

COMPARISON OF CONVENTIONAL, PARAMETRIC AND EVOLUTIONARY OPTIMIZATION APPROACHES FOR THE ARCHITECTURAL DESIGN OF NEARLY ZERO ENERGY BUILDINGS

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ABSTRACT

The research investigates how different design approaches and computational methods can be integrated in the design process of energy efficient and comfortable buildings. Three approaches were studied: a scenario-by-scenario conventional design approach, a parametric approach and an evolutionary optimization approach.

To explore the potential and limitation of such methods, a nearly Zero-Energy Building (nZEB) prototype, named Autarki 1:1 (Greek word for self-sufficient), was designed and built on the campus of the Royal Danish Academy of Fine Arts in Copenhagen.

The performance optimization was achieved with different tools: EnergyPlus, jEplus and jEplus+EA. The experiment allowed the evaluation and discussion of optimization techniques compatibility with an architectural design process. The user-friendliness, the time required for inputting and computing, the related need of hardware resources and the effectiveness of each strategy are described.

INTRODUCTION

On a global average, building-related activities consume more than 40% of a country's energy. The reduction of buildings' energy consumption is an issue that the architecture, engineering, and construction (AEC) industry is facing. In this context, the EU sets ambitious targets to ensure that from 2020 all new buildings will consume very little energy and has created the term "nearly Zero-Energy Building" or nZEB.

Despite the availability of design technology currently used in science and the availability of powerful computational technologies, the AEC industry is far from implementing them in daily practice. The consequence is that architectural designs rarely reach or get close to the "greenest" solutions.

Today, building energy simulations are normally used on a scenario-by-scenario base, with the designer generating a solution, evaluating it, and then creating a new solution based on the previous results. This process is related to the iterative nature of design processes in architecture, but its effectiveness may be limited since just few design scenarios can be

evaluated. Thus, the most "performative" design solution is never reached.

Conversely, researchers argue that the ability to investigate a large number of design alternatives is critical for finding energy efficient designs. To explore multiple design scenarios two approaches have emerged, parametric optimization and evolutionary optimization. A parametric strategy is based on creating multiple design options (often in the region of hundreds of thousands) by the combination of chosen design variables, as a way to identify a range of optimal solutions (Paoletti et al., 2011; Pratt et al., 2011). Despite its potential, parametric studies are rarely used in architecture because they require long computing times. Previous research was conducted to overcome the issue by porting parametric simulations on a cloud service (Naboni et al., 2013).

Another approach, which focuses on reducing the number of simulations required for exploring large search space intelligently, is evolutionary optimization. This is a technique inspired by the Darwinian evolution theory, and is used to automate the process of searching for an optimal solution. A most widely used evolutionary optimization algorithm, the genetic algorithm (GA), starts by generating a number of possible 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 (Fasoulaki 2007; Palonen et al., 2009). This process generates a new population with higher average performance than the previous one. Commonly, the algorithm terminates when either a maximum number of generations has been produced, or a satisfactory performance has been reached for the population. The advantages of the system seem to be related to its effectiveness in reaching (near) optimal solutions in a short time. Despite the potential and the interest shown by some of the leading architectural practices, evolutionary optimization has not been used in real world design projects due to the lack of tools and expertise in the architectural community.

In order to compare how (and if) the different approaches can be used in an architectural building design, and what the opportunities and the limitations

are, the Autarki prototype was designed, built, monitored and optimized with different methods. The initial design of Autarki was developed with a conventional scenario-by-scenario design, where only a few options were tested according to the designer experience and intuition. The model was created with OpenStudio, an architect-friendly modeling interface for EnergyPlus [1], the popular US Department of Energy's building energy simulation tool.

Subsequently, the building performances were monitored and opportunities for optimization were evaluated with a parametric study ran with jEplus [2], a parametric shell for EnergyPlus. In order to reach nZEB targets, the parametric study was carried out in order to analyze the operation of the building and drive small modifications of it. The parametric study (see Table 2) would have required 3840 hours on a standard dual core pc, therefore, it was run on a cluster with 256 cores to reduce the time of computation to 30 hours.

However, the majority of the architectural practices does not have access to a cluster or cloud computing. The development of cloud services for parametric simulation is emerging (Naboni et al., 2013), but a logical question is whether it is convenient to develop such services (now that evolutionary optimization may become available), or not. Thus, in order to evaluate how a typical architectural practice utilizes design optimization and how it can be fluently integrated into the design process, an evolutionary optimization method was explored. The tool used in this study is jEplus+EA [3], a genetic algorithm coupled with jEplus. We aim to find out whether jEplus+EA helps to remove the barriers, existing until now, for the designer to enter into the field of optimization.

AUTARKI PROTOTYPE EXPERIMENT

The Autarki prototype was designed and simulated with EnergyPlus. Simulations were conducted on a standard dual-core pc. Only a few design options, mainly related to form, shading systems and material optimization, were evaluated (Fig. 1). The design evolved in accordance to the designer's typical routine. In total, 10 design options were generated according to the designer's intuition, expertise and experience.

The objective was the creation of a nZEB by using solely passive means, therefore no mechanical or active systems are added to the building (see Table 1). The concept of "extended comfort zone" was implemented as a strategy, as well as the cooperation and education of the building's users. To guarantee a proper air exchange rate, an air-to-air recuperative heat exchanger, inspired by studies carried out in the early '90s at the Technical University of Denmark (Shultz, 1993), was integrated. The heat exchanger is solely driven by natural convection.

Autarki (Fig. 2) was built and placed on a site in the middle of the campus of the School of Architecture in Copenhagen. The building has a floor area of 14 m² and it is fully made of a double shell of Cross Laminated Timber (CLT).

Table 1 Main energy design strategies and features of Autarki

List of possible Strategies	Implemented Design Features in Autarki 1:1
Reduce loads and increase comfort by Architectural Design	Adaptation to Site Form (surface area-to-volume ratio) Size Orientation Program Envelope Design (Windows to Wall Ratio, Façade Colour and surfaces properties, Insulation, Windows, glazing, exterior and interior shadings) Daylight Harvesting Construction Materials Thermal Mass
Reduce Loads by other means	Efficient Computer Extension of Thermal Comfort Zone Air-to-air Recuperative Heat Exchanger
Control, Lighting and HVAC Design	Efficient Lighting Building Monitoring
Alternative Energy Technology	None
Renewable Energy and Active Systems Design	None

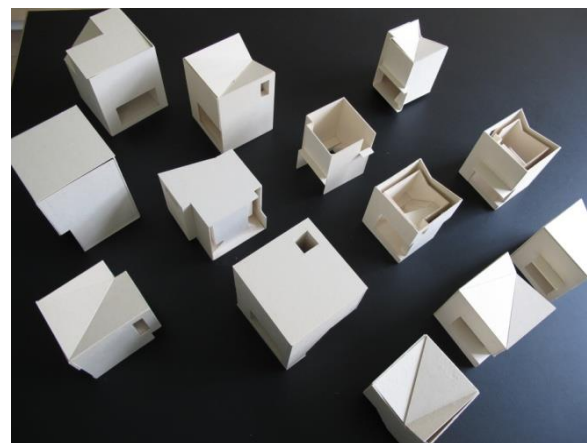


Figure 1 Autarki form studies: the high compactness is the common denominator of all the proposed and tested schemes

Data monitoring and actual performances

Autarki thermal performances are recorded with nine installed sensors and a weather station. All data recorded by loggers are displayed on a dedicated website (www.autarki.dk). During occupation and for the period of study (winter), several discomfort hours

were recorded (35%), in contrast with performance predicted by simulation. Existing EnergyPlus model was improved by using the recorded data for calibration. A new EnergyPlus weather file was generated by using the data from the weather station. In addition to the weather parameters, the inside air temperature was monitored for multiple weeks, as well as users behavior (with occupancy sensors) and the air-to-air heat exchange air rates (with anemometers). Subsequently the energy model was calibrated in order to limit the inside air temperature difference (between monitored and simulated data) below 1.5 °C. On average, the difference between the monitored and simulated indoor air temperatures was within an acceptable tolerance (+/- 0.5 °C). After calibration, a simulation was run for a whole year.

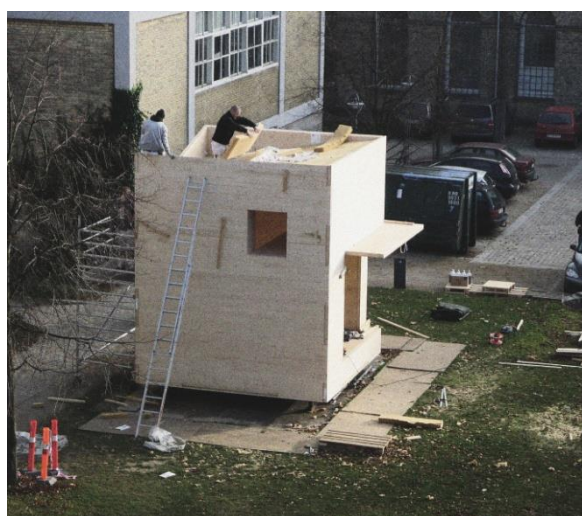


Figure 2 View of the prototype few steps before its completion

The calibrated model showed a yearly (ideal, since no mechanical plants were installed) total energy consumption of 98.6 kWh/m², the 95% of which is related to heating. The discrepancy between design simulation and real performances highlighted an issue: it was clear that the designer had not properly modeled the building users' behavior and their control of the air-to-air ventilation system.

In order to improve the performance of Autarki at low cost, the role of the users (and their education), the operation of the air-to-air naturally ventilated heat exchanger (Fig. 3), and a few adjustments of the prototype (e.g. addition of floor thermal mass and optimization of the shading system size) were investigated. Few scenario-by-scenario modifications of the model were explored. While opportunities for improvements were showed, those were limited and many more variables needed to be tested. Given the interdependent character of all the mentioned design variables and the necessity to passively guarantee comfort, the investigation was performed with parametric simulation.

Parametric studies

A parametric simulation was conducted in order to quantify the impact of design and user behavioural patterns. The parametric analysis was carried out using jEplus. Table 2 lists the 11 design variables and their available options, allowing 139,968 different design alternatives in total. To overcome the computing time issue, simulations were executed on the 256-core cluster made available by the Institute of Energy and Sustainable Development, De Montfort University. The whole parametric project took 30 hours to run, while the overall process from inputting, to results retrieval was around 50 hours, which is considered reasonable for a typical building design process workflows. The parametric simulation showed a series of optimal solutions and the main design factors impacting performances (Fig. 5)

Table 2 Description of the simulated parametric variables

Variables tested	N°	Selected Parameters
Building Connection To The Ground	2	Standing on the ground plate or suspended
Wall Insulation Thicknesses	3	0.334 m, 0.384 m, 0.434 m
Floor Insulation Thicknesses	3	0.334 m, 0.384 m, 0.434 m
Roof Insulation Thicknesses	3	0.334 m, 0.384 m, 0.434 m
Main Window Overhang Depth	4	0 m, 0.55 m, 1.1 m, 1.65 m
Natural Ventilation Schedules (Natural Heat Exchanger Control)	4	Always on, always off, summer on, 9-17 on
Concrete Thermal Mass Thicknesses	3	0 m, 0.05 m, 0.1 m
Number Of Users (Daytime)	3	1, 2, 3 persons
Computer And Lighting Internal Gains	3	30 W, 125 W, 220 W
Colour Façade	2	Black, white
Heat Exchanger Internal Insulation Thicknesses	3	0 m, 0.05 m, 0.1 m
Total Of Simulated Design Alternatives	139,968	

OPPORTUNITY FOR ENERGY OPTIMIZATION

The designer was able to relate the parametric results to other factors (e.g. construction costs and architectural considerations), identifying a range of modifications that would bring the building to an annual energy consumption of 8.50 kWh/m² at very low construction cost. Such low energy consumption would fit the definition of nZEB (Fig. 4).



Figure 3 The naturally ventilated air-to-air heat exchanger

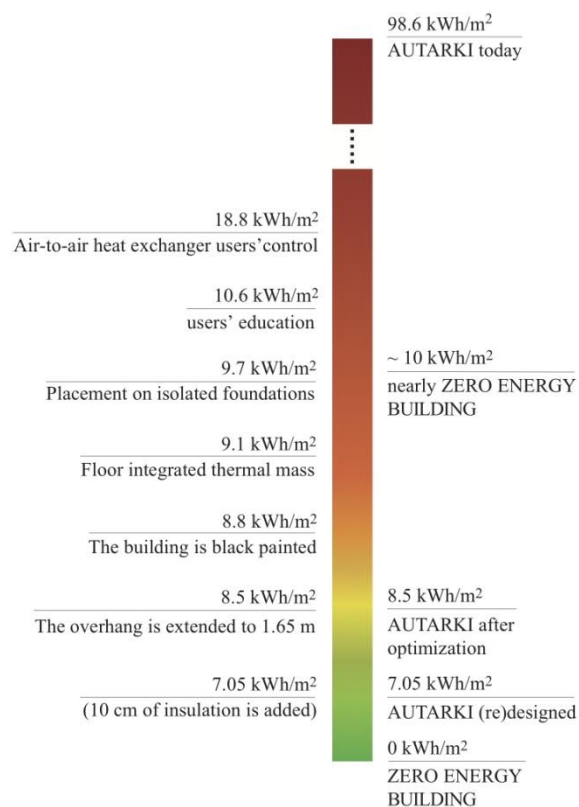


Figure 4 The path toward a nearly Zero Energy Building is described in few adjustments of the prototype

In particular the use of parametric simulation allowed the understanding of how certain user scenarios would improve performances, leading to the conclusion that the building's users play the major role in Autarki energy performance.

Specific users of the space and their manual control of the heat exchanger could indeed maximize the comfort levels at no energy costs. The real-time visualization is a determining factor in improving the interaction between users and the prototype.

EVOLUTIONARY OPTIMIZATION IN ARCHITECTURE

The use of parametric simulation was necessary to achieve the above mentioned conclusion. It was possible to perform a large study thanks to the availability of a computer cluster. Can a building design be optimized without an expensive computer cluster? To answer this question, we look into evolutionary optimization methods and tools. A recent and easy-to-use optimization tool for EnergyPlus users, jEplus+EA, is tested. jEplus+EA couples a popular optimization algorithm (Genetic Algorithm, or GA) with the jEplus parametric tool. To answer to the following questions, the same design parameters of the Autarki model were used.

- How an architectural office can access design optimization techniques using jEplus+EA and computers that are typically in their own availability?
- To what extent evolutionary optimization could optimize the design energy performances and how long does this take?
- And, what is the degree of architect-friendliness of the jEplus+EA?

Performance Optimization

Some adjustments to the jEplus parametric project are required, before it can be used with jEplus+EA. The population size of Genetic Algorithm in jEplus+EA was set to 10. Optimization was run for 135 generations, and in total 1350 simulations were executed.

The results of the optimization process were overlaid the ones from the parametric experiment on a scatter plot (Fig 5). Highlighted are the Pareto Fronts (curve representing the set of optimal solutions) achieved by GA after 5, 60 and 135 generations, with corresponding computing time 18 minutes, 3 hours and 36 minutes and 8 hours, respectively.

Such study is performed to understand how many generations are required to allow the Pareto Front move toward the optimal solutions obtained by parametric simulations. The GA optimization found a satisfactory number of solutions on the Pareto front after 60 generations.

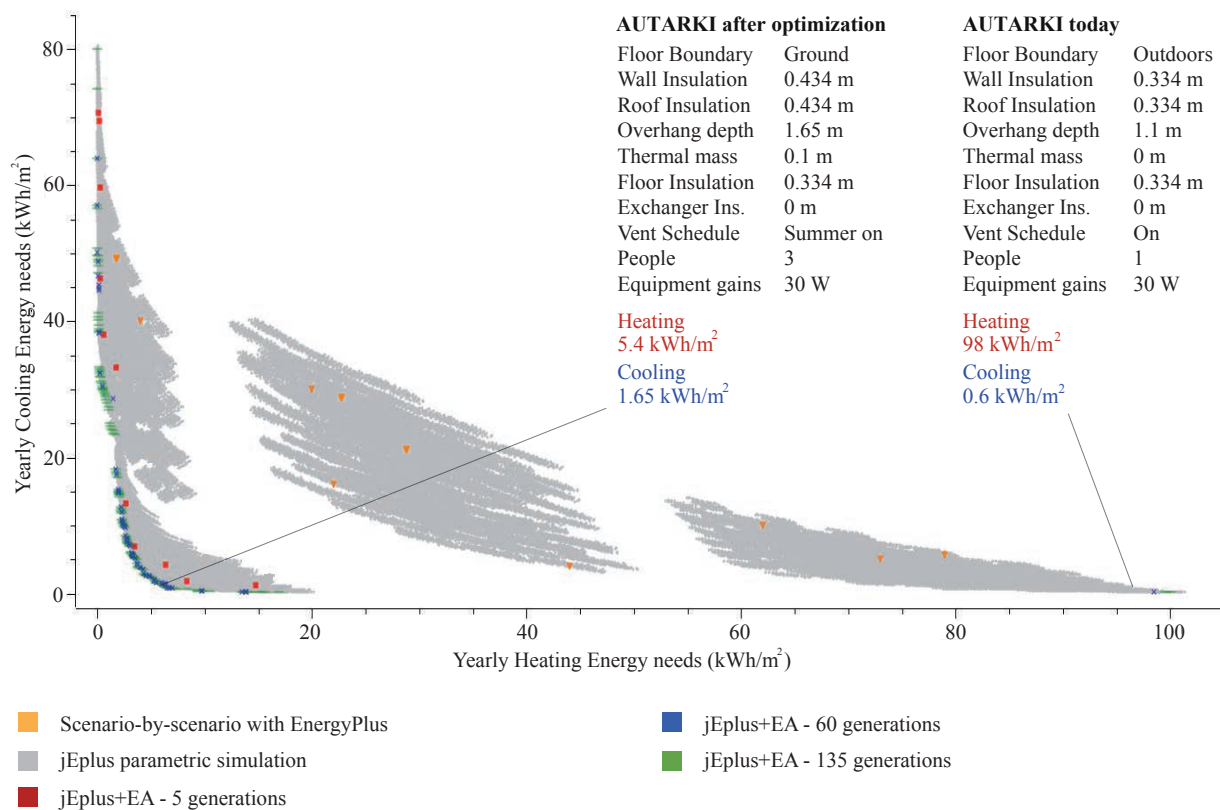


Figure 5 Energy needs comparison: scenario-by-scenario with EnergyPlus, jEplus parametric simulation and evolutionary algorithm with jEplus+EA

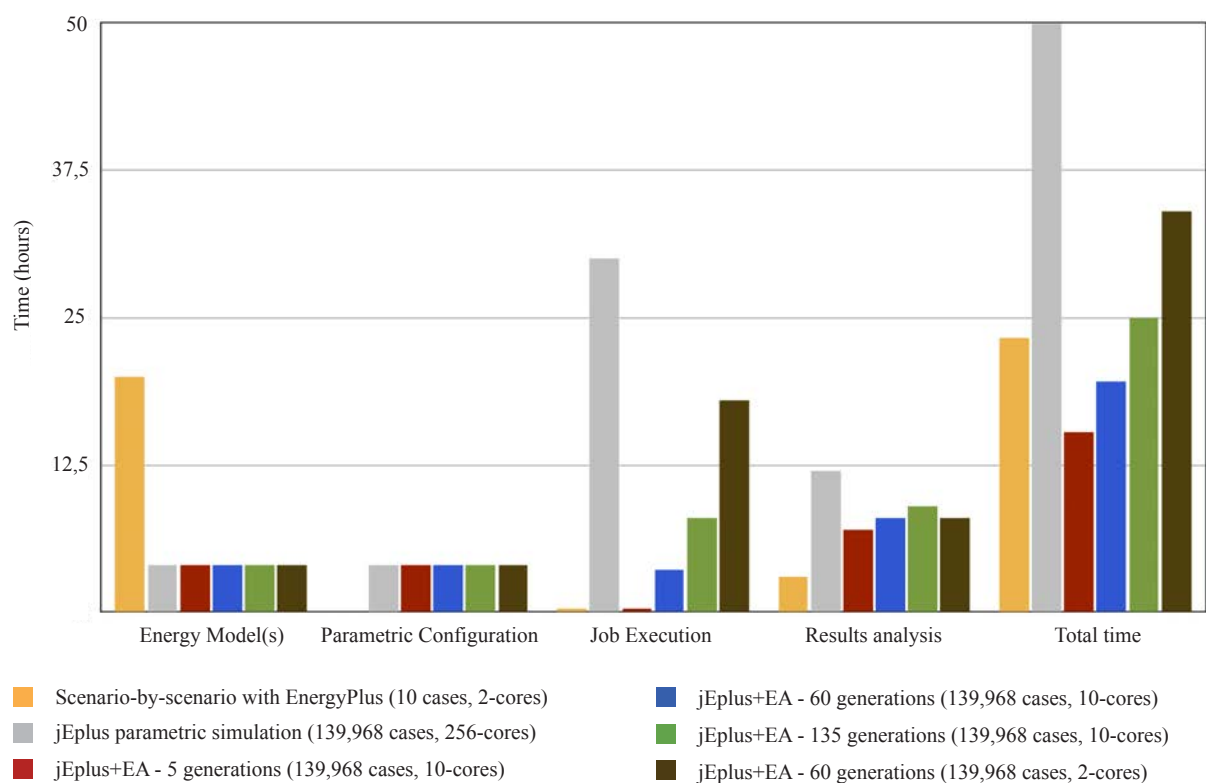


Figure 6 Time comparison: scenario-by-scenario with EnergyPlus, jEplus parametric simulation and evolutionary algorithm with jEplus+EA

After 5 generations, the Pareto front is fairly close to the range of most “performative” solutions defined by the parametric study, and after 60 generations they overlap. Therefore, in this case, the optimal solutions can be found within 18 hours on a dual-core pc, or in 3 hours on a 10-core mini-cluster. 3 hours is a very convenient time frame for an architect in the most real world design projects.

Time efficiency of evolutionary optimization

In practice, the architectural design process dictates the rhythm of energy simulations. Architects need quick feedback and they are reluctant to use tools that require long computation time. It is therefore useful to explore how the different approaches described in the present research are related to hardware (local or remote – with cloud computing) and to time. The results described in figure 6 show that the total design time required by the genetic algorithm approach (from the energy model creation to the results’ retrieval) is 34 hours on a dual-core pc. A slightly minor amount of hours (23) is required for a conventional scenario-by-scenario design, with the crucial difference of how many design options have been evaluated (139,968 vs. 10). Therefore, the time needed by the evolutionary optimization approach clearly optimizes the energy design process and performances.

Assessing the Efficiency of Evolutionary versus Parametric Optimization

It should be noted that the explored methodologies are based on different hardware resources. A useful way to compare computational times is to employ the unit “cores-hours” (also called CPU time or processor hours).

Both, the parametric study and the GA optimization were ran on Intel Xeon E5440 processors. The parametric simulation took 30 hours on the 256-cores cluster, resulting in 7680 cores-hours. Conversely, the simulation using GA lasted 3.6 hours (leading to similar results after 60 generations) running on a 10-cores mini cluster, with a CPU time of 36 cores-hours.

As a consequence, GA reduced the time of computation by a factor 213. This means that, if running the simulation on the same hardware, GA is 213 times faster than parametric simulation in finding the most “performative” solution (minimum amount of total energy needs).

Finally, the advantage of running the simulation for 135 generations was decisive to add more solutions on the pareto front, making designers able to choose from a wider range of optimal solutions when compared to results after 60 or 5 generations. In this case, GA reduced the time of computation by a factor 96.

Architect-Friendliness of Evolutionary Optimization

The lack of user-friendliness has been a factor which limits the use of energy simulation in architecture. Its implementation has just recently become possible, after “architect friendly” interface of EnergyPlus were introduced (e.g. DesignBuilder, OpenStudio, and lately Simergy). It is therefore necessary to understand whether or not parametric and optimization tools can offer the same degree of architect-friendliness. While jEplus is designed to assist energy analyst on preparing and executing parametric runs with EnergyPlus, its use by an architect may require certain effort. The software presents a relatively user-friendly GUI to script idf files and it is able to define and modify parameters of a design alternative in a flexible environment in order to regenerate and re-assign attributes.

To use jEPlus, a user needs knowledge of EnergyPlus model files and utility tools. Despite the spread of user-friendly graphical interfaces, this remains the main barrier for practicing architects to take up this tool. In addition, further developments of jEplus should consider the parametric modification of the building forms, which is one of the main areas of architectural based energy optimization. This step is however complicated given the possible complexity of a building and its thermal zones.

jEplus provides also a convenient way to interface EnergyPlus models with optimization algorithms. With jEplus+EA, users can have access to efficient optimization methods without the burden of learning optimization techniques. jEplus+EA hides the complexity of GA by optimizing the internal algorithm for building design applications. In most cases, jEplus+EA can search the solution space defined by a jEplus parametric project straight out of the box. However, users still need to understand the structure of EnergyPlus models before they can take full advantage of jEplus and jEplus+EA’s capabilities.

CONCLUSION

The authors have tested three different energy design methods in order to achieve extremely high energy and comfort performances of AUTARKI 1:1 building prototype. Results show that the use of evolutionary optimization with jEplus+EA allows users to find optimal solutions of large design options space simulations in a reasonable time while using a standard dual-core pc. The use of parametric and evolutionary methods allowed understanding how the building user could impact its performance. Without a large number of tested variables such conclusion could not be achieved.

Additionally, starting from the same amount of design variables combinations, the genetic algorithm was 213 times faster than the parametric approach.

The integration of the different approach in architectural practices were explored. A scenario-by-scenario method is the most used in offices since it can be developed with standard pc and common energy performance tools. However, figure 5 shows that the simulation of few options rarely reach optimal solutions and the energy performance are often quite poor.

The parametric approach is an extended simulation of a large number of possible design combinations and it allows to identify the optimal solutions. However this strategy is still poorly used in architectural practice due to need of powerful hardware resources. The latest are nowadays only available to large private, academic and government research laboratories.

As demonstrated in the present research, evolutionary algorithms optimization leads to finding optimal solutions in a reasonable computational time, also by running the simulations on standard PCs. Therefore, its integration in architectural practice, overcomes the issues of conventional and parametric processes, and seems to be an achievable possibility in the near future.

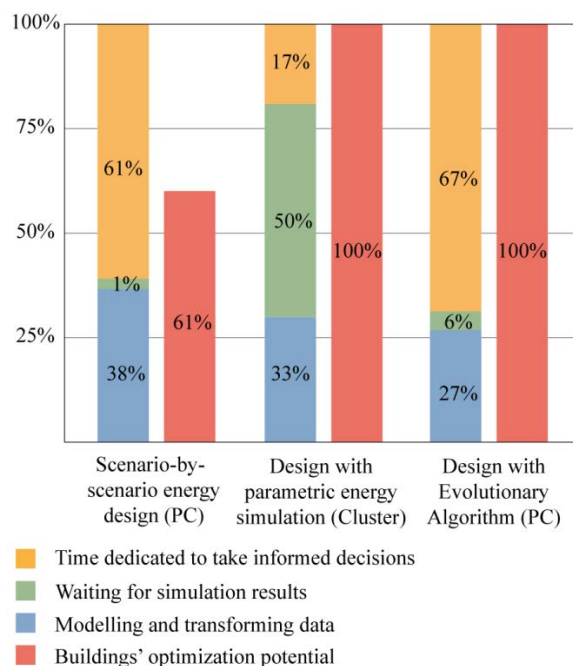


Figure 7 Efficiency of the different methods seen from an architectural process perspective

It is clear that an extend integration of optimization algorithms can drastically change the usage of time within architectural design processes, allowing designers to focus their attention on taking informed design decisions (Fig. 7).

In conclusion, evolutionary optimization can impact significantly the way buildings are designed. Architects used to be limited by what they could calculate. Now with the use of genetic algorithms

they can model a large number of design options or even suggest the optimal solution allowing the computer to handle the geometrical and materials complexity of today's buildings. The possibility for architect to evaluate many variables is functional to design optimization, speeds up the learning process and support the creation of knowledge in the field of sustainable design.

Further investigations should aim to understand how the described processes can be applied to more complex buildings.

Last, it may be worth to question how the nature of design may change, shifting from a scenario-by-scenario conventional design approach, to evolutionary optimization. As simulation begins to determine the character or quality of architecture, the human component may be marginalized. The design sensibility of architects coupled with their unique ability to relate design to social and cultural factors needs to temper the power of performance related computing.

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