INTRODUCTION
The word “compromising” is defined by the dictionary as “a settlement of differences by mutual concessions; an agreement reached by adjustment of conflicting or opposing claims, principles, etc., by reciprocal modification of demands.”[1] During the design process, designers need to achieve compromise between conflicting characteristics of a building or an object: cross-ventilation against protection, transparency against insulation, economy of materials against strength, form against constructability, and so on.

Kolarevic (2009) calls “integrative design” the cooperation between different disciplines “from the earliest stages of design, fluidly crossing the conventional disciplinary and professional boundaries to deliver an innovative product at the end” (p.337). He also points out the possibility of integrating “almost instantaneously produced” physical models into this process, as “a valuable feedback mechanism between conception and production” (p.338). Similarly, in her seminal paper Theory and design in the first digital age, Oxman (2006) points out the importance of interacting digital and physical models during the design process in different categories of digital expertise.

This paper describes an integrative design experiment in which different types of virtual and physical models were used in order to achieve a design that compromises aesthetics, lightness, fabrication, assembly and structural performance. It is part of a trilogy of conference papers in which three aspects of the design and fabrication process of the same object are described. The first aspect is the parametric design thinking process used to achieve

Samba Reception Desk

Compromising aesthetics, fabrication and structural performance in the design process

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Abstract. The present paper describes an integrative design experiment in which different types of models were used in order to achieve a design that compromises aesthetics, lightness, fabrication, assembly and structural performance. It shows how an integrative approach, through the use of both virtual and physical models, can provide valuable feedback in different phases of the design and fabrication process. It was possible to conclude that the design method used allowed solving many problems and had a significant impact in the resulting object.

Keywords. Design process; structural analysis; parametric design; digital fabrication; integrative design; models in design.
not only the object’s final shape but also the interaction between its parts and connections. The second aspect is the integration of virtual and physical models during the design process and structural analysis, presented in this article. The third publication focuses on fabrication issues with the use of plasma cutting technology, and its relations with the design process.

The result shows that structural analysis and the definition of production methods can be integrated within the design process by means of computational and physical modeling, with an impact on the object’s final form. The study was developed as part of a master degree research at the School of Civil Engineering, Architecture and Urban Design at the University of Campinas.

**METHODOLOGY**

The method in which the study was carried out was participatory action research. The authors were involved with the experiment from the earliest stages of the design process, passing through digital modeling and structural analysis until the production of the parts at a local industry. Tripp (2005) considers action research a type of action inquiry that allows improving practice as the researcher has an active role during the investigation process:

“Action Inquiry is a generic term for any process that follows a cycle in which one improves practice by systematically oscillating between taking action in the field of practice, and inquiring into it. One plans, implements, describes, and evaluates an improving change to one’s practice, learning more about both the practice and action inquiry in the process”. (p.445-446)

An important part of the research was the documentation of the whole process, through the use of photographs as well as video shooting of the design and fabrication processes. This allowed further investigation of the procedures used in a reflexive manner and the evaluation of the process.

**DESCRIPTION OF THE EXPERIMENT**

The design exercise consisted of developing a reception desk for the university’s Exploratory Science Museum. The desk should express the museum’s mission to promote the dissemination of scientific culture and technological innovation. The design was developed by students from the School of Civil Engineering and Architecture, both from undergraduate and graduate levels, in two phases.

Initially, a group of undergraduate students working at the school’s experimental architecture office (EMOD) developed the design concept: a piece of furniture that could be used in different layouts (fig.1-left,right), which should be at the same time innovative and interesting, but also light and easy to move around, depending on the needs of each exhibition. The students proposed a curved desk made of three discrete parts, to be built with CNC-cut flat material, structured by egg-crate style joints (fig.1-centre).

They produced 2D technical drawings (fig.2-left) using standard CAD software and made a laser-cut MDF scale model to check the joints and the stabil-
ity of the desk. The first problem encountered was the fact that the production drawings (fig.2-right) presented inconsistencies in many aspects, such as notch matching, continuity of curves and stability issues. Moreover, the width of the notches could not be updated automatically to adapt the design to different material widths. Full scale parts of the desk were CNC-cut in 18 mm plywood to check different notch widths, span deflection, and the overall stability of the structure. The physical models showed that the structure would be very stable, but assembling the desk would be difficult because of the rigidity of the plywood. The possibility of using a more flexible sheet material, such as steel plate, was then considered. It was estimated that the metal sheet should not be thicker than 2mm, or else the parts of the desk would be too heavy to be carried around. However, it was not clear if the horizontal surfaces would bend with the use of this thin metal sheet.

At this point, the team realized that the development of this project required an interdisciplinary approach to correctly resolve fabrication and structural problems. In the second phase of the project a master degree candidate and an undergraduate researcher focused respectively on each of these issues, combining their efforts to achieve an integrated result. A parametric approach was then considered and Rhinoceros CAD software was used, with three different plugins: Grasshopper, for the parametric definition of the shape and parts connections; Scan & Solve, for finite element computational structural analysis; and Rhino Nest, for optimizing the parts layout for fabrication. Besides, different rapid prototyping techniques were used: white and coloured 3D printing, laser cutting, and plasma cutting for final production (fig.3).

This phase included parametric modelling, structural analysis, the production of physical models and the final production of the reception desk at a local industry. Even though, the process was prob-
ably less time-consuming than if a non-parametric CAD representation had been used. The five stages of this phase are described in detail below, showing how the integrative approach through the use of both virtual and physical models provided valuable feedback to the design process.

**Checking mass stability**
- **Virtual:** This stage started with the parametric definition of the general massing of the desk in Rhinoceros, using Grasshopper plugin (fig.4-left).
- **Physical:** The massing model was 3D-printed in order to be tested for stability. Adjustments were made to the parametric model to ensure that the desk would not tilt (fig.4-centre,right).

**Planning fabrication and assembly**
Virtual: This stage consisted of slicing the massing model to generate the profile of each shelf (fig.5-left). The material thickness and the distance between the shelves were parameterized and the definition file allowed projecting all profiles on the XY plane. Although the metal sheet thickness for fabrication had been fixed in 2mm, the parameterization of this element allowed to easily adapt the drawings for producing study models at different scales and with different materials (fig.5-centre,right).
- **Physical:** A cardboard laser-cut 1:10 scale model was produced to check joints and easiness of assembly in a flexible material. The production of this physical model and all the other laser cut models was facilitated by the use of Rhino Nest plugin for optimizing the use of materials (fig.6-left). The parametric model allowed to automatically generate all the intersection notches. It also allowed changing their widths for different material thicknesses. The model could be changed quickly to generate multiple alternatives, in a form-finding exercise for best performance comply (fig.6-centre,right).

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*Figure 4*
Left: parametric model defining final desk shape.
Centre, right: 3D-printed massing model.

*Figure 5*
Left: sliced mass model defining final desk parts for fabrication.
Centre, right: 1:10 laser cut model parts.
Analyzing the structure

- Virtual: In this stage Scan & Solve plug in for Rhinoceros was used to generate a finite element model showing vulnerable areas, such as shelves with longer spans and cantilevered shelf ends (fig.7-left). However, the program could not predict the lateral instability observed in the physical scale model. (In order to test the reliability of the Scan and Solve plug in, the same structural analysis was carried out in Ansys software, with the help of a structural engineer. Although the overall results were very similar, the plug in did not have as many connection options as the specific software.)
- Physical: The colour-coded finite element analysis model was 3D-printed in colour, to show the result of the analysis (fig.7-centre,right).

Solving structural problems

- Virtual: The two structural problems detected –horizontal surface deflection and lateral instability – were solved with different strategies. The first problem was solved with the introduction of metal beams under the longer shelves for structural reinforcement. The second problem was solved with cross cable bracing. Bracing was also used to hang the cantilevered shelf ends. Cylinders representing the bracing cables were introduced in the parametric model to correctly define perforations throughout intermediate shelves (fig.8-left).
- Physical: At this stage larger scale laser-cut models (1:5) were produced to check the efficiency of the bracing and the beams under the shelves. In this model, 1.1mm thick cardboard was used to simulate the metal sheet flexibility and a thin copper wire represented the cross cable bracing, simulating deflection in the horizontal surfaces with longer spans and lateral stability correction (fig.8-right).
These solutions did not significantly increase the weight of the object, which would have happened if we had increased the thickness of the metal sheet. If MDF had been used, for example, the model would have seemed relatively more stable.

**Addressing material-specific fabrication issues**

In this step of the design process three fabrication issues were addressed: (a) best notch width, (b) welding of the parts and (c) paint finishing.

- **Virtual:** The first model in this phase consisted of finding the best notch width for the 2mm steel sheet as shown previously (fig.1-centre). The joints had to be tight, but should allow easy assembly. Thus, a simple 2mm thick steel plate containing five different notch sizes, varying from 2.1mm to 2.6mm, were 3D modeled and sent to fabrication in the CNC plasma cutter (fig.9). While having a closer look, it was possible to detect that some of the notches would come out obstructed by the material waste due to the steel cutting process (fig.9-right). Therefore, the team decided to perform a 3mm width notch to allow free fit, followed by a welding procedure. The second experiment was a small egg-crate structure specially designed for this test, and parametrically modelled in Grasshopper (fig.10-left). This experiment allowed a deeper investigation on assembling and welding methods (fig.10-centre, right). Again, the nesting plugin was used to optimize parts layout for fabrication through CNC plasma-cutting machine.

- **Physical:** This time, instead of using the laser cutter, the parts were sent to a CNC plasma-cutting machine in a steel-cutting company. Next, a partial full-scale prototype, with only three shelves, was plasma-cut, assembled and welded in order to evaluate the lateral stability gained with welding (fig.11). This time, no adjustments were necessary.

The second issue was related to the use of welding as an extra strategy for bracing. This issue could not have been predicted in the virtual models or even in the laser-cut cardboard models. The third assessment was the paint finishing and each of the egg-crate objects was sent to a different painting process.

The project was finally sent to CNC plasma cutting and post-production processes (fig.12-top left to centre right). It was finished with electrostatic paint and assembled on top of industrial-style wheels to allow for easy displacement around the museum (fig.12-bottom left and right). It also received a couple of light-weight boxes for storing and displaying products sold at the museum as souvenirs (fig.12-bottom right).

**DISCUSSION**

The design exercise herein described allowed us to draw conclusions related to the use of integrated software and to the use of physical models in the design process. The experiment showed the importance of integrating virtual and physical models in order to solve structural and fabrication issues. The use of physical models in different scales and with different materials along the different stages of the design process was fundamental to achieving a successful result. Even in a small scale and with different material properties one can identify possible structural problems in physical models that cannot be seen in virtual models.

The finite element analysis plugin was important for predicting structural vulnerabilities, which were displayed in a visual colour-coded language, directly on the parametric modelling environment, without requiring further knowledge in structural analysis. However, this evaluation by itself could not have given us all the responses needed as it could only demonstrate the object’s weakness due to vertical load. Lateral instability and the solutions for it could only be evaluated by physical models and full scale prototypes. Despite the limitations of the structural analysis plugin, the integration of parametric definition, generation of STL files for 3D-printing, structur-
al analysis and the automated generation of layouts for laser and plasma cutting within a single CAD environment was very positive.

In summary, it is possible to say that this exercise illustrates an integrative design process combined with the advances of fabrication. In this case, fabrication cannot be seen as just an output of a virtual modelling technique; it is completely intertwined in the design process. According to Oxman (2006):

“Digital technology has contributed to the emergence of new roles for the designer according to the nature of his interaction with the media. The designer today interacts with, controls and moderates generative and performative processes and mechanisms. Information has become a ‘new material’ for the designer” (p. 242).

We hope that the description of this design exercise can be applied to other design situations, and thus be used as a systematic method for integrative design.
Figure 11
Assembling 1:1 mock-up.

Figure 12
Top left: CNC Plasma torch cutting the steel plate.
Top right: tagging cut parts.
Centre left: organising parts for assembly.
Centre right: welding the parts.
Bottom left: electrostatic powder gun paint.
Bottom right: final assembly at the museum.
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REFERENCE


