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SAMBA RECEPTION DESK: COMPROMISING AESTHETICS, FABRICATION AND STRUCTURAL PERFORMANCE WİTH THE USE OF VİRTUAL AND PHYSİCAL MODELS IN THE DESIGN PROCESS

Balcão Samba: Compatibilizando Estética, Fabricação e Desempenho Estrutural com o Uso de Modelos Virtuais e Físicos no Processo de Projeto

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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 aproach, 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.

RESUMO Este artigo descreve um experimento de projeto integrado no qual diferentes tipos de modelos foram utilizados com o objetivo de compatibilizar questões estéticas, leveza, fabricação, montagem e desempenho estrutural durante o processo de projeto. O trabalho mostra como uma abordagem integrada, com o uso de modelos virtuais e físicos, permite obter respostas importantes ao longo das diferentes fases do processo de projeto e fabricação. É possível concluir que o método utilizado permitiu resolver diversos problemas, tendo um impacto significativo no produto final.

PALAVRAS-CHAVE Processo de projeto, Análise estrutural, Modelagem paramétrica, Fabricação digital, Design integrado, Prototipagem.

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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."* 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 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 [...]". (KOLAREVİC, 2009, 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 [...]" (KOLAREVİC, 2009, p. 338). Similarly, in her seminal paper, 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 also embraces three aspects of the design and fabrication process of the same object. The first aspect is the parametric design thinking process used to achieve 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. The third aspect focuses on fabrication issues with the use of plasma cutting technology, and its relations with the design process.

The objective of this paper is to show, by means of this design exercise, how information can be embedded in the models and prototypes produced along the design and production process, providing continuous feedback for the designer. Along the whole process, a series of different physical and virtual representations were produced. These were not simply representations. They contained lots of information about what was going on in the design process, such as the result of the finite element structural analysis or the stability of the different parts.

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 Engeneering and Architecture , both from undergraduate and graduate levels.

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 (Figures 1a, c), 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 (Figure 1b).

They produced 2D technical drawings (Figure 2a) using standard CAD software and made a laser-cut MDF scale model to check the joints and

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* Definition from http://dictionary.reference.com.

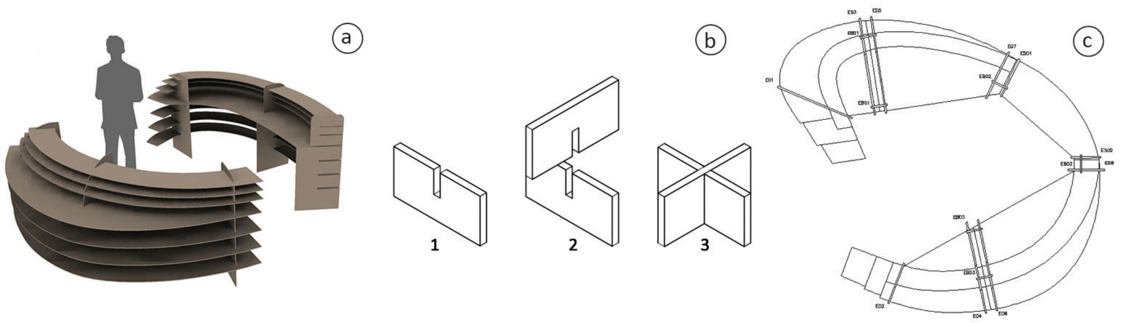


Figure 1. (a) Initial desk concept. (b) Egg-crate type joint. (c) Initial desk concept plan.

the stability of the desk. The first problem encountered was the fact that the production drawings (Figure 2b) 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 2 mm, 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.

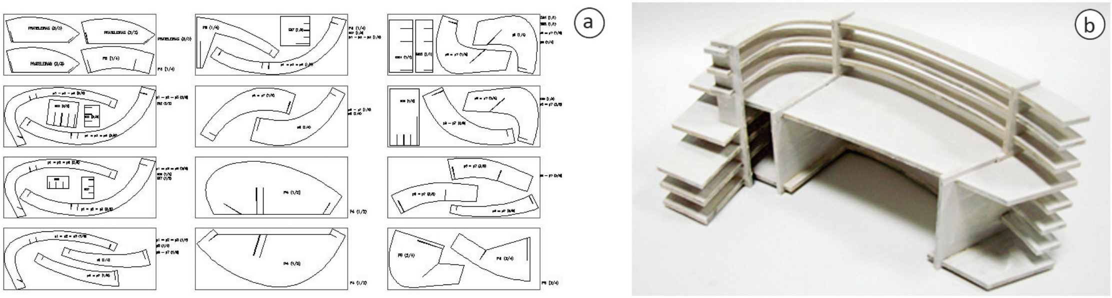


Figure 2. (a) Nesting of the parts showing material consumption. (b) 1:20 MDF physical model of the initial design.

At this point, the team realized that the development of this project required an interdisciplinary approach to correctly resolve fabrication and structural problems. From this point on, this design exercise became a more complex project, involving a team of researchers from the Laboratory of Automation and Prototyping for Architecture and Construction (LAPAC).

METHODOLOGY

The method with 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, p. 445-446) 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.

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.

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-and-Solve and Ansys, 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 (Figures 3a-c).

Figure 3. (a) Zcorp 3D printer. (b) Universal laser cutting system (c) Messer Multi Therm CNC plasma cutter.

From now on, the challenge was to design a 3D parametric model that would not only meet the client´s brief but also comply with the automated production capabilities. This experiment are described in detail below, showing how the integrative aproach through the use of both virtual and physical models provided valuable feedback to the design process (Figure 4).

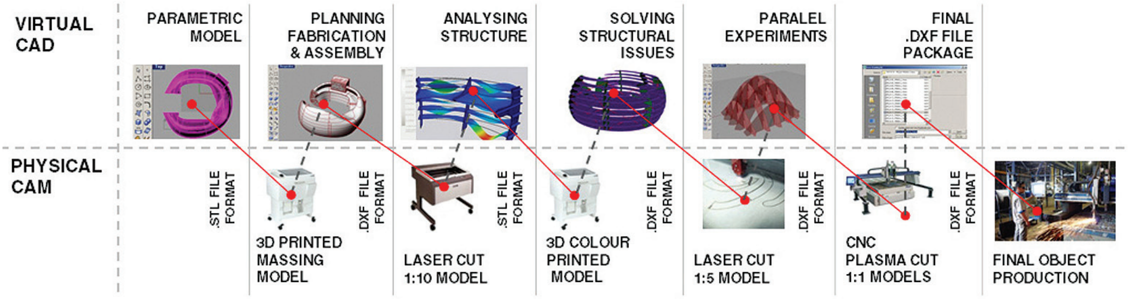


Figure 4. Virtual and physical workflow.

PARAMETRİC MODELİNG

Parametric design software are also known as "associative geometry" software. According to Burry (2003), this type of software makes the design process look like a search in a data bank. Along this path, design decisions are codified at the same time as shape is defined. These decisions can be retrieved at any point during the process.

In this exercise, Rhinoceros 3D-modeling software and the Grasshopper plugin were used to build a 3-dimensional parametric model. Rhino's interface allows to display in real time the rule-generated geometry built in Grasshopper. As the parameters set up in Grasshopper are modified, the model displayed in Rhino is simulatneously updated.

MASS STUDY

By developing an initial prametric mass model it was possible to easily generate a number of different variations of the basic shape. The search for the best alternative was initially conducted by aesthetic and ergonomic criteria.

The geometry of this initial mass model was generated by seting up a master curve on the base plane (Figure 5a). Next, this curve was divided into 8 equal segments. Each division point received a vertical plane, perpendicular to the master curve (Figures 5b). After that, a set of points that could be individually controlled by their x and y coordinates was positioned on each vertical plane (Figure 5c). Each of these sets of points were connected by a spline curve. Finally, a lofted geometry was generated by connecting all the spline curves (Figures 5d-f).

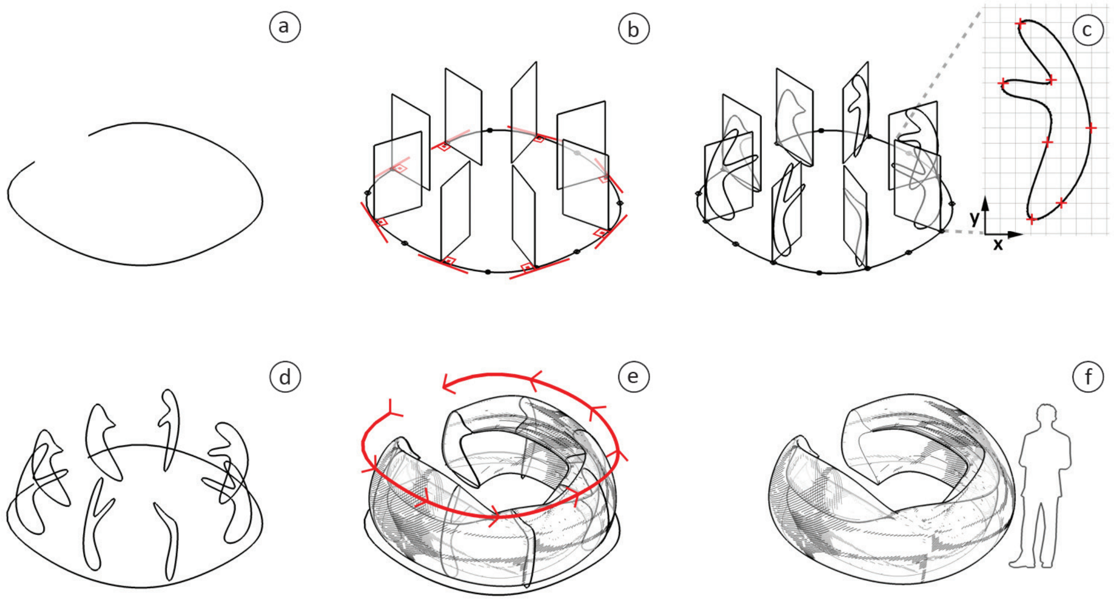


Figure 5. Steps in the generation of the mass model.

The possibility of controlling this mass model, through the manipulation of the x and y parameters of the points that defined each vertical spline, allowed using this model to dynamically search for the best shape (Figures 6a-c). It saved the time usually spent in adjusting and correcting the geometry that is common in traditional, non-associative design methods.

According to Francisco (2005, p. 21-23 apud DEAMER; BERNSTEIN, 2010, p. 30), that is exactly what parametric design tools are used for:

> [...] establish particular relationships between predetermined elements so that a change in a variable will automatically result in a "chain reaction" between elements that have been programmed to react that way [...]

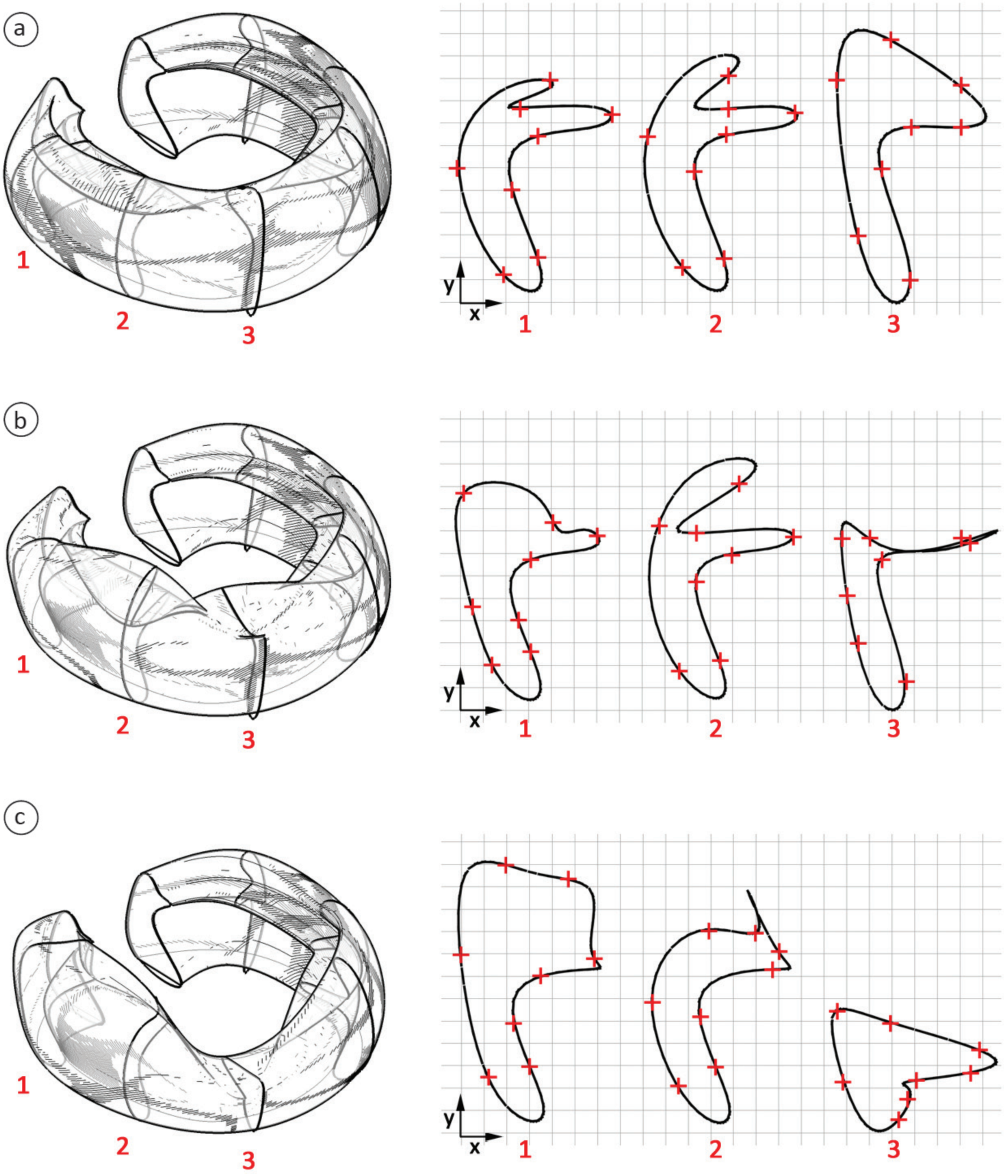


Figure 6. Three examples of parametric variations of the mass model, based on changes in the coordinates of the spline points.

CHECKİNG MASS STABİLİTY

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 (Figures 7a, b).

PLANAR SECTİONS

After the definition of the mass model, the parts of the object, such as the shelves and their vertical supports, were generated through planar sections. Firstly, two vertical planes were used to split the mass model in three separate parts. Next, a series of horizontal planes was created, with a parametric distance between them. The interesections between these planes and the mass model resulted in the shelves (Figures 8a). The variation of the distance between the planes (delta h) allowed to test different design alternatives (Figures 8b, c), in order to achieve the appropriate use of the shelves. Finally, each part was extruded at a parametrically defined thickness, which could be changed at any time.

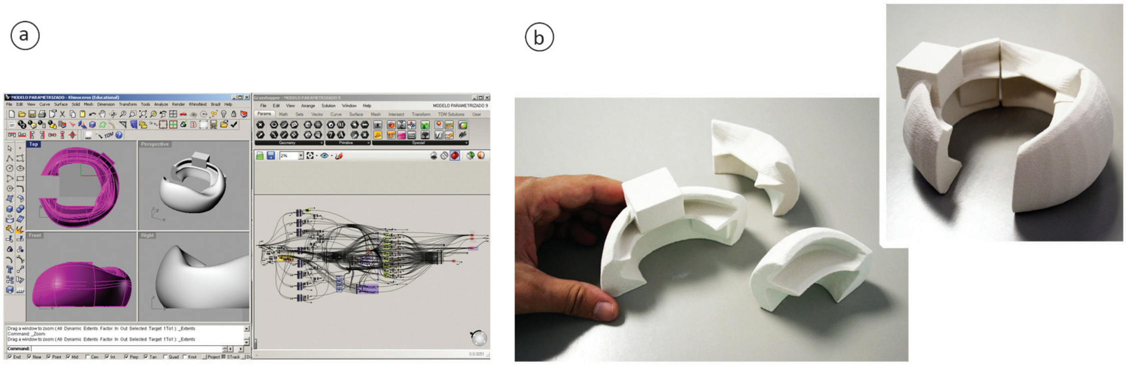


Figure 7. (a) Parametric model defining final desk shape. (b) 3D-printed massing model.

CREATING THE NOTCHES

In order to physically build the model without the need of connection parts, the “egg-crate structure” strategy was used. With the parametric model it was possible to automatically generate the notches in the vertical and horizontal parts, through solid subtraction, as shown in (Figure 9a-c). This strategy allowed the notches to be automatically updated as the main curve and the vertical splines were changed.

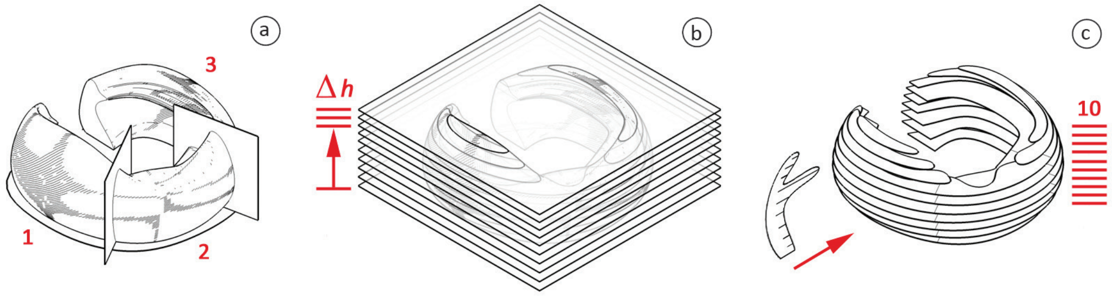


Figure 8. Section plane creation steps.

GENERATING THE FABRİCATİON DRAWİNGS

The scale models in this stage and the final object were produced with machines that can automatically cut flat materials, based on a digital file: a laser cutter and a plasma cutter. Thus, it was necessary to generate 2D digital drawings based on the 3D model. The RhinoNest plug in for Rhino was used to flatten the parts and organize them in the material sheets. Different cutting layouts had to be generated for the laser cutter and the plasma cutter, due to differences in each machine’s parameters, such as table size and security margin.

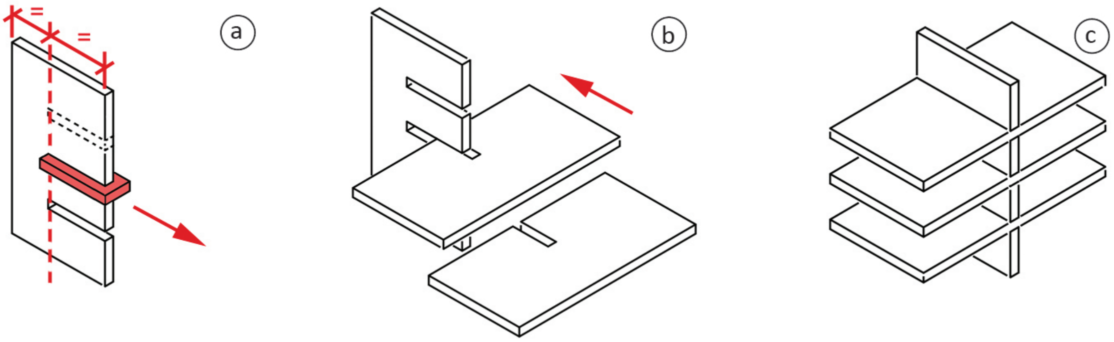
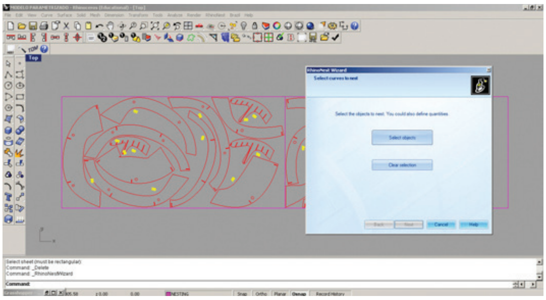


Figure 9. Automatic generation of the notches by solid subtraction.



Select the objects to nest. You could also define quantities.

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Select sheet (must be rectangular):
Command: _Delete
Command: _RhinoNestWizard
Command:
```

Figure 10. Optimizing parts in flat material surface.

This phase started with the alignment of all the object's parts on the horizontal base plane. Next, each part was automatically identified by the plugin with a number corresponding to its position in the 3D model. The parts were then automatically laid out by the plug in within the limits of the available sheet of material for each case (the cardboard used for the model and the metal sheet used for the final object). This operation was performed with the Rhino Nesting's "wizard" function (Figure 10).

ANALYZING THE STRUCTURE

In this stage Scan-and-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 (Figure 11a). However, the program could not predict the lateral instability observed in the physical scale model. The color-coded finite element analysis model was 3D-printed in color, to show the result of the analysis (Figure 11b).

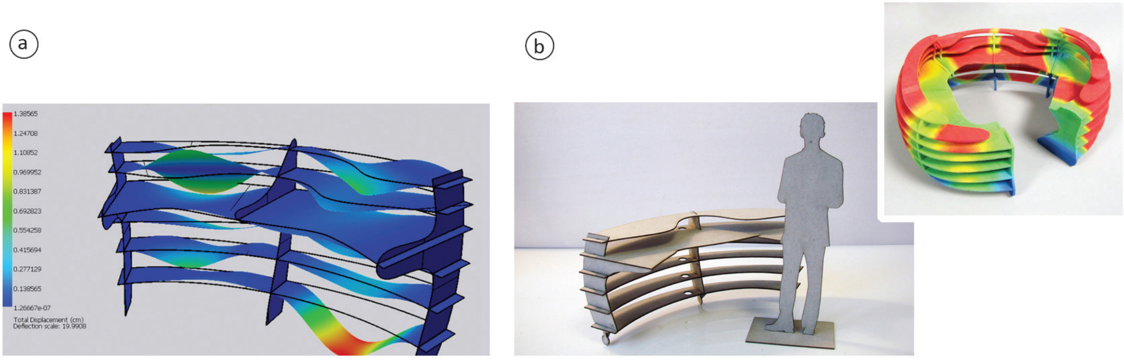


Figure 11. (a) Finite element analysis with Scan-and-Solve plug-in. (b) 1:10 laser cut model and full 3D colloured model.

Two structural problems were detected – horizontal surface deflection and lateral instability – and 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 (Figure 12a).

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 (Figure 12b).

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.

In order to have an imediate feedback of the structural performance of the designed object, we used a structural analysis plugin that was integrated in the parametric modeling software. This allowed to embed the performance information into the same model that was being used to generate shape and to resolve production issues. The plug-in used was Scan-and-Solve for Rhino.

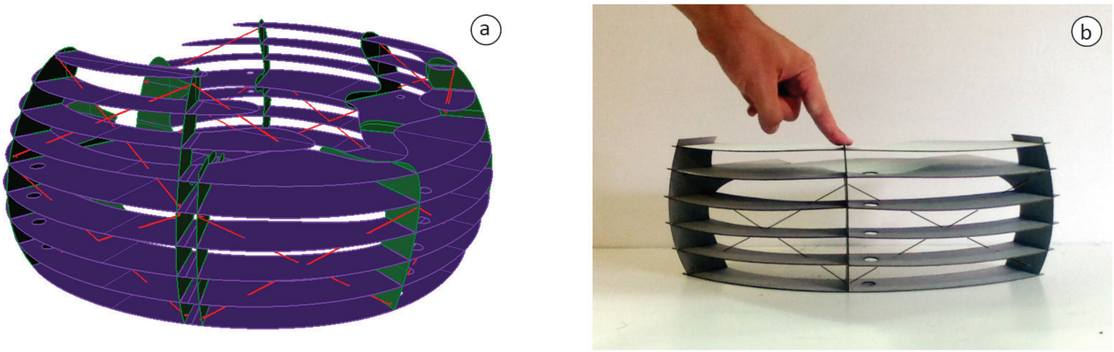
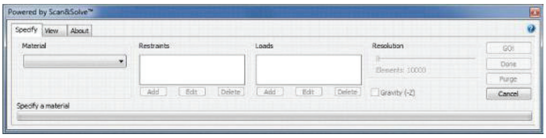


Figure 12. (a) Parametric model defining cross bracing cable and shelves intersection. (b) 1:5 laser cut model testing cross bracing eficiency.

Scan-and-Solve does not require a high knowledge of structural analysis by the user. It generates a simplified finite-element model. The finite-element method (FEM) was originally developed in the 1940's by Richard L. Courant (PELOSI, 2007). It consists of a numerical technique for finding "piecewise-linear approximants on a set of triangles" in order to solve complex structural analysis problems. FEM can also be applied to heat transfer, elasticity, vibration, hydrodynamics and other types of problems. One of the advantages of the FEM is the flexibility in manipulating parameters and making adjustments.

After being installed, Scan-and-Solve can be activated from Rhino's interface by typing "SnS" in the prompt or by clicking on its icon on the menu bar. Its interface consists of a window with three tabs: specifications, visualization and information about the plug-in (Figure 13).



Elements: 10000

Specify a material

Figure 13. Scan-and-Solve's interface.

Initially, a model with 2 mm-thick plates was "baked" from the Grasshopper model (converted from a parametric, instable model to a stable geometric model in Rhino). The process of analyzing the model started with the indication of the areas of reaction. In our case, the base plane of the vertical plates were selected as reaction areas. Next, one must specify the object's material properties. All the parts were specified as steel (Steel AISI 1020). The vertical and horizontal parts had to be unioned by a boolean operation, as if they were welded, because Scan-and-Solve only allows to analyze one object at a time, thus it does not allow to specify articulated connections between parts. Other elements, such as the object's wheels, were also not taken into account for the structural analysis.

In order to evaluate the precision of the Scan-and-Solve plug-in, the analysis of the geometric model of the museum's reception desk was also performed with a more sophisticated finite-element software, Ansys. This analysis was carried out by a structural engineer from CTI Renato Archer.

The main difference between the two applications was the limitation of Scan-and-Solve in simulating joints, while Ansys allows the analyses of each discrete structural parts and its connections. Scan-and-Solve currently only allows faces to be restrained. Although its website says that "future versions of Scan-and-Solve will feature the ability to restrain edges and vertices" (http://www.intact-solutions.com/sns_documents/faq.htm#lnr-1), this present limitation reduces considerably the accuracy of the results. Even though, Scan-and-Solve allows to uderstand structural behaviours that can easily remain unnoticed during a digital design process. A typical example is the visualization of parts of the model that are subject to bending or buckling due to insufficient thickness, for example. Scan-and-Solve's interface includes a sliderbar with which this type of deformation can be exagerated, thus pointing to the designer the need to reinforce certain parts of the object. The Figure 14 shows two graphic represenations of the analysis performed with Scan-and-Solve. The color scale from blue (smaller) to red (higher) allows to easily visualize the concentration of Von Mises tensile stress in the different parts of the model. Instability situations are due to the ratio between the lenght of the overhang and the insuficient thickness of the plate.

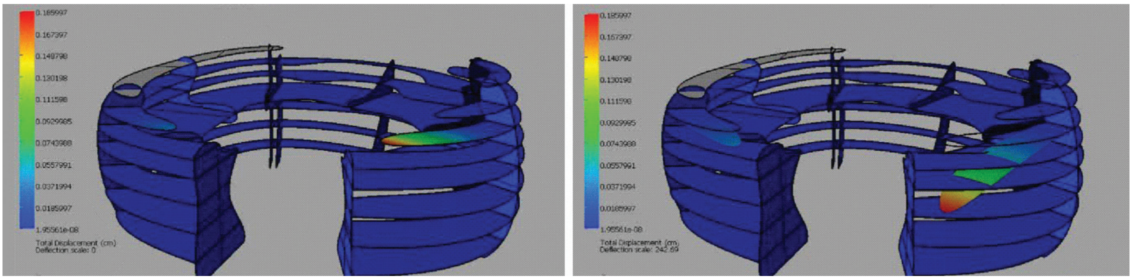


Figure 14. Structural analysis in Scan-and-Solve with two different loads.

Ansys, on the other hand, can consider virtually any type of link between the components of an object, because it can consider them as discrete parts. Thus, the variation in their thiknesses and the restriction in their connections, as well as exterior forces can be considered in the structural analysis.

Figure 15 shows two graphic results of the Ansys analysis of the model of the museum's reception desk, simulating the "egg-crate" connections. Although this analysis has a higher level of detail if compared to Figure 14, it is possible to say that the overall behavior of the two objects is very similar, especially regarding the bending of the longer shelves and overhangs.

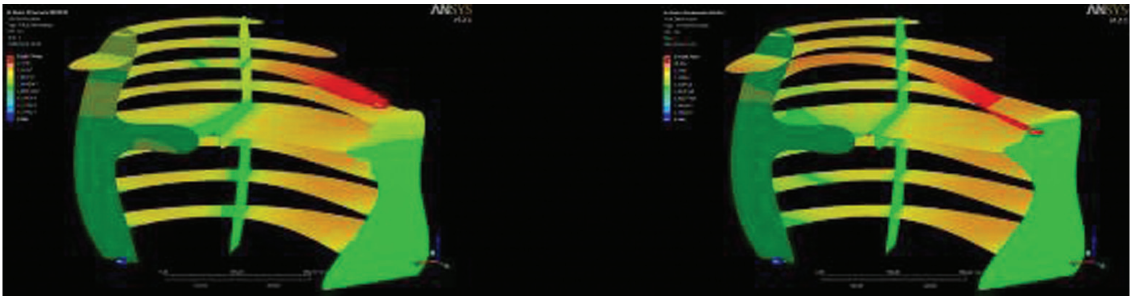


Figure 15. Structural analysis in Ansys with two different loads.

The main difference between the two analyses was the lenght of the deflection and the overall instability of the models. Scan-and-Solve shows only local, limited instabilities, while Ansys points out the need to stiffen the connections to achieve higher overall stability. In other words, Ansys can show the consequences of designing the connections with a greater degree of freedom towards a specific direction. If we run the analysis in Ansys considering all connections to be stiff, then the result is very similar to Scan-and-Solve's results. In this case, the main difference if the deflection: in the longer shelf it is 8,62 cm for no Scan-and-Solve and 9,10 cm for Ansys. This small difference is probably due to the input of material properties, which is much more accurate in Ansys, where properties such as elasticity, density and type of steel can be specified individually.

In order to better visualize the results of the strucutral analysis run in Scan-and-Solve, a physical model was produced with a 3D Spectrum Z510 color 3D-printer. Scan-and-Solve's "Bake" button allows to save the result of the analysis with or without the resulting deformations. The .3dm file was then exported as the two formats needed for the color 3D-printing: .png (portable network graphics), which cotains the color image applied to the surface of the model; and .wrl wich contains the geometry of the model. Both files were imported in the Z-print software and the scale model was thus produced (Figure 16).

Figure 16. 3D collour printing.

Despite its limitations, it is possible to say that Scan-and-Solve is a good alternative for simulating real-world behavior of a digitally modeled shapes, especially in the case of monolithic, rigid structures. In the case of structures with flexible joints, it can still be used for preliminary results, which can then be refined with the use of more specific structural analysis software. In any case, the use of Scan-and-Solve in the initial steps of the design process can lead to better solutions regarding structural performance. The facts that it is embedded in a popular geometric modeling application (Rhino) and it has a very simple interface encourage its use even by those with limited knowledge of mechanics of materials and structural dimensioning.

FABRICATION

In the past decade there has been an increasing application of computer-numerically-controlled machines in the production of building parts. CNC techniques, originally used in industries such as aerospatial and ship-building, have recently started being incorporated in architecture production. This method of fabrication, which has been called "file-to-factory", eliminates the necessity of intermediate representations between the designer and the final building components. Authors such as Kolarevic (2003) have proposed that these new fabrication technologies, along with modeling and evaluation performance software, will challenge the traditional approach to design. However, even though architects have already become familiar to digital software to draw and model their designs, they are not ready for dealing with more specific production issues, such as CNC machine parameters, materials properties, and so on. As a result, the file-to-factory process is usually not so straightforward as it should be, requiring multiple adjustments and often getting stuck due to issues such as file format incompatibility.

The objective of this section is to show how it was important to get closer to the industry in order to find out which are the most typical difficulties in this type of process, and infer, from this experience, what architects should know to make it seamless. The importance of this approximation has been clearly stated by Kolarevic (2010, p. 71):

> Knowing the production capabilities and availability of a particular digitally driven fabrication equipment enables designers to design specifically for the capabilities of those machines. The consequence is that designers are becoming much more directly involved in the fabrication process, since they create the information that is translated by fabricators directly into the control data, which drives the digital fabrication equipment.

The final piece production was carried out ata local plasma cutting company called Oxipress. Although this firm has invested in state of the art steel cutting machines, they are not used for producing complex design objects simply because there is no demand from their clients, its main field being simple mechanical parts (Figure 17).

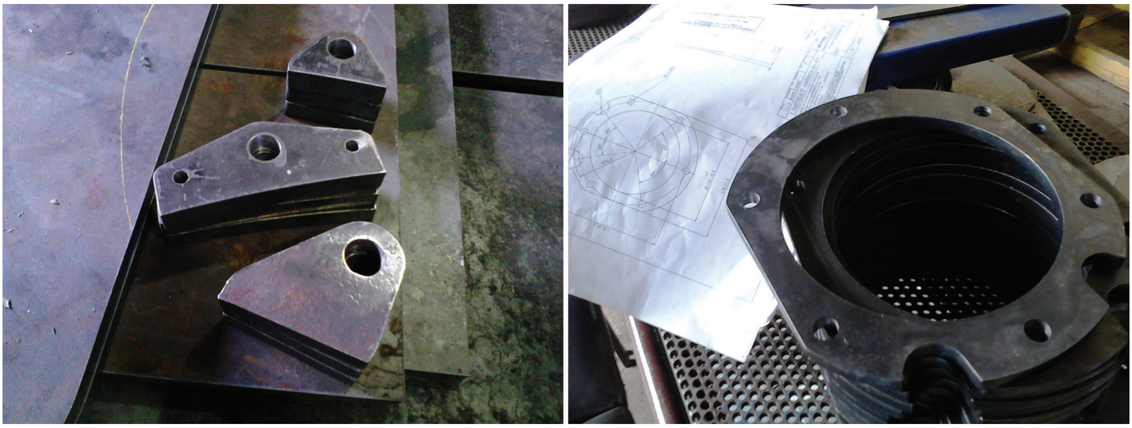


Figure 17. Parts commonly produced by the company´s CNC plasma cut machines.

During this time, the authors followed the everyday production process, being able to experience from the early stages of the preparation of CAD files, through cutting steel sheet routines, until the final steps of assembling parts and post-processing. The idea was to learn about the capabilities of the machines and introduce a new scope of production in the factory.

The period of study in the factory was divided into two major steps:

- (A) Exploratory Stage, which involved the production of a series of experiments to investigate material properties and to learn about the capabilities of the CNC machines.
- (B) Production Stage, which allowed the implementation of the knowledge gathered in the previous stage to complete the file-to-factory process.

The equipment used during this study consists on a Messer Multi Therm 4x14m CNC machine with a Hypertherm HPR 400 plasma source supply capable of cutting up to 60 mm stainless steel sheets (Figure 18). The CNC machine is basically composed by the following set of parts: (1) a cutting table equipped with a smoke extraction system, (2) a power supply

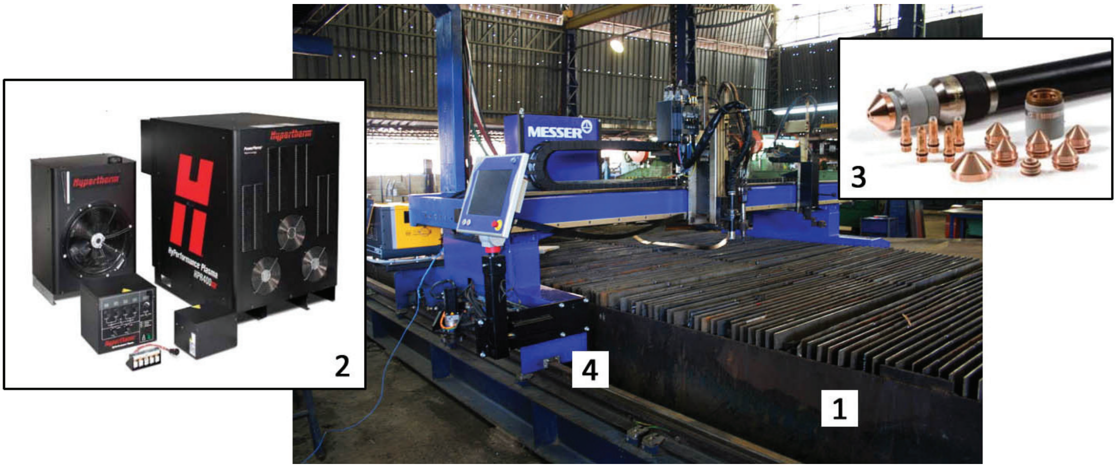


Figure 18. Plasma CNC machine.

which provides the plasma arc starting circuit; (3) a torch that holds a set of consumables parts enabling an extremely constricted plasma arc and (4) a software that controls the process.

According to the manufacturer's 'these system components provide the electrical energy, ionization capability, and process control that is necessary to produce high quality, highly productive cuts on a variety of different materials[**].

During the development of the Exploratory Stage in the factory, it was necessary to perform a series of experiments related to a range of issues, such as assembly of the parts, thickness of the cuts, and so on. During the fabrication process, many adjustments had to be made in the design to comply with the material's properties. The close contact with the factory's team allowed for a better transition between the original files and the CNC machine files. This experience resulted not just in an original piece of design, but also in an invaluable body of knowledge about the file-to-factory method.

The first experiment was a plasma cut test. The purpose of this excercise was to understand the basic procedures and functionality of the CNC machine, as well as the behavior of three different materials: carbon steel, stainless steel and aluminum. A set of irregular sized shapes was cut in three 400 x 400 x 2 mm plates to perform the tests.

The designs were generated through a parametric rule using Grasshopper plug-in for Rhinoceros CAD software and the 2D information saved as .dxf file format in layer 0. It is important to note that there was no text or dimensional lines in the drawing. Then the file was e-mailed to the company's engineering department for the following procedures: check the file for drawing or layer mistakes, check the pieces size and thickness to match material availability and check machine time consumption to inform the production schedule. These procedures are compulsory for any file submission to this particular CNC machine avoiding software malfunction.

The first material to be cutted was the stainless steel plate (Figure 19). This type of steel is popular for its corrosion-resistant properties and its hardness. For this reason it is required that a particular set of consumable parts are placed in the torch to match the material's specifications, in order to perform a good cut.

Figure 19. CNC plasma cutting process showing different designs.

Next, the cutting process was performed on the carbon steel and the aluminum plates. Each of these materials was cut with its specific set of consumables (Figure 20). These consumable parts control the size and the shape of the plasma arc and they eventualy wear out and need to be replaced. Thus, another important information that arised was the fact that multiple initial piercings, to cut isolated shapes, would cause a higher expenditure of consumables in the torch, shortening its lifetime. This could be a point to

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[**] Information available at Hypertherm 'Training and Education': www.hypertherm.com

Figure 20. Changing torch consumable parts (photos by Wilson Barbosa).

be considered at the initial steps of the design process, since the higher the consumables consumption is, the higher will be the final production cost.

Moreover, it can be suggested, when suitable to design, that multiple shapes could be arranged to be cutted from a single perforation, as shown in Figure 21.

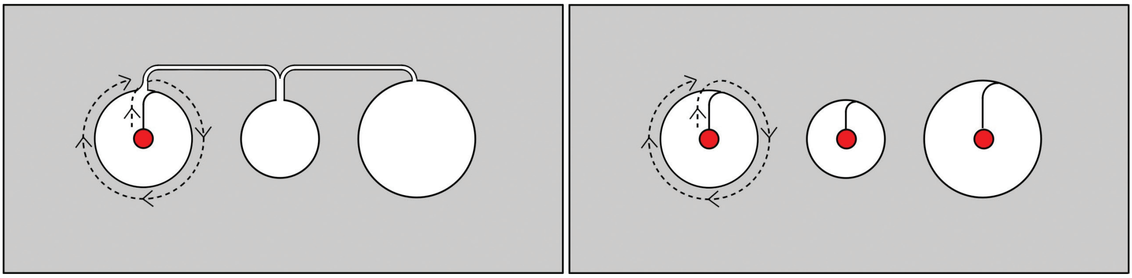
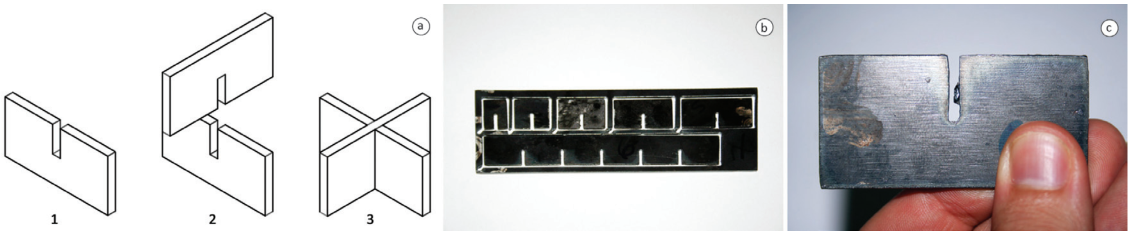


Figure 21. Scheme showing multiple shapes perforation with a single piercing point.

To evaluate the most appropriate connection between two 2 mm-thick transversal pieces of plates, a second test was performed. This type of junction between plates is commonly known as egg-crate fitting, where a notch is cut on both parts (Figure 22a). Firstly a 3D model of a simple structure containing notches with five different widths was developed in Rhino/Grasshopper and 2D vector files were produced to be sent to the machine, as described above. Next, each piece was cut in a 2 mm carbon steel plate. Each notch in this drawing had slightly different widths, varying from 2.1 mm to 2.6 mm (Figure 22b). When the parts were assembled it was possible to observe some relevant issues. Although in the first option the notch was thicker than the material, the parts did not fit. A closer look revealed that the notches were obstructed by the material waste (Figure 22c), due to the cutting process, and had to be removed manually with an orbital sander.

Depending on the part dimensions or the number of parts produced it would be too difficult or take a long time to manually fix each of the notches for best fitting. To improve notch cut, a couple of slightly different egg-crate structures were developed. At this stage, two 3D parametric models were designed with a more complex shape to further evaluate fittings: (1) a small size curved egg-crate sample and (2) a full size egg-crate chair (Figure 23).

Figure 22. Both virtual model and phisical prototype of fitting sample.



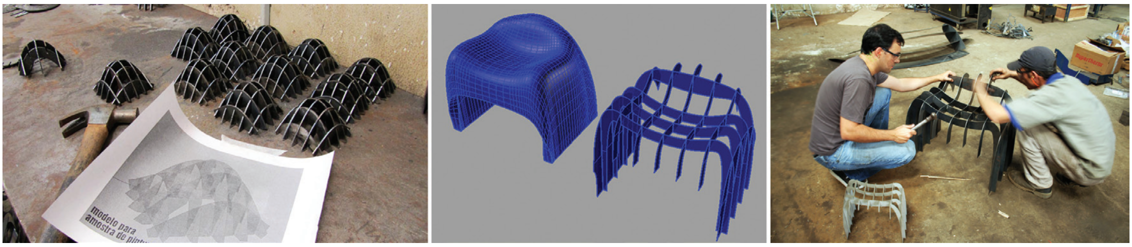
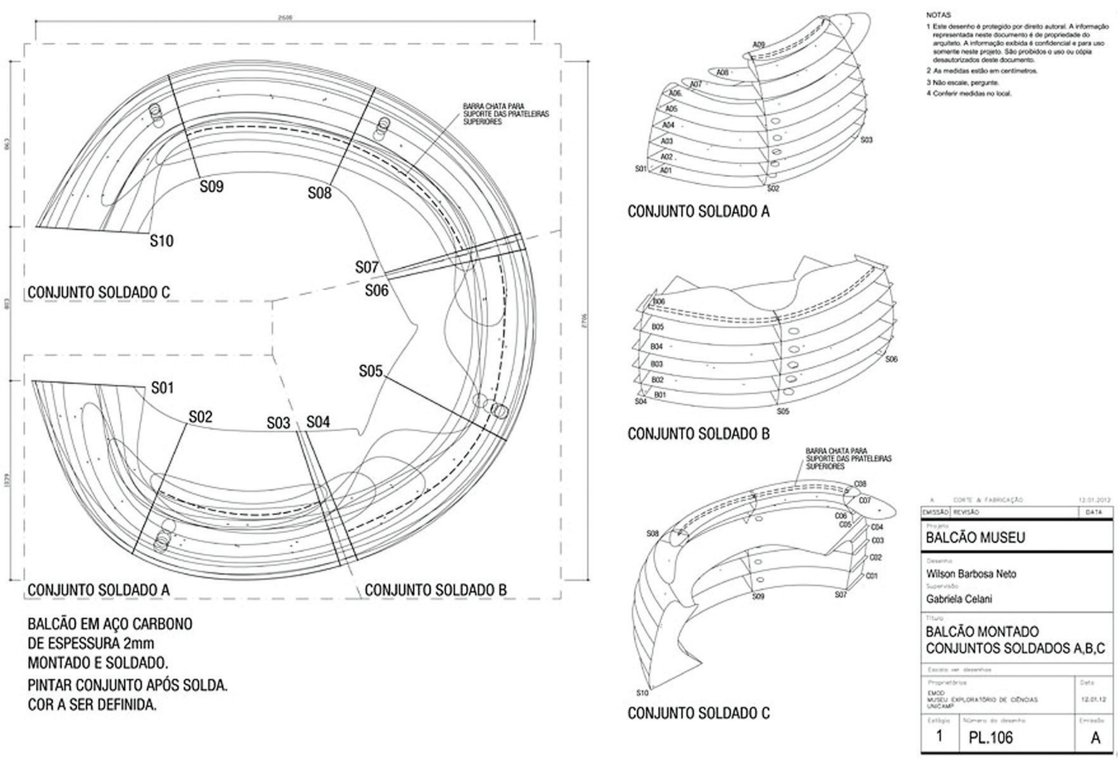


Figure 23. Images of both egg-crate experiments virtual models and phisical prototypes.

Both prototypes were made with the same 2 mm-thick carbon still sheet used in the previous experiment. However, the notch thickness was set-up as 3 mm wide, allowing a correction-free notch and a perfect loose fitting. Then, the parts were assembled and its joints welded together to make a stable structure. Fifteen small size egg-crate samples were made to be submited to different painting treatments.

After the completion of the exploratory stage it was possible to transform the gathered information into design principles that would lead to a quite seamless production process. The entire object was made from 33 individual



BALCÃO EM AÇO CARBONO
DE ESPESSURA 2mm
MONTADO E SOLDADO.
PINTAR CONJUNTO APÓS SOLDA.
COR A SER DEFINIDA.

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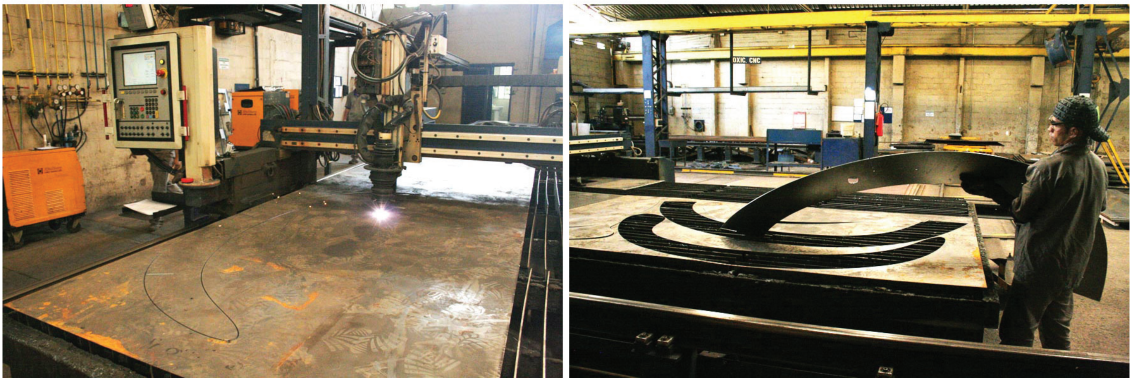

Figure 24. CNC plasma cutting process.

parts. The 2D information of each part was saved in a separately .dxf file under layer 0. Then, the 33 CAD files were e-mailed as a compressed file format package to the company's engeneering department for 'nesting' set up and other procedures described above. Regarding material consumption efficiency while cutting the parts, the 'nesting' process can be considered the most important step. The word 'nesting' is defined as 'the process of efficiently manufacturing parts from flat raw material'[***]. So, the better the optmization of the parts on the material surface is, less will be its consumption and, consequently, product final cost.

Next, the entire file package was imported in a specific nesting software and its 2D information arranged on 1200 x 3000 x 2 mm thick carbon steel sheets, which resulted in a material consumption of 16 plates. After that, the nesting files were placed inside the 'job order' folder where they could be accessed by the CNC machine operator. The plasma cutting process took approximatley 7 hours (Figure 24).

After the parts had been cut they were manually tagged according to design. The pieces were transported to the metalworking shop and then separated by assembling order. Two workers were necessary to move the parts and position them for assembling and welding the joints. In order to compensate for the flexion of certain parts of the object, in special the cantilevered parts of the shelves, a metal ribbon was welded underneath them. This part of the production process took two days (Figure 25).

Figure 25. Assembling and welding process.

CONCLUSION

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 color-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 plug-in, the integration of parametric definition, generation of STL files for 3D-printing, structural

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[***] Definition from wikipedia.org

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, using both computational and physical modeling. In this case, fabrication cannot be seen as just an output of a virtual modelling technique; it is completely intertwined in the design process, with an impact on the object's final form. According to Oxman (2006, p. 242).

> 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.

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.

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