Integrating Energy in the Conceptual Design Stage to Optimize Building Form

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Abstract

In architecture, Integrated Energy Design (IED) entails considering energy during each design phase, especially in the early design stage. The form of a building is an important factor in this stage due to its considerable impact on energy consumption. Finding the optimal form is a time-consuming process, and computational design techniques can help designers to facilitate this process and achieve a design solution with acceptable performance in terms of CO_2 emission. Moreover, the surrounding buildings, trees and urban elements can affect the energy and daylight of the project by casting shadows. Considering all these elements throughout the design process can be very demanding and take several working days. Today, digital tools make it possible to parametrically analyze morphological characteristics of buildings to identify the most efficient solution. The present study proposes an environmental-simulation based design workflow to be used in the early design stage to determine the building's form parameters (height, angle,..) in a given urban area based on the weather data and the surrounding context. This process is done by parametric design tools and environmental simulations in Rhino3D®, Grasshopper®, and ladybug Tools®. The typical Norwegian cabin's form parameters are applied in the visual coding program (Grasshopper®) to generate the initial geometry for optimization. Due to the great effect of the energy consumption on the CO_2 emission, minimizing energy, maximizing thermal comfort and the sky view percentage were the main objectives. To test the workflow the weather data of Tromsø (Norway) and 3d model of the surrounding context of a design location was applied as inputs. The output of this application was several building's form alternatives for that specific location. This study showed using the digital tools and parametric design thinking can help the designers to apply the climatic data in the design process to narrow down the design solutions.

Keywords: parametric-design, optimization, morphology, Integrated-Energy-Design

1 Introduction

The building industry is responsible for 40% of the carbon emission (Huang et al., 2018). The decisions made in the early design stage are having a great effect in terms of CO_2 emission. In this stage, many design alternatives are generated, and their performances are evaluated (Miles et al., 2001). Among the building factors the building's form can have an considerable impact on energy consumption. A study showed that by changing design parameters such as the roof slope and skylight length and width, daylighting performance can be increased to nearly 40 percent, and energy demand reduced by around 20 percent (Miles et al., 2001). Zou et al. (2021) showed that the average performance of the building could increase by up to 24% by optimizing the design variables, including wall length and glazing ratio with the objective of having minimum air conditioning and lighting energy and maximizing the average Useful Daylight Illuminance (UDI). Zhang et al. (2017) investigated the effect of the building shape parameters such as window-to-wall ratio, room depth, orientation, and shading type on energy consumption and thermal discomfort. The optimized solution could perform better near 13% and 4% in energy and thermal comfort, respectively. Konis et al. (2016) introduced a new method to improve the performance of the passive strategies in conceptual design and investigated the building morphology optimization to achieve desired daylighting and to minimize energy consumption in four different climates. The result showed that the performance of the building improved, especially in warmer climates. It also revealed a huge impact of shape optimization on daylight improvement, between 24% to 65% depending on the local context and the climate. Harkouss et al. (2018) presented a comprehensive study on optimal passive design. In this study the optimal solution showed the potential of saving up to 54% of cooling and 87% of heating demands compared to the initial values. The present study aims to introduce a workflow for an investigation of building morphology with geometry generation parameters as variables and optimization using an evolutionary multi-objective optimization, so-called Non-dominated Sorting Genetic Algorithm II (NSGA-II) (Deb et al., 2002). regarding the energy, occupants' thermal indoor comfort, and sky view percentage.

2 Methodology

The present study is addressed to designers and engineers who need to evaluate the environmental performance of their design in the early design stage but they do not have computational design knowledge to write the analysis by digital tools. In this study Grasshopper® (Visual programming plug-in in Rhino3D®) is used as the parametric design tool. The defined workflow is applied to the design of small cabin with the sloped roof but the process can be applied more widely. The order of used applications and the process are shown in Fig. 2. Procedure is explained in detail in 2.1.

Figure 1: left) a typical Norwegian cabin outline (svenskoedegaard, 2020), and right) the extracted geometry showing different parameters.

2.1 Simulation Procedure

The first step in the workflow was generating an initial 3D geometry as the building's form in Grasshopper®. Inspired by a typical Norwegian cabin form with a polygon as the plan and the sloped roof (Fig. 1), the main framework of the geometry was defined, and the geometry parameters such as plan shape, the height of the wall, wall angle, and roof slope were set as the variables in Grasshopper® (Table. 2) for which numeric values are assigned. Changing each variable's numeric value could generate a new form with different height and angles. Next step is to evaluate the performance of the form in Energy consumption, occupants' thermal comfort , and the sky view by the Ladybug Tools® and EnergyPlus® plug-in in Grasshopper®. The Energy analysis is conducted by running the Energy component in EnergyPlus® inside Grasshopper®. After that the indoor thermal comfort will be calculated by the same plug in. Finally, the sky view will be analyzed by Ladybug Tools® in Grasshopper®. The optimization is conducted by Wallacei X® plug-in in Grasshopper®. This workflow could generate thousands of form possibility and calculate their environmental performance and compare each form to the others regarding the result of the performances. Therefore, it can find the numeric values for geometry parameters that generate the optimal form, with having an average of good performance in all the objectives (Energy, comfort, sky view). The inputs of this workflow are weather data of the desired location and the context geometry as a 3D model in Rhino3D®, and the output is several form alternatives with minimized energy consumption, maximized occupants' indoor comfort, and sky view among all the form possibilities (design solutions).

2.2 Setting the geometry parameters

The initial geometry framework was inspired by the typical Norwegian cabin having a polygon as the plan and a sloped roof (Fig. 1). The building geometry paramters was decoded and translated into visual coding (Grasshopper®) to generate the initial geometry. Considering the initial construction form, a polygon was generated as the base surface. Since this study aimed to use a parametric design approach, the location of the corners of that polygon could be defined in a parametric way. Therefore, a circle was chosen as the base of the polygon creation. Then by connecting the subdivision points on the circle the plan polygon is created. After that, getting the center point of the polygon will produce the sloped roof geometry. By connecting each corner to the center point and moving the center point, the degree of the roof is changed (Fig. 3). In the morphology investigation process, the geometry parameters generating the shape of the building were considered as the variables (Fig. 3). To achieve the appropriate percentage of the glazing, the area of the walls was multiplied by a number between 0.1 to 0.8, resulting in the window-to-wall ratio. Then the location of the glazing is made by a random function. Random selection of the exterior wall surfaces produced the location of the glazing in the initial solid geometry. Although this is a random function, the possibilities of window locations can be modified.

2.3 Setting the Objectives

2.3.1 Total Energy Consumption

In this study, energy demand minimization was the first objective calculated using the EnergyPlus® engine (Delgarm et al., 2016) in Ladybug Tools®. The output of this analysis was heating and cooling energy load. The addition of these values is used in this study to calculate the total energy demand. The Energy and comfort simulations are done with the opaque material of the EnergyPlus® database, with a

Figure 2: Diagram showing the workflow process and the order of used applications.

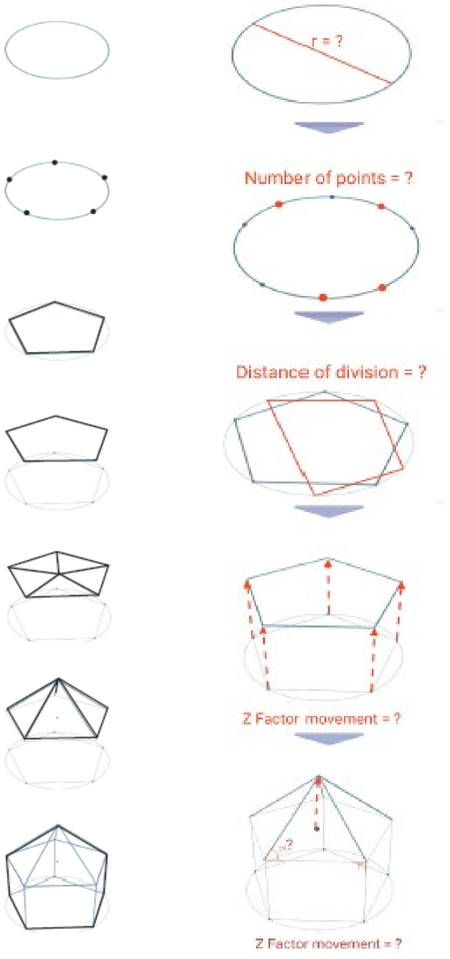

Figure 3: left) generating the simple geometry of typical Norwegian house with parametric design tools, and right) showing the geometry parameters as the variables (in red) to generate different forms.

U-value of 0.13 W/m²K, which is the heat transfer rate through the opaque material. The glazing U value is set as 0.7 W/m²K for the initial analysis. In the current study material was not the in focus of the study, therefore the simulations are considered without insulation. The general comparison of the form's performances has been under investigation. The numeric result of the simulations were higher than standards expectedly.

2.3.2 Occupants' Indoor thermal comfort

Thermal comfort is a state of mind in which a person expresses full satisfaction with their thermal surroundings (Moser et al., 2001). Design variables under the architect's control can affect the indoor environment. These design variables are general layout, shape, location of windows, and insulation. Comfort is evaluated by predicted mean vote (PMV), a well-known example of a thermal comfort performance indicator which was developed by Povl Ole Fanger as an empirical fit to the human sensation of thermal comfort. It was later adopted as an ISO standard. PMV is a seven-point sensation scale from -3 to +3. According to the ASHRAE standards, this should be kept at 0 with a tolerance of ±0.5 to ensure a comfortable indoor environment (Srebric et al., 2015). The PMV Comfort in Ladybug Tools® has three main inputs, including dry bulb temperature, mean radiant temperature of the surrounding surfaces in degrees Celcius, and metabolic rate of the human and the output will be predicted mean vote showing the degree of the occupants' comfort. Wallacei X® Plug-in can only minimize the objectives' values; Therefore, the result of the comfort calculation was changed into the formula below and then connected to the Wallacei X® to be minimized.

$$N = 3 - |X| \quad (1)$$

where, N is an objective to be minimized, and X is the result of the comfort simulation from Ladybug Tools®. The closer the result of the comfort simulation be to zero, the better comfort is provided. The result of formula (1) should be close to three. (Tab. 1) gives the assumed ranges for nine main variables.

2.3.3 Sky View

If the energy was the only objective of the workflow the result would be a form with no window to save the energy consumption due to less heat loss. Another objective is needed to balance the glazing ratio. Therefore, sky view percentage from inside of the form is chosen as an objective.

Since Wallacei X® can only minimize the objectives, to maximize the objective it was multiplied by minus one (-1) and then connected to input of Wallacei X®.

2.3.4 Area

Optimization results showed disregarding the floor area can lead to solutions with smallest floor area and high energy efficiency. Therefore, floor area was also added as an objective to drive the optimization in favor of the floor area as close as 35 m2. The objective function appears as formula(2).

$$A = |\, 35 - (\text{Floor area of the case}) | \quad (2)$$

2.4 Optimization

In this project, Wallacei X® version 2.7 is used as the optimization tool using an evolutionary algorithm (NSGA-II) suitable for multi-objective optimization with four objectives and nine geometry variables. The evolutionary algorithm is the genetic algorithm that uses the natural selection principles to evolve a set of solutions towards an optimum solution (Machairas et al., 2014). Wallacei X® is the key built-in and integrated multi-objective optimization algorithm widely employed in many studies (Wang et al., 2021). This tool tests each numeric value for each variable, test the results with objective functions, compares the results and goes to another set of variables which generate another solution (form). For the first generation (iteration) it conducts random numeric values to evaluate the resulted forms. Then using the analyzed data it produces another set of geometries in the next generation (iteration) and compared them with the previous generation (iteration). The goal is to minimize the numeric value of the result. So, it is expected after multiple generation the last one be containing the optimized solutions (Deb et al., 2002). The overview of optimization process is shown in Fig. 4.

2.5 Case Study (Tromsø)

To test the developed workflow in Grasshopper®, a real location in Tromsø was chosen because of its severe cold climate and critical energy demand. The surrounding of a residential area in Tromsø in Petterburggate is modeled in Rhino3D® as the cabin location (Fig. 5(Right)).

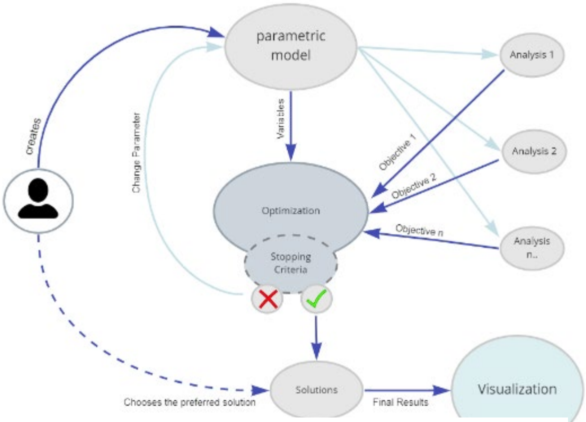

Figure 4: Diagram showing the workflow process.

2.5.1 Tromsø climate

Tromsø lies in Northern Norway (69.6492° N, 18.9553° E). The temperature typically varies from -6 to 15 °C and is rarely below -13 °C or above 21°C. The coldest month in Tromsø is January, with an average low of -6 °C and a high of -1 °C. Fig. 5(right) shows the total radiation rose in Tromsø, having the most radiation on the south side up to near 770 kWh/m^2.

2.5.2 Applying Tromsø Weather Data

The weather data[1] of Tromsø was the climate input for the environmental simulation. The surrounding area was modelled in Rhino3D® and connected to the context input of the Ladybug Tools® plug-in.

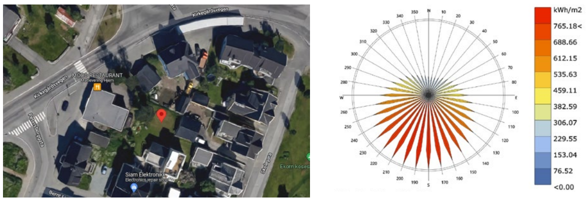

Figure 5: Left) Tromsø location in "Petterburggate," with the surrounding Right) Radiation Rose of Tromsø extracted from Ladybug Tools® weather data analysis.

The optimization is operated with the default setting of Wallacei X®, having 50 as the number of

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[1] Extracted from https://climate.onebuilding.org/

generations to iterate and a maximum population of 30 forms for each iteration.

Table 1: Variables' assumed ranges

Variables	*Range*
Number of plan Polygon corners	3< <10
Ellipse Division Distance_ Plan shape	0.0 < <1.0
Roof Point x Coordinate	-3.0< <+3.0
Roof Point y Coordinate	-3.0< <+3.0
Roof Point z Coordinate	-3.0< <+3.0
Glazing Ratio	0.1< < 0.7
Glazing Plane location (Randomness between choosing which surface to be glazing)	0.0< <1.0
Scale factor of the roof surface (responsible for the wall angle)	0.0< <1.0
Tilt angle of the roof	-25< <+25

Table 2: Variables' assumed ranges and chosen values for sensitivity analysis.

Variables	*Range*
Number of plan polygon corners	3< <10
Ellipse division distance plan shape	0.0 < <1.0
Roof point X coordinate	-3.0, -1.5, 0, +1.5, +3.0
Roof point Y coordinate	-3.0,-1.5, 0,+1.5, +3.0
Roof point Z coordinate	-3.0,-1.5, 0,+1.5, +3.0
Glazing Ratio (customized based on location)	0.1,0.2,0.3,0.4
Glazing plane location (randomness between choosing which surface to be glazing)	0.2,0.3,0.4,0.5
Scale factor of the roof surface (responsible for the wall angle)	1.0, 1.3, 1.5,1.7,2.0
Tilt angle of the roof	-25,-12.5, 0, +12.5, +25

Algorithm parameters for optimization were as follows: 0.9 for crossover probability, 20 for crossover distribution index, 20 as mutation distribution index, 1 as random seed, and the mutation probability is *1/n*. The result was 30 individual forms in Generation (iteration) 49, 12 forms of the 3d models are shown in Fig. 7 in the plan view.

Due to the time-consuming nature of the optimization and simulation in this study, energy and comfort simulations were done for the most critical month of the year in Tromsø which is January, with the highest demand for heating. Regarding the nine main variables (Tab. 1) and to narrow down the number of simulations, the limited number of numeric values as variables were chosen among all the possibilities so that the number of generated 3D models was reduced from millions of shapes to a few thousands of models to do the sensitivity analysis which narrows down the number of possibilities to see the most affective range of the numeric values of the variables (Tab. 2).

3 Results

The generated solutions were exported from Wallacei X® as shown 3D in Fig. 6 and 2D in Fig. 7. The optimization process showed that with a ready to use workflow developed by parametric design tools, achieving an efficient form based on the climatic data will take less than one working day.

The plan shape of the pareto front solutions Fig. 7 shows that according to the weather data in January and surrounding buildings in that context, the southeast has a wider side to receive more radiation, while in the north, the walls are more compact. The roof is tilted toward the sun in the south, and in most cases of the pareto front solutions, the skylight in the north side. As Fig. 6 shows, the wall angles are slightly leaning towards the outside, helping them to receive better solar radiation since the sun's altitude is low in that location. Observations showed that no single solution is doing the best in all the objective values. The solution that performs the best in Energy consumption is expected to be the worst in sky view since the glass ratio is low to avoid heat loss.

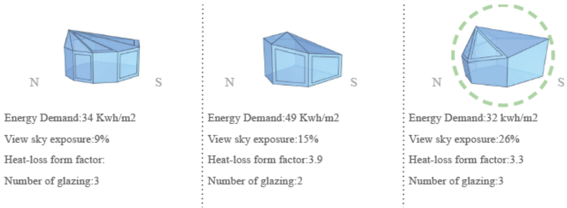

Figure 6: showing three different alternatives with their objective values as the outputs from *Wallacei X®* .The highlighted form is showing more efficiency.

5 Discussion

Due to the environmental simulations' complexity and the time-consuming optimization process, not every designer and engineer know the environmental simulation techniques to apply to the project's location.

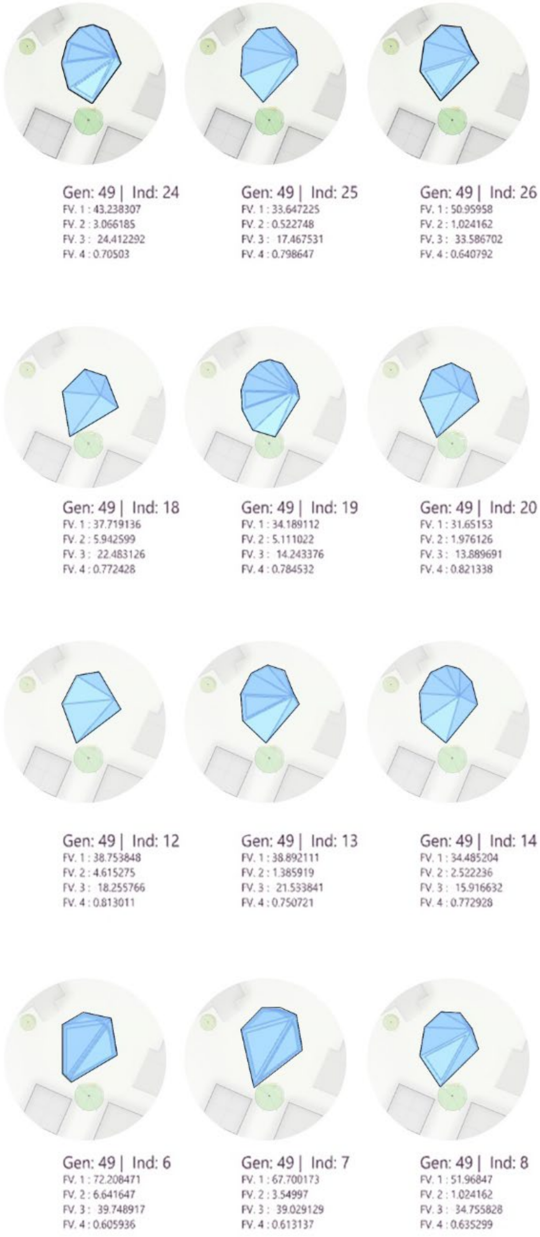

Figure 7: 20 Pareto front Solutions top view in generation(iteration) 49 exported from *Wallacei X* ® Fv.1 : Energy Demand , Fv.2 : A, Fv.3 : percentage of View, Fv.3 : N gen= generation, Ind = Individual.

Therefore, an integrated workflow is needed to facilitate the decision-making in the design space regarding the performance of the building in environmental simulations to enhance the use of the climatic data and energy efficiency in the design process. Previous studies mentioned earlier have investigated the possibility of optimization for the constructed shape. In this study the generation of a new form is studied to prepare a workflow regarding the energy efficiency. This workflow shows the power of using the digital tools to narrow down design solutions.

6 Conclusion and further study

The introduced workflow used parametric design tools such as Rhino3D® and Grasshopper®, and Ladybug Tools® for environmental simulation to investigate the morphology of buildings and introduce a form generation method inspired by typical Norwegian cabin geometry. The geometry parameters were considered as numeric variables, and the objectives for optimization were total energy demand, occupants' thermal indoor comfort, sky view percentage, and area. This workflow helps the designers to narrow down the design solutions and make better decisions based on the environmental performance of the. Still, the designer's role is to choose among the generated form solutions manually. This innovative approach introduced the potential of generating geometry and its modification based on the climatic data.

This study considered energy, occupants' comfort , the sky view percentage, and the area as the objectives for optimization, and it is suggested that further work be conducted to include daylight availability, wind analysis for natural ventilation, and cost of the elements. Further studies can be done to find another geometry generation process, such as a complex geometry for the form of the building. Interesting study as further work can be suggested by allocating material and analyzing the different material options and their effect on each objective value. This workflow has the potential to be used as a plug-in for Grasshopper®, which generates a set of optimum design solutions for given weather data. Comparing the optimized shape for different locations also can be another interesting topic in future studies.

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References

Deb, K., Pratap, A., Agarwal, S., & Meyarivan, T. (2002). A fast and elitist multiobjective genetic algorithm: NSGA-II. *IEEE Transactions on Evolutionary Computation*, *6*(2), 182–197. https://doi.org/10.1109/4235.996017

Delgarm, N., Sajadi, B., Kowsary, F., & Delgarm, S. (2016). Multi-objective optimization of the building energy performance: A simulation-based approach by means of particle swarm optimization (PSO). *Applied Energy*, *170*, 293–303. https://doi.org/10.1016/j.apenergy.2016.02.141

Harkouss, F., Fardoun, F., & Biwole, P. H. (2018). Passive design optimization of low energy buildings in different climates. *Energy*, *165*, 591–613. https://doi.org/10.1016/j.energy.2018.09.019

Huang, L., Krigsvoll, G., Johansen, F., Liu, Y., & Zhang, X. (2018). Carbon emission of global construction sector.

Renewable and Sustainable Energy Reviews, *81*, 1906–1916. https://doi.org/10.1016/j.rser.2017.06.001

Konis, K., Gamas, A., & Kensek, K. (2016). Passive performance and building form: An optimization framework for early-stage design support. *Solar Energy*, *125*, 161–179. https://doi.org/10.1016/j.solener.2015.12.020

Machairas, V., Tsangrassoulis, A., & Axarli, K. (2014). Algorithms for optimization of building design: A review. *Renewable and Sustainable Energy Reviews*, *31*, 101–112. https://doi.org/10.1016/j.rser.2013.11.036

Miles, J. C., Sisk, G. M., & Moore, C. J. (2001). The conceptual design of commercial buildings using a genetic algorithm. *Computers & Structures*, *79*(17), 1583–1592. https://doi.org/10.1016/S0045-7949(01)00040-2

Moser, A., Schäulin, A., Davidson, L., Corrado, V., Dorer, V., & Koschenz, M. (2001). 11—DESIGN WITH MODELING TECHNIQUES. In H. Goodfellow & E. Tähti (Eds.), *Industrial Ventilation Design Guidebook* (pp. 1025-p3). Academic Press. https://doi.org/10.1016/B978-012289676-7/50014-X

Rizzo, G., Beccali, M., & Nucara, A. (2004). Thermal Comfort. In C. J. Cleveland (Ed.), *Encyclopedia of Energy* (pp. 55–64). Elsevier. https://doi.org/10.1016/B0-12-176480-X/00551-9

Santamouris, M. (2019). Chapter 3—Urban Heat Island and Local Climate Change. In M. Santamouris (Ed.), *Minimizing Energy Consumption, Energy Poverty and Global and Local Climate Change in the Built Environment: Innovating to Zero* (pp. 65–102). Elsevier. https://doi.org/10.1016/B978-0-12-811417-9.00003-9

Srebric, J., Heidarinejad, M., & Liu, J. (2015). Building neighborhood emerging properties and their impacts on multi-scale modeling of building energy and airflows. *Building and Environment*, *91*, 246–262. https://doi.org/10.1016/j.buildenv.2015.02.031

Wang, W., Liu, K., Zhang, M., Shen, Y., Jing, R., & Xu, X. (2021). From simulation to data-driven approach: A framework of integrating urban morphology to low-energy urban design. *Renewable Energy*, *179*, 2016–2035. https://doi.org/10.1016/j.renene.2021.08.024

Zhang, A., Bokel, R., Van den Dobbelsteen, A., Sun, Y., Huang, Q., & Zhang, Q. (2017). The Effect of Geometry Parameters on Energy and Thermal Performance of School Buildings in Cold Climates of China. *Sustainability*, *9*(10), 1708. https://doi.org/10.3390/su9101708

Zou, Y., Zhan, Q., & Xiang, K. (2021). A comprehensive method for optimizing the design of a regular architectural space to improve building performance. *Energy Reports*, *7*, 981–996. https://doi.org/10.1016/j.egyr.2021.01.097