Overheating risk and cooling demand in residential buildings: performance prediction and improvement using a prescriptive approach

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Abstract. Depending on general climatic trends and specific (urban) microclimatic conditions, the reliable estimation of the overheating risk in buildings has become increasingly important. As such, detailed simulation of the related phenomena can provide useful information. However, deployment of detailed simulation involves a number of challenges, including time and effort expenditures not accounted for in typical building delivery processes. In this context, careful application of prescriptive 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 assessed via both numeric simulation and regression-based methods, assuming the latter can provide the basis for development and validation of a prescriptive approach. Toward this end, a number of independent variables were considered and the level of their association with the computed values of the designated building performance indicators was observed. Comparison of the regression-based and simulation-based methods revealed a reasonable level of agreement. This suggests that the proposed prescriptive method may provide an attractive alternative to highly detailed simulation.

1 Introduction

The contribution of buildings to both the total energy consumption and climate harming GHG (Green House Gas) emissions is well-known. Thus, there is a world-wide interest pertaining to adopt energy efficiency measures in the building sector. As such, measures need to be globally implemented to reach sustainability goals in the building sector via subsidy initiatives and performance threshold values stipulated by laws, standards and guidelines. Regulative instruments such as energy codes are considered to be one of the most effective policy mechanism, in their enforcement is secured [1].

In general two different approaches regarding the evaluation of energy efficiency of (yet to be built or yet to be refurbished) buildings can be distinguished:

The **performance-based approach** requires sophisticated calculation or simulation methods to derive key performance indicators (KPIs), whose bench-mark values are mandated. Such methods provide very comprehensive and detailed insight into the

performance of buildings and the tools are considered to be state-of-the-art. Moreover, via parametric modifications, the sensitivity of specific building designs regarding design changes or changing boundary conditions can be evaluated easily. However, the performance-based approach requires in-depth knowledge and experience in use of the tools. Furthermore, it typically requires large expenditure of effort, time and cost.

The **prescriptive approach** follows a different philosophy. Thereby, a combination of different geometric and semantic design variables is used to set up so called prescriptive variables/indicators. Different combinations of geometry and semantic data would lead to different performance indicator values. If this connection is known, it is possible to define threshold values for the prescriptive variables, so that planners can simply consider these thresholds to ensure a certain performance of their building design. It is obvious that such prescriptive indicators may not provide the same specificity and resolution as KPIs derived via the performance-based approach. Nonetheless, they could facilitate building quality benchmarking in case the performance-based approach cannot be deployed. Despite the fact that such codes may lead to missing opportunities to increase energy efficiency in some cases, they can still contribute to performance improvement of large building populations if they are based on comprehensive and systematic parametric simulation results and are reviewed by a panel of experts [2].

In this contribution, we illustrate the potential of the prescriptive approach pertaining to cooling demand and overheating tendency as possibility for increased building sustainability for the Gaza Strip (Palestine). Gaza Strip has very limited energy resources and is entirely dependent on importing such resources from neighbouring countries. It is thus essential to develop energy efficiency measures towards creating a more sustainable built environment. In such context, a prescriptive method can support efforts toward better building designs. Specifically, the goal of the efforts described in this contribution (see also [3] and [4]) is to create a prescriptive building index based on the regression analysis of numeric simulation results. The index can be used by architects and engineers during the early stages of the design process to account for energy efficiency in buildings. It will use simple characteristics of building envelope and can be easily derived from design plans.

Past research efforts pertaining to similar topics, and thus forming a base for the present study include – amongst others – Mahdavi and Gurtekin [5], Mahdavi and Pessenlehner [6][7], Markovic et al. [8], and Pont and Mahdavi [9].

2 Methodology

2.1 Objective

The main objective of this contribution is to deliver a proof of concept regarding the utilization of prescriptive indicators for design decisions pertaining to the cooling energy demand in the specific context of Gaza.

2.2 Building sample and thermal envelope quality.

A building sample of 50 typical residential buildings from the Gaza strip was generate. All of these buildings are multi-storey, multi-family buildings, but with variance in building design variables regarding buildings morphology, glazing area, and number of floors. An overview of the buildings and some of their characteristics and prescriptive indicators is provided at the end of this contribution (Figure 6). Table 1 provides an overview of the basic assumptions regarding the thermal quality of the buildings' envelopes.

Table 1. U-values and thermal properties of buildings' envelopes.

Building Element	Construction layers (Thickness [m]; thermal conductivity [$\text{W.m}^{-1}.\text{K}^{-1}$])	U-value [$\text{W.m}^{-2}.\text{K}^{-1}$]
External Roof (ribbed slab system)	Reinforced concrete (0.08; 2.3) Hollow block with reinf. concrete (0.17; 0.92) Plaster (0.025; 1.4)	2.668
External Wall (Hollow Block Wall)	Outside Plaster (0.025; 1.4) Block Wall (0.2; 0.56) Inside Plaster (0.025; 0.7)	1.784
Floor to ground	Tiles (0.05; 1.3) Sand with cement (0.1; 2) Reinforced concrete (0.08; 2.3) Hollow block with reinf. concrete (0.17; 0.92)	2.338
Interior Ceiling	Tiles (0.05; 1.3) Sand with cement (0.1; 2) Reinforced concrete (0.08; 2.3) Hollow block with reinf. concrete (0.17; 0.92)	1.462
Interior Wall	Outside Plaster (0.025; 1.4) Block Wall (0.1; 0.56) Inside Plaster (0.025; 0.7)	2.028
Ceiling to unheated	Reinforced concrete (0.08; 2.3) Hollow block with reinf. concrete (0.17; 0.92) Plaster (0.025; 1.4)	2.668
Wall to unheated	Outside Plaster (0.025; 1.4) Block Wall (0.2; 0.56) Inside Plaster (0.025; 0.7)	1.784
Windows (single glazing)	Clear glass (0.003; 0.9)	5.894
Doors	Wood (0.0254; 0.15)	6.68

2.3 Simulation input parameters and settings

EnergyPlus (Version 8.9 [10]) and OpenStudio [11] were used as simulation engine. Buildings were modelled in SketchUp [12]. Obtaining accurate weather data for the Gaza strip is difficult due to the unavailability of default weather files in most simulation tools for this location. Thus, Meteonorm [13] was used to generate a weather data file, based on surrounding weather stations' data and considering the specifics of the location (transition zone between coastal area wetlands and dry desert region). Table 2 illustrates the simulation settings used in the EnergyPlus simulations. Figures 1 and 2 illustrate assumptions regarding urban embedment and shading obstructions for the simulations of the sample buildings.

Table 2. Simulation settings / Boundary conditions

Input parameters	Unit	Value
Air-conditioning design temperature	$^{\circ}\text{C}$	25
Heating design temperature	$^{\circ}\text{C}$	20
HVAC System	Default Ideal loads air systems	
Infiltration rate	h^{-1}	0.2
Ventilation rate	h^{-1}	0.4
People	$\text{m}^2.\text{Person}^{-1}$	20
Occupancy activity level	$\text{W}.\text{Person}^{-1}$	100
Lighting load	$\text{W}.\text{m}^{-2}$	1.3
Electric Equipment Load	$\text{W}.\text{m}^{-2}$	3
Shading	Horizontal overhang for Windows (Balconies)	
Thermal zoning	One floor zoning

Fig. 1 (left) and Fig. 2 (right). Isometry and Plan view of the outside obstructions / shading settings as assumed for the sample buildings.

2.4 Prescriptive building variables.

Table 3 illustrates the examined prescriptive building variables (prescriptive indicators). Note that in Figure 6 some of the variables are illustrated for each of the sample buildings. Some of the indicators consider very simple planning parameters (e.g. volume, conditioned floor area), while others integrate even orientation (e.g. effective Window to Wall ratio). A detailed description of each of the variables and associated derivation methods from architectural plans can be found in [3].

Table 3. Building Design variables

Abbreviation	Description
Physical properties	
V	Conditioned volume [m ³]
A _{cn}	Conditioned floor area [m ²]
A	Thermal building envelope area [m ²]
A _w	Window area [m ²]
A _{wall}	Area of wall [m ²]
Form factors	
C	Compactness (surface area to volume ratio) [m ⁻¹]
RC	Relative compactness
l _c	Characteristic length
Properties of transparent elements of building envelope	
WWR	Window to wall ratio [%]
WWR _{os}	Effective window to wall ratio [%]
WFR	Window to floor ratio [%]
Thermal properties	
U _e	Effective average envelope U-value [W.m ⁻² .K ⁻¹]
C _t	Thermal compactness [m]
LEK	LEK Value
A _e	Effective envelope area [m ²]

3 Results

Figure 3 shows the simulated overheating index (see [6]) for all sample buildings (in average 12138 Kh.a⁻¹). It is evident that these buildings have severe overheating issues.

Fig. 3. Overheating indices for all 50 sample building, (indicator based on [6]).

The relationship of the different design variables with the overheating tendency was explored via linear regression. Thereby, the different candidate prescriptive variables displayed R² values between 0.1426 and 0.5561. The highest R² could be found in the regression analysis of the derived overheating hours indicator and the Windows to Floor ratio (WFR) as per Figure 4.

Fig. 4. Overheating indicator values vs. Window to Floor ratio (WFR)

Subsequently, combinations of different prescriptive indicators were explored toward a better fit to the overheating indicators. One rather good fit was found in a combination of the shape factor (SF) and the effective Window to Wall ratio (WWR_{OS}). Equation (1) illustrates the resulting regression equation. Figure 5 illustrates the performance of the derived equation in comparison to the results obtained from the simulation.

$$Y' = 6450.359 + 6779.444X_1 + 178.476X_2$$

(1)

Y'... predicted value (overheating index)
X₁... Shape Factor
X₂... effective Window to Wall ratio

Fig. 5. Simulated versus regression-based overheating index

4 Conclusions and Future Research

The present contribution explored the potential of regression-based processing of simulation results to provide a basis for the derivation of simple prescriptive methods for benchmarking buildings' thermal quality. Specifically, the relationship of easy-to-derive building design variables (such as shape factor or window-to-wall ratio) with key performance indicators (such as overheating index) was studied, focusing on the densely built context of Gaza. Prescription of bench-mark values for such design variables is expected to warrant a certain overall quality assurance for the general building population. This approach is not meant to replace detailed simulation tools, which should be of course deployed whenever possible. Needless to say, that the underlying simulation results must be ultimately validated through comparison with the actual energy use data, even if the latter is difficult to come by due technical and procedural challenges. Moreover, the present results consider a rather specific climatic context. It might be beneficial to consider additional variables that would account for the variance of the contextual circumstances, including microclimatic conditions. Further limitations of the study pertain to its focus on residential buildings only.

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<div>Building sample and derived values of a number of candidate variables to be implemented in a prescriptive building quality assurance approach</div>	Building Characteristic		Unit
	Shape factor (SF)		[m ⁻²]		B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12	B13	B14	B15
	Characteristic Length (lc)		[m]		1.66	1.81	2.93	2.14	2.51	1.98	2.1	2.44	1.67	2.09	1.36	1.77	2.46	2.18	2.26
	Relative compactness (Rc)		[%]		0.87	0.83	0.63	0.77	0.92	0.86	0.83	0.89	0.91	0.95	0.88	0.91	0.8	0.77	0.79
	Window to Wall ratio WWR		[%]		11.28	15.55	16.69	13.08	12.48	19.13	25.61	11.77	11.76	13.21	18.45	15.15	13.07	12.13	17.21
	WWRto south equivalent		[%]		8.39	12.54	13.5	11.67	10.1	14.83	21.96	8.12	6	9.97	10.76	8.82	8.47	7.1	10.27
	WWRto south equivalent weighted for shading		[%]		8.39	12.41	12.66	10.05	9.26	13.06	21.96	8.12	6	9.97	10.76	8.82	8.47	7.1	10.27
	Window to Floor Ratio WFR		[%]		12.14	13.76	8.15	8.51	10.67	18.31	20.73	10.39	11.51	11.16	20.01	13.18	7.54	8.19	6.33
	Thermal Compactness Ct		[m]		0.46	0.49	0.3	0.41	0.35	0.45	0.44	0.36	0.51	0.42	0.63	0.48	0.35	0.39	0.39
	Effective Envelope U value		[W m ⁻² K ⁻¹]		1.69	1.85	1.8	1.79	1.78	1.9	1.94	1.62	1.83	1.76	1.62	1.87	1.81	1.73	1.79
	LEK value		-		152.03	163.13	124.16	146.52	132.68	169.38	152.52	141.45	175.24	147.06	187.23	173.48	138.14	144.26	142.24
	Building Characteristic		Unit
	Shape factor (SF)		[m ⁻²]		B16	B17	B18	B19	B20	B21	B22	B23	B24	B25	B26	B27	B28	B29	B30
	Characteristic Length (lc)		[m]		0.92	0.24	0.55	0.48	0.62	0.45	0.88	0.72	0.21	0.68	0.67	0.82	0.21	0.45	0.58
	Relative compactness (Rc)		[%]		2.39	2.95	1.8	2.1	1.6	2.24	1.13	1.36	3.19	1.48	1.5	1.22	1.42	2.24	1.73
	Window to Wall ratio WWR		[%]		9.89	16.53	21.82	25.06	22.89	27.92	18.27	11.77	23.53	17.92	19.41	19.03	20.66	12.45	16.62
	WWRto south equivalent		[%]		8.75	14.45	15.81	20.14	19.1	17.82	12.82	9.65	18.93	9.36	12.68	11.14	13.47	11.36	9.26
	WWRto south equivalent weighted for shading		[%]		8.75	12.33	13.27	20.14	19.1	17.82	12.82	8.12	17.55	9.36	12.68	11.14	13.47	10.81	8.96
	Window to Floor Ratio WFR		[%]		6.66	7.91	19.92	19.36	25.54	15.48	6.68	16.38	10.26	15.78	12.57	23.73	18.72	9.6	12.4
	Thermal Compactness Ct		[m]		0.36	0.3	0.47	0.42	0.54	0.38	0.73	0.59	0.24	0.59	0.57	0.74	0.61	0.38	0.49
	Effective Envelope U value		[W m ⁻² K ⁻¹]		1.76	1.8	1.74	1.77	1.74	1.79	1.96	1.73	1.64	1.96	1.84	1.89	1.85	1.76	1.81
	LEK value		-		137.43	121.54	158.42	146.09	166.69	146.01	235.13	188.65	119.22	182.15	187.4	194.19	186.76	143.81	171.11
<div>Building sample and derived values of a number of candidate variables to be implemented in a prescriptive building quality assurance approach</div>	Building Characteristic		Unit
	Shape factor (SF)		[m ⁻²]		B31	B32	B33	B34	B35	B36	B37	B38	B39	B40	B41	B42	B43	B44	B45
	Characteristic Length (lc)		[m]		0.4	0.34	0.72	1.38	1.75	2.13	2.61	2.08	1.34	2.02	1.44	2.64	2.73	1.59	2
	Relative compactness (Rc)		[%]		2.52	2.93	0.57	0.63	0.81	0.7	0.63	0.61	0.79	0.61	0.78	0.68	0.72	0.79	0.8
	Window to Wall ratio WWR		[%]		12.62	12.24	7.47	11.81	17.9	13.11	8.56	12.92	6.36	17.09	15.66	11.12	16.82	8.52	14
	WWRto south equivalent		[%]		7.44	7.62	5.65	8.63	14	8.55	6.68	12.2	6.5	14	12.47	8.57	13.46	6.99	11.09
	WWRto south equivalent weighted for shading		[%]		7.33	6.24	5.65	7.84	12.95	8.3	6.68	12.02	5.67	12.76	12.47	6.54	12.31	6.48	11.09
	Window to Floor Ratio WFR		[%]		7.74	8.29	4.7	13.1	10.2	10.88	4.81	12.96	12.06	11.72	15	5.98	8.27	10.1	14.51
	Thermal Compactness Ct		[m]		0.34	0.29	0.62	0.51	0.3	0.4	0.31	0.42	0.65	0.41	0.36	0.33	0.32	0.55	0.43
	Effective Envelope U value		[W m ⁻² K ⁻¹]		1.85	1.84	1.9	1.77	1.68	1.77	1.82	1.8	1.76	1.68	1.78	1.85	1.78	1.75	1.77
	LEK value		-		143.17	130.47	211.36	172.68	140.38	150.46	143.7	152.66	180.16	149.32	190.33	139.95	133.88	167.35	147.51
	Building Characteristic		Unit
	Shape factor (SF)		[m ⁻²]		B46	B47	B48	B49	B50										
	Characteristic Length (lc)		[m]		0.52	0.54	0.53	0.55	0.71										
	Relative compactness (Rc)		[%]		1.94	1.84	1.88	1.81	1.4										
	Window to Wall ratio WWR		[%]		0.73	0.78	0.57	0.8	0.96										
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	Thermal Compactness Ct		[m]		18.05	8.21	10.39	12.08	20.38										
	Effective Envelope U value		[W m ⁻² K ⁻¹]		0.45	0.44	0.46	0.49	0.35										
	LEK value		-		152.81	171.85	161.82	161.96	184.58										

Fig. 6. Building sample and derived values of a number of candidate variables to be implemented in a prescriptive building quality assurance approach