Building performance simulation as a guide to design decision making: an analysis of architecture students’ design process.

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Abstract

Many architects agree that building performance simulation should be embedded in the design process (Alsaadani and Bleil De Souza 2019). This paper analyses architecture students’ design process using building performance simulation to assist in design decision making. First, they analysed potentials regarding bioclimatic strategies with Ladybug. Then they performed thermal simulations with Honeybee to assist the design changes. The students had a simple one-room residential volume with urban context. Each group received a different city, and many groups used adaptive comfort improvement and cooling load decrease as a guide to decision-making. Some of the groups reached near 80% of adaptive by reducing more than 70% of the cooling load in the final building composition.

Key Innovations

- Early design changes made by students using building thermal simulation.
- Simulation outputs that are more meaningful to architecture students.
- Different design changes made regarding different climate.

Practical Implications

Consider different building changes in the design process regarding different climate. It is important to always teach climate analysis and bioclimatic strategies as the first step to design changes regarding better building thermal performance, as building performance simulation should be the second. The study has the potential to be replicated by other lecturers and tutors.

Introduction

Although most architects agree that building performance is crucial in architecture education, the two academic subjects are distant (Alsaadani and Bleil De Souza 2019). The creative design process is far different from the building performance teaching method (Maciel 2006).

The knowledge acquired during academia is the base for future design practice. Consequently, most of what students learn from building performance could be applied. Therefore, if there is a considerable disparity between design and thermal performance in academia, it could be arduous to implement it in the architect's professional life (AIA 2019).

It results in segregated knowledge, and that leads to a non-concurrent design process. Without bioclimatic and building performance simulation practical application, building designers rarely test bioclimatic strategies, and it will not lead to the building's desired performance. Most building performance analyses are carried out in the final design stages when most design changes to improve building performance are not possible. Architectural education could overcome this problem by testing new ways and software that could be more effective in the design process (Bleil de Souza and Tucker 2015). For that, it is essential to understand the creative process. The design process cannot be defined as something linear, considering the designers' complex and diverse thoughts. The author defines it as a problem-solving system: a searching for problems and solutions and subsequently evaluating them. The evaluation relies on analysis, synthesis, and later evaluation. In the design process, the problem and the solution coexist, as the designer seeks a solution, and evaluating it also means seeking a new problem to solve (Mitchell 2009).

Furthermore, the problem-solving system should embrace all design areas. A study developed by Lucchi and Delera (2020) describes a user-centred design-driven approach by designing social housing in Milan. In order to reach multiple possible problems, the designers had some design phases, such as historical research, interviews with the inhabitants, and training (architectural and technological design), together with regular on-site visits. That way, the participants combined studies of design practice, architectural and technological design, urban planning, energy efficiency, environmental sustainability, and social innovation.

Lawson (2011) argues that observational studies of designers’ creative processes do not match the actual process. The author emphasises that the architects tend to behave differently from the usual in these experiments. Nevertheless, interviews allow architects to describe their work, and it is unlikely that they do not speak the truth. On the other hand, even if they do not distort information in interviews, they describe it more logically than it occurs.

Architects are visual thinkers; they develop and present their ideas with visual images, videos, and schema. At the
same time, building performance calculation and simulation results are not commonly visual. Some of the problems between the two areas involve the lack of tools to support design decision making during the creative process. The thermal performance analysis tools development is not carried out the same way as design tools, making interoperability even more challenging (Bleil de Souza and Tucker 2013).

Bleil de Souza and Tucker (2015) agree that data visualisation can provide a structured framework when combining design with thermal effects. Processing thermal simulations data during creative design is crucial to solving design problems. Therefore, the authors agree that the valuable data must come from the designers and how data could be meaningful in their decision-making cycle (Elbelltagi et al. 2017).

It means that the designer must be the thermal performance simulations developer during the early design stages. The architect should not be an expert but rather know how to consciously act on the design decisions through BPS results (Alsaadani and Bleil De Souza 2019).

Thus, the tools used in thermal performance analysis and the design process must be cohesive. However, most existing simulation tools have the same methods and do not vary as much in technology. Not only that, but the results obtained are little related to design strategies and are challenging to make design decisions. Unfortunately, solving design problems is difficult when data is challenging to analyse. The distance between both design and performance simulation tools could be because developers do not have as much contact with the creative process. It results in the architects' unfamiliarity with BPS methods and, consequently, do not use them during their design process (Østergård, Jensen, and Maagaard 2016), i.e. simulation software developers should see architects as one of the end-users of the software and research their needs and preferences.

However, the path to improving tools is continuous and seeks better integration between simulations and design. Therefore, it is also essential to have an effective design analysis method, knowing which information is essential to pass on to the software developers, enabling the creation of new tools or the improvement of existing tools (Østergård, Jensen, and Maagaard 2016). One thing we know: we need imperceptible interoperability between software, in addition to rapid and visual results combined with interactive modelling (Shi et al. 2016).

The study presented by Østergård, Jensen, and Maagaard (2016) classifies building performance simulation software regarding the design phase, the interoperability between modelling and energy simulation programs, complexity, and results. Noteworthy is the Honeybee, which allows simulations in the conception and subsequent phases of the design process. Likewise, Shi et al. (2016) also mention the Grasshopper algorithm's graphical editor as great software regarding interoperability and data visualisation, which works integrated with Rhinoceros' modelling tool and EnergyPlus through Honeybee.

Tools should help not only the design process but also improve teaching methods for architecture students. When building performance studies can be applied in teaching, it enhances its use in future architect's design process. Some authors developed studies regarding building performance teaching methods in the past few years. Different methods and tools were applied.

In an experiment developed by Reinhart et al. (2012), the authors adopted that the designers would not work with simulations. They made design decisions based on the results obtained by consultants. The students managed to reduce the project EUI considerably through changes in the form of the building. Finally, the authors defend the "learning by doing", in which the teaching method reinforces learning through practical experiments. Thus, the students gain more experience and autonomy for future projects.

Later, Bleil de Souza (2013) carried out another experiment. The students should reduce the use of cooling heating systems due to changes in the building facade. In this case, the designers relied on ambient temperature results to make their design decisions and achieve better configurations. The author concludes that temperatures are more usual for designers to seek building passive behaviour.

Another experiment was developed by Reinhart et al. (2015), in which architecture students applied simulation tools during a semester-long class. After some instructions, the students were able to run a series of daylight and energy simulations in Rhinoceros 3D using Radiance/Daysim (through DIVA) and EnergyPlus (through Archsim) as engines. Students reported feeling confident to use BPS in future projects.

De Luca (2019) also presented a study of teaching solar radiation simulations regarding urban context to architecture students. The software used was also Rhinoceros 3D with Grasshopper through DIVA4. One of the lessons learned in this study was to search for better/more simulation input options and allow sensitivity analysis. Furthermore, the author enhances using simulations from early design stages for more effectiveness.

More recently, Beausoleil-Morrison (2019) presents a structure for teaching simulations to graduate students. In this study, the author divided the method into four modules: the theory, the simulation exercise, the products analysis, and the changes. In this way, the author created a design cycle, as previously mentioned by Mitchell (2009). The students created a problem search system and, later, refined it.

Teaching simulation to architects is still in development. There are different teaching methods applied in different places, and there is still no evidence of more or less effective methods. Thus, more experiments in the area are essential for its development. It could be possible to understand: what should be taught, when, and how to
apply, only then to measure the real impact of its use (Souza 2013).

Over the past few years, some researchers developed teaching experiences to combine performance simulations and design. In the end, they reinforce that there is no practical method for teaching simulation to architects. The need for more experiments in the area is essential for its development.

This study evaluates the design changes made by architecture students using Ladybug and Honeybee as a simulation software tool. The software connects the modelling software Rhinoceros Grasshopper with EnergyPlus, which allows parametric design changes with BPS. Using interoperable design and simulation software could evaluate interoperability problems and the students’ meaningful results regarding thermal performance simulations. The most important result and outcome of this study is which indicators and changes enriched each climate’s decision-making analysis.

Methods

We considered the teaching methods developed by Reinhart et al. (2012), Bleil de Souza (2013), Bleil de Souza and Tucker (2015), and Beausoleil-Morrison (2019) in this study. At the same time, notes by Mitchell (2009) and Lawson (2011) were incorporated.

The proposed workflow is congruent with the design process when considering it as a problem-solving system. First, it is essential to introduce concepts through theoretical classes and simulation exercises (Beausoleil-Morrison, 2019). Practical exercises and subsequent application in a simple one-room residential building enhance the “learning by doing” (Reinhart et al., 2012), a good strategy for consolidating and encouraging future experiences. The main exercise has analysis, synthesis, and evaluation phases of the solutions (Mitchell 2009). Regarding data analysis, the building performance improvement occurs by reducing the thermal cooling and heating load and analysing other possible parameters, such as operative temperature (BleilDeSouza and Tucker 2013), envelope surface temperatures, and thermal comfort indicators. Therefore, the simulation software chosen should both allow good interoperability with design process programs (Østergård, Jensen, and Maagaard 2016) and allow the visualisation and analysis of results quickly in the same software (Bleil de Souza and Tucker, 2015).

With the previous considerations, the following subsections describe the simulation tool chosen to assess the teaching method; the teaching method proposed in this study; the proposed final exercise in evaluating students’ comprehension, analysis and design changes made; and the case study description.

Simulation software

As mentioned before, Honeybee has good interoperability with modelling programs and good data visualization of building performance simulations. Besides, it supports early design stages simulation. Honeybee and Ladybug are plug-ins for Grasshopper, which integrates with Rhinoceros’ 3D modelling tools.

Rhinoceros 3D is a three-dimensional modelling program based on a mathematical model for generating curves and surfaces. The Grasshopper plug-in is a graphical algorithm editor integrated with Rhinoceros, which does not require any programming knowledge and allows designers to create different shapes quickly.

The Honeybee plug-in connects the modelling with important building thermal performance simulation engines such as OpenStudio and EnergyPlus. On the other hand, the Ladybug tool allows analysis of weather files, generating graphs that facilitate the climate analysis. Both Ladybug and Honeybee are part of the Ladybug tools, a set of different climate analysis tools. Thus, this study used Ladybug and Honeybee's tools to teach bioclimatic design and thermo-energetic simulations to architecture students.

Teaching method

The teaching method has two phases: the first presents the bioclimatic design, and the second introduces building performance simulation. The two phases had a learning cycle, starting with theoretical classes, followed by practical classes, and, finally, the final exercise, which is continuous in both phases.

The exercise also had two phases, as well as the classes. The first consisted of analysing the climate according to climatic variables and bioclimatic strategies, applying them to a terrain with the urban context, and then adjusting the proposed strategies according to sun and wind availability. The second phase consisted of making design changes seeking the building’s best thermal performance through building performance simulations.

Also, we created a booklet to support teaching and encourage later practice. Initially, the booklet helps to become familiar with the modelling in Rhinoceros. Then, the components of climatic analysis in Ladybug are presented, and later, how to configure the model to perform building performance simulations with Honeybee. In the end, the booklet presented the data visualisation components.

Early design changes exercise

The authors developed an example file of building performance simulation in Honeybee to assist the teaching method and practical studies. The file has an initial volume consisting of an open plan residential building, 7 m x 7 m in area, and 3 m in height, placed in the centre of the terrain of 15 m x 30 m. Each façade has a window of 6 m x 1 m of dimension (WWR 29%) with no shading, and the roof also has a window of 3 m x 3 m. The envelope materials assigned were: brick wall (white painted), fibre cement tiles (white painted) on the roof, simple glass on windows (U = 5.7 W/(m².K) SHGC = 0.83) and concrete floor. Figure 1 represents the model created in the example file and the different terrains of study.
All parameters of the initial volume can be changed. Room size can be enlarged (until the size of the terrain) and reduced as needed, as well as window dimensions that could be changed or removed. The building placement on terrain can also be changed: to the front, to the back, and also on both sides (right or left), and also rotated (solar orientation). The file also had a bank of possible changes on envelope materials (types of wood, stone, and insulation), thickness and absorptance. Also, the students could add shading.

Regarding simulation results to support design decision making, the available data are surface temperatures, room temperature (air, operative, and average radiant thermal comfort results: the adaptive method (percentage of hours in comfort or discomfort) and PMV). Heating and cooling loads were also an output. The students can analyse the data in periods: annual, monthly, daily, and hourly, or by average, maximum and minimum values. The design changes and simulation outputs chosen for analysis were at the discretion of the students. All students used the same file to develop the exercise, changing only the studied climate and the surroundings.

Besides, we developed a report model better to analyse design decision making during the design process. The report has three main parts: climate analysis, terrain analysis taking bioclimatic strategies to account, and, finally, simulation analysis. The students reported their thoughts, assessments, and decisions they made based on each simulation result obtained.

In climate analysis, they did the city’s description based on climate. They analysed climatic variables and bioclimatic strategies according to the psychrometric chart. The second part described the terrain analysis according to sun and wind availability, as shown in Figure 2. Also, they should reanalyse bioclimatic strategies. Finally, the students report the design process from a baseline simulation without changes and later analyse each result chosen to make subsequent project alterations, seeking better building thermal performance.

At the end of the report, it was necessary to describe the result briefly and the general conclusion of the work, from the solutions, different configurations, coherence, limitations, and process. To describe the design changes made based on simulation results, the students analysed, synthesised, and evaluated each solution found. They told simulation results and analysed which parameters they thought influenced it. After, they reported what building alteration would solve the problem encountered. They should also document what results were expected by the building alteration made and images of the building. We based the choice of cities on four main factors:

- The existence of a TMY (Typical Meteorological Year) weather file, which allows data visualization in Honeybee.
- Cities outside Brazil located in climates other than the Köppen-Geiger classification and ASHRAE 169-2013.
- Brazilian cities located similar climate as international cities already selected.

The cities chosen were:

- Mumbai – India (CZ0A, Am); Singapore – Singapore (CZ0A, Af); Brasília – Brazil (CZ 2A, Aw); Petrolina – Brazil (CZ 1A, Bsh); Cairo (CZ2B, BWh); Cairo – Egypt (CZ 2B, BWh); Maringá – Brazil (CZ 2A, Cfa); Melbourne – Australia (CZ 3A, Cfb); Warsaw – Poland (CZ 5A, Cfb); Chicago – USA (CZ 5A, Dfa); Egilsstadir – Iceland (CZ 7, ET).

The research results will be analysed according to the reports obtained by the students. By the report, it will be essential to note important points in the design changes made, such as:

- Number of design changes.
- The type of design changes during the process regarding climate.
- More effective simulation results in design changes.
- Comparison between initial and final simulation results, analysing the improvement obtained in the project.

**Case study application**

The experiment lasted two months in the thermal comfort discipline of the architecture and urbanism course at the Federal University of Santa Catarina - Brazil. The course
had 35 undergraduate students and took place during the second semester of 2019.

The students developed the work in pairs, totalising 17 groups: 16 pairs and 1 group of 3 students. Most of the groups worked with different climates to compare their results after each presentation. However, the groups with the same climate had different building context situations to analyse other effects. Besides, the final comparison between design change processes in different climates, and the same climate with different context, could reveal exciting results.

There were overall five simulation classes, theoretical and practical. The other classes presented the discipline's original subject: climatic variables, thermal comfort, bioclimatic strategies, thermo-regulation, thermal sensation, and adaptation to the environment.

Results

The groups were analysed by three different clusters: cluster 1 (7 groups, 15 students), cluster 2 (7 groups, 14 students), and cluster 3 (3 groups, 6 students). Cluster 1 consists of the groups that carried out complete work, from climate studies, climate strategies adaptations and simulation analyses, and understood all variables. Unlike cluster 1, in cluster 3, there was little development of work, since the climate analysis, often without an understanding of temperature indices, and the same happened in the simulation exercise. In other words, the results were poor. Cluster 2, on the other hand, consisted of the intermediate level between these two, in which some parameters were well presented, and a good understanding of parameters was perceived, while others were not.

The groups with good climate analysis and site location adequacy managed to achieve good design changes and practical simulation outputs. It is essential to note that the percentage of adaptive comfort in the building was the most analysed result among the groups, being unanimous among the best works. Besides, these groups obtained satisfactory improvements in adaptive comfort by reducing the building's cooling and heating loads.

The surface temperatures analysis served as support for decision making in extreme climate cases, as in Mumbai and Egilsstadir. The operative temperature analysis did not bring great results to the groups since most of the groups analysed it by annual average, and it was not possible to see a significant difference during each change in some instances. The PMV analysis was also erroneous in some cases, again when considering the result of long periods. Finally, the PPD started to serve as a reaffirmation of the results obtained by the percentage of hours in comfort by the adaptive method. We chose the groups with the same output analysis to facilitate the comparison between them. Besides, the groups managed to achieve interesting building configurations with an average of 5 changes. Each group is described in Table 1.

<table>
<thead>
<tr>
<th>Group</th>
<th>City</th>
<th>Cluster</th>
<th>Number of design changes (simulations)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Mumbai</td>
<td>1</td>
<td>17</td>
</tr>
<tr>
<td>7</td>
<td>Petrolina</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>8</td>
<td>Petrolina</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>9</td>
<td>Cairo</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>13</td>
<td>Warsaw</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>15</td>
<td>Chicago</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>17</td>
<td>Egilsstadir</td>
<td>1</td>
<td>3</td>
</tr>
</tbody>
</table>

Figure 3 represents the initial and final results of thermal loads (in bars) and the percentage of hours in comfort (as “x” in green). The colour blue represents cooling loads and the colour red heating loads.

There is a significant increase in the percentage of hours in comfort between the initial and final analysis. Besides, except for groups 1 and 7, all other groups achieved a thermal load reduction above 60%. We can notice that it was easier to improve the initial building’s thermal performance in cold climates than in hot climates.

After analysing the simulation results and improvements, we analyse the design changes according to the design change type. Figure 4 summarises the works presented, and each colour represents one type of design change. The blue colour depicts any modifications made to the compositions of materials and colours (walls, roof, floor and openings), yellow indicates changes in the dimensions of the building, such as the room size, height and size of the openings, as well as placement or exclusion of windows. Finally, the green colour reflects any change concerning the module's location on the terrain, such as implantation and orientation changes.

Like Figure 3, the results presented in Figure 4 are organised from the hottest to the coldest climate. Group 01, which had 17 changes, was considered only up to the seventh, noting that they made only cooling setpoint changes from this point on. There were occasionally
changes in dimension but did not have great significance for the final result.

![Table of design changes](image)

**Table 1: Steps of design changes.**

<table>
<thead>
<tr>
<th>Change</th>
<th>Material</th>
<th>Dimensions</th>
<th>Site Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CZ 0A</td>
<td>Am</td>
<td>Mumbai</td>
</tr>
<tr>
<td>2</td>
<td>CZ 1A</td>
<td>Bsh</td>
<td>Petrolina</td>
</tr>
<tr>
<td>3</td>
<td>CZ 1A</td>
<td>Bsh</td>
<td>Petrolina</td>
</tr>
<tr>
<td>4</td>
<td>CZ 2B</td>
<td>BWh</td>
<td>Cairo</td>
</tr>
<tr>
<td>5</td>
<td>CZ 5A</td>
<td>Ctb</td>
<td>Warsaw</td>
</tr>
<tr>
<td>6</td>
<td>CZ 5A</td>
<td>Dfa</td>
<td>Chicago</td>
</tr>
<tr>
<td>7</td>
<td>CZ 7</td>
<td>ET</td>
<td>Egilsstadir</td>
</tr>
</tbody>
</table>

**Discussion**

In general, the groups achieved a significant improvement in the percentage of adaptive comfort and reduction in the thermal load from some change in the envelope materials. Several groups reported expecting more effectiveness in the first changes (plantation and size of openings in hot climates). In contrast, changes in envelope materials and glass types were later more relevant. Others already had the envelope materials variation as a guideline since the climate and bioclimatic strategies. In this case, the readjustments described before the first simulation made simulation changes more effective subsequently. It enhances the significant impact that climate analysis has since the beginning of the design process. It is also evident that the more distant the climate to be projected is from each reality, the more climate analysis and bioclimatic strategies adaptation are crucial.

The link between adaptive comfort and thermal load analysis provided more exciting results in this early design phase. Even though the simulation had several default configurations, the students understood the phenomena that the guidelines caused in the building performance by comparing them in each simulation. Nevertheless, when the students analysed operative temperature, they analysed by the annual or monthly average. The guidelines did not affect the result as expected. The room operative temperature did not bring great reflections to the students and was not a palpable parameter to apply design changes.

Another critical point is data visualisation choice. In the experiment, the colour change of surface temperatures served as a support to decision making. For example, they noticed that the roof had a higher temperature than the walls. Therefore, it should have another type of material or colour in a hot climate. However, the absolute thermal load value and the percentage of hours in comfort allowed students’ greater autonomy and confidence about their decisions. It reaffirmed that they had carried out the changes correctly. Figure 5 represents the results visualisation method used by Group 01, which was the same for all groups.

![Graph of Group 01 results visualisation](image)

**Figure 5: Group 01 results visualisation.**

While surface temperatures are shown on the left of Figure 5, together with 3d sun chart with outdoor dry bulb temperature (Rhinoceros 3D), numerical results as the percentage of adaptive comfort and cooling or heating loads are shown yellow in Figure 5 (Grasshopper).

The materials and colours are relevant in the initial phases when seeking the best performance in the exercises. Some groups that worked with cold climates had as initial design guidelines changes in walls and roof materials. In contrast, in hot climates, some groups still did not consider this as an essential guideline from the beginning. On the other hand, hot climate groups that thought the roof’s heat gain crucial since the beginning had significantly improved building performance. It shows the value of climate studies and building adequacy in an urban context. Figure 6 represents some groups’ final building configurations. The colours represent the surface temperature analysis. Most hot climate groups changed the site location to use context shading, removed the roof window and reduced most of the windows. On the other hand, cold climate groups sought more sun exposure,
avoiding context shading, and enlarged windows with better sun orientation and reduced the shaded ones.

Another critical factor is the designers’ autonomy to make decisions concerning the acquired knowledge. The experiment with undergraduate students showed that, based on the knowledge gained, exciting changes and adjustments were made in the project, reinforcing the “learning by doing” method. Besides, it enhances designer’s autonomy to make design decisions regarding better performance using simulations. The student develops a critical sense about building performance simulation’s design decisions by analysing different results. It is evident, mainly, that the simulation program’s information does not need to inform what must be modified in the building, but it can be merely numerical. Nevertheless, it does not exclude the data visualisation with colours to differentiate surface temperatures (and possibly operative temperatures per room, in case of buildings with more than one room) as a support for decision making. However, the project guidelines and changes’ effectiveness analysis was able through numerical responses, based on the students' knowledge of the given result. Understanding the percentage of comfort hours by the adaptive method and increasing this percentage, and concurrently reducing thermal loads provided autonomy in most of the studied groups’ design decision-making.

However, there is still a need for improvement in simulation programs concerning interoperability with design programs. The great challenge of this research was to implement an unknown modelling program to the students. That was the case of cluster 3, in which the students had difficulties operating the new modelling software, and consequently, the simulation. It is also important to emphasise that such an experience during an architectural design discipline would show the link between building thermal performance problems and other problems presented in the design process. Thus, the problem-solving would be more complicated, as other limitations would appear. However, concerning the building performance simulation training itself, the software’s response to the students' design changes was satisfactory. Both the analysis and the design decision-making proved to be not only executable but exciting, feasible and with good results.

**Conclusion**

Many architects agree that the design process should embed building performance simulation. Unfortunately, in most cases, thermal physics and design teaching are two separate courses with different teaching methods in architectural education. It results in segregated knowledge, and that leads to non-concurrent project development. Without expertise, building designers rarely apply bioclimatic strategies and test if it leads to the building’s desired effect. It is why most building performance analyses are carried out in the final stages of design when better changes to improve building performance are not available. Architectural education could overcome this problem by testing new ways and software that could be more effective in the design process. Over the past few years, some researchers developed teaching experiences to combine performance simulations and design. In the end, they reinforce that there is no practical method for teaching simulation to architects. That said, the need for more experiments in the area is essential for its development.

This research analyses the design process of groups of architecture students using building performance simulation to assist in design decision making. To do so, they learned how to use Ladybug and Honeybee from Ladybug tools. They evaluated the site location potentials with Ladybug and then simulated the building performance with Honeybee. In the exercise, they had a simple one-room residential volume with the urban context. They could change building parameters such as building’s dimensions, materials, colours, orientations, location on-site, and windows’ dimensions and materials to improve building performance. Each group received a different city with a very different climate, but the baseline simulation and end reports were the same for each group. First, they analysed the site location potentials regarding bioclimatic strategies (such as sun and wind availability). Then they performed a reference simulation in which they made no changes in the building to start analysing and making decisions in design. They described every later analysis, proposal, and changes in design before and after each simulation.

The study had 17 groups, of which seven were analysed. The groups had cities located in different climate zones both by the Koppen-Geiger and ASHRAE climate classification. The final performed analyses of initial and final thermal load (cooling or heating) and the percentage of hours in comfort by the adaptive method. They had the same output analysis, which makes it easier to compare them. Besides, the groups managed to achieve interesting
building configurations with an average of 5 changes. Some groups achieved near 80% of adaptive comfort by reducing more than 70% of cooling or heating loads at the end of the project. Also, most groups needed from 4 to 6 design changes to reach such a design configuration. The main differences between groups were de changes in the design process. While some groups started by changing orientation and site location dimensions to block or use the sun with the urban context, the cold climate groups improved the materials first, which they described as the most relevant change.

The experiment shows that the simulation software's output does not need to inform the designer what must be modified in the building. In fact, the study shows that the result can be just numerical, as the designer is capable of understanding it within the design changes. Some groups achieved significant building performance improvements by combining different types of simulation outputs and data visualisation. Based on the knowledge acquired, the students made exciting changes and adjustments in the design. Besides, it reinforces the autonomy that the designer has to make design decisions regarding better performance using simulations, considering the learning acquired in his training. The student develops a critical sense about his design decisions from the building performance simulation by analysing a result. However, building simulation programs must have imperceptive interoperability with design programs.

References