AUTOMATED OPTIMUM GEOMETRY GENERATION OF A BUILDING FOR THE MINIMIZATION OF HEATING AND COOLING ENERGY DEMANDS

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ABSTRACT

This paper reports first results of our work in using simulation-based optimization in automatic generation of building shapes considering multiple objectives, variables and constrains. An optimization problem is presented for finding the optimum geometry solutions for an office building that has a basic cross-shape. The problem is solved as a two-objective optimization problem with the aim of finding the optimal trade-off solutions between the cooling energy and heating energy as two conflicting objectives. The solutions are generated by re-distributing the building's zones in four orientations and selecting the number of floors while keeping the total floor area of the building constant. Different challenges were faced in the representation of the building with undefined exact dimensions in the simulation program during the optimization process. The optimal solutions showed the trends of the distribution of the zones and the number of the floors and gave guidance for exploring other new solutions.

INTRODUCTION

The EU legislation of the Energy Performance of Buildings Directive (EPBD) requires all new buildings to be nearly zero-energy buildings from 2021 and two years prior to that for public buildings. In order to meet this challenging requirement, the first step to be taken is to decrease the energy demand of a building before applying other measures like on-site energy generation, conversion and storage. Demand reduction gives the opportunity for using small-scale on-site energy generation units and to minimize imports from grids, therefore minimizes the impact on the grids. The target can be reducing the energy demand for both cooling and heating energy, or putting more importance or focus on one type of energy by giving different weights for them due to different reasons (limitations in available energy system capacities, higher value of energy quality of one type of energy, price, availability from on-site-generation, import from different grids, etc.). One way to reduce the energy demand is by adjusting the geometry of the building and thus trying to compromise between the heating and cooling energies. The geometry of the building will affect the interaction of the building envelope with the surrounding weather. An example is the solar energy gains through the glazing. However, higher solar gains will reduce the heating load of the building but as well increase the cooling load in order to prevent over-heating. On the other hand, minimizing the solar gains will minimize the cooling demand but will increase the heating demand.

Simulation-based optimization can be used to find the optimal solutions for the reduction of energy demand, increase of the on-site generation, optimum grid-interactions and to provide thermal comfort with minimum required energy. A variety of methods have been applied to conduct simulation-based optimization for buildings, as presented by (Evins 2013; Nguyen et al. 2014).

Optimization studies that deal with some aspects of the building geometry by using genetic algorithms (GA) focus on individual features of a building. For example, the number of windows, their position, size (width x height), options for glazing type, and thickness of the masonry wall for an open office space were evaluated to minimise energy consumption (Méndez Echenagucia et al. 2015). NSGA-II optimization algorithm coupled with EnergyPlus software was used to carry out this study for four climate zones in urban and sub-urban context. The results of this study confirmed that window arrangements on a facade affect the energy consumption. Another example is reported by (Rahmani Asl et al. 2015) who used BIM-based parametric integration between Revit and a web-based energy simulation engine of Autodesk Green Building Studio connected to DOE-2.2 simulation engine to optimize the energy and daylighting performance for window optimization. Geometric optimization of fenestration to minimize the energy use was conducted for finding the shape, number, aspect ratio and position of windows with innovative architectural forms (Wright et al. 2014). The building performance simulation was conducted using EnergyPlus and the optimization method used binary-encoded GA. The results suggested that placing a window on the top-west corner allowed penetration of light, while correspondingly reducing energy consumed by artificial lighting.

Minimization of heating and cooling load in a Mediterranean climate was conducted using CHEOPS combined with GA by (Znouda et al. 2007). The studied parameters included two types of roofs with and without insulation, five types of wall compositions, four facades provided with a glazed surface as a variable function of the facade, and five configurations of shading elements applied on a test cell of 36 m^2 area. The results showed the variation of choices made to save the energy consumption and investment cost.

A study particularly useful for highly glazed office buildings was conducted by (Manzan & Pinto 2009). ESP-r software was used to assess the thermal loads, Radiance software for the daylighting factors, and modeFRONTIER for the optimization. The optimization was carried out for one office room on a first floor with a roof area of 20 m^2 and a height of 2.7 m. The studied parameters included six types of window glass and shading to reduce the primary energy consumption (heating, cooling and lighting). The optimization algorithm MOGA II was used to assess the coupling of a shading device with different types of window glazing. The shading device was characterized by shading height, width, angle and distance from the wall of the shading device, which was positioned parallel to the window at an inclination. The results showed a substantial reduction in energy consumption with a wider shading panel. A more simplified approach by (Torres & Sakamoto 2007) used Radiance software coupled with GA accounting for 21 parameters regarding size, number, position of windows and fixed shading elements to maximize energy savings calculated by the amount of daylight entering the building and the amount of glare from the source of light.

The closest co-relation to our study on automated optimum generative design is the work of Caldas & Norford (Caldas & Norford 2002), where they presented an approach based on GA to evaluate lighting and thermal behaviour using the DOE 2.1E program on a UNIX platform and used AutoLisp procedure for visual purposes to present the obtained results. Later work introduced an optimization tool named GENE-ARCH able to alter the building shape and generate different geometries using GA with multiple objective functions, such as building energy use, embodied energy, and thermal and lighting assessment (Caldas 2008).

Published studies that demonstrate automated shape generation using simulation based optimization are limited in the literature and only deal with some individual features of the building shape not the variation of the whole shape of a building. The potential of automated shape generation needs to be explored more in order to give guidance to building designers in designing buildings. This article reports first results from our work in this field. It is a contribution to support further exploitation of optimization tools in automated generation of building shapes considering multiple objectives, design variables and constrains.

In this paper, optimum geometry solutions for an office building are automatically generated using combined simulation-optimization by re-distributing the building's zones in four orientations and selecting the number of floors. The objective is the minimization of the cooling and heating energy loads of the building.

DESCRIPTION OF THE BUILDING

The studied building is an office building with a basic cross-shape where the zones are distributed on four wings (expanding in the north, east, south and west directions) and on the floors (Fig. 1). The total floor area of the building is 5292 m^2. There is a central open office zone in each floor with dimensions of 18 m x 18 m. The width of a wing is 18 m. The floor height is 3 m. In the simulation, the wings are built from slices, where each slice contains two office rooms (each is 2.5 m x 5 m) on the two opposite sides of a wing and a secondary space in between. This space represents storage room, corridors and multipurpose areas. This slice is called "zone" in this paper. The minimum number of zones in each floor in a wing is two: a wing-end zone and a middle-wing zone (see Fig. 1).

The building is assumed to be located in Budapest-Hungary with the aim of having both cooling and heating energy loads on comparable levels. Therefore, the building was modelled with Hungarian building specifications and hourly annual weather data (ASHRAE International Weather Files for Energy Calculations 2.0, Budapest-Pestszentl). The used U-values are: external walls 0.45 W/m^2K, roof 0.25 W/m^2K, floor 0.49 W/m^2K and windows 2 W/m^2K (ADENE, 2012). The g-value of windows is 0.68. The infiltration in the external surface is 0.13 m^3/m^2h. There is a 3 m^2 window in every office room and additionally a 6 m^2 window in every corner office.

The heating and cooling systems are modelled with an ideal controller that is very fast in responding to changes in the indoor air temperature. The systems are assumed to have sufficient capacities to keep the temperature between given set-points of 21 and 25 °C. The ventilation system is modelled with a constant airflow, a Specific Fan Power (SFP) of 2 kW/m^3s and a temperature heat recovery efficiency of 60%. The design values for internal gains are lighting 12 W/m^2, equipment 15 W/m^2 and three occupants per every 20 m^2 of the floor area. The internal loads follow an hourly profile, which reflects a typical use in an office building (FINVAC 2014).

There is internal shading between the two panes of the windows that face south, i.e. the south-facing windows of the east and west wings in addition to the windows of the end zones of the south wing. This could represent e.g. the effect of shading from an adjacent building. This feature was included to give a different effect on the cooling and heating energy demands of the south-facing rooms over the other rooms in order to study how the optimization will handle this feature with respect to the two set-objectives. The internal shading changes the g-value of the windows from 0.68 to 0.36, T-value from 0.6 to 0.08 and U-value from 2 to 1.9 W/m^2K.

METHODOLOGY

The aim of this optimization problem is to find the optimal trade-off solutions for the cross-shape of the building with two objectives: minimisation of the cooling energy and minimisation of the heating energy of the building. These two objectives are, respectively, represented by the cooling load and the heating load calculated by the IDA-ICE program, and therefore do not depend on any technology that can be used to generate them. In order to find the optimal solutions, the optimization program will stretch the building in the four directions of the wings and as well select the proper number of floors.

For this purpose, two tools were combined: the building energy performance simulation tool IDA-ICE (http://www.equa.se/en/ida-ice) and the multi-objective building performance optimization tool MOBO (http://ibpsa-nordic.org/tools.html) using a pareto-archive genetic algorithm.

IDA-ICE (IDA Indoor Climate and Energy program) is a building performance simulation program (Sahlin et al. 2004). IDA- ICE has been validated by CEN 15255, CEN 13791, ASHRAE 140-2004, and IEA SHC task 34.

MOBO is generic optimization software able to handle single and multi-objective optimization problems with continuous and discrete variables and constraint functions. MOBO was developed through a previous project funded by the Academy of Finland where the first author of this paper was the PI. MOBO has been coupled to several simulation programs (IDA-ICE, TRNSYS, EnergyPlus, etc.). It has a library of different types of algorithms (evolutionary, deterministic, hybrid, exhaustive and random). The implementations of MOBO were first demonstrated by a building performance optimization example, which was solved using three algorithms (Palonen et al. 2013). Later MOBO was implemented in several other optimization studies (e.g. Magny 2014, Niemelä 2015, Phdungsilp 2015). MOBO has been highly recognised by the scientific community after a short time of its release. Here is a quotation of what (Nguyen et al. 2014) stated about MOBO "*On the building optimization point of view, the free tool MOBO shows promising capabilities and may become the major optimization engine in coming years*".

In this paper, a pareto-archive genetic algorithm was used in the optimization. It is based on the well-known elitist multi-objective genetic algorithm NSGA-II (Deb et al. 2002). The pareto-archive genetic algorithm keeps an active archive of the non-dominated points that would be otherwise rejected by the original NSGA-II. It was successfully tested and used for finding the cost-optimal solutions in a nearly-Zero Energy Building optimization problem that had a large discrete solution-space (Hamdy et al. 2012).

In the current building geometry optimization problem, there are five design variables: four variables expressing the lengths of the four wings in the four directions: N, E, S, and W, which determine the number of zones in the north-wing, east-wing, south-wing, and the west-wing, respectively, each with a possible number of 2 to 26 zones per floor. As was indicated earlier, each zone is composed of two office rooms on the two opposite sides of a wing and a connecting space in between. The fifth design variable is the height of the building expressed as the number of the floors ranging from 3 to 7 floors. The total floor area of the building is kept constant (5292 m^2), which is a constraint in this optimization problem. The selection of the five design variables should, therefore, keep this constraint valid at each run; otherwise the runs will be infeasible and will lead to inefficient optimization runs. A simple calculation with the above-mentioned options for the number of zones and floors indicates that the total number of the possible combinations is 1953125 cases.

Part of the challenges faced in this work were related to how to represent the variable building geometry in the IDA-ICE simulation tool as floating dimensions and in selecting feasible values of the building geometry variables by the optimization that have to fulfil the constant total floor area of the building, which is not directly applicable in MOBO.

In order to avoid getting infeasible simulation runs that will violate the constant area constrain during the optimization, the variables that represent the wing lengths were defined as normalized lengths with respect to the length of one reference wing (the north wing is considered here). This lowered the number of variables to four (three normalized wing lengths and one for the number of floors). This way, the normalized wing lengths are taken as continuous variables and the number of floors as a discrete variable in MOBO. The constraint is satisfied implicitly by equating the total floor area to 5292 m^2 and, therefore, finding the absolute values of the wings in each run and feeding them to the simulation program as dimensions of the building. This is represented by the following equations:

$$A = n_{Floors} * (324 + 45(n_N+n_E+n_S+n_W))$$

$$r_{EN} = L_E / L_N$$

$$r_{SN} = L_S / L_N$$

$$r_{WN} = L_W / L_N$$

$L_i = 2.5\ n_i$,

where $n_i \geq 2$ and i = {N, E, S, W}.

In the above equations A is the total floor area, n_{Floors} is the number of floors, n_i is number of zones per floor in wing i, L_i is the length of wing i and r_{iN} is the normalized length of wing i to the length of the north wing. The simulation program script gets the three values of r_{iN} and the value of the number of floors as input from MOBO and, accordingly, modifies the building body geometry, zone locations and zone multipliers in the IDA-ICE model.

The existence of the absolute value of the number of floors with the three normalized values of the wings that are all satisfying the constraint value at each run keeps a relation between the variables for MOBO to trace during the optimization in order to find more fit solutions from one generation to another.

In the simulation model, a middle zone in a wing is taken to represent all zones between the end zone and the central core zone of that wing and as shown by Figure 1. For the number of zones per floor in a wing, a floating-point number was enabled, where its decimal part is assumed to represent one of the zones in the middle that is proportionally wider than the others. The total energy consumption of the middle zones in a wing is calculated by multiplying the energy consumption of the representative middle zone by the number of zones it represents. Correspondingly, the energy consumption of the middle floors is calculated by multiplying the result of one middle floor by the number of the middle floors, which is equal to $n_{Floors} - 2$ (the total number of floors excluding the top and the ground floors).

Guided by hints from MOBO, the following were set in the optimization: number of generations 42, number of populations 32, crossover probability 0.9, and mutation probability 0.1. This made a total of 1344 simulation runs. A 16-core PC with 32 logical processors was used for running the simulations on parallel. The simulation runs were quite heavy and time consuming since the building zones were described in details. One simulation run took about 30 minutes. The multiple processors helped in carrying out 32 simulations on parallel during each generation, but the script execution, which could not be run on parallel, took about an hour in each generation. Therefore, the 1344 simulation runs took almost 72 hours in one optimization run.

RESULTS

Fig. 2 shows the candidate solutions of the simulation iterations during the optimization run for the minimization of the two objectives, the cooling energy and heating energy calculated based on hourly values for one-year. A trade-off can be seen between the two objectives. The ratio between the maximum and minimum cooling energy in the solution space is 110% and it is 107% for the heating energy.

Fig. 3 shows the non-dominated optimal solutions for the two selected objectives. They consist of a total of 79 points. Seven solutions are selected and visualised as a representation of the trends of the variables in the optimal solutions. The seven building shapes are produced by the simulation program by feeding it by the found dimensions from the optimization. Table 1 indicates the building geometry of these seven points sorted according to their appearance on Fig. 3 from right to left with descending cooling energy. The second column indicates the number of floors (n_{Floors}) and the rest four columns refer to the number of zones per floor in each wing (N, E, S and W), respectively. As indicated earlier, a decimal of a zone means that the length of one zone in the middle of that wing extends in proportion to that decimal value.

Table 1 Geometry of the selected optimal solutions sorted with descending cooling energy.

No.	n_{Floors}	n_N	n_E	n_S	n_W
1	5	2.3	2.0	9.9	2.0
2	5	2.2	2.1	7.6	4.4
3	5	2.2	2.3	6.2	5.5
4	5	2.3	2.3	3.8	7.9
5	5	2.2	6.4	2.0	5.6
6	4	2.3	9.5	2.2	8.2
7	3	2.6	13.4	2.1	13.9

It can be noted from Fig. 3 and Table 1 that solution no. 1, which has the highest cooling energy and lowest heating energy, is that with a very low number of zones per floor in the east, west and north wings, while most of the zones are located in the south wing. Since the south-facing windows of the east and west wings have blinds, the optimization therefore aims to avoid having these shaded windows. This is done through minimizing the number of zones in these two wings. Instead, the amount of zones in the south wing is increased which leads to maximizing the solar gains and hence minimizing the heating energy and maximizing the cooling energy. This solution is also more compact and therefore minimizes the heat losses through the external surfaces by using five floors, which is the highest number found in the optimal solutions. On the contrast, the other extreme solution no. 7, with the lowest cooling energy and highest heating energy, has more zones distributed on the east and south wings, and hence utilizes more shaded windows that face south. By this, the required cooling energy is minimized, but then, the heating energy is maximized. The intermediate solutions express the transformation of the geometry through intermediate configurations between the two extreme solutions, from more zones on the south wing to more on both the east and west wings.

Figures 4-9 show the features of the optimal non-dominated solutions of the buildings. Fig. 4 shows the number of floors for all the optimal solutions. It can be noted that the solutions with the higher cooling energy (and lower heating energy) have five floors, which make them more compact for the heat loss through the exposed outer surfaces. The rest of the optimal solutions as we go towards the left-hand side of that Figure have four and then three floors. The exposed surface area of the building (opaque and glazing) for the five floors configuration is 5% smaller than that for the four floors and it is 15% smaller with respect to that for the three floors. The exposed glazing area is also different. The reason for these differences is that with a higher number of floors, the central internal zone connecting between the four wings takes more area from the constant total floor area of the building and therefore reduces the exposed surface area to the outdoors. However, the optimization tries to find the best compromise between having higher number of floors and the distribution of the zones on the four wings related to managing heat losses and solar gains through the external surfaces. For example, the extreme optimal solution no. 1 has five floors (and not the maximum of seven) because the optimization found that with five floors and more zones on the south wing the building can get higher solar gains.

In Fig. 5, we can note that there is only small effect of the number of zones in the north wing, which is due to its low interaction with the solar gains. There is a small increase in the number of zones to a maximum of 3.7 on the left-hand side of the Figure causing lower cooling energy. On the other hand, Fig. 6 indicates the importance of the number of zones in the south wing on the solutions. The trend is so that when the number of zones on the south wing decreases, the cooling energy also decreases due to less solar gains.

Fig. 7 indicates that with higher number of zones in the east wing, the cooling energy decreases. This is due to the existence of the blind on the south facing windows of this wing. The same trend can be noted with the number of zones in the west wing in Fig. 8. However, the number of zones in the east wing exhibit higher values than that for the west wing (maximum 24.3 compared to 14.9). Putting the data of the east and west wings together in Fig. 9, we can note that the distribution of the zones in the east and west wings is interchanging some of their positions, from which it can be concluded that the trend of the distribution of the zones in these two wings can follow their average values and as shown in the Figure.

It can be concluded that the optimization is basing its solutions on managing the distribution of the area and orientation of the glazing related to the solar gains and the distribution of the exposed surfaces of both the glazing and opaque surfaces related to heat losses. This also considers the effect of the imposed condition of having blinds on the south-facing windows on the solar gains.

Guided by the above results for the distribution of the zones, it was possible to explore new solutions by ignoring a wing length when the number of the zones per floor is close to 2. This latter was a limitation by the simulation tool to allow representing at least one middle zone and the end zone per floor in a wing. Instead, equivalent lengths were added proportionally to the other wings. The new solutions were clearly better in terms of the two objectives. Due to the space limitation in this paper, it is not possible to elaborate on these solutions.

CONCLUSION

This paper presents a method for guiding building designers and architects in generating optimal building shapes that can simultaneously minimize multiple-objective like energy, cost and thermal discomfort in buildings. A bi-objective optimization problem for generating optimal geometry for an office building starting from a cross-shape was solved using a combination of IDA-ICE simulation program and MOBO optimization program. It was found that it is not straightforward to implement building dimensions optimization due to special considerations by the simulation software for the representation of different possible zones in the simulation iterations during the optimization. The scripting feature in IDA-ICE is not widely used for this kind of tasks and it certainly was not optimal for this work. Sometimes changing the coordinates in a wrong order led to structures that were too complex for the modelling and caused the program to report error messages and interrupt the script. However, it was possible to handle this difficulty by manipulating the shape of the template-model before running the script.

The solved optimization problem showed results that can produce a maximum reduction of the cooling energy of the building by10% and the heating energy by 7%. This was done by the re-distribution of the zones on the four orientations of the building and selecting the number of floors in order to best utilize the solar gains and manage the heat losses through the exposed surfaces. The optimization solutions gave guidance about the optimal trends of the distributions of the zones in each direction and accordingly hints were concluded about how to explore better solutions.

The continuation of this work is planned to include combining the simulation-optimization tools with BIM (Building Information Modelling) so that the simulation program can import the basic building information from the BIM model and the optimization program can export the optimum solutions back to the BIM for visualization. Other possible directions include setting the optimization for the minimization of the operating cooling and heating energy costs.

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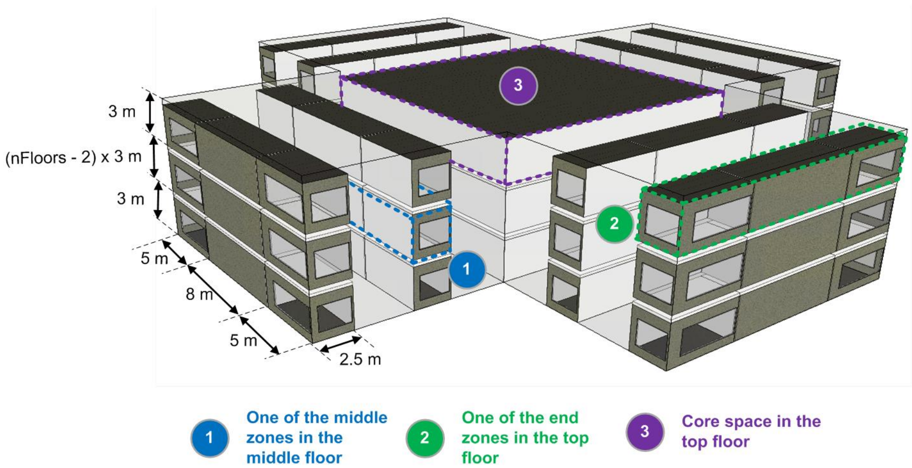

Figure 1 Basic shape of the building.

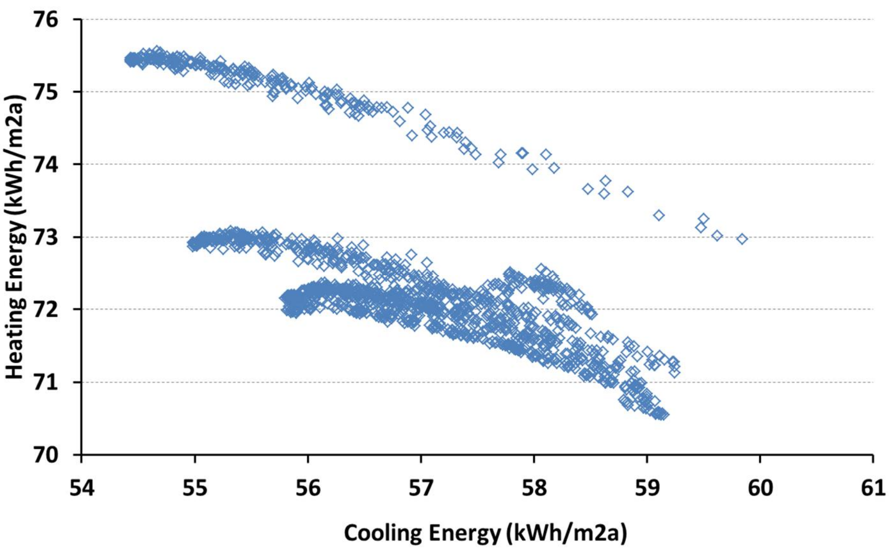

Figure 2 History of the simulation runs.

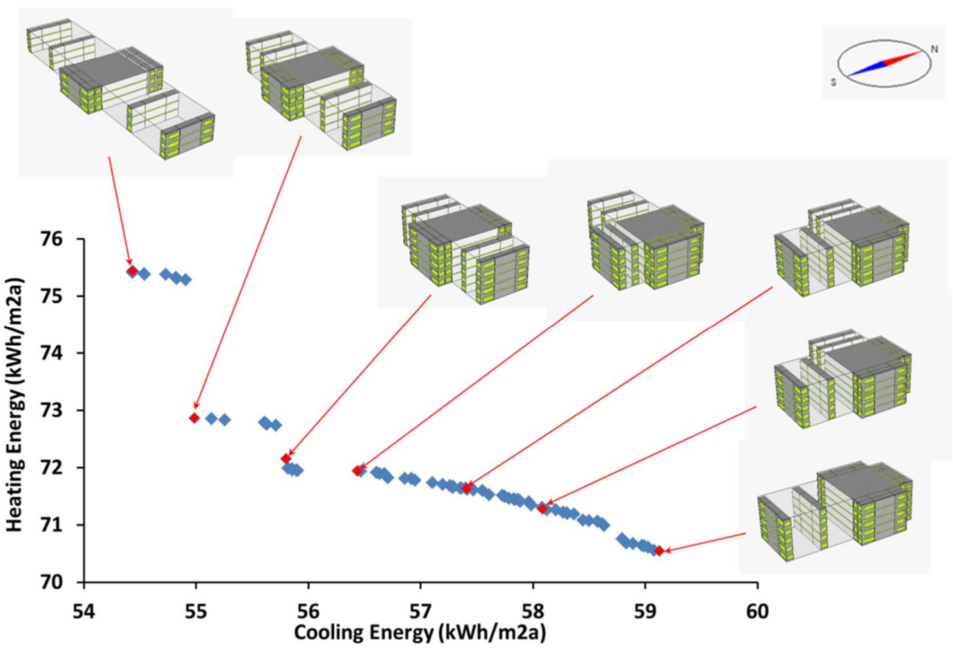

Figure 3 Selected representations of some solutions on the non-dominated front.

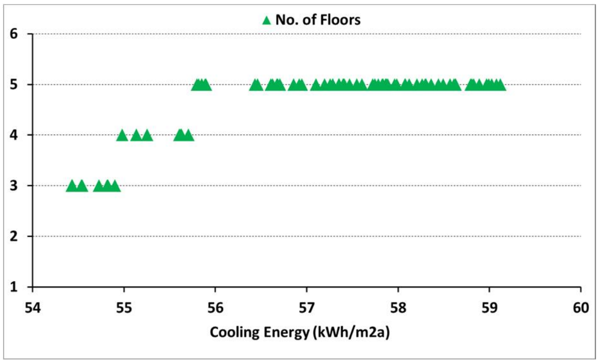

Figure 4 Number of floors in the optimal solutions.

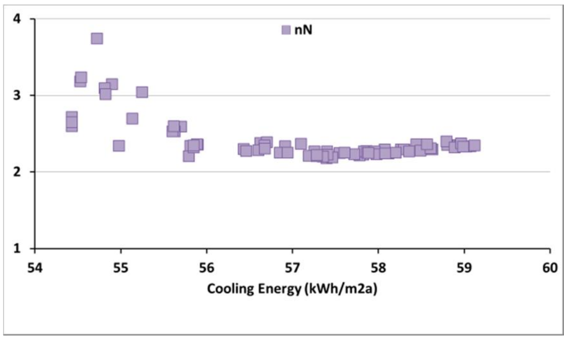

Figure 5 Number of zones per floor in the north wing.

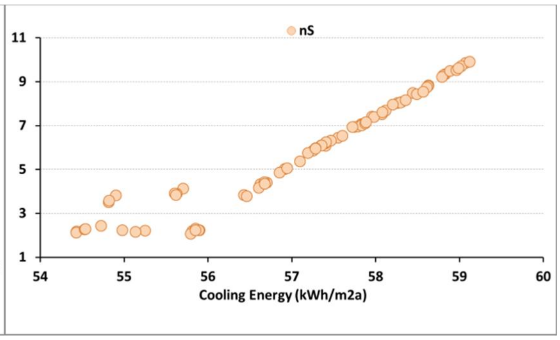

Figure 6 Number of zones per floor in the south wing.

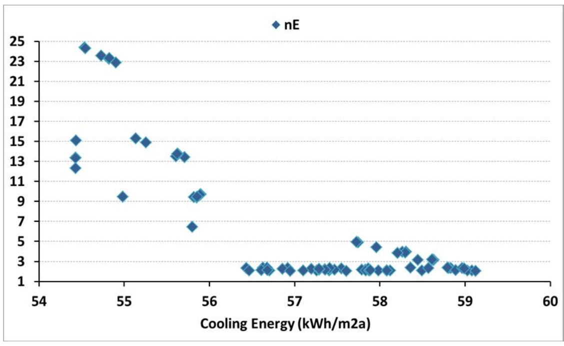

Figure 7 Number of zones per floor in the east wing.

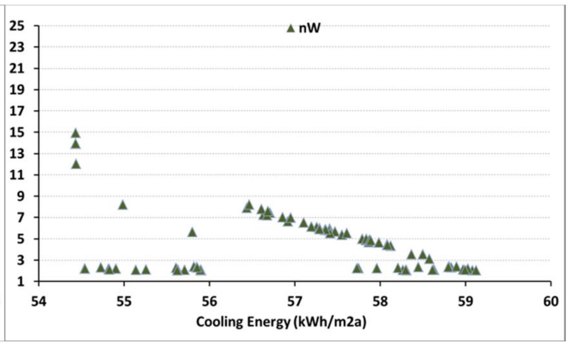

Figure 8 Number of zones per floor in the west wing.

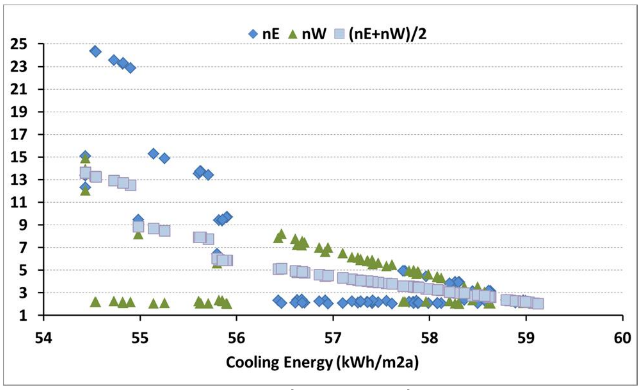

Figure 9 Average number of zones per floor in the east and west wings.