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Defining The Energy Saving Potential of Architectural Design

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Abstract

Designers, in response to codes or voluntary "green building" programs, are increasingly concerned with building energy demand reduction, but they are not fully aware of the energy saving potential of architectural design. According to literature, building form, construction and material choices may be powerful drivers of energy efficiency – but a very few studies have quantified their actual effect in different climate, and none of the study is based on today computational possibilities. This research was inspired by, and attempts to verify, the ideas from two of the most influential books on sustainable design: "Design With Climate" by Olgyay (1963), which discussed strategies for climate-adapted architecture, and Lechner´s "Heating, Cooling and Lighting" (1991), on how to reduce building energy needs by as much as 60 – 80 percent with proper architectural design decisions. Both books used results from building energy simulations made with limited computational resources available at the time. The research presented in this paper uses a genetic algorithms based approach for the optimization of heating, cooling and lighting energy demands of different building designs. In total, over 25 million different buildings constitute the optimization search space, and the most energy efficient design solutions were explored for 8 different climate zones. The building designs are varied by shape, orientation, window to wall ratio, component and construction types, materials, and different occupant behaviour. The research shows the best solution for each of the climates and compares them with Olgyay´s findings. Finally, for each climate the energy saving potential is defined and then compared to Lechner's conclusions.

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Keywords: climate adapted architecture; energy performance; genetic optimization

1. Introduction

It is recognized that architectural and construction design decisions have an important effect on environmental and energy performance of buildings. In his book "Design with Climate" (1963), Victor Olgyay described how architecture should be inspired by biology for a definition of the measure and purpose of comfort requirements; by meteorology for a precise description of the existing climatic conditions and by engineering sciences for a rational solution and execution. Using the findings from other sciences and applying them to four distinct climate regions, temperate, cool, hot-arid, and hot-humid, Victor Olgyay showed how we can arrive at new interpretations and exactness in architectural theories of orientation, shading, building form, air movements, site location, and effects of materials. Almost 30 years later, Lechner (1991) discussed how the sustainable

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design of heating, cooling, and lighting systems in buildings could be more easily accomplished by understanding the logic of a three-tier approach, of which the first and second tiers are deeply rooted into Olgyay's research. The first tier consists of architectural and structural design decisions of buildings. If all the right decisions are made for the sake of minimizing energy consumption, up to 60 percent reduction of the heating, cooling and lighting energy demand is achievable. The second tier involves the use of natural energy sources through such methods as passive heating, passive cooling, and daylighting systems. Proper decisions taken at this point can reduce the energy demand by a further 20 percent. Thus, according to Lechner, the strategies in tiers one and two, both purely architectural, can reduce the energy demand of buildings by up to 80 percent. Tier three consists of designing the mechanical equipment to be as efficient as possible. When Olgyay wrote his book, building energy simulation was at its inception, whereas when Lechner made his claims, energy simulation allowed for a small number of simulations with simplified building models. The aim of this research is to verify the climatic design opportunities effectiveness with state-of-the-art computing technology and building performance simulation tools.

2. Methods

Both publications support the idea that buildings are living entities whose characteristics evolved in vernacular architecture towards an optimal integration with their sites. As leaders in the research on bioclimatic architecture, Olgyay and Lechner could be considered among the few 'fathers' of contemporary environmental building design. Their research and publications laid the foundation for much of the energy simulation software in use today. They described how, similar to what happens in nature with the evolution of species, buildings can be optimized using the same process. In this paper, the process of optimization is used to reduce the number of simulations required to explore a large search space of building designs. The specific technique, Evolutionary Algorithms, is inspired by the Darwinian evolution theory, and has been widely adopted in searching for optimal building designs (Fasoulaki 2007; Palonen et al., 2009). Software tools including EnergyPlus [1] and jEPlus+EA [2] are used in this study. The procedure starts with generating a number of building designs by randomly combining shapes, materials and other design parameters. Their performance is evaluated in terms of heating, cooling and lighting energy demands, in order to identify the most performative designs. The multi-objective optimization algorithm implemented in jEPlus+EA allows to reach near-optimal design solutions in a short time and with limited computation capabilities. The experiment attempts to identify, for the given locations, the set of architectural and construction design parameters that are best fit for the particular climate. Moreover, the research answers the question that to what extent proper architectural design decisions can reduce buildings energy consumption in the context of different climatic conditions?

3. Search Space and Building's Form, Façades and Materials

The research has the main target of evaluating the influence of some of Olgyay and Lechner design climatic design strategies on the energy performance of buildings in different climatic zones. A series of basic building models are created with EnergyPlus and the design variables are defined using jEplus+EA. More than 25 million building designs constitute the search space, each of which results from the combination of three groups of design variables (Table 1). The first group is related to form, defined by shape, compactness and building's orientation, the facades layout and the glazed systems types define the second; a third refers to building materials. The selected weather data are representative of 8 American geographical locations.,. These location are representative of the climate zones defined in the ASHRAE Standard 90.1-2010 but they can refer to other areas in the world (Table 2). In a previous experiment on the impact of the geometry of the building on its energy performance (Ordoñez, et al.), sixteen building shapes were analysed. Four prototypical cases (Fig. 1) representing both extreme and average values of compactness (Table 3) are extracted from Ordoñez's experiment. Compactness is defined as the ratio of total internal volume divided by total external surface area (Gratia and De Herde). Total external surface is the sum of external walls, roof and ground floor. All the building shapes have an internal volume of 15,552 m^3 and a 3m floor-to-ceiling height. The basic idea is to generate a discrete range of building forms, but standardizing their geometric characteristics.

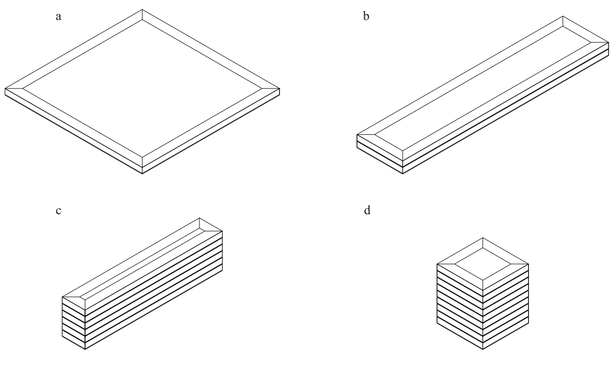

Fig.1 Prototypical Building shapes: a) 3_72_72; b) 6_108_24; c) 18_12_72; d) 27_24_24

Table 1. Description of the simulation variables

Variable	N°	Simulated Options
Location	8	(Table 2)
Users Scenario	2	High internal loads, Moderate internal Loads
Building Shape (based on compactness)	4	Table 4
Building orientation	4	0°, 90°, 180°, 270°
Window to Wall Ratio	6	(Sout, West,_North, East)
Window Solar Heat Gain Coefficient	3	0.3, 0.5, 0.7
Window Visible Transmittance	3	0.4, 0.6, 0.8
Glazed System U-value	3	0.8, 1.3, 1.8 [W/K·m^2]
Shading Device: Overhang Depth	2	0, 2 [m]
Shading Device: Overhang Tilt Angle	2	90°(flat overhang), 45° (tilted overhang)
Building Envelope: Opaque Wall External Surface Solar Absorptance	2	0.1, 0.9
Building Envelope Insulation Thicknesses	11	0.00 0.03, 0.06, 0.09, 0.12, 0.15, 0.18, 0.21, 0.24, 0.27 0.30 [m]
Building Envelope Concrete Thicknesses: Thermal Mass	7	0.00, 0.05, 0.1, 0.15, 0.2, 0.25, 0.30 [m]
Search Space Size	**25,546,752**	

Table 2. Climate zones included in the study and reference cities

Climate zone	Definition	Reference city	Data source
1A	Very Hot - Humid	Miami	TMY3
2B	Hot - Dry	Phoenix	TMY2
3C	Warm - Marine	San Francisco	TMY3
4A	Mixed - Humid	Baltimore	TMY3
5A	Cool - Humid	Chicago	TMY3
6A	Cold - Humid	Burlington	TMY2
7	Very Cold	Duluth	TMY3
8	Sub Artic	Fairbanks	TMY3

Table 3. General Dimensions of the Building shapes

Name	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]	S/V [m^2/ m^3]
3_72_72	3	72	72	1	864	5 184	5 184	11 232	1,38	0.72
6_108_24	6	108	24	2	1 584	2 592	2 592	6 768	2,30	0.44
18_12_72	18	12	72	6	3 024	864	864	4 752	3,27	0.31
27_24_24	27	24	24	9	2 592	576	576	3 704	4,15	0.24

As suggested by Ordoñez et al, building shapes are modular; zoning uses a "four and core" approach, defining a perimeter zone that extends 4.6m inwards from the exterior wall. To allow for daylight, internal partitions are glazed. Light sensors are included to measure the level of indoor daylight and to gradually increase/decrease artificial light in order to maintain ta required level of illuminance (300 lux) during occupied periods. External windows have variable properties such as Solar Heat Gain Coefficient (SHGC), visible transmittance (VT) and U-value. More solutions are studied combining Window to Wall Ratio (WWR) and building orientation. Shading devices of different sizes and angles are also used. External walls are made of external insulation (EPS R-value=0.27 m²K/W) and a reinforced concrete shell. The insulation thickness varies from 0 (no insulation) to 0.30m, while the depth of the concrete shell is variable from 0 to 0.30m. Only Ideal Loads Air System are modelled in EnergyPlus". Heating operates during occupied periods with a set point temperature of 21ºC, and during unoccupied periods with a set point of 15.6ºC. Cooling operates during occupied periods with a set point temperature of 24ºC and during unoccupied periods with a set point of 26.7ºC. The set points are within the ranges advised by ASHRAE Standard 90.1.

4. Optimized set of architectural and construction design solutions.

Giving the number of decision variables are considered in this experiment, it is impossible to perform full parametric analysis of the possible design solutions. Optimization offers a suitable alternative approach for establishing the boundary of the solution space, especially with the Pareto trade-offs between the objectives of minimizing heating, cooling and lighting energy demand. The optimization procedure was carried out with jEPlus+EA's non-dominated sorting genetic algorithm (NSGA-II) for multi-objective problems. In the initial trial we found that after 80 generations (with population size 20), the Pareto front is fairly close to the range of the most performative solutions, and after 200 generations they overlap. The main experiments are then carried out using 80 generations for each climate conditions. In average, the optimization run completes within 14 hours on a quad-core PC. Table 7 summarizes the best solutions found by jEPlus+EA for different climates. It was found that, depending on the climate, some of the variables may have antagonistic effects on the objectives. For example, WWR and shading types may have opposite effects on seasonal energy demand, because increasing indoor solar heat gains in winter may be lead to overheating problems during summer time. Therefore, the used genetic optimization finds the best solution that compromises among seasons. One major advantage of the optimization consists in dealing with the interaction between variables to reach the best design alternative.

Building Geometry. High compactness (4.15 m^3/m^2) is efficient for the Sub-artic climate, whereas for other climates a value of 2.3 m^3/m^2 is called. Low WWR is proposed for warmer climates (Very Hot Humid, Hot Dry, Warm Marine): small windows minimize solar heat gains. High values of WWR are proposed for Mixed Humid climate. For Cold Humid climates a 90 percent WWR for south façade contributes to passive heat gains accumulation. In sub artic areas low WWR minimizes heat losses.

Glazed systems. A SHGC of 0.5, which corresponds to a median value, is suggested for Mixed Humid, Very Cold and Sub-artic climates, a value of 0.3 is proposed in Warm climates. Window VT is optimized by the objective function of lighting, therefore sky illuminance local conditions and solar angles are an impacting factor. A VT of 0.8 could be found in different types of climates (Very Hot Humid, Warm Marine, Mixed Humid, cold Humid, Very Cold and Sub -Artic). In Hot Dry and Warm Marine climates a U-value of 1.8 W/K·m² is optimal. A U value 0.8 $W/K{\cdot}m^2$ is proposed for Cool Humid, Cold Humid, Very Cold, Sub-Artic. 1.3 W/K·m² is proposed for Mixed Humid climate and Very Hot Humid climate. Overhangs are optimal in Very Hot Humid, Mixed Humid, Cool Humid, and Cold Humid climates with a tilt angle of 45°. Horizontal overhangs are the optimized option for Cool and Cold Humid. No shading is suggested for Very Cold and Sub-Artic climates.

Opaque Walls. Optimization trends were towards reducing the U-values of both the walls and the roof for all buildings at all selected locations in order to decrease conduction losses. A solar absorptance of 0.9 is optimal for Cool, Cold and Sub-Artic climates. An insulation thickness of 0.09 m is proposed for Very Hot Humid climate and the highest insulation (0.30 m) for Sub-artic. Thicknesses vary from 0.15 m for the Very Cold climate to the 0.24 m shown in Cool and Cold Humid climates. Thermal mass thicknesses fluctuate between 0.15 m in Sub- Artic and Warm Marine climates and 0.30 m in Cool Humid and Cold Humid cases. 0.20 and 0.25 complete the range by being associated to Very Hot, Mixed Humid climates, and Hot Dry and Very Cold. Thermal mass is influenced by the seasonal and daily variations that determine the need for thermal resistance and mass of the building structure. Accordingly, insulation is more critical in climates with extreme seasonal variations and small daily variations, while the thermal mass of the building plays a more significant role in balancing the indoor temperatures in climates with large diurnal ranges. The experiment provides, for given locations, what set of architectural and construction design solution is best fit. It was found that proposed solutions are aligned with rules of thumb proposed in books such as "Design with Climate" and "Heating, Cooling and Lighting". Although the books were written in the 60s and the 90s when genetic optimization was not available it is interesting to highlight how they provide design suggestions validated by the study.

Table 7. Optimized design solution for a residential scenario

Location	Miami	Phoenix	San Francisco	Baltimore	Chicago	Burlington	Duluth	Fairbanks
Climate Type	Very Hot Humid (1A)	Hot Dry (2B)	Warm Marine (3C)	Mixed Humid (4A)	Cool Humid (5A)	Cold Humid (6A)	Very Cold (7)	Sub Artic (8)
Building Shape (based on compactness) [m^3/m^2]	2.3 (b)	2.3 (b)	2.3 (b)	2.3 (b)	2.3 (b)	2.3 (b)	2.3 (b)	4.15 (d)
Window to wall ratio [percent] S_E_N_W	40_40_40_40	40_40_40_40	40_40_40_40	40_90_90_90	40_40_90_90	90_40_40_40	40_90_40_40	40_40_40_40
Window Solar Heat gain coefficient	0.3	0.3	0.3	0.5	0.3	0.3	0.5	0.5
Window Visible transmittance	0.8	0.6	0.8	0.8	0.4	0.8	0.8	0.8
Glazed System U value [$W/K{\cdot}m^2$]	1.3	1.8	1.8	1.3	0.8	0.8	0.8	0.8
Shading Device: Overhang: Depth [m]	2	2	2	2	2	2	0	0
Shading Device: Overhang: Tilt Angle [°]	45	45	45	45	90	90	0	0
Building Envelope: Opaque Walls External Surface Solar Absorptance	0.1	0.1	0.1	0.1	0.9	0.9	0.9	0.9
Building Envelope Wall Insulation: Thickness [m]	0.09	0.18	0.21	0.18	0.24	0.24	0.15	0.30
Building Envelope Concrete Thickness: Thermal Mass [m]	0.20	0.25	0.15	0.20	0.30	0.30	0.25	0.15

5. Measuring the Energy Saving Potential of Climate-Adapted Architectural Design

Cumulative energy loads of heating, cooling and lighting for each of the buildings generated across the 200 generation of optimizations are displayed in Fig.3. The black mark (X) indicates a distance of 1.5 times from the interquartile range (IQR), measured from the top of the box. By convention, values beyond this mark are considered atypical. Cumulative energy loads vary from climate to climate with a median value ranging between 88,7 kWh/m2 and 131,3 kWh/m2. The lower values correspond to the solutions described in Table 7. The box shows the concentration of buildings with performances close to the median value. After the optimization process, solutions tend to focus between limited ranges of values shown into the interquartile ranges (IQR). Fig.4 displays the achievable global energy loads savings. It is found that architectural design decisions can considerably reduce them from 63 to 76 percent depending on the climate. These values are close to Lechner´s claim that proper architectural design decisions can lead to savings ranging from 60 to 80 percent. Proper design and selection of building components can greatly help in achieving thermal comfort with minimum reliance upon HVAC systems and, therefore, minimizing energy demands.

6. Conclusion

This research confirms well-known literature assertions regarding the best climate-based architectural design strategies and their energy saving potential by using an extensive and systematic approach in analyzing a large amount of data in order to compares the results with the references. We found the energy saving potential of architectural design decisions varies from 63 to 76 percent depending on the climate. It was found that the maximum impact could be achieved by strategizing the building elements such as orientation, form, opening, sun shading devices and materials according to Olgyay and Lechner findings. Future analysis of the current set of data will answer to a series of design questions, including the relative importance of each of the design factors. In this perspective it will necessary to use parametric simulation with the use of large computing clusters organised in cloud infrastructures.

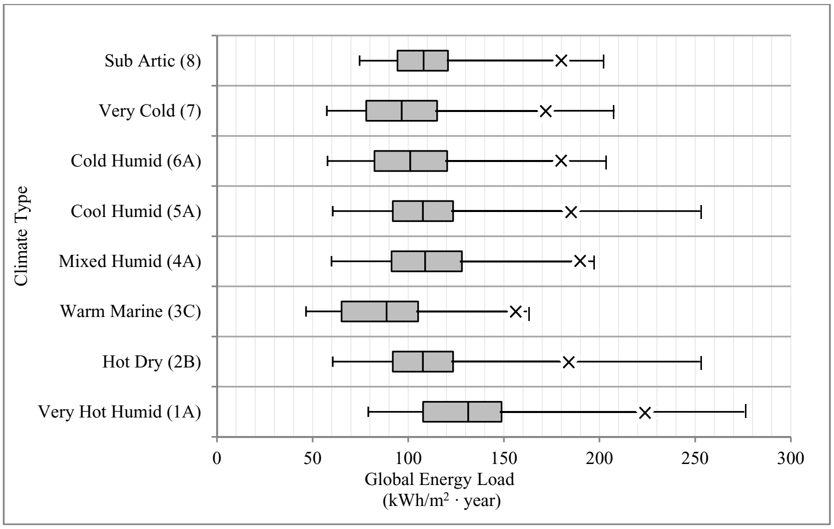

Fig.3 Box plot showing distribution of cumulative energy loads

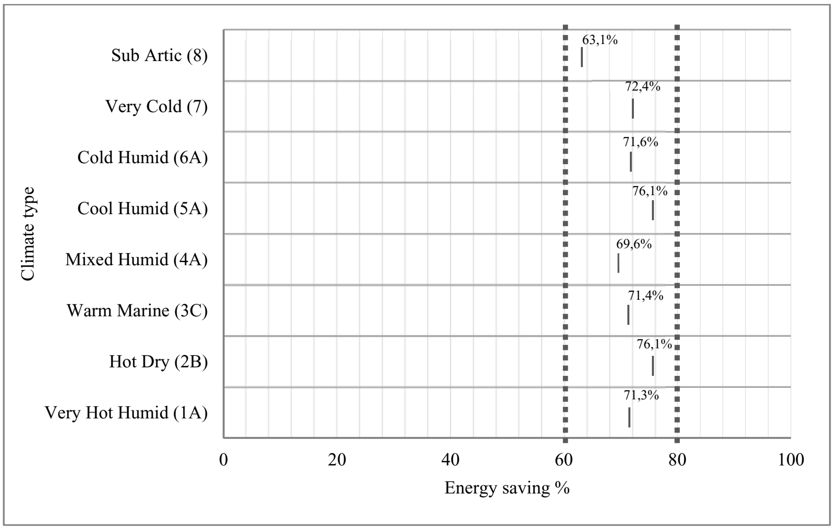

Fig. 4 Achieved global energy savings by the use of genetic optimization. The dashed lines define the range of effectiveness of architectural design defined by Lechner,

7. Acknowledgement

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