each output is mainly driven by a few inputs, e.g. the 5 to 10 most sensitive inputs [11]. We will therefore fixate variables that have negligible influence on thermal comfort (overheating only). To identify the most important inputs, we perform sensitivity analysis using the extended Morris Method [12][13]. Thus, we sample distributions of the so-called elementary effects, EE's, from a global input space in

Table 1. Distributions for 15 inputs used in the evaluation of thermal comfort.

| | Parameter | Unit | Discrete values | | | | | Min. | Max. |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Orientation | - | W | SW | S | SE | E | | |
| 2 | *UA*, envelope | W/K (m²) | | | | | | 0.1 | 0.3 |
| 3 | *U*, windows | W/m² K | | | | | | 0.7 | 1.1 |
| 4 | Recess | % | | | | | | 0 | 15 |
| 5 | Ventilation, day | l/s m² | | | | | | 0.9 | 5 |
| 6 | Ventilation, night | l/s m² | | | | | | 0 | 3 |
| 7 | Ventilation, winter | l/s m² | | | | | | 0 | 3 |
| 8 | Glass-floor-ratio | % | | | | | | 10 | 40 |
| 9 | *g*-value | - | 0.23 | 0.3 | 0.35 | 0.42 | 0.5 | | |
| 10 | Heat capacity | Wh/K m² | 60 | 80 | 100 | 120 | 140 | | |
| 11 | $F_c$ (shading) | - | 0.2 | 0.4 | 0.6 | 0.8 | 1 | | |
| 12 | Overhang | ° | 0 | 20 | 40 | 60 | | | |
| 13 | Horizon | ° | 10 | 25 | 40 | | | | |
| 14 | Fins, left | ° | | | | | | 0 | 30 |
| 15 | Fins, right | ° | | | | | | 0 | 30 |

which each input is discretized into *p* levels. The distributions are created by following a number of trajectories, *r*, where only one factor is changed at-a-time. Finally, we obtain two sensitivity measures for each input. The mean of the absolute values of $EE_i$'s ($\mu*$) estimates the $i^{th}$ input's total influence on the output. The standard deviation ($\sigma$) of the $EE_i$'s is a measure of the interaction with other inputs or non-linear effects. To perform the sensitivity analysis, we first need to assign probability distributions for all inputs.

The probability distributions shown on table 1 reflect the possible variations of inputs that may produce a critical room. With aid from practitioners, limits have been defined for typical low-energy buildings.  For example, heat loss from building envelope, "*UA*, envelope", primarily depends on geometry and insulation. By comparing five low-energy, multi-story buildings, we estimated the variation of heat loss to vary between 0.1 to 0.3 W/K per square meter floor area.

Since the Morris analyses involve discretization into *p* levels, continuous uniform functions are preferable for the sensitivity analysis. In contrast, discrete uniform functions are used to create the final sets of "pre-calculated" simulations. For some variables, discrete values represent actual options better and they help the design team to the narrow the solutions. Repeated runs of the Morris analyses showed that a large number of trajectories were necessary before the ranking of the parameters' importance were consistent. This is due to the irregular, aggregated output "hours above 26 °C". For example, evaluation of a cold room with no heat loads will result in zero hours, which also is a possible result for a moderately warm room. To confirm this non-linear behavior, we applied multi-linear regression to 1.000 simulations using quasi-random

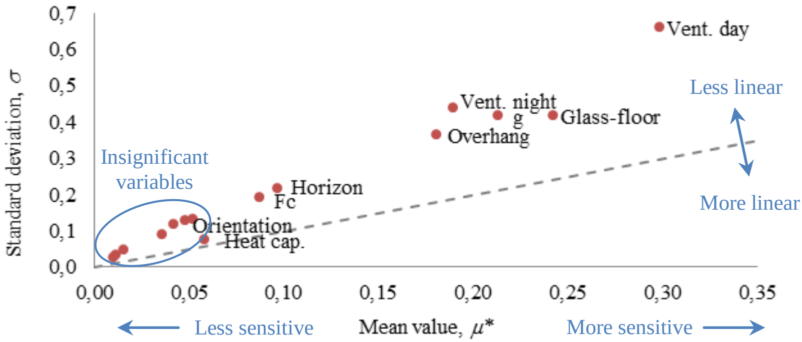


Fig. 3 Estimated means and standard deviations of the distributions of EE's in relation to the simulation output "h > 26 °C". Number of levels, $p$, is 8 and number of trajectories, $r$, is 500. The dashed line corresponds to standard-error-of-mean.

sampling (Sobol's $LP_\tau$). The resulting standardized regression coefficients had a very low coefficient of determination, $R^2 = 0.28$, which emphasizes the need for a sensitivity technique that can handle non-linearity and interaction effects. Fig. 3 shows a plot of the sensitivity measures, $\mu^*$ and $\sigma$, for $r = 500$ and $p = 8$. The most influential variables are the ventilation rates, glass-to-floor-ratio, $g$-value, and overhang. The encircled variables close to the origin have negligible influence. This includes the averaged heat loss, "*UA*, envelope", which means that the proposed method should be valid for any geometry of well-insulated, multi-story buildings. All of the insignificant variables will be kept fixed during the upcoming stochastic simulations.

## Sampling and Visualizing

The idea of simulating all design combinations requires discrete inputs and factorial sampling. Table 2 shows how the number of simulations increases when applying factorial sampling for an increasing number of discrete variables. The number of choices for each input can be interpreted as the "design resolution" for that input.

Alternative to factorial sampling, the modeler may apply low-discrepancy sequences such as Sobol's $LP_\tau$ sequences [14]. Such sampling allows for continuous distributions and produces the same factorial simulations if all inputs are discrete. The benefit of continuous distributions is that they are easier to visualize and interpret. For example, this applies to the parallel coordinate plot in which limits and line density becomes more apparent (see Fig. 4).

Table 2. Accumulated number of factorial samples when successively adding inputs.

| Rank | Parameter | Unit | Steps | Factorial sim. |
|---|---|---|---|---|
| 1 | Ventilation, day | *l/s m²* | 10 | 10 |
| 2 | Glass-floor-ratio | % | 10 | 100 |
| 3 | *g*-value | - | 5 | 500 |
| 4 | Ventilation, night | *l/s m²* | 10 | 5.000 |
| 5 | Overhang | ° | 4 | 20.000 |
| 6 | Horizon | ° | 3 | 60.000 |
| 7 | $F_c$ (shading) | - | 5 | 300.000 |
| 8 | Heat capacity | *Wh/K m²* | 5 | 1.500.000 |
| 9 | Orientation | - | 5 | 7.500.000 |

To visualize and explore the many simulations, we implement the interactive parallel coordinate plot shown on Fig. 4. Each line represents the input and output values of a single simulation. The design team may interactively apply filters to the output coordinates to remove simulations not meeting the requirements. Afterwards, the team may explore different designs by adding more filters to the varying inputs. A computational limit of the applied interactive plot is roughly 100.000. In order to manage millions of simulations, we separate the simulations such that “heat capacity” and “orientation” are chosen before rendering the plot. The logic behind this is that “heat capacity” is usually fixed for a given project whereas the “orientation” is fixed for a given room. By removing these, the total number factorial simulations in table 2 would be “only” 300.000 which are closer to the computational limit of the plot. The ordering of the remaining coordinates is made from a combination of the sensitivity indices and an intuitive work flow. To appreciate the strength of the interactive plot, the reader is encouraged to get a “hands-on experience” on *buildingdesign.moe.dk*.

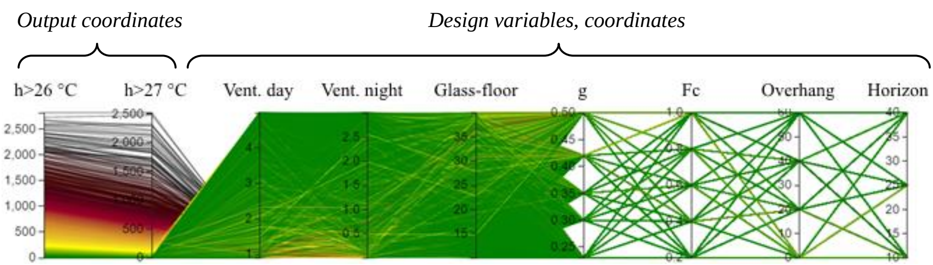


Fig. 4 Interactive parallel coordinate plot showing inputs and outputs for 100.000 simulations. Coloring is used to highlight simulations that meet the requirements (green), exceed the limits slightly (yellow), and exceed the limits extremely (red/brown).

## 3. Case study

To illustrate the use of the proposed method, we consider again the multi-story residential building shown on Fig. 1. The building has a rectangular shape with a floor area of 4.776 m² divided into five stories. The potentially "critical rooms" are located at the south-faced, elongated facade that has almost no shading obstructions. All of rooms may be represented by the four proposed room types within the limits described on table 2. The following examples are based on an 11 m² bedroom with openings in one wall (indicated by a blue rectangle on Fig. 1). The heat capacity is estimated to 100 Wh/K m² based on the combination of wooden floors, concrete ceiling, and exposed concrete in the facade. First, we demonstrate a "forward" approach suitable for the early design stage in which the design team seeks limits or wants to test different design paths. Secondly, we illustrate a "backward" approach showing how to find possible solutions for a design not meeting the requirements.

In the "forward" approach, we assume that the designer prioritize daylight and seeks a glass-floor-ratio of at least 25 % (corresponding to 2.75 m² glass and ~3.1 m² windows). The engineer estimates a maximum ventilation rate of 3 l/s m² and half of that during nights due to the risk of draught, noise, and burglary. As shown on Fig. 5 (top), we can now filter the simulations based on these constraints; the thermal requirements, and the fixed values (orientation, heat capacity, horizon, and overhang). Despite, these limitations more than 200 simulations still remain. These include full variability of either *g*-value or shading factor, $F_c$. A next step might be to set a lower limit of the *g*-value to 0.42 as a way to reduce heating demand. Consequently, the remaining simulations indicate an upper limit of 0.8 for the shading factor, $F_c$. In Fig. 5, histograms show that most remaining simulations are located near the lower limits of *g*-value and $F_c$.

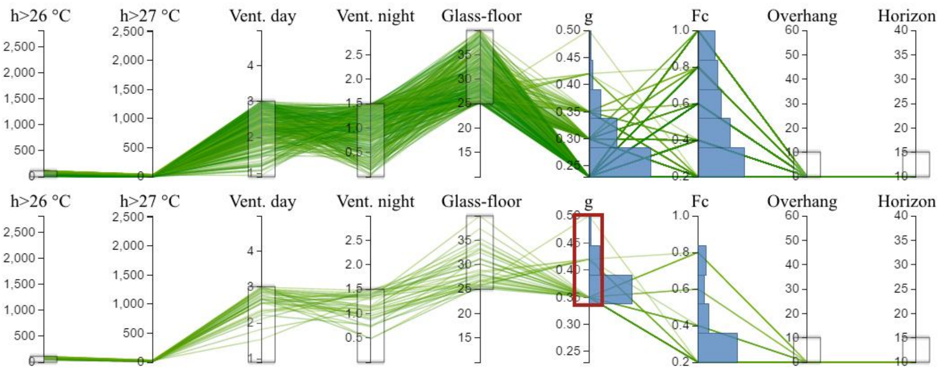


Fig. 5 Remaining simulations in the "forward" approach after successively applying filters using sliders (black rectangles). The red rectangle highlights a changed filter. Histograms show distributions of possible solutions for the non-fixed variables.

In the "backward" example, we assume that a design proposal is already given. First, an openable French door and fixed window correspond to a glass-to-floor ratio of

25.4 %. To reduce energy demand, the mechanical ventilation is turned off during summer. From these assumptions, the maximum value for the ventilation level is estimated to 1.1 l/s m². There is no shading and the *g*-value is preferable 0.5 in order to reduce heating demand and to match other rooms. As shown on Fig. 6 (top), this setup results in exceedance of the comfort criteria with 2.200 – 2.600 hours above 26 °C. To remedy this, we interactively adjust the filters to find limits for ventilation and solar shading that meet the thermal criteria. Fig. 6 (bottom) shows one feasible scenario in which the *g*-value is reduced and higher ventilation rates are achieved by making the window openable and by turning on mechanical ventilation.

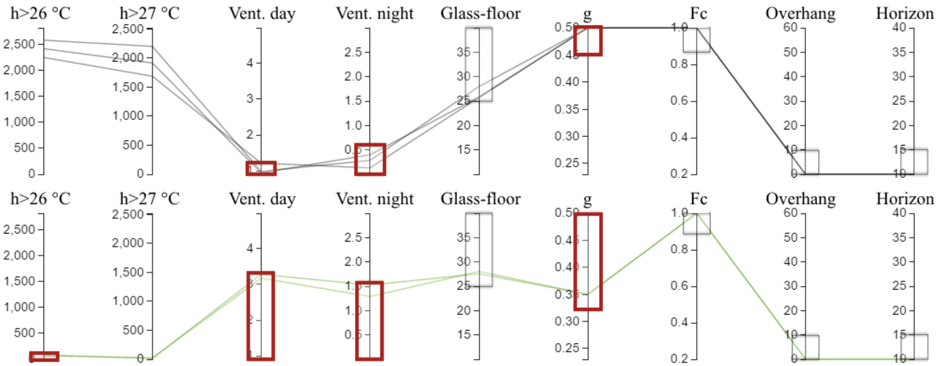


Fig. 6 Top: A few simulations corresponding to a design proposal not meeting the requirements. Bottom: Possible solutions when expanding the initial limits and constraining the output.

## 4. Discussion

The proposed method is not meant to document thermal comfort for the final critical room. Instead, it facilitates quick identification of approximate limits and helps test various design paths for multiple rooms. Feedback from practitioners will tell if the number of simulations and room variations are sufficient.

An exhaustive representation of the design space requires fewer simulations when using an idealized model with few inputs. Though, the method may be improved by using a detailed model that addresses energy, illuminance, glare, etc. The increased level of detail will require more inputs and thus more simulations are needed. In that case, sensitivity analysis can again be applied to reduce the number of variable inputs and to investigate the influence of varying room layouts, window positions, loads, and more.

## 5.Conclusion

A novel method was proposed to support building design in relation to thermal comfort in residential buildings. Initially, we performed sensitivity analysis, using the method of Morris, to identify the most influential inputs in an idealized model used for code compliance. This analysis helped reduce the number of design variables from roughly 15 to 7. While varying this reduced set of inputs, 100.000 simulations were performed for each combination of four typical room types, five orientations, and five discrete values of building heat capacity. An interactive parallel coordinate plot enabled rapid exploration of the vast amount of simulations. The large dataset and the interactive plot will make it possible to test many different designs during meetings between building owner, architects, and engineers. Presumably, this will reduce the number of time-consuming and costly design iterations. Moreover, the large dataset helps to quickly identify critical rooms and enable optimization of non-critical rooms.

A multi-story residential building was used to show the challenge of evaluating thermal comfort in the critical room and to demonstrate implementation of the proposed method. The method may be further improved by using sophisticated simulation software to quantitatively assess energy, daylight, and other performance objectives.

## Acknowledgements

Innovation Fund Denmark and MOE A/S provided funding. The work was part of an industrial doctorate program with Aalborg University and consultancy company MOE A/S.

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