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A computational workflow to analyze simplified metrics of environmental building performance in a northern climate

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Abstract. The research presented expands the knowledge on the use of simplified metrics for environmental building performance analysis, addressing recent urban neighborhoods in the northern climate of Tallinn, Estonia. It also introduces a computational workflow performing building data acquisition, geometry preparation, calculations, simulations and results collection through automation. Several metrics present a strong correlation. For instance, the area-to-perimeter ratio and sky exposure factor when correlated with energy use have R^2 values of 0.96 and 0.90, respectively. Thus, they can be used to compare schematic design solutions instead of laborious simulations, enabling designers to improve the sustainability of buildings and cities. Detailed results, a new metric and their reciprocal influence are presented and discussed.

1. Introduction

The scientific and design communities agree that improving the sustainability of the built environment is a key factor for tackling the global challenges of resource depletion, climate change and human health. Thus, architects and planners are urged to consider environmental aspects in the design of buildings and cities. For the task, standards, guidelines, metrics, and environmental design tools have been developed. However, several difficulties remain unaddressed, notably acquiring urban data, as well as performing energy and environmental simulations that require long computation times and expert knowledge, particularly in the context of neighborhood and district-scale design [1].

Nowadays, building and urban energy modeling can leverage GIS datasets that include building geometry at various level of detail (LOD), floor areas, construction year, functions, materials, and energy use [2]. Digital data of building shape with LOD2 and construction year acquired from the Estonian Building Register (EBR) was used to automatically generate building models of a residential district in Tallinn, Estonia, and to transform them into LOD3 (windows and balconies) through typology-based archetypes, to analyze the influence of model detail on façade solar irradiation [3].

A large body of research analyzed the correlation of building and urban form with solar irradiation and energy use, and developed simplified metrics used to analyze urban-scale design solutions instead of simulations. The ratio of (passive) floor area within 6m of the façade to the total area (PZR) has proven to be a reliable indicator of energy use in urban environments [4]. Using six urban visions and 768 parametric variations of a masterplan in Switzerland, a study found that metrics such as surface-to-volume (SV) and window-to-floor ratio (WFR) strongly correlate with heating and daylighting, except in dense environments, and that solar irradiation per floor area strongly correlates with energy generation through photovoltaics (PV) [5]. The correlation between urban form descriptors, mean

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global irradiance, and sky view factor (SVF) of urban surfaces was analyzed in 24 areas of London. The study found that density has a strong and weak negative correlation with façade and ground irradiance, respectively, while SVF is mainly affected by building distance [6]. Using 30 urban blocks in Singapore it was found that density metrics such as site coverage, open space ratio and roof-to-floor area have a strong correlation with cooling loads, and that sky exposure factor (SEF) and SVF are indicators of PV electricity generation [7]. Using 1944 parametrically generated block variations in Tel Aviv, a study showed that geometry metrics present a weak correlation with energy use intensity (EUI), while solar exposure indices have a strong correlation with PV generation and load match [8]. A large number of parametric variations based on three typical neighborhood typologies in Sweden showed that geometry metrics can be used for solar and daylight evaluation due a to strong correlation, but not for single day sunlight requirements [9]. Using real urban fabrics of Athens, London and Helsinki, and the annual, January and July sky models, researchers found that urban density and façade SVF have a strong negative and positive correlation, respectively, with global irradiance [10].

Building on the existing research, we analyzed the correlation between building form and urban density metrics, solar irradiation metrics and energy use in Tallinn, Estonia. The novelty of the work is threefold. Firstly, we used recent residential developments, whereas existing studies were based either on consolidated urban fabrics or on parametric variations of ideal typologies. Thus, our work will provide actionable knowledge for architects to use in the design of future neighborhoods. Secondly, such metrics have not been yet analyzed in the local climate. Thirdly, we propose a new metric, we compare floor area non- and normalized metrics, and we analyze the reciprocal influence of metrics.

2. Methods

To conduct the research, we developed a parametric design workflow through Grasshopper (GH) for Rhinoceros that uses digital cadaster data to automate building cluster generation, form and density calculations, solar irradiation and energy use simulations, and data export for statistical analysis. We selected 28 residential developments with 3 to 57 buildings realized in Tallinn (59.4°N, 24.7°E) since the year 2000, representing the current building forms, sizes and neighborhood patterns.

2.1. Building data acquisition, clustering and geometry preparation

The geometry of the development buildings is imported from EBR where they are available as Mesh objects with LOD2. Then, the parametric workflow performs four main operations. Due to the requirement for simple volumes in simulations, the algorithm transforms the building geometry into LOD1 by rounding the building height to a multiple of 3m (floor-to-floor height), selecting the footprint, and extruding it to obtain a polysurface. Then, due to wideness and heterogeneity of several developments, the buildings are clustered using the Gaussian Mixture model to capture urban metrics for more homogeneous areas, obtaining 60 clusters with 3 to 15 buildings, and instead of the cadastral parcels, bounding plots offsetting the half of the mean buildings distance are generated (figure 1a, 1b).

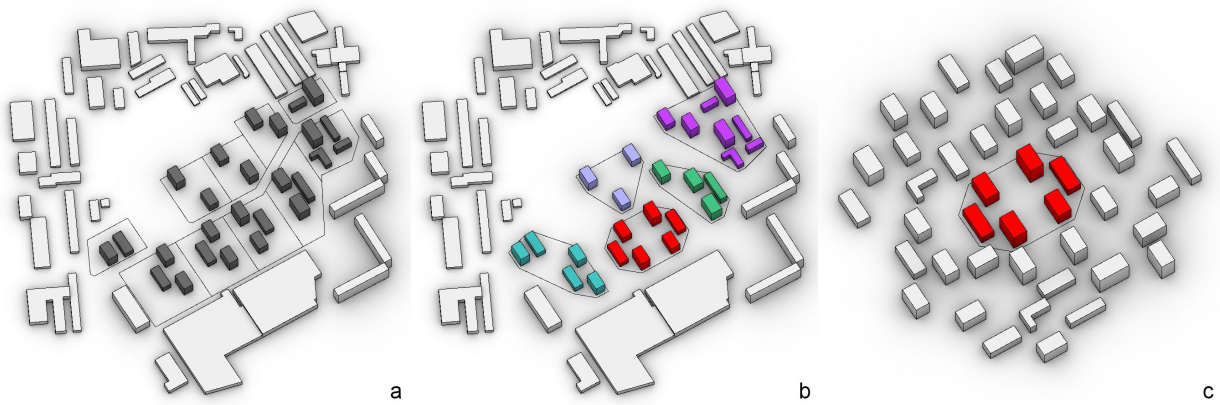


Figure 1. a) Residential development. b) Clustering. c) Realization of the homogeneous environment.

Consequently, to eliminate the bias caused by different existing surrounding environments the cluster buildings are located in a homogeneous environment [11]. Thus, the algorithm automatically populates the surrounding area with the same development building volumes and using the same cluster density (figure 1c). Finally, the algorithm generates the building surfaces for form and density calculations and solar irradiation simulations, as well as the floors and thermal zones for energy simulations.

2.2. Form, density, and solar metrics

For the research we selected metrics from literature and proposed a new one. Additionally, we analyzed new correlations and examined the impact of using floor area normalization for sky (density) and solar metrics. The metrics are of three types: building form; urban density; and solar irradiation (table 1). We analyzed their correlation with EUI, i.e., the sum of electric lighting, heating, and cooling, using the coefficient of determination (R^2). For the task, the algorithm calculates form and density metrics using GH components. Sky metrics are computed with Ladybug Tools for GH, applying the Tregenza 145-patch sky subdivision and a 3m resolution grid for both façades and plot. In parallel, the algorithm performs solar irradiation simulations with the Radiance-based ClimateStudio (CS) tool for GH, using an urban surface reflectance (R) of 35% and the same grid size.

Table 1. Metrics. (fa) = Floor area non- and normalized metrics. Normalized = Average metric value × façade area / floor area). Area and volume = Cluster total.

Type	Name	Calculation (in consideration of all the buildings)	Abb.	Ref.
Form	Surface-to-volume ratio	Building floor area / Volume (m^2/m^3)	SVR	[5,8]
	Area-to-perimeter ratio	Average floor area / Average floor perimeter (m^2/m)	APR	[7]
	Passive zone ratio	Floor area 6m from façade / Floor area (m^2/m^2)	PZR	[5]
	Glazing ratio	Window area / Floor area (m^2/m^2)	GR	[5]
Density	Plot ratio	Building footprint area / Whole plot area (m^2/m^2)	PR	[6–8]
	Floor-to-area ratio	Building floor area / Whole plot area (m^2/m^2)	FAR	[5,6]
	Surface-to-area ratio	Building envelope area / Whole plot area (m^2/m^2)	SAR	[9]
	Open space ratio	Outdoor plot area / Building floor area (m^2/m^2)	OSR	[7,9]
	Sky view factor	Average outdoor plot whole sky / Visible sky (%)	SVF	[6,8,10]
	Volumetric sky view factor	SVF × whole plot area / Building floor area (-)	VSVF	New
	Sky exposure factor (fa)	Average façade whole sky / Visible sky (%)	SEF	[7,8]
Solar	Solar irradiation façade (fa)	Average façade solar irradiation (kWh/m^2y)	SIF	[5,8]
	Solar irr. facade and roof (fa)	Average façade and roof solar irradiation (kWh/m^2)	SIFR	[5,7]

2.3. Thermal model

In the last step of the workflow, the algorithm divides the floors in core and perimeter zones with 6m width, creates glazing with 50% window-to-wall ratio (WWR) that reflects construction trends, and performs electric lighting, heating and cooling energy use simulations through EnergyPlus in CS. The thermal and envelope parameters of local best practice and recommendations of the Estonian energy regulation [12] were used. The core envelope parameters are the same as the perimeter zone (table 2).

Table 2. Parameters. U_{tot} = Total thermal transmittance. WOA = Window operable area. ACH = Air change per hour. SHGC = Solar heat gain coefficient. OLS = Occupancy Equipment Lighting. (x) = Core parameter. (-) = No parameter. (=) = Same parameter as perimeter zone.

Thermal zone parameters				Envelope parameters
People density	0.035(0.006) p/m^2	Heat Cool. setp.	21 27(18 -) °C	External wall U_{tot} 0.16 W/m^2K
Equipment den.	3(0.5) W/m^2	Mech. ventilation	14.15(2.5) L/s/p	Int. wall-Slab U_{tot} 0.44-0.14 W/m^2K
Light. pow. den.	8(2) W/m^2	Natural ventilation	0.1(-) WOA	Roof-Ground U_{tot} 0.11-0.14 W/m^2K
Ill. threshold	300(=) Lux	Infiltration	0.1(=) ACH	Window U_{tot} 0.84 W/m^2K, T_{vis} 0.71
OLS schedule 23-6 1, 7-9 0.5, 10-13 0.1, 14-16 0.2, 17-19 0.5, 20-22 0.8				Window SHGC 0.6

3. Results and discussion

Here we present the correlation of the form, density and solar metrics with EUI (kWh/m^{2}y), i.e., the sum of electric lighting, heating and cooling, and between density and solar metrics (figure 2). We also analyze correlation variation due to the mutual influence of metrics. Before the analysis, outliers have been eliminated using the interquartile range method to account for possible faulty simulations. We use the term "correlation" to refer to a direct correlation, while any inverse one is stated explicitly.

3.1. Correlation analysis

The results show a fairly strong correlation of SVR with EUI (R^2 = 0.63) (figure 2a), adding new evidence to previous studies conducted in different climates showing a strong correlation [5] or no correlation [8]. The correlation is less strong than expected in a cold climate due to the low thermal transmittance used for walls and roofs. APR has a very strong inverse correlation with EUI (R^2 = 0.96) which makes it a reliable energy use indicator. This is because APR reflects building slenderness, which increases energy use, and emphasizes glazing that has a higher transmittance than walls and allows solar gains. In fact, studies conducted at low latitudes showed a strong but smaller correlation of APR with EUI [7]. PZR has a strong correlation with EUI (R^2 = 0.83), matching previous studies [5]. This finding indicates a greater impact of the WWR used on increasing cooling than decreasing heating, as also shown by the fairly strong correlation of GR with EUI (R^2 = 0.67) (figure 2b).

PR presents a low inverse correlation (R^2 = 0.14) with EUI, due to not accounting for built volume. In contrast, FAR, which takes into account total floor area, has higher, though still moderate inverse correlation (R^2 = 0.47). Unlike at low latitudes, where the shading effect of density is more beneficial [5], FAR is a moderate indicator of energy use (figure 2c). SAR has a low inverse correlation (R^2 = 0.16) with EUI, whereas OSR has a moderate correlation (R^2 = 0.46) (figure 2d), smaller than at subtropical latitudes [7], due to a smaller cooling need. The ground SVF presents a low correlation with EUI (R^2 = 0.20), because these buildings are heating-dominated, but also have significant cooling demand. This contrasts studies in hot climates, where similar correlation was observed but opposite [8]. The new metric VSVF presents a higher though still moderate correlation (R^2 = 0.49), highlighting

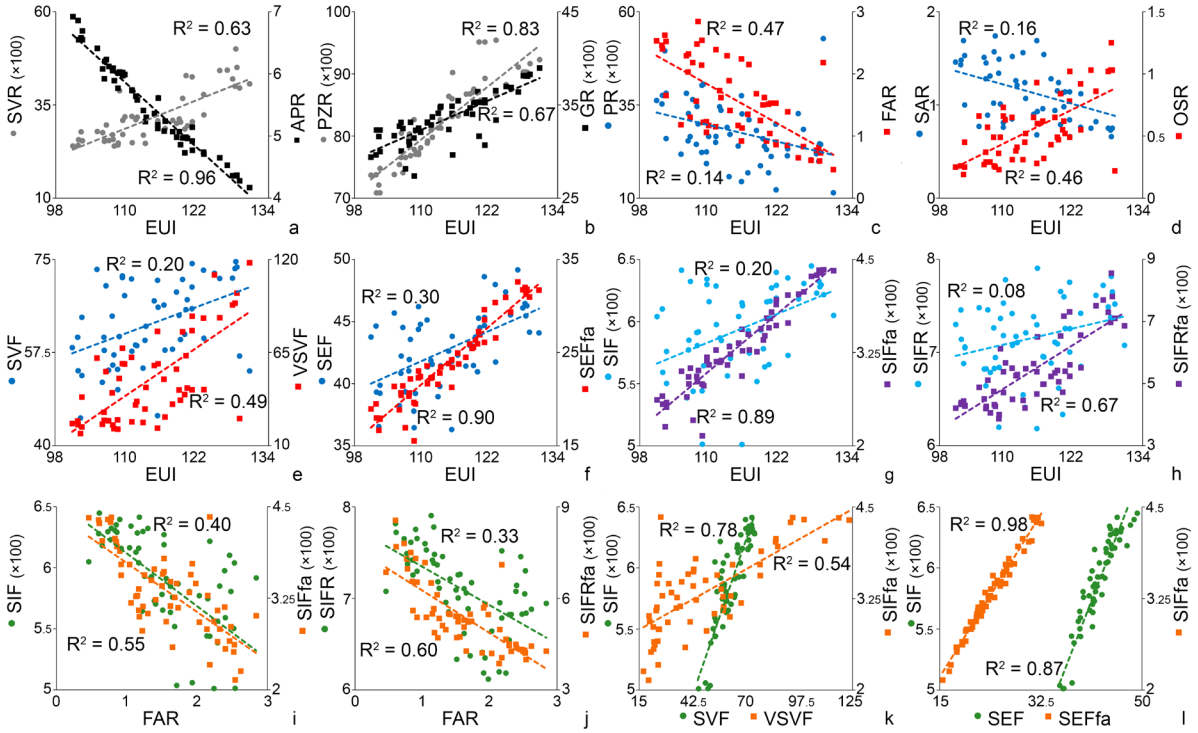


Figure 2. Plots of the metrics correlation.

the importance of considering the building volume in the ground sky-based density metric (figure 2e). The façade SEF has a higher correlation with EUI ($R^2 = 0.30$) than SVF due to a direct relation with the building through its facade, though still low due to not considering the building volume. The importance of considering the building volume is evidenced by the very strong correlation of the floor area-normalized SEFfa with EUI ($R^2 = 0.90$), which is a reliable indicator of energy use (figure 2f).

Accordingly, the results show a strong correlation of the floor area-normalized façade solar irradiation (SIFfa) with EUI ($R^2 = 0.89$), comparing the low correlation of the average solar irradiation per unit of façade area SIF ($R^2 = 0.20$) with energy use (figure 2g). This reinforces existing studies that proved the strong correlation of SIFfa with heating energy use [5], and PV energy generation [5,8]. When façade and roof solar irradiation is considered, both SIFR and SIFRfa present a lower correlation with EUI, i.e., $R^2 = 0.08$ and 0.67, respectively, compared to SIF and SIFfa, because the façade plays a major role in heat transfer and solar gains through glazing (figure 2h). Also in this case the results underline the higher correlation of floor area-normalized metrics with building energy use.

Density and solar irradiation metrics correlate in different ways. FAR presents a moderate-low inverse correlation with SIF ($R^2 = 0.40$) and SIFR ($R^2 = 0.33$), and a stronger inverse correlation with SIFfa ($R^2 = 0.55$) and SIFRfa ($R^2 = 0.60$) (figure i, j). The correlation is in line with studies conducted in urban areas with similar densities [9], but is lower than findings in high density urban areas [6], denoting a complex interrelation of metrics, climate and the built environment. SVF is a good predictor of solar irradiation per unit of façade area (SIF) ($R^2 = 0.78$), as proved also by previous research [9], whereas the correlation is moderate taking into account the built volume analyzing the new metric VSVF and SIFfa ($R^2 = 0.54$) (figure 2k). Results show a strong correlation of SEF with SIF ($R^2 = 0.87$), and an almost linear correlation of SEFfa with SIFfa ($R^2 = 0.98$), confirming research at similar latitudes [10], and making this the best density metric for solar studies (figure 2l).

3.2. Mutual influence of metrics

Here we briefly analyze the influence of two varying form and density metrics on the correlation between selected form, density and solar metrics with EUI, and sky (density) with solar metrics.

The increase of APR (figure 3a), which corresponds to more squared and larger footprints, changes the inverse correlation between FAR and EUI from $R^2 = 0.14$ to 0.72. Thus, FAR is a reliable energy use indicator when compact buildings are used. Conversely, as APR increases, the correlation of solar irradiation (SIFfa) and sky-based density (SEFfa) metrics with EUI decreases from $R^2 = 0.86$ and 0.75, respectively, to as low as $R^2 = 0.3$ in both cases, making them more reliable for narrower or articulated buildings. The reason behind the non-linear alteration of correlation for some metrics is the complex influence of several metrics and the specific building parameters of smaller samples. The correlation of SVF and SEF with SIF changes only slightly when APR changes, indicating that these density metrics can reliably represent availability of façade solar irradiation on a variety of building shapes.

When FAR varies the correlation between APR and EUI is affected only slightly, indicating that APR is a reliable building form indicator of energy use in all the tested urban density conditions (figure 3b). When FAR increases, the correlation of the solar irradiation and sky-based density metrics

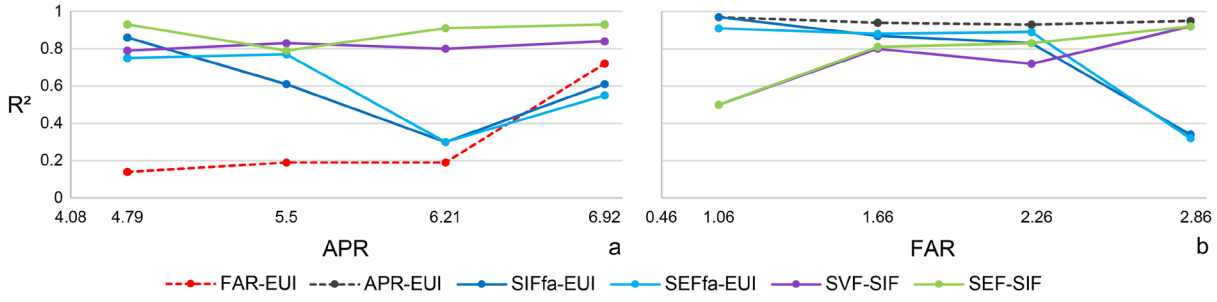


Figure 3. Charts of the mutual influence of metrics. Dashed lines = Inverse correlation.

decreases, and in similar ways. SIFfa correlation with EUI decreases from R^2 = 0.97 to 0.34, while SEFfa-EUI correlation decreases from R^2 = 0.91 to 0.32. This is evidence that these floor area-normalized metrics are good predictors of energy use in case of low and medium built densities. Unlike form metrics, if FAR increases, then the correlation of the two sky-based (density) metrics SVF and SEF with SIF also increases in both cases from R^2 = 0.5 to 0.92. This result shows that such sky-based density metrics can predict façade solar irradiation more reliably in denser environments.

4. Conclusion

The study analyses the correlation between building form and urban density, solar irradiation and energy use in consideration of recent residential developments in the northern climate of Tallinn, Estonia. A computational workflow uses digital cadaster data to automate building and cluster generation, form and density calculations, environmental and energy simulations. Results show that several metrics allow to compare schematic design solutions through fast calculations and simpler environmental analyses instead of energy simulations. The APR and PZR are strongly correlated with EUI (R^2 = 0.96 and 0.83) as does SIFfa (R^2 = 0.89), whereas SEFfa is a strong predictor of solar irradiation (R^2 = 0.98). Results also show the higher correlation of floor area-normalized metrics with EUI. Limitations of the study are represented by the use of only one type of building and envelope. Future work will involve office buildings, and different WWRs. The computational workflow will be of interest for researchers conducting urban studies. The metrics will be used by architects and researchers to develop solutions and strategies to improve the sustainability of the built environment.

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