Prediction of buildings' cooling energy demand: A comparison of simulation-based and prescriptive approaches

M Alhayek¹, A Wadi¹, U Pont¹ and A Mahdavi¹,∗

¹ Department of Building Physics and Building Ecology, TU Wien, Vienna, Austria
∗ amahdavi@tuwien.ac.at

Abstract. Detailed simulation of buildings' thermal performance can provide useful information for building designers and engineers. However, deployment of detailed simulation involves a number of challenges, including time and effort expenditures not accounted for in many typical building delivery processes. In this context, careful application of simplified methods may provide – at least for a specific class of applications – a reasonable alternative. The present contribution explores this possibility via a specific case study involving a large sample of residential buildings in Gaza, Palestine. This sample includes some fifty multi-unit apartment buildings representing the bulk of residential building stock in Gaza. These buildings were subjected to computational cooling energy demand assessment, whereby both numeric simulation and derivative simplified methods were applied. Numeric simulations were performed using EnergyPlus. For simplified calculations, a regression-based procedure was derived. Toward this end, a number of candidate independent variables (e.g., compactness, effective window-to-wall ratio, LEK value, mean effective U-value) were considered and the level of their association with the computed values of the designated building performance indicators was observed. The comparison of the results of the simplified and simulation-based methods revealed a reasonable level of agreement. In other words, the application of the simplified method provides in the majority of the cases performance indicator values that are close enough to the corresponding results of the simulation-based method. This implies that simplified methods and associated prescriptive procedures may provide an attractive alternative to highly detailed simulation studies in cases were the paucity of information and/or computational resources may represent a challenge (e.g., early design stages, insufficient preparedness of the professional community, contextual constraints).

1. Introduction

The global contribution to energy consumption and emission of GHG (Greenhouse gases) emissions by residential buildings is mentioned in multiple studies. For instance, the international Energy Agency (IEA) states that residential buildings are responsible for up to 25% of the global energy usage. Moreover, as 17% of the GHG emissions can be attributed to housing [1]. Lechtenböhmer et al. [2] suggest that up to 80% of the emissions caused by housing units could be avoided by rather simple measures, such as better insulation of the thermal envelope and intelligent operation schemes. Toward this end, instruments and methods to model and estimate the performance of buildings are of importance. Estimation of future energy demand of buildings is a complex task. This is – amongst others – due to the multitude of parameters that need to be considered, including building fabric, systems, occupants, and boundary conditions [3]. Within the last decades, industry and government initiatives have catalysed the design of energy efficient buildings via different measures, including Energy Building Codes (EBC), which stipulate certain performance thresholds for buildings in many countries of the world. Thereby, EBCs contain different methods to specify buildings' energy performance. The two most common methods are the performance-based approach and the prescriptive approach.

The performance-based approach targets a specific performance of a building, usually expressed in terms of one or several key performance indicators (KPI), which need to meet certain thresholds. For instance, the heating demand (or cooling demand) of a specific building could be such
an indicator. There is no prescribed way to achieve a certain performance. Rather, planners have the freedom of choice in optimizing buildings to reach the desired thresholds. To be able to predict the performance of buildings, state-of-the-art computational simulation tools are deployed, which enable experienced planners to get detailed information on a wide set of parameters and indicators. Heidarinejad structures the necessary input data for such whole-building simulation tools (e.g. TRNSYS, EnergyPlus) into 8 different categories (system variables, internal loads, internal load schedules, systems schedules, building geometry, real time weather data, thermal characteristics of building envelopes, and urban environment influence)[4]

The prescriptive approach follows a different concept. Thereby, it is assumed that if a building design meets certain target values of (semantic and/or geometric) design variables, a certain level of performance can be expected. For instance, if the average U-value of a building envelope is below a certain threshold value, it can be assumed that the heating demand also can be assumed to be under a threshold value for this performance indicator. Needless to say, the prescriptive approach does not allow the same depth of analysis of the performance of a building. However, there are other advantages associated with this approach: First, the approach can be utilized if the performance-based approach is not feasible due to effort, complexity, lack of knowledge or experience, or expenses. Moreover, stakeholders – even if not experienced utilization of simulation – can perform a rough assessment of their designs with respect to key performance data already in early design stages. If buildings are understood as matrices of parts and attributes, the main difference between traditional prescriptive and performance-based approaches can be explained as follows: In the prescriptive path, the building components are specified to have an explicit of attributes. In the performance-based approach, many combinations of different building parts can be explored to arrive at a desired level of performance. Figure 1 provides a schematic illustration of these approaches [5].

Most design briefs agreed upon between building owners/clients and designers are a combination of prescriptive and performance specifications. The more performance-oriented the specification is, the more freedom the designers have to provide alternative solutions. A lower-level specification is more prescriptive and constraining. But the higher the level of specification in terms of performance, the more challenging it is to find a universally acceptable method for the verification of performance [6]. The required information bridge between design variables that can be determined by architects and key performance indicators (such as those related to operative energy usage and cost), needs to be established based on scientific principles.

In this contribution, we illustrate the establishing of such an information bridge by utilizing a multiple regression model. We examined different explicative building design variables for a sample of buildings in the city of Gaza, Palestine. Thereby, the sample buildings were subjected to detailed simulation to determine their key performance indicators. At the same time, a structured set of design variables were examined in view of their correspondence with KPI values. Design variables with little or no impact on the KPIs were omitted, and further investigations via mathematical combination of design variables were conducted. The efforts resulted in a multiple regression model, which allows – with a certain degree of accuracy – to estimate KPIs based on the knowledge of the actual values of some design variables.
Needless to say, the regression model is limited in application to a specific type and location of buildings, namely residential buildings in the climate zone of Gaza Strip/Palestine. Nonetheless, it enables designers to simultaneously vary their building designs and directly gain early impressions of the resulting performance of different design options, without iteratively deploying numeric simulation. This contribution focusses on the cooling demand, which for buildings in Gaza is the predominant building energy usage effort. The primary research question of the study was as the degree to which a prescriptive approach can enable decision makers to evaluate the thermal performance of designs particularly in early design stages. Thereby, the research is the continuation of a number of previous research efforts, mostly conducted at our Department [7][8][9][10][11][12].

2. Methodology
Figure 2 highlights the principle workflow of the study in a flowchart. The study has been conducted for Gaza City in Palestine, which is characterized by a desert-influenced climate of high average temperatures and very little precipitation. Following the Köppen-Geiger definition the climate is of character (hot desert climate). Figure 3 illustrates the average outside air temperature distribution for Gaza City.

![General workflow](image_url)
A set of 50 typical multi-storey, multi-family buildings were selected to form a building sample corresponding to the most typical residential building type in Gaza city. Figure 4 illustrates the typical urban morphology of Gaza city, the density of the city, and the translation of the urban situation into a 3D model, later used for simulation purposes. Figure 5 illustrates an excerpt of the building database, including some of the building design variables. Energy Plus 8.8.0. [15] was used as the simulation engine to derive KPI values. For data input the OpenStudio SketchUp Plug-in 2.3.0 [16] was used. Regarding boundary conditions, a meteonorm-generated weather data file was utilized. Table 1 summarizes the most important input data settings as used in the simulation. A comprehensive illustration of all input variables as well as of all simulation efforts is documented in [17]. Along with other KPIs, the annual cooling energy demand was derived from simulation. A set of 10 design variables were selected for this investigation. These are described in Table 2.
Table 1. Summary of input data parameters for EnergyPlus.

| Input parameters                | Unit          | Value |
|---------------------------------|---------------|-------|
| Building envelope               |               |       |
| Exterior Wall U-value           | W.m².K⁻¹      | 1.784 |
| Roof U-value                    | W.m².K⁻¹      | 2.668 |
| Window U-value                  | W.m².K⁻¹      | 5.894 |
| Ground floor U-value            | W.m².K⁻¹      | 2.338 |
| Space loads and space conditions|               |       |
| Air-conditioning design temperature | °C           | 25    |
| Heating design temperature      | °C            | 20    |
| HVAC System                     |               |       |
| Infiltration rate               | h⁻¹           | 0.2   |
| Ventilation rate                | h⁻¹           | 0.4   |
| People                          | m² Person⁻¹   | 20    |
| Occupancy activity level        | W Person⁻¹    | 100   |
| Lighting load                   | W.m²          | 1.3   |
| Electric Equipment Load         | W.m²          | 3     |
| Shading                         |               |       |
| Thermal zoning                  |               |       |

Table 2. Design variables.

| Abbreviation | Description                                                                 | Calculation routine |
|--------------|-----------------------------------------------------------------------------|---------------------|
| SF           | Shape factor: Sum of building’s thermal envelope area (Σ Aᵢ) divided by its heated volume (Vₜ) | SF = Σ[Aᵢ / Vₜ] [m²] |
| lₙ           | Characteristic length: reciprocal value of SF.                             | lₙ = Vₜ / Σ[Aᵢ] [m] |
| R_c          | Relative Compactness: Relation of a shape factor in comparison to a cubic reference building (see [7][8]) | R_c = 6 x Vₜ³/₄ x Σ[Aᵢ] |
| WWR          | Window-to-Wall Ratio (Window area expressed as percentage of the gross wall area) | WWRₜ = Σ[Aᵢ x SEF] / Vₜ [%] |
| WWR₀         | WWR weighted for the orientation (different oriented window areas multiplied by a South-equivalent-factor (SEF)) | WWR₀ = Σ[Aᵢ x SEF] / Σ[Aᵢ] [%] |
| WWR₀⁺s       | WWR weighted for orientation and mounted fixed shading (different oriented window areas multiplied by a South-equivalent-factor (SEF) and a Fixed Shading coefficient (FSC)) | WWR₀⁺s = Σ[Aᵢ x SEF x FSC] / Σ[Aᵢ] [%] |
| WFR          | Window to Floor Area ratio (Window area expressed as percentage of the gross floor area) | WFR = Σ[Aᵢ] / Vₚ [m²] |
| C_t          | Thermal Compactness Cₜ: Similar to SF, however, the area of different components factored by a temperature correction factor | Cₜ = Σ[Vₚ x Aᵢ / Σ[Aᵢ x fₜ]] [m²] |
| Uₑ           | Effective Average Envelope U-Value (area-weighted and temperature-correction-factor weighted average U-Value) | Uₑ = Σ[Aᵢ x Uₜ x fₜ] / Σ[Aᵢ] |
| LEK          | Line of European K-values: Formula encompassing area-weighted average U-Value (Uₚ) and characteristic length lₙ | LEK = 300 x [Uₑ / (lₙ + lₙ)] |

To explore the computability of building performance based on design variable values, different statistical methods were deployed. Using (bivariate) correlation analysis, the strength of a relationship between two variables can be examined. In the present case, these two variables are the annual cooling demand, as derived from the simulation, and individual building design variables. Via regression analysis, the variation of a dependent variable (often denoted by y) caused by the variation of an explanatory variable (usually denoted by x) is examined. A multiple regression model was developed.
that allows to use a linear combination of different design variables to estimate the corresponding annual cooling demand without performing a full-fledge numeric simulation.

3. Results and discussion

Table 3 illustrates the correlation between the annual cooling demand and the examined building design variables. Based on the Pearson correlation coefficients and the significance of correlation at 5% and 1% significance levels, almost all variables showed a high degree of correlation with the total annual cooling demand (all variables except the relative compactness are significant at 0.01 level). Figure 6 and 7 illustrate the relations of Shape Factor (SF) and window to wall ratio to the cooling demand.

Table 3. Correlation between building design variables and total annual cooling demand.

|   | R   | R²  | Sig   |
|---|-----|-----|-------|
| 1 | SF  | 0.74** | 0.55  | 0.000 |
| 2 | lₚ | 0.72** | 0.51  | 0.000 |
| 3 | Rₚ | 0.29* | 0.08  | 0.045 |
| 4 | WWR | 0.54** | 0.29  | 0.000 |
| 5 | WWRₒ | 0.61** | 0.38  | 0.000 |
| 6 | WWRₒ+s | 0.66** | 0.44  | 0.000 |
| 7 | WFR | 0.75** | 0.56  | 0.000 |
| 8 | Cₜ | 0.75** | 0.56  | 0.000 |
| 9 | Uₑ | 0.45** | 0.21  | 0.001 |
| 10 | LEK | 0.79** | 0.63  | 0.000 |

** Correlation is significant at the 0.01 level (2-tailed).
* Correlation is significant at the 0.05 level (2-tailed).

Figure 6. Shape factor and total annual cooling demand.

Figure 7. Window to Wall area ratio weighted for orientation and fixed shading and total annual cooling demand.
Based on an extensive analysis of the correlations between design variables and the annual cooling demand, a multiple regression model was developed for prediction of the cooling demand (in form of an regression equation of type \( y = B_0 + B_1X_1 + B_2X_2 \)). As regression coefficients the Shape factor and the Window-to-Wall-ratio weighted for orientation and fixed shading were considered. Amongst the potential combinations of independent variable candidates, this selection displayed the best fit. The resulting equation was as follows:

\[
\text{Cooling Demand} (y) = 51.765 + 95.867SF + 2.244\text{WWR}_{O+S} \tag{1}
\]

The performance summary for this equation is provided in Table 4.

### Table 4. Performance summary of the developed multiple regression model.

| Model Summaryb |  |
|----------------|---|
| Model | R | R Square | Adjusted R Square | Std. Error of the Estimate |
| 1 | 0.90a | 0.80 | 0.80 | 9.5302 |

| a. Predictors: Constant, \( \text{WWR}_{O+S} \), SF |
| b. Dependent Variable: Cooling Demand |

### 4. Conclusion, limitations, and future research

In the present contribution, we presented an approach to estimate the total annual cooling demand for buildings in Gaza City, Palestine based on the values of selected building design variables. Thereby, it could be demonstrated that, for the presented sample of buildings, the derived multiple regression model can yield fairly reliable estimations of buildings' cooling demand, in that these model results were consistent with detailed simulation results. This facilitated the generation of a prescriptive index table based on values for the Shape factor and the Window-to-Wall-ratio (weighted by orientation and fixed shading device deployment). An excerpt of this index table can be seen in Figure 8. Needless to say, the present study entails a number of limitations, such as the limited scope of the index in terms of the examined building typology, climatic context, and urban situation. Nonetheless, such a table can be seen as a potentially useful instrument to support planners in early design stages, especially in those cases, where more detailed design support tools (such as simulation applications) cannot be deployed due to constraints pertaining to factors such as time, expenses, and expertise.

### Figure 8. Excerpt of the developed index table for energy performance regarding cooling demand based on SF and \( \text{WWR}_{O+S} \)

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