Generative Design for Energy Efficiency

Energy Analysis and Optimization

Extended Abstract

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Architectural design consists of presenting a solution to a given problem. This problem, even with its various constraints, such as site, climate, construction cost, and regulations, has a plethora of possible solutions. Being so, designing implies selecting amongst several viable solutions, depending on the criteria applied. 'Design can be seen as an evolutionary process' (Alfaris, 2009). As environmental sustainability becomes a core topic of our society, architects are lead to design buildings with better energy performance, in order to achieve a more sustainable architecture.

An energy efficient building is the 'one that uses the minimum necessary energy to be built and used' [1]. Ideally, a building should be auto-sufficient, i.e., it should have methods of reducing energy consumption, of reusing energy and resources, and even of producing its own energy. Being able to design energy efficient buildings will not only bring environmental benefits, but also economic ones, since it reduces consumption and thus the economic burden of a building, compensating for the initial investments.

To promote energy-efficient buildings, regulations were created, ensuring a sustainable consumption of energy and resources. Due to these regulations, it is mandatory to ensure certain consumption limits when designing a new building. There are simulation tools that allow architects to evaluate energy consumption, such as Autodesk Insight 360 [2], a simulation engine used to perform energy analysis. Some of these tools also allow for simulations throughout the different stages of the design process. Hence, the user is able to perform a general analysis on a more conceptual stage of the work, and more detailed ones in the final stages.

Nowadays, there is also a growing body of knowledge on parametric modeling, which considerably helps architectural practice, allowing a faster method of reproducing and changing a three-dimensional (3D) model of a building. Parametric modeling consists in describing an object through different parameters and relationships between those parameters, which enables variations on the model itself (Alfaris, 2009). A mathematical approach is used to describe certain aspects of the general design intent, creating functions describing the object. The values applied to the different functions allow them to create several design options, all following the same principles and deriving from the same parameters. This approach can generate a wide variety of design options in a short amount of time. By combining a parametric approach with an efficient evaluation system, architects can find better design options, having in mind the energetic behavior, even in initial stages of the design process.

This work proposes a parametric approach for the creation, evaluation, comparison, and improvement of models, regarding their energy consumption.

Energy Performance in Architecture

According to the International Energy Agency, 'energy efficiency is a way of managing and restraining the growth in energy consumption. Something is more energy efficient if it delivers more services for the same energy input, or the same services for less energy input.' [1]

To ensure efficient buildings, there are regulations, at national and international level, regarding the construction of new buildings and renovation of existing ones. There is a wide variety of energy analysis tools available that comply with the existing regulations, some more complex than others, and requiring different levels of expertise. The following sections present two of the most common tools used to reproduce architecture projects, and both allow energy analysis without exporting the model to another software.

Revit & Insight 360:

Revit is Autodesk's reference Building Information Modeling (BIM) tool [3]. As a BIM software, it is able to apply semantics to modeled objects, integrating in just one file all the necessary information about the building. Revit works with building components, like walls and slabs. Unlike in Computer-Aided Design (CAD) tools, such as AutoCAD or Rhinoceros 3D, the user creates specific architectural elements, instead of abstract geometric elements. These components belong to *families*, where all the construction details are specified, including the thermal characteristics of the elements.

Revit has a connection to an online simulation platform called Insight 360 [2]. This platform uses Energy Plus (a reference tool in energy analysis) to run the simulations, and works directly from Revit. When using this energy analysis tool, the user needs to generate the model in Revit and then define the options for the energy simulation. The simulation is performed by Autodesk's servers and the results shown in Insight 360's website.

Rhinoceros 3D & DIVA:

Rhinoceros 3D [4] is a three-dimensional modeling software that uses NURBS curves (Non-Uniform Rational B-Splines, a mathematical representation of 3D geometry [4]), which allows the user to create free-form surfaces and solids.

Rhinoceros has a plug-in for daylighting and energy simulation called DIVA [5]. This plug-in reads the 3D model created in Rhinoceros and asks the user to apply the materials to the model. It then runs the simulation for daylighting or thermal loads, according to what the user wants. DIVA also uses Energy Plus.

Generative Design

> 'Generative design is not about designing a building.
> It's about designing the system that designs a building.'
> by Lars Hesselgren, Director of KPF Research (Stocking, 2009)

Generative Design (GD) is a process that produces various design solutions from a set of rules and constraints defined by algorithms. An algorithm is a mathematical description of an action that we want to perform. We can view them as a set of steps to follow in order to achieve a specific goal.

Algorithmic systems are the basis of GD, expressing, by a set of rules written in a specific language, the goals of the design, and the steps to achieve them. ‘Thinking in terms of algorithms is a mapping process of design objectives onto step-by-step descriptions’ (El-Khaldi, 2007). In this case, we are talking about computers understanding and performing actions defined by humans, and so the language used to communicate is necessarily a programming language, i.e., a methodical communication system to transmit a thought process to a machine (Leitão, et al., 2012).

In GD, a computational approach is used, creating functions that describe the design intent. The different values applied to the parameters of these functions are what allow them to create several design options, all with the same principles (Alfaris, 2009). GD is nowadays seen as a way to combine the creative mind of the architect with the effectiveness of modern technologies, thus leading to a more efficient work and to greater opportunities and different options of design (Fernandes, 2013).

GD started more connected to CAD tools. These tools are mainly used for representation purposes, as they only work with geometry, such as lines and solids, without giving them attributes, like the simple constructive difference between a wall and a slab. In terms of geometry, these two elements are just two parallelepipeds that happen to have different orientations in their spatial arrangement, i.e., walls are mainly vertical and slabs are mainly horizontal. With BIM tools, the paradigm shifts considerably. These tools consider the attributes of each constructive element, as well as their natural interdependence between each other. For example, one cannot design a window unless it is hosted in a wall, which changes the design methodology (Feist, et.al, 2016).

The application of GD to BIM tools is what interests us in this research, for it provides both the benefits of an algorithmic approach as well as the advantages of using a tool that works with all the constructive attributes of each building element.

GD as a tool for energy analysis

By associating a GD approach to an efficient evaluation system, architects can explore more design options which take into account the building’s energy behavior, even in early stages of design.

When we want to run an energy analysis simulation, we provide the analysis tool with a 3D model, or a set of parameters that describe that same model, depending on the tool being used. Once we have the model described, the tool performs the energy analysis.

When using a traditional modeling approach, if we wanted to change some aspects of our building to try to improve energy consumption, we would have to manually introduce those changes, either on the 3D model or on the parameters that describe it. Either way, we would do this probably just a few times, comparing the results and choosing one option among two or three. Considering that each analysis simulation takes time to run and produce results, and that changing the model to test new options also takes time, we would spend several hours of work on each building variation.

Assuming a good knowledge of the modeling tools and good programming skills, the time spent on manually producing a building model can be close to the time spent on creating a set of algorithms to generate it. The big difference only comes afterwards, when it becomes necessary to change the model to generate variations of it. After having the model in the analysis software, the time that the simulation itself takes depends on the complexity of the model and on the settings defined in the software for the detailing of the analysis. When we run the first simulation, we evaluate the results and change the model according to the total energy consumption value given by the simulation. These changes can be easily made manually if the model isn't too complex but, usually, architects need to perform this kind of analysis in big and complex models. Changing a large and complex 3D model can take a lot of time, and this time increases considerably according to the number of changes that the architect wants to make. On the other hand, GD can make the process of changing the model much faster. The architect just needs to adjust parameter values according to the changes needed, and run the program again to rapidly generate a new model.

Using GD with Energy Performance Simulation Tools

The Case Study

The building chosen as a case study for this research was Beirut Terraces, an habitational building in Lebanon, designed by Herzog & de Meuron. ‘The building will comprise five different modular floor slabs used in varying combinations to create a mixture of overhangs and terraces’ [6].

This modular concept creates a sense of randomness in the 25 residential floors of the building. The lower floors have more and smaller apartments, while the top floors have fewer and bigger ones. The main goal of this concept is to differentiate all the apartments available, creating 130 ‘living experiences’, as described in the project’s website [7]. In Figure 1 we can see some views of the existing building.

Figure 1.
Beirut Terraces, by Herzog & de Meuron. Available in www.beirutterraces.com.

Modeling Strategy

The generation of the model in Revit was made using Rosetta. Rosetta is a programming environment that connects front-end programming languages to back-end CAD/BIM applications (Lopes and Leitão, 2011). Through Rosetta, we were able to parametrize the model used as a case study and then perform the energy analysis using the same software as a back-end for both stages of the process. This was possible since the chosen software itself provides the tools needed to perform the simulation. Revit and Insight 360 were used in this research as model generation and energy consumption simulation tools.

The building chosen as a case study for this approach was decomposed in its essential constructive elements to generate a simple model representative of its concept. The set of algorithms created has in mind the natural evolution of the architectural design, starting by evaluating the expected energy consumption of a building in its initial stage of design, and then performing more analysis along the way, promoting a sustainable design process. This way, architects can define their general concept and evaluate its different variations, choosing the one that achieves a better energy consumption, and then maintain this method throughout the whole design process.

We started by defining the basic elements that compose the essential form of the building. In this case, the building has 25 residential floors, and is divided in the following constructive elements: slabs, columns, core area, and walls.

Each slab has a shape that follows one of five different types. All of them are based on a square, but the edges have some breaks, forming polygons with 8, 10 or 12 edges, depending on the type of the slab.

When designing the model, we wanted to take advantage of GD to ensure that the randomness factor would be present, just like it was intended in the original design by Herzog & de Meuron. As we only had to write the script, instead of drawing each slab by hand or relying on a copy-paste process, we could easily make all the slabs different from each other. For the building to resemble its original form, we analyzed the five types of slabs in the plans provided by the architects in [7], and created a set of dimensional limits and constraints for each corner of the slab, thus producing numerous hypothesis from a single script. We used the same approach for the exterior walls, since they have the same behavior in terms of randomness. This way, we can increase the randomness of the model without the extra working hours that it would take with the traditional approach.

Another defining element of the building is the column arrangement, that has a specific pattern, continuous from the first to the top floor. For this element, we created a script to distribute the columns in the specific pattern intended and we used a specific column family provided by Revit. For elements like columns, we can import a family file, that allows us to choose from round columns, square columns, H-shaped columns, etc., or even create our own column and use it in the project.

Another important element is the core of the building, where we can find the staircases, the elevators, and the entrance foyers of each apartment. This area was considered as a unique area during an initial stage of the design, since it will have a very similar behavior in terms of energy consumption. This happens because these type of spaces are considered as non-heated spaces, due to being common areas outside of the apartments.

Regarding energy analysis, when inside an apartment we need to look at its limits. The interior walls that divide the various rooms are not designed to be isolators, only space separators. Thus, in an initial stage, and having in mind that we want glazed areas surrounding all the floors of the building, the impact on global energy analysis of the interior walls will be close to none. In a more advanced stage of the design, we should detail them, making it possible to compute the energy consumption of each apartment. As we are now focused on whole building energy consumption, this is not a main concern, and therefore the interior walls need not be considered and we only defined the glazed walls that separate the interior areas from the exterior.

This whole process allowed us to parametrically define every component of a simplified version of the building, making it very easy for us to change some aspects of the generated model by only modifying a few values in the code and waiting less than 20 seconds for the computer to generate the whole building with the new values.

Energy Analysis Process

For this research, we chose Autodesk Revit as a modeling tool, since we can generate the building using GD, through Rosetta, and then run the energy analysis simulation by sending the model to the online platform Autodesk Insight 360. In these tools, the energy analysis simulation is very simple to perform.

Since Revit is a BIM tool, the materials are already applied to each constructive element and we only need to make sure that the thermal characteristics of the materials are active.

Then, we need to provide some additional information, like site, usage typology, and complexity of the simulation, e.g., whether it is a simple simulation using conceptual volumes, or a more complex simulation using building elements. Once the energy settings are defined and Revit produces the analytical surfaces, Revit can send the necessary information to Insight 360, which will perform the energy analysis. Once the analysis is complete, the architect can consult a report with information regarding the energy performance of the building.

For this research, we simplified the chosen building to its basic constructive elements, thus starting by analysing an initial stage of the concept and trying to understand the energy performance of the volume created. Because we are using GD, we can easily produce several variations of the same concept, by only changing a few values in the original script. This will help us considerably in the next stage of this research.

Improvement Process

Having the possibility of quickly generating a 3D model of the building in Revit (less than 20 seconds for each model), we can then start the improvement process.

On a first approach, we created a script to produce what we considered as a default stage of the building, considering this model the starting point for our analysis. Its dimensional constraints were defined having as base the original design proportions. The result will never be exactly the same as the original, as we are using random dimensions within specific intervals, instead of the actual dimensions of the existing project.

After having the model in Revit, the energy analysis is performed, the results read, and a new hypothesis tested. On a first glance, the typical architect cannot ascertain the exact elements that have an impact on the energy performance, and so a comparison phase is initiated.

We created ten different sets of values for the dimensional variations. This means that although the concept of the building will stay the same, as well as the number of floors and its composing elements, we changed the limit values for the variations of the slabs and exterior walls, since they are the elements that confer the sense of randomness in the building. By changing these values, we create new slabs and exterior walls, resulting in new living areas. We chose to compare the different generated buildings using the Energy Use Intensity (EUI) value, which represents the global energy used per square meter per year. A higher EUI value translates in greater energy consumption and greater economic costs. A lower EUI value means a lower energy demand and a more sustainable building. After running the energy analysis on the models, we chose the best performing one, i.e., the one with the lowest EUI value, as a starting point for the next step.

Then a second set of variations was created. This time we took the intervals of the best performing building of the first set and reduced the range of values in that interval. Whereas in the first set, the decision of values was random, in the second set, the values were analyzed and restricted. Once again, we took the best performing one, and chose that to continue this process. In the third set of variations, only five models were created, to adjust some values in order to improve the building's consistency.

Besides changing the limit values that defined the variations of slabs and exterior walls, we opted to test three other components, which we considered would affect whole building energy consumption, and therefore could contribute to the improvement of our model. One of the options tested was the rotation of the building. Since the plot available is a square with approximately the same dimensions as the building, we only had three possible variations. None of these variations contributed to a better energy performance. We also changed the dimensions of the core area, where one of the options contributed to a better energy performance. One other variation was the height of each floor. Figure 2 shows the results obtained.

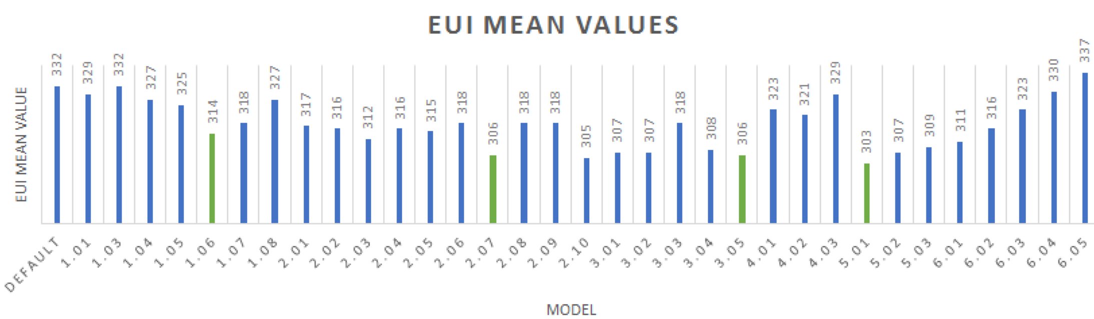

Figure 2.
EUI mean values resulting from the energy analysis performed using Autodesk Insight 360, connected to Autodesk Revit 2017.

As we can see in Figure 2, the green bars represent the models chosen to continue on to the next set. The first three bars indicate the evolution of the first three tests described. As these three were a continuation of each other, progressively improving the model, they appear in a chronological order. The other three variations proposed were applied without a specific order. After applying them, we concluded that the best performing model (model "5.01") among the ones tested, had no need for rotation of the building or variation of the height of the floors, but benefited from the variation of the dimensions of the core area. In Figure 3, we see the model resulting from this process, which corresponds to model "5.01".

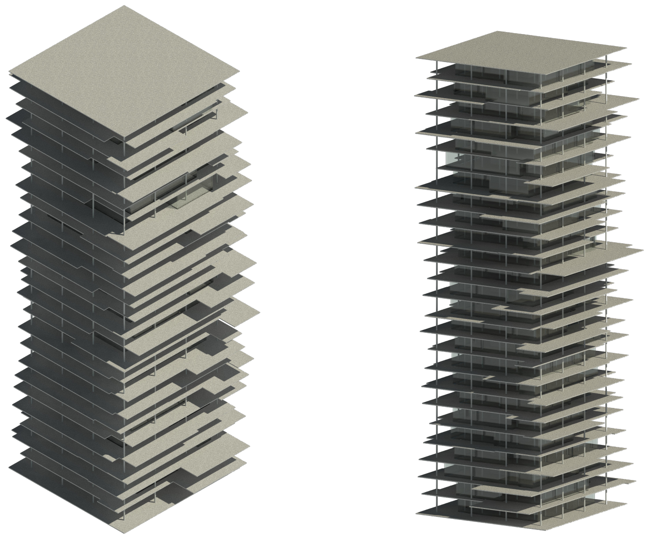

Figure 3.
Model "5.01", produced in Autodesk Revit 2017. Different views.

Conclusions and Future Work

Energy analysis tools are increasingly important in Architecture and Generative Design allows us to automate their use, reducing time and effort and greatly expanding the design options available to the architect.

Using energy analysis tools in early stages of the design process helps improve sustainable architecture, as energy consumption concerns start at the beginning of the design and not only at the end, where the energy analysis is nowadays typically done.

In this work, we took the principle of genetic evolution and applied it to our model, creating the variations by hand. This process was already made faster by the use of GD, as it took less than 20 seconds for each model to be generated, instead of doing all the changes in the model by hand. To automate the process even further, we can use a Genetic Algorithm, an evolutive procedure based on the Darwinian notion of 'the survival of the fittest' (Caldas, et al., 2002), by defining the EUI value as the objective to be achieved (in this case, the smallest EUI value possible).

As future work we are planning to develop an automatic optimization tool, improving the presented workflow and taking it further. We can already see some examples of optimization being applied, like Asl (2013), who proposes an optimization tool that uses Autodesk Revit and Autodesk Green Building Studio (recently updated to Insight 360), generating alternative options in BIM and automatically performing energy simulations, giving as a result the optimal solution found between the ones tested. This work uses file exportation to send the model from Revit to Green Building Studio, and then again back to Revit, providing the results via CSV (comma-separated values) files. It receives the parameters that are allowed to change and generates Green Building Studio gbXML files to be analyzed. This work was used to improve window dimensions in a two storey house.

The goal is to take this further, since we want to change several parameters in different elements and in different stages of the design. For example, in the case study presented in our research, we improved whole building energy consumption but, in the future, we plan to reach a stage where we also optimize the interior divisions, creating a better distribution of apartments.

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