Architectural Design: 
form follows sustainability?

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ABSTRACT
This paper describes different technological and architectural designs developed as the 2013 fall term project for the studio “Architectural Design VII” in partial fullfilment of the Architecture and Urbanism undergraduate programme belonging to the Federal University of Rio Grande do Sul, Brazil. The pedagogical aim of this project was to stimulate students to achieve high-level technological results along with expressive architectural solutions. The chosen case study was a residential unit ranging from 60sqm to 70sqm, able to house a married couple. The design brief was similar to the one adopted by the competition Solar Decathlon, held in the USA, Europe and China. The Studio methodology consisted of three steps: shape concept, performance evaluation and technological and architectural refinement. The shape concept is an exercise addressed to support the emergence of creative shapes with the contingent risk of getting unpredictable technological results; the following step consisted of the proof-of-concept of the house’s energy autonomy, whereby the students were asked to demonstrate the project’s electrical energy consumption and its capacity to autonomously supply at least the equivalent amount of energy. The performance tests involved evaluations related to natural lighting and thermal balance, daily and annual energy balance and reciprocally, the contribution of renewable energy and input sources such as photovoltaic cells and rainwater collection. In its final stage, the term project featured the refinement of the conceptual architectural design focusing on the integrated design of three building systems (structural, construction and installations). As a result of the term, it was observed that the adopted methodology produced reliable results for the pedagogical purpose in the fourteen projects presented, however the final stage may require more temporal importance in the schedule of the discipline.

1. INTRODUCTION

This work aims at describing the architectural design process using different technological and architectural designs developed during the 9th semester of the five year undergraduate program in Architecture and Urbanism at the Federal University of Rio Grande do Sul, Brazil. The main pedagogical aim of this term project is to encourage students to achieve high-level technological results along with expressive architectural solutions (Corrêa & Cruz, 2012). The chosen case study was a residential unit, 70 sqm, home for a married couple, and with a design brief similar to the one adopted by the Solar Decathlon (U. S. Department of Energy (1), 2014), held in the USA, Europe and China.

A previous evaluation of certain architectural solutions form the Solar Decathlon had raised the question about the limitation of sustainable homes regarding their form. Therefore, the term’s challenge was to answer the question as to whether it would be possible to design an expressive architectural shape...
while maintaining a consistent relation between form and environmental performance, specifically the balance between energy consumption and production. This assessment is based on the assumption that sustainability issues naturally cause considerable modifications in the architectural language of the designed houses. The need to use photovoltaic and solar panels, new building materials as well as assembly and disassembly techniques and last but not least, the need to optimize the architectural form in order to maximize the reception of solar radiation destined to create major implication in the final designs. It was observed that a significant number of projects featured very conventional house designs concealing the visual impact of the technical elements responsible for the environmental performance of the house. From the students’ points of view, various Solar Decathlon solutions — although featuring high scores according to the competition standards - did not introduce any particular contribution regarding their respective architectural form. All this reasoning has led to the question of how to achieve a good and optimized architectural design standard along with an optimized energy performance. Consequently, the problem of how to evaluate the students’ designs, when considering the consistency between sustainability issues and architectural form, arose. In order to accomplish this goal a pedagogical strategy has been set whereby a) the students were asked to start from an architectural vocabulary inspired by sustainability issues such as natural forms used for solar radiation capture, b) the students were submitted to an evaluation system which provides them with a permanent assessment during their design process in relation to the studio’s theme, i.e. the consistency between sustainability and architectural form, among others. The 9th semester studio methodology consisted of three sequential steps or exercises: i) the development of the shape concept, ii) a proof-of-concept including computational performance evaluations of the proposed architectural shapes and iii) final technological adjustment.

The remaining paper is divided into four parts: In the first part, the three stages are described. The second part presents the evaluation system and its results are analysed. In the fourth and last part, some conclusions are drawn in order to clarify the limitations and point out perspectives of the adopted methodology.

2. THE THREE STAGES METHODOLOGY

2.1 Development of the Shape Concept

The shape concept exercise was intended to support the emergence of expressive shapes with the contingent risk of provoking unpredictable structural solutions and energy performance results. Other issues, such as gray water collection and treatment, energy consumption and building materials, were at this stage considered peripherally as indicated by the structured list of requirements establishing the main design goals to be developed at certain points of time during the term.

This first phase was subdivided into two exercises: in the first one, the students analysed one entry to the Solar Decathlon competition and, in the second exercise, the students developed their own shape concepts. The analysis of the competition’s house was divided into four topics.

Varios aspects have been highlighted during the teaching, the first among those was the architectural language and to what extent it expressed the materials, technologies, equipments and strategies for the production and conservation of energy as well as the achievement of environmental comfort. The question is: Are the “green” characteristics visible or not? These features may exist but they might not be visible or distinctive.

The second topic was about building technology and implies prospecting two factors: on the one hand the description of basic structural characteristics of the building, on the other hand the identification of novel components not found in conventional constructions. Building technology also involves materials, which are used for structure, waterproofing, foundations, thermal insulation, internal and external coating. The student should describe aspects of employed technological innovation in materials by linking these factors to corresponding goals, such as energy conservation, thermal comfort, cooling, among others.
The third issue involved the analysis of passive strategies and materials proposed for thermal insulation on horizontal and vertical planes. The shape, size, position and orientation of the openings and sealing elements also should be presented and the students were supposed to verify the way each element contributes to the thermal and visual comfort of the analysed project.

The fourth focus, denominated Ergonomics, was related to the technological innovations articulated throughout the arrangement of spaces and the flexibility offered by furniture components. This variable was intended to assess different levels of ease of use during the operation of spaces such as kitchen, bathroom, living room and bedroom by the end-user.

The second exercise was referred to as “conceptual shape”, which would be used by the students during the term’s subsequential time. Its purpose was to encourage the students to research more creative concepts, in a process which may require taking a step backward to achieve the principles of sustainability. The use of materials, technologies, devices and strategies intended to produce and maintain energy, as well as achieving a suitable level of environmental comfort may generate a relative tension between the architecture of the building and the need to achieve one or more specific performances. The authors sustain the hypothesis that the process of challenging freedom of expression on the one hand and a technological and environmental performance on the other will intrinsically produce a pedagogical gain.

The shape concept exercise took about two weeks, and the students were asked to respond to the four major areas already established in the previous exercise: the architectural language, the structural system and materials, sustainability and ergonomics. This strategy was useful to inform the role of these different aspects visually and allowed greater control, increasing the likelihood of design success during these first steps of the form finding process (Turkienicz & Westphal, 2012). Using a storyboard strategy, the students described the main design ideas by means of images and text, which reflect the origins of the formal concept (Aroztegui, 2013). The resulting storyboard - describing the relation of chosen objects to the basic ideas of sustainability, such as mainly energy production or conservation - has led to the student’s preliminary design (Fig. 1, all future figures refer to the project from the same authors). In sequence, the students proposed transforming specific geometric concepts of the generating object, suffering mutations and evolutions in such a manner that it finally incorporates aspects of form as well as structure, but also left a appropriate degree of uncertainty in order to accept future peculiarities regarding the envelope, materials and ergonomics (Fig. 2).

Figure 1  Student work “Solar House”: (a) concept based on the Eno Rubik magic cube; (b) and (c) rotations of the slices providing different positions for better insolation; (d) summer insolation; (e) the final form (students: Fernando Netoux, Rodrigo Lima).

Figure 2  Generative strategy: (a) the insertion of an inner tube inspired by the Airbus’s structure; (b) external shape: the seventeen square structures are rotated 10° in relation to the adjacent ones, the exterior components work as an external envelope.
2.2 Proof of Concept

The second stage consisted of the proof of concept regarding the house’s performance whereby the students were asked to demonstrate required inputs, outputs and other specific performance values. Throughout the presentation of the project’s energy, thermal comfort, and natural lighting performance, it was required to demonstrate the consistency between form and environmental performance, at a point when the preliminary study had been concluded. The results were obtained by means of computational simulations and aided stipulations of contributions of the photovoltaic panels and rain water collection. The proposed building assessment creates a quick preview of the concepts, such as electrical energy consumption, thermal comfort and natural lighting, based on assumed simplifications or annual, monthly, daily, and hourly data derived from a global database of weather information. By using these results the students may improve their designs (Bergman, 2012). The stipulation and simulation of environmental variables required a theoretical base on specific technologies, which - in the beginning of the term – were disseminated during a series of lectures on Structural Building Systems, Photovoltaics, Passive Houses, Efficient Lighting, Environmental Comfort and Waste Water Treatment.

In more detail, the results were achieved using dynamic spreadsheets and the computation tool Autodesk Ecotect Analysis (Autodesk Inc., 2014), importing the model either from Google/Trimble SketchUp or from CAD. This tool was chosen due to its free access and ease of use, also guaranteeing quick results due to short processing times. Another alternative would be EnergyPlus (U. S. Department of Energy (2), 2014), but its use was discarded because time constraints are making it impossible to guarantee the student’s necessary theoretical and practical capacititation.

The students were able to determine whether the model was receiving suitable natural lighting levels using the Daylight Factor analysis (Fig.3a). In other words, a model with satisfying results is very likely to achieve savings of artificial lighting during daytime hours. Furthermore, the analysis of the Incident Solar Radiation contributed to the evaluation of the project’s potential to produce and store solar energy consequently resulting in the capacity to heat the interior space during winter and attending the need for shade in the summer month (Fig. 3b, 3c, 3d). The thermal comfort analysis uses discomfort expressed as Degree Hours in order to evaluate and compare the projects’ performance (Fig. 4).

Figure 3 Solar Analysis: (a) daylight analysis shows daylight factors between 2 and 10% in the interior zone, (b) solar radiation analysis for 21/JAN, (c) solar radiation analysis for 21/MAR, (d) solar radiation analysis for 21/JUL.
The energy balance evaluation should consider the entire amount of electricity consumed by appliances such as electric lighting, refrigerator, dishwasher, washing machine, and microwave oven as well as the energy produced by renewable sources such as photovoltaic panels (Fig. 5). The performance tests also involved the water balance created by the comparison between the points of consumption such as showers, washbasin, toilets, kitchen sink, dishwasher, washing machine and the water generated by the process composed of rainwater as well as gray water collection and respective treatments. In more detail, the autonomy from external fresh water sources is in most cases addressed by using stored and treated gray water for irrigation, cleaning and toilets. Indeed, the harvested and treated rainwater is reused for drinking and washing purposes.

Figure 4  **Annual Discomfort Degree Hours**: shows a total number of 3138.3 DegHrs of discomfort (too hot), 9176.6 DegHrs of discomfort (too cool), totaling an annual total of 12314.8 DegHrs, thereby the design should be refined for the winter month of the southern hemisphere.

Figure 5  **Energy Balance**: a positive balance was achieved (blue), with a greater amount of energy produced (green) than consumed (red).

### 2.3 Final Technological Adjustment

In its third stage, the term project featured the refinement of the architectural design through the integration of aspects related to structure, construction and installations. This step emphasized the
importance of correlating the architectural language with the technological demands. In other words, the students were encouraged to propose architectural solutions, which absorbed the technological demand (Fig 6). This phase enabled formal refinement, since at this point the student had the quantitative data needed to improve or change the qualitative aspects of his/her design. Energy consumption tables with negative results meant that energy demands had to be reduced or, alternatively, production had to be increased. As the production of energy is basically the result of the performance of the photovoltaic panels, it may be necessary to increase the efficiency of the product, optimizing the position related to the solar incidence or implementing a larger area of panels. In this final stage, the term project featured the refinement of the conceptual architectural design, which can enhance the conceptual form, but needs to additionally consider the building as it is conceived as a whole system, where the structure integrates the installations and the constructive system solves every different type of joint and/or interface between all components. For example, the structural systems as well as the sealing components may be designed as part of the solutions for HVAC, electricity and hydraulics systems (Fig. 7).

![Figure 6](image1)

Figure 6  Sections: (a) hot water tank supplied by the solar thermal collectors integrated into the eternal envelope’s structure; (b) technical equipment such as drinking-water tank, gray water tank, non drinking-water treated water tank, gray water treatment tank, black water tank, hot water tank, water pump, and solar inverters are placed under the house’s flooring.

![Figure 7](image2)

Figure 7  Technological adjustments: (a) the tube section forms the structural system of the house; (b) the final design.

3. THE EVALUATION SYSTEM AND RESULTS

The evaluation results showed that, during the first steps of the form finding process, the students obtaining above average scores for the conceptual integration of elements responsible for the environmental control presented the best solutions for the architectural and technical realization of the building envelope as well. The detailed resolution of the architectonical elements, such as photovoltaic panels, solar thermal collectors, solar protection and/or insolation, has been handled best by students who had managed to integrate these concepts into the overall idea at the beginning of the course. The same group of students would be expected to achieve the best performances. However this is not confirmed by the results at hand. Throughout the performance analysis of these student’s designs, the results have no obvious correlation with either the successful integration of the concepts into the idea or their detailed solution in the architectural elaboration of the project. A typical example is the balance...
between solar gains for daylighting on the one hand and heat accumulation caused by the same source of energy. These aspects involve a combination of profound studies of theory and practical experience, which students typically do not present at this given academic level.

When analysing the results by standard deviation for the categories related to the architectural elaboration of the building envelope as well as the resulting performance, two main observations can be made. Firstly, the lowest deviations are found in the categories regarding the photovoltaic panels and the energy balance, respectively; these categories also present the highest average scores. Secondly, by far the greatest deviation among the categories for the building envelope was found regarding warm-water production, while for the performances most differentiated scores have been obtained for thermal comfort, which consistently presented the lowest average scores. The first fact can be explained by prior education and the project’s focus in this specific criterium. An enquiry, although performed during a later semester, shows that students consider solar energy as the topic on which they have the most complete knowledge base compared to other technologies like thermal power generation or waste water re-utilization. Starting the semester with the analysis of case studies from the Solar Decathlon has predictively led to concepts and consequently technical solutions that are fit for this type of technology and have resulted in well elaborated energy generation mainly based on it. The second co-relation shows that the students either did not have sufficient prior knowledge of certain other technologies, such as warm water generation, or were not able to acquire such knowledge either from the theoretical lessons, from examples such as the analysed case studies or on their own during project development. Especially in the case of the thermal comfort the deviation must be explained by the low scores some groups obtained with wrongly executed simulations or erroneous representation and misinterpretation of the results they obtained with Autodesk Ecotect.

4. FINAL CONSIDERATIONS

In general, it may be affirmed that throughout the 14 projects turned in at the end of the term, the proposed methodology has ensured a relative homogeneity of results with respect to the pedagogical objectives outlined at the beginning of the semester. The evaluation of pedagogical procedures indicated the importance of emphasizing a constructive awareness even in the initial stages of the design process. Although the designs developed in 2013/2 reached high levels of formal exploitation (Fig. 9), the projects show a difficulty in reconciling this exploitation, especially with the constructive systems employed.

In more detail, the initial phase of the course, dedicated to the student’s analysis of one project from the Solar Decathlon competition, functioned as an introduction to the methodology developed for the course. Nevertheless, the authors noted that the students did not assimilate sufficient knowledge during this stage in order to incorporate innovative solutions from the analysed projects into their own. As improvement, the authors will try to implement the use of fisical models of the analysed projects in future semesters to improve the three-dimensional understanding of the implemented solutions and consequently raise the level of detailed understanding of the system as a whole. Another desired enhancement would be additional time for the refinement of the project based on the performance results obtained. Two weeks dedicated to this revisitation of the proper project would not only sharpen the understanding of the results itself, but also strengthen the understanding of the intertwined processes of sustainability, architectural form, and employed materials.

Finally, the integration of the architectural language, the building energy consumption and other described sustainability issues, involving building systems and requirements, have both process-related and aesthetic aspects. The concern with the process of all parts of the design emphasizes that sustainability is at the core of the design process together with other design parameters such as function, structure, construction and installations. The teaching strategies used is leading the authors to develop a methodological path to design, evaluate, demonstrate and qualify the object at all design stages, from conception to installation. The exploration of architectural language during the conceptual phase and preliminary studies of the house gave the students an opportunity to bind architectural forms to the goals of environmental performance. The three-step methodology has helped students to expand their
awareness of the risks of designing without attention to environmental aspects. At the same time, the manipulation of performance models throughout computational tools allowed the students to feel confident in their environmentally tested designs.

![Figure 9 Results: (a) Shadow House; (b) Cube House; (c) Gigogne House; (d) Fold House; (e) Cell House; (f) Origami House; (g) Tree House; (h) Energy House; (i) Allegro House; (j) House T; (k) Vitori House.](image)

**REFERENCES**


