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The Impact of Basic Architectural Design. Thinking beyond BR10 and Passivhaus Standard Prescriptions with the Use of Genetic Optimization.

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SUMMARY

The research explores the impact of the shape, construction type, materials and components of buildings and users' scenarios – on buildings' key energy loads (heating, cooling and lighting) in Copenhagen's climate. Applying a genetic algorithm, a search space consisting of over 408,000 simulated buildings was used to extrapolate the optimal solutions. All buildings are compliant with the Danish Code BR10 and some with the most restrictive Passivhaus standard, enabling a discussion about the two systems effectiveness. Finally it is highlighted how much it is possible to reduce building energy loads by proper basic design choices based on energy simulation coupled with genetic optimization.

KEYWORDS

Energy performance, basic design, genetic optimization, cold climate

INTRODUCTION

Although the agenda of sustainability encompasses several domains, energy and environmental issues are among the most critical. Considering that heating, cooling, and lighting are processes accomplished by adding or removing energy from a building – and that Denmark has a target of reducing building energy use – it is important for Danish architects to design low energy sustainable buildings. In response, this paper aims to provide architects with information to design low energy and low carbon-emission buildings in Copenhagen, specifically focusing on the basic design decision. According to a previous research (Naboni, 2015), the optimization of basic architectural and construction design solutions can reduce, depending on the climate, the primary energy needs of buildings up to 76%.

The information provided in this paper supports the first and the second of the three-tier approach to sustainable design towards the heating, cooling, and lighting of buildings described by Lechner (2015). Accordingly, the first tier is load avoidance by efficiency of building design. Here, the need for heating, cooling, and lighting can be minimized by the design of the building itself. The second tier consists in the use of natural forms of energy through methods such as passive solar design and daylighting; this tier is also accomplished mainly by the design of the building itself. The third and last tier is represented by the use of mechanical and electrical equipment. According to Lechner, tier one and two can easily reduce buildings' energy loads by 50%, and – with a little effort – 80% reductions are also possible. Therefore, this paper aims to verify how, basic building design decisions, can be effective within the Copenhagen's climate zone.

To overcome the limitations of previous studies, this research encompasses an approach including a large number of basic design options and construction variables to evaluate their impact on energy optimization and daylighting. To the aim of the multi-objective optimization, an evolutionary algorithm is used, which focuses on reducing the number of building energy simulations required for exploring a large search space with over 400,000 buildings' options. This research aims to answers to the following question: to what extent, in Copenhagen, proper basic design decisions can reduce buildings energy consumption?

METHODS

The research aims to evaluate the influence of basic design decisions on the energy performances of buildings in Copenhagen. According to ASHRAE Standards 90.1 and ASHRAE Standards 90.2-2007 Copenhagen has a Cool-Marine climate (type 5C). In order to identify basic design solutions that are suitable to the local climate, a genetic optimization algorithm (GA) was used to explore the potential reduction of heating, cooling, and lighting energy demand. Genetic Optimization is a technique inspired by Darwinian evolution theory, and automates the process of searching for optimal design solution. A most widely used evolutionary optimization algorithm, the genetic algorithm (GA), starts by generating a number of possible buildings design solutions to a problem, evaluating them and applying the basic genetic operators (reproduction, crossover and mutation) to that initial population, according to the fitness ranking of each individual building (Fasoulaki, 2007; Palonen et al., 2009). This process generates a new population with higher average performance than the previous one (against a range of set indicators). This system has the advantage of reaching (near) optimal solutions in a short time of computation that a full parametric study (Naboni, 2013).

A series of basic models were created with EnergyPlus [1] and parametrically defined with JEplus+EA [2]. More than 400,000 buildings' options constitute the optimization search space, each resulting from the combination of three group of design variables. The first group relates to the building geometry, defined by compactness and orientation; the second concerns with the design of glazed systems; the third refers to building materials. Table 1 lists altogether the design variables. Two users' occupational scenarios are tested (Table 2), each referred to the source of the prevailing energy load: "internally-dominated" buildings, such as large office buildings; and "envelope-dominated" buildings, such as houses. In a previous study on the impact of the building form on its energy performance, sixteen building shapes were analysed (Ordoñez, 2014). Three cases from the study were taken into consideration (Fig. 1), representing extreme and average values of compactness (Table 3). The latter is defined as the ratio of total internal heated volume divided by total external surface area. Total external surface area is the sum of external walls, roof and ground floor.

Every shape has a volume of 15,552m^3 and 3m floor-to-ceiling height. Building shapes are modular, each floor is divided into five thermal zones (Fig. 2) and partitions walls are placed at a distance of 4.6m from the building façade. To allow for daylight penetration and distribution, internal partitions are glazed. A light sensor is placed at the centre of each thermal zone. Light sensors measure the amount of daylight, and the information they provide is used to gradually increase/decrease artificial light in order to maintain the required level of illuminance (500 lux) during occupied periods. External windows have variable properties of visible transmittance (VT), solar heat gain coefficient (SHGC), and U-value. External walls and roof are made of a concrete shell with an external insulation (EPS, R-value=0.27 K m^2/W). The thickness of the concrete shell varies from 0 to 0.30m, insulation varies from 0.15m to 0.60m, Outer and inner walls are cladded with plasterboard panels (0.01m). All the building solutions comply with the Danish Building Regulation BR10, some of the solutions comply with Passivhaus standards.

Table 1. Search Space

Variable	N°	Simulated Options
Location	1	Copenhagen
Users Scenario	2	Internally-dominated Envelope-dominated
Building Shape (based on compactness)	3	See Table 3
Window to Wall Ratio	3	40 ÷ 90
Window Visible Transmittance	3	0.7, 0.8, 0.9
Window Solar Heat Gain Coefficient	3	0.4, 0.6, 0.8
Glazed System U-value [W/K·m^2]	4	0.4, 0.8, 1.2, 1.4
Air Infiltration [ACH]	3	0.3, 0.6, 1.2
Building Envelope: Solar Absorptance	3	0.1, 0.5, 0.9
Building Envelope: Wall Insulation Thicknesses [m]	10	0.15, 0.20, 0.25, 0.30, 0.35, 0.40, 0.45, 0.50, 0.55, 0.60
Building Envelope Concrete Thicknesses (Thermal Mass) [m]	7	0.00, 0.05, 0.1, 0.15, 0.2, 0.25, 0.30
Search Space	**408,240**	

Table 2. Users Scenario

	Internally Dominated	Envelope Dominated
Occupancy [people/m^2]	0.0714	0.0283
Lighting [W/m^2]	11	11
Equipment [W/m^2]	8.15	3.87
Outdor Air Flow per Person [m^3/s person]	0.00236	0.00236
Outdor Air Flow per Zone Floor Area [m^3/s m^2]	0.000254	0.000305

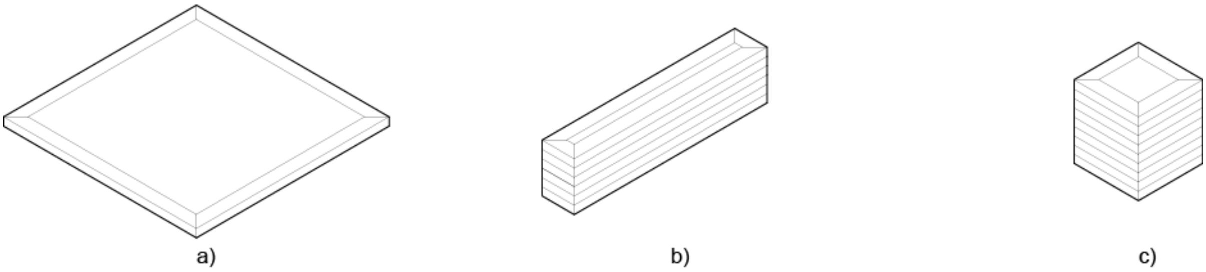

Figure 1. Building Shapes: a) Low compactness with the largest facade facing south; b) Medium compactness; c) High compactness

Table 3. General Dimension of the building shapes

Building Shapes	General Dimensions								
	H [m]	L [m]	W [m]	No. of Levels	Walls [m^2]	Roof [m^2]	Floor [m^2]	Ext. Surf. [m^2]	Compactness [m^3/m^2]
a) Low	3	72	72	1	864	5 184	5 184	11 232	1,38
b) Medium	18	12	72	6	3 024	864	864	4 752	3,27
c) High	27	24	24	9	2 592	576	576	3 704	4,15

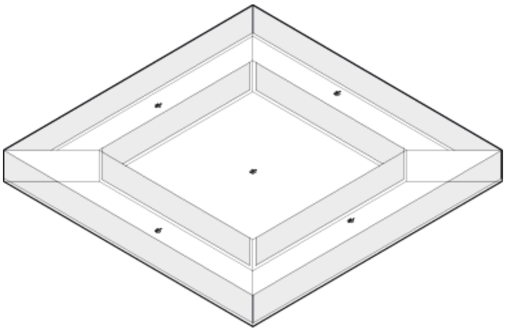

Figure 2. Positioning of daylighting sensors (typical floor)

The HVAC system was modelled with the EnergyPlus object *IdealLoadsAirSystem*. The heating and cooling system operates during occupied periods with a set point temperature of 20ºC and 25ºC respectively. The set points are within the ranges advised by the BR10 (design temperatures as for DS418 and DS469). Energy and daylighting -based optimized solutions could be found within 7 hours on a quad-core pc for each of the two users' scenarios for a total of 14 hours of simulation. The optimization of the design variables was carried out with JEPlus+EA through the non-dominated sorting genetic algorithm II (NSGA-II). The settings of the initial evolutionary algorithm are listed in Table 4.

Table 4. Evolutionary algorithm settings

Population Size	10
Max Generation	200
Crossover	1
Mutation	0.2
Tournament	2

RESULTS

Energy Load reduction by basic design decisions

Table 5 shows the reductions achievable in terms of energy loads by comparing the value for the best solution and for the worst case scenario among the population of generated buildings for heating, cooling and lighting. Table 5 illustrates the achievable by design cumulative energy load savings. This shows that by *efficiency of building design,* the need for heating, cooling, and lighting can be minimized by 58÷59% depending on the user scenario. Considering that all solutions are BR10 code compliant, including the worst case, this shows that basic architectural design decisions can have a significant impact on reducing energy needs and the sizing of mechanical and electrical systems. Code compliancy is therefore not enough, within code compliant solution it is possible to focus on architectural and construction optimization reducing the need of HVAC systems.

Table 5. Load reductions

Energy Demand [kWh/m^2 · year]	**Internally-dominated**		**Envelope-dominated**	
	Best Solution	**Worst Case**	**Best Solution**	**Worst Case**
Heating + Cooling + Lighting	67.75	165.59	101.25	241.23
Reductions Achieved	59.08%		58.13%	

Influence of design and construction factors

The scatter plots stress the optimal solutions for both commercial (internally-dominated) and residential (envelope-dominated) users' scenarios. The graphs display the population of buildings' annual energy loads (Fig.3). It is highlighted how a single design variable, for example compactness (Fig.4) influences heating and cooling. Two types of graphs plot are shown. The first presents annual energy demand for heating (x-axis) and cooling (y-axis). The second is related to the annual energy demand for lighting (Fig.6).

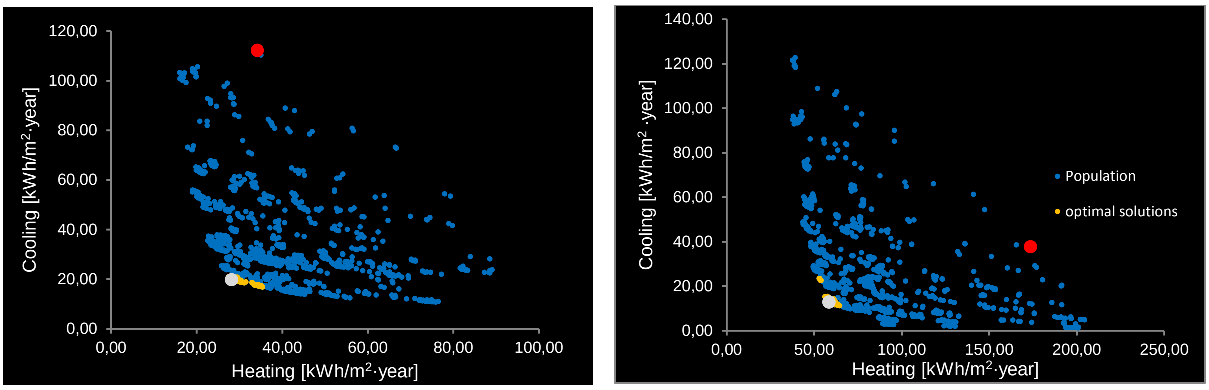

Figure 3. Scatter Plot of the whole buildings population. Best Solution is a white dot. Optimal Solutions are in yellow dots. Worst-case scenario is in red. Internally-dominated (left) and Envelope-dominated (right)

Air Infiltration Rates

The data breakdown shows that solutions are divided in three main groups with substantial differences in heating loads (Fig. 4): 0.3 ACH (air change per hour) reduces heating needs in both users' scenarios (Internally-dominated and Envelope-dominated). According to the Passivhaus standard, a value equal or lower than 0.6 ACH at 50Pa is the benchmark not to be exceeded. This research, is however not debating the issue of quality of air and integration with mechanical systems.

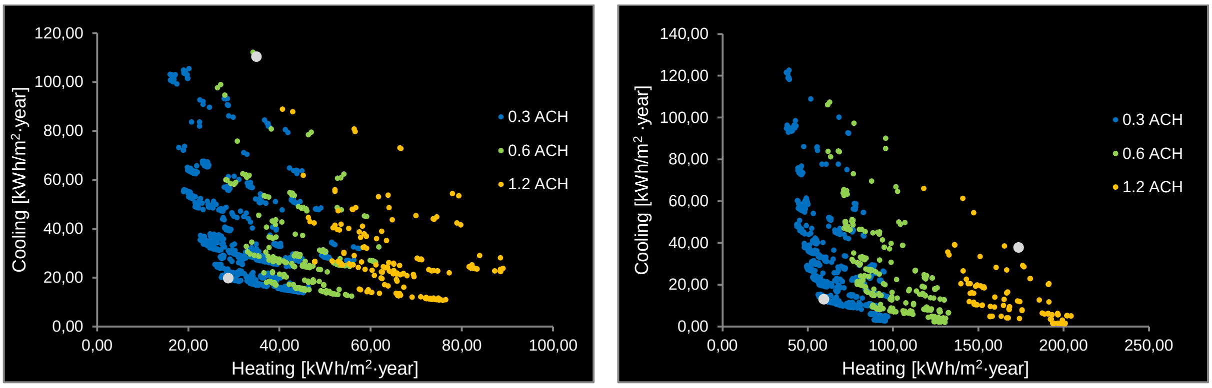

Figure 4. Impact air-infiltration on thermal energy loads: Internally-dominated (left) and Envelope-dominated (right)

Building Form

Figure 5 and 6 underline a direct correlation between the internal loads and the compactness of the building. Shapes between 3.27 – 4.15 m^3/m^2 (medium to high compactness) convey to optimal performance. With the internally dominated energy loads scenario (e.g., commercial buildings), a low compactness (1,38 m^3/m^2) allows more potential for reduction of cooling loads due to the higher amount of surfaces that can dissipate heat. Such compactness allows for reduction of lighting loads (Fig.6). More compact solutions would require top lighting solutions or the presence of an atrium for adequate daylighting.

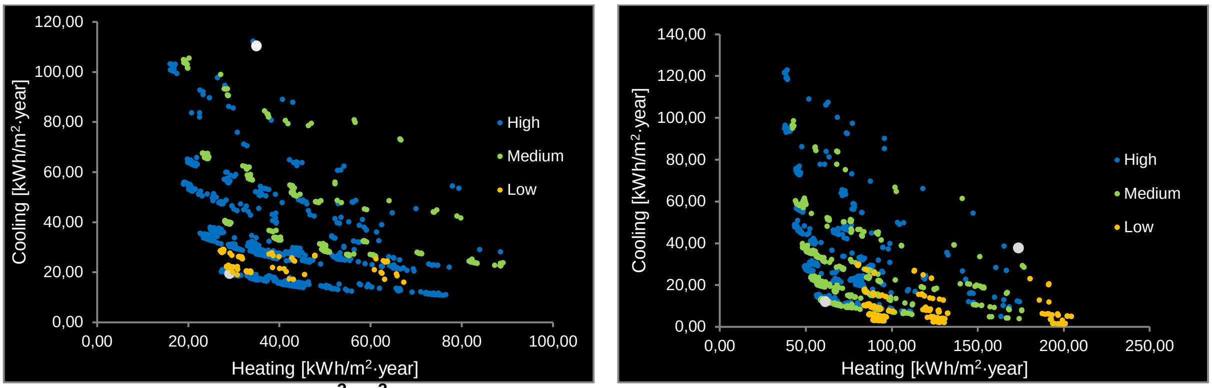

Figure 5. Compactness [m^3/m^2]: Internally-dominated (left) and Envelope-dominated (right)

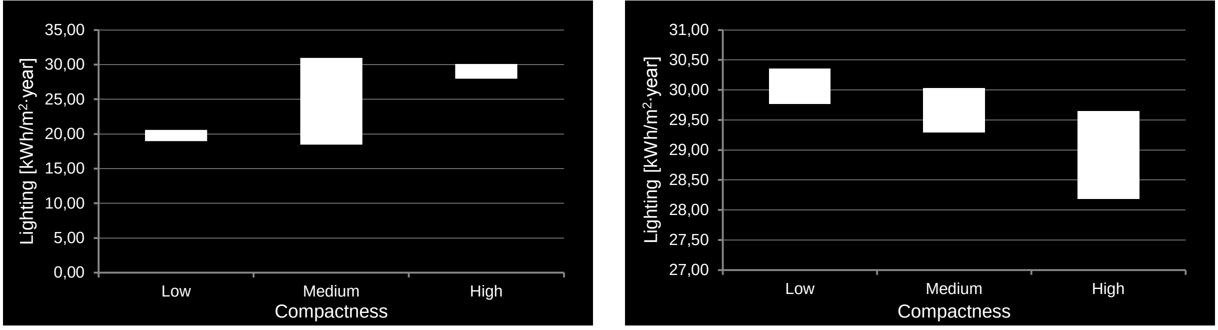

Figure 6. Compactness: Internally-dominated (left) and Envelope-dominated (right)

Façade design

The optimal solutions presented in Fig.7 follow the common rule of thumb that the window-to-wall ratio (WWR) should be 40% or lower in cold climates, to avoid excessive thermal losses. High-performing windows with low U-values can allow higher WWR. Fig. 8 shows that a WWR of 90% on every of the facades minimizes energy consumption for lighting, although it clearly triggers an increase in the energy expenditure for heating and cooling. This suggests that adopting high performance glazing with low U-value (i.e., triple glazing) and high visible transmittance (VT) can provide significant advantages. Future research with multi-objective algorithms should aim to include high performance, well above standard, glazing systems. Fig. 9 shows that optimal solutions corresponding to low energy loads are achieved for with the U-value of 0.4 W/Km2, which matches Passivhaus standard prescription. The

BR10 recommendation for new buildings (U-value ≤ 1.4 W/Km2) seems not to be abundant. Fig. 10 explains the big impact of windows Solar Heat Gain Coefficient (SHGC). Obviously, minimized lighting consumptions are achieved for visible transmittances comprised between 0.8 and 0.9 (Fig. 11 - 12).

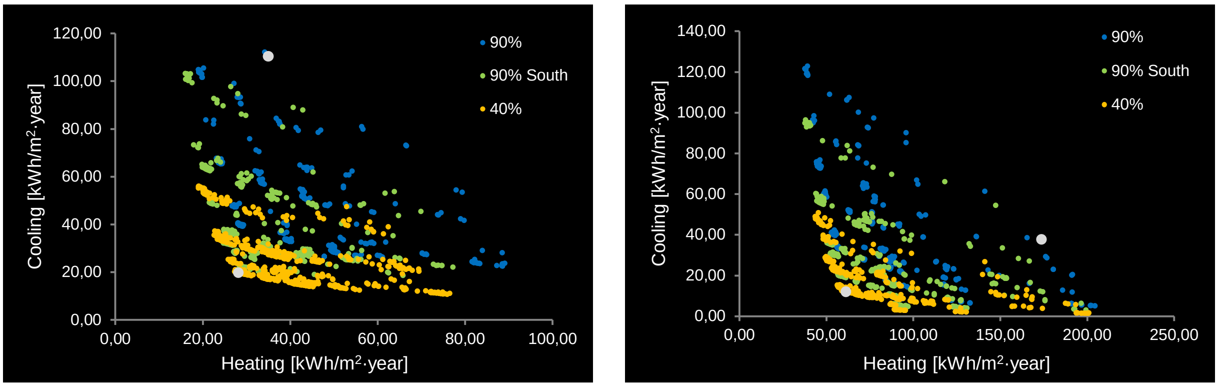

Figure 7. Window-to-wall ratio: Internally-dominated (left) and Envelope-dominated (right)

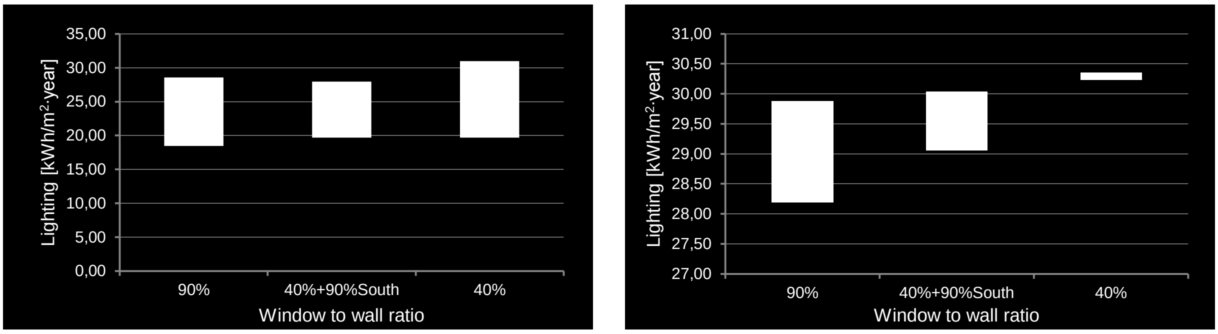

Figure 8. Window to wall ratio: Internally-dominated (left) and Envelope-dominated (right)

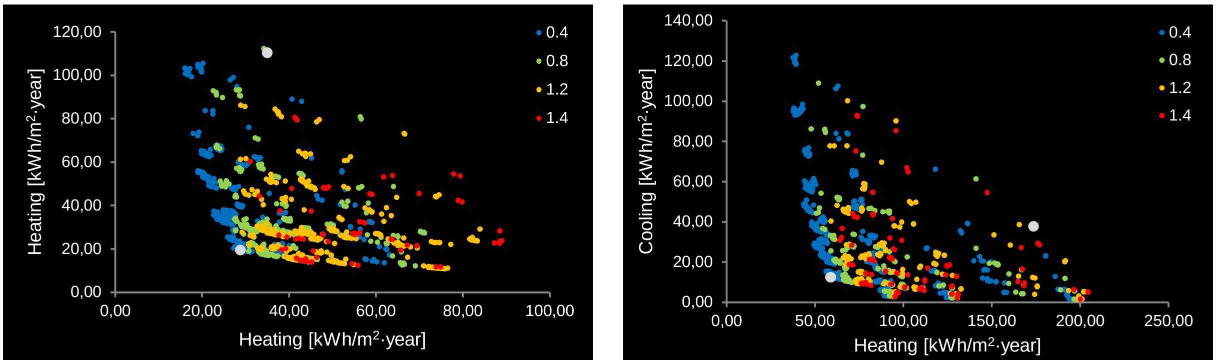

Figure 9. Glazed System U-value [W/K·m^2]: Internally (left) and Envelope-dominated (right)

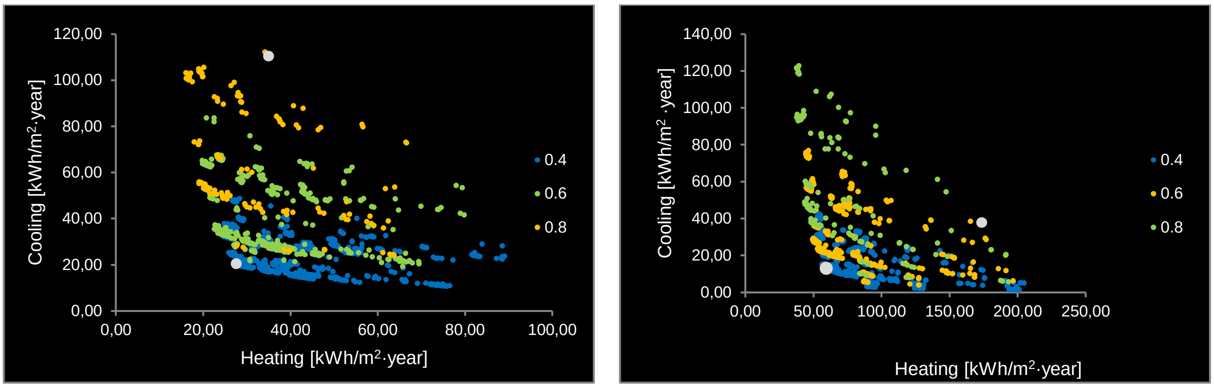

Figure 10. SHGC: Internally-dominated (left) and Envelope-dominated (right)

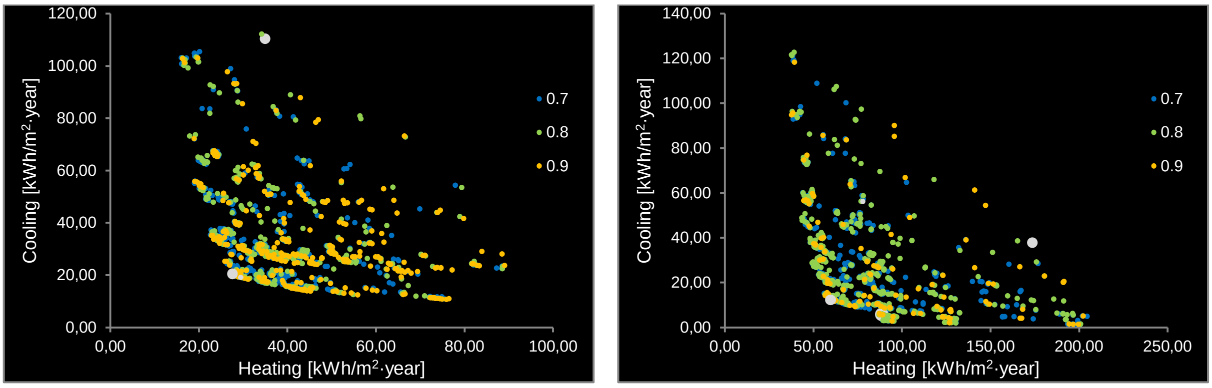

Figure11. Visible Transmittance: Internally-dominated (left) and Envelope-dominated (right)

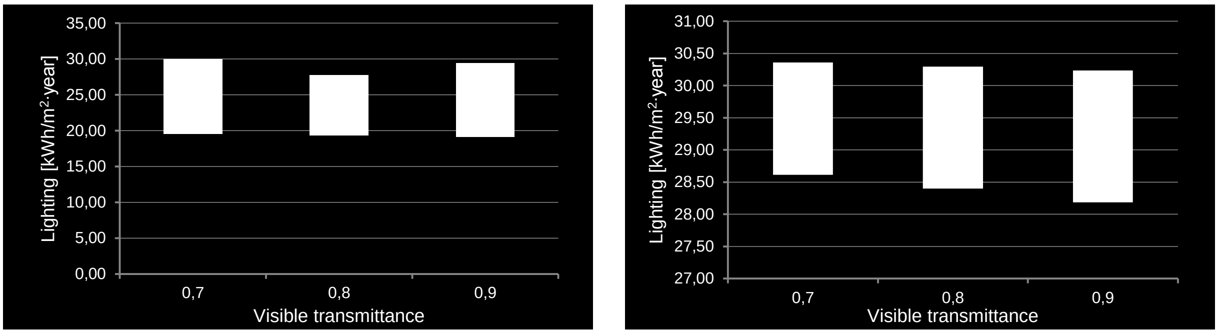

Figure12. Visible Transmittance: Internally-dominated (left) and Envelope-dominated (right)

Wall assemblies

With no surprise, high thickness insulation (0.45, 0.50, 0.55, 0.60 m) is suggested for the climate of Copenhagen (Fig.11). A thickness of the concrete shell of 0.15m matches the lowest annual heating load in the internally dominated scenario (Fig. 12). Contrariwise, a value of 0.25m is associated with the lowest annual heating energy load in the envelope-dominated scenario. This difference proves the need of customize thermal mass thickness according to the program type. A preliminary conclusion is that highly insulated buildings as allowed by both the BR10 and the Passivhaus standard, with no exposed thermal mass, may be underperforming for certain programs. The optimum U-value for opaque external surfaces (wall, roof and ground floor) is comprised between 0.086 and 0.065 W/m^2 K. These values are much lower of the ones suggested by the Passivhaus standard, which suggests a value ≤ 0.15 W/m^2 K, and with the recommendations of BR10, which indicate for new buildings (class 2020) a value ≤ 0.15 W/m^2 K for external walls and ≤ 0.1 W/m^2 K for roofs and floors in contact with the ground.

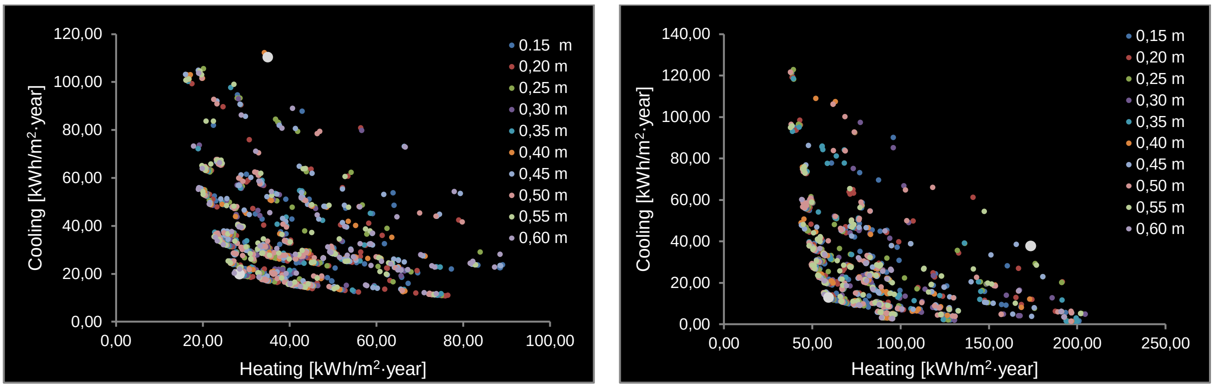

Figure 13. Insulation Thickness: Internally-dominated (left) and Envelope-dominated (right)

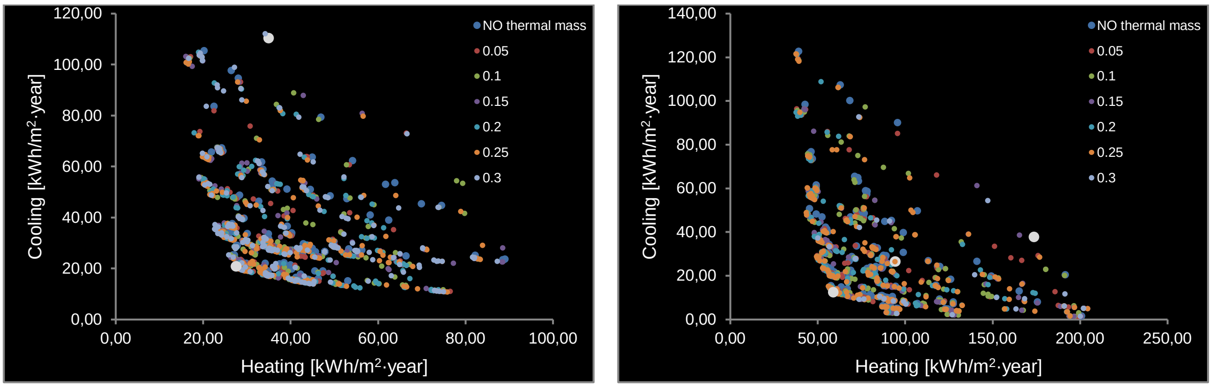

Figure 14. Thermal mass: Internally-dominated (left) and Envelope-dominated (right)

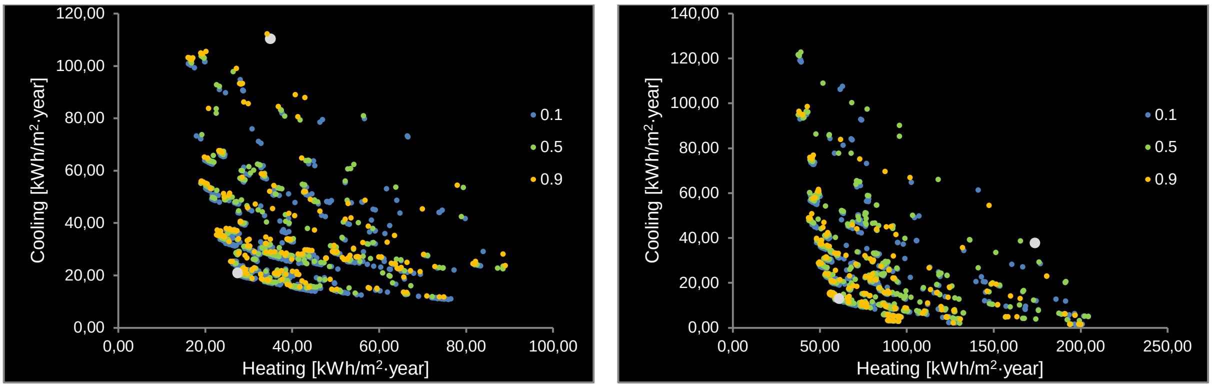

Figure 15. Solar absorptance: Internally-dominated (left) and Envelope-dominated (right)

CONCLUSIONS

The research findings reveals that design a building to comply with the prescription of BR10 and Passivhaus may not always conduct to architectural and construction based energy efficiency. Prescriptive criteria and recipes for energy efficiency may not always lead to optimization. Results show that energy demand can be reduced up to 58% can be obtained in the climate of Copenhagen by basic design decision supported by the use of genetic optimization methods. Results from the Pareto-based study proved to be a valuable tool to comprehend the trade-offs between conflicting objectives. Future research should be targeted to a comprehensive parametric study that analytically describes the relative weight of design variables.

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