H-CNC Supported Design: Computer Numeric Control for Heritage environments.

Habitáculo temporário para a receção a visitantes.
O caso do Parque da Pena, em Sintra.
[Extended abstract]

Cristina Golebiowska Leite de Sousa
Instituto Superior Técnico | MA 2018/2019

Abstract: The presented study associates the application of CNC technologies with heritage environments. The application of these technologies has been a target of experimentation in the field of architecture, using tools like CAD/CAM and CNC.
In order to fully comprehend the workflow of digital fabrication, a construction of a small temporary support structure, for Pena Palace and its Park, at Sintra protected landscape, was developed. The integration of a case study related to heritage with digital fabrication allows one to fully understand and analyze such application in this specific area: the built heritage. The design cycle had inputs from parametric modeling and it resulted in outputs of digitally manufactured prototypes Such approach allowed us to identify advantages, disadvantages of digital processes and fully comprehend the relationships between these two, apparently, very distinct topics: technology and heritage. And thus concluding the full contribute of this technologies in the preservation of heritage.

Key words: Digital Fabrication; Parametric Design; Heritage; CAD; H-CNC; Sintra.

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1 I INTRODUCTION

The development of CNC technologies has been drastically changing the industries such as aerospacial, nautical and automobile in the last decades. Nonetheless the interest in the application of this technologies in the field of architecture and construction, has been expanding since the end of the 20th century, with early experimentations using milling machines dating the 70's (Kolarevic, 2001). We've seen the works of Frank Gehry such as Experience Music Project (EMP) in Seattle (1997-2000), the Guggenheim in Bilbao (1993-1997) and Zollhof Towers in Dusseldorf. In every project, CNC machines helped the construction of complex shapes paving a new way of approaching design and production. The EMP project took advantage of the software CATIA – previously created for aerospacial industry – allowing to translate complex shapes into ruled surfaces and thus providing the means to produce aluminum parts using 2D CNC cutting machines (Januszkiewicz, 2016). The Guggenheim was one of the first projects that really allowed to fully comprehend the potentials of this applications in the field of construction, in the end 33,000 titanium parts where fabricated using CNC's, and doing this in a period of 5 years instead of the previously estimated 7 years (Guggenheim Bilbao, 2017).

The experimentation was not only applied in the field of construction and fabrication but also in the design process, creating digital driven methods using CAD software. Methods like parametric design come into the equation of most of these projects. Parametric design is understood as a digital tool that allows one to translate complex objects into parameters, where each geometry is associated with one or more parameters (Hinton and Hardy, n.d.). They are characterized for their dynamic approach and are in constant and rapid transformation (Kolarevic, 2001).

In the field of historic conservation and heritage the most recognized project is the Sagrada Familia of Antoni Gaudí. With the help of these technologies the complex forms and shapes of the building were translated into mathematical equations in order to gain a better control of the design process. And with the introduction of 3D printing machines the team lead by Josep Gómez was able to produce study models to better comprehend their architectural solutions (Gómez, Espel and Faulí, 2008) (Volner, 2014). In the actual construction of the cathedral, CNC milling machines where introduce to help experienced artisans and sculptors to fabricate big stone pieces for the columns and windows (Gómez, Espel and Faulí, 2008).

The use of digital design methods in the field of heritage were also applied, with the example of BIM. The application of BIM in heritage, also known as H-BIM, helped the documentation and conservation of important buildings (López et all, 2018). Subsequently, comparing the concept of H-BIM - a methodology where BIM is used to better document and manage heritage - it is understood the need of such a term for the application of digital fabrication in the field of heritage. We propose the term H-CNC for the use of digital fabrication in the problematics related to historical sites.

2 I STUDY CASE

This study case aims to explore the potentials of CNC technologies, as well as digital design processes using CAD tools, in the development of small structures intended to support historical sites. Such historical contexts are full of specific requirements related to the respect, authenticity and identity of the site and their symbolic historical values. It is understood that such respect must be guaranteed during the whole design process, specially since this small structure is intended to give assistance to the visitor of the palace.

The small structure is located in the base of Pena Palace, constructed in the 19th century on the top of the mountain, which is surrounded by a park with 200h. It was considered cultural heritage by UNESCO in 1995 (Marques, Gomes and Camara, 2004). There were approximately 1.7 million visitors in 2017 making one of the most famous palaces in Portugal (Parques de Sintra Monte da Lua, 2018). Keeping in mind such numbers, it is clear the difficulties the palace management has been going through specially in structures directed to giving guidance and information, since new construction is nearly impossible. It is only possible to accommodate this functions in new small structures or in already existing buildings. So, a case like this must rely on custom design products to fully respond to the needs encountered in this location. Therefore the application of CNC machines appears very equipped to respond to such requirements since digital fabrication and rapid prototyping are very quick and flexible in producing several solutions and optimizing them.

Bearing in mind the requirements, a small structure must be produced, that accommodates a person inside, comfortably sitting with a good environment. With a door for the entrance and a small window that allows the worker to exchange information, money and tickets with the visitor.

The proposal aims to produce a modular structure with easy assembly and rapid production.

Since the location is mostly a natural park- also declared Natural Heritage – it was only fitting that the material selected was wood, this way the structure will be contextualized in the natural scenery instead of contrasting with it.

So it was proposed a small wood structure with 2,20x2,20m and 2,20m high. The structure is composed of modular panels connected with each other through wood joints and fixed to a hidden structure that lies behind the panels. Regarding the composition of the panels, by taking inspiration in the natural movements of the trees and wood, it is proposed a configuration with vertical simulated slats where each slat has its own curve. This way the difference between curves creates a visual contrast with shadows and light therefore creating the vertical difference between each slat (figure 1). For the window cover we opted for a solution where the cover was composed with two smaller panels that projected to the outside creating a protection, from the rain and sun, for the visitor (figure 2).

Figure 1 | Wood decoration panel

Figure 2 | Window cover

The wood joints needed for this assembly have to consider coplanar and perpendicular panels. For this we have a double lapped dovetail for coplanar joints and secret fingertip tenons for perpendicular (figure 3 and 4).

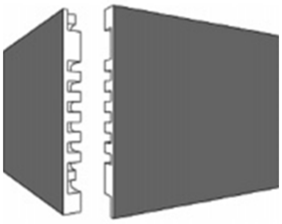

Figure 3 | Secret Finertip Tenons

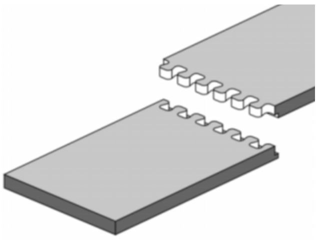

Figure 4 | Double lapped dovetail

3 I DIGITAL DESGIN PROCESS

Digital fabrication goes hand in hand with digital design process. Therefore, this part explores parametric design approach in the digital fabrication context.

It's important to understand that most of the choices of the design process have to consider inputs from the fabrication and construction process. It is extremely difficult to be efficient in this phase without taking into consideration initial requirements. The shift between the digital product and the physical product is very relevant and it dictates some of the choices made in this project. Therefore the parametric design needed inputs from material, fabrication, assembly, structure, machines and software.

The software chosen was Rhino with the installation of the algorithmic plugin Grasshopper, which allows to edit and code in Rhino and it's easy to comprehend and learn since it's a more visual programming language (Davidson, 2009).

To manufacture the panels with the composition envisioned, the best process was subtractive fabrication, - where a pre-determined volume is cut out form the original material block (Kolarevic, 2001) - producing the desired shape and curve.

The machine available was a MultiCam 3000 series, CNC milling machine with 3 axis. It had a work table of 1,25x1,25m, which was the first limitation that the design process encountered. All wood panels had to respect this size. Another difficulty encountered was the fact that every job done in this machine required the material to be fixed (with clips) and the origin point to be set. Since its very difficult to set the exact origin point twice, thus establishing the exact coordinates, the choice to simplify the wood joints had to be made because it was too risky to do two jobs in the same panel. The double lapped dovetail was simplified to a dovetail joint. Subsequently, the addition of a secondary structure was needed to compensate the lack of resistance from the wood joints (figure 5).

The digital model was created with these inputs already set. The creation of the curved wall was the most challenging part regarding the parametric design. Three splines were created with the maximum points and minimum points respecting the maximum thickness of the CNC available (0,035m) (figure 6). In the end, the simplification of the wood joints ensured a wider amplitude of the splines, since doing complex wood joints required more material thickness. Then a lofted surface was created, which was subsequently divided into several contours. From those contours the profile of each slat was formed and then extruded to the necessary volume to fill the space (figure 7). With the base curved wall all the panels that composed the different walls were created. Regarding the corners of the structure since doing two milling jobs was impossible, a small wood piece was created to finish this detail. This small piece was created with the intention of connecting the two splines that made the last contour of the panel, since the two splines were identical the sweep function was used (figure 8).

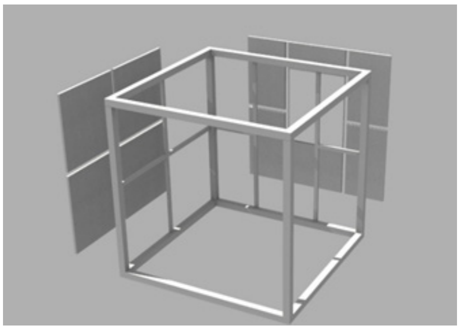

Figure 5 | Main structure + secundary structure

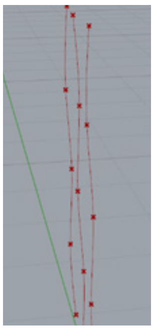

Figure 6 | 3 original splines

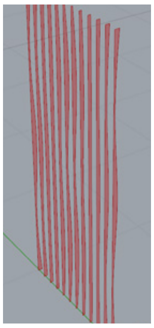

Figure 7 | Slats profiles

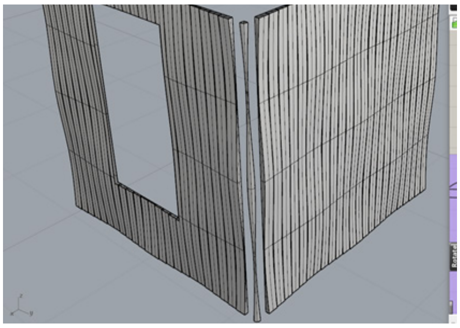

Figure 8 | Corner detail

The structure was composed of: 1) two standard walls, each composed of 4 panels; 2) a wall with the window cover, which had 8 panels and 3) the wall with the door, that had 6 panels (including the door) (figure 9, 10 and 11).

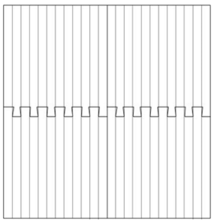
Figure 9 | Standard wall

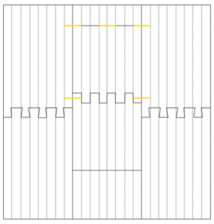
Figure 10 | Window wall

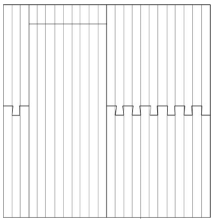
Figure 11 | Door wall

4 I DIGITAL FABRICATION PROCESS

In order to fully understand and verify the true benefits of digital fabrication there where some prototypes that were executed. With the fabrication of prototypes at different scales there were some issues easily identified, that in the virtual model were not so clear. This way we could confirm our choices for the proposed solutions.

The first prototypes where made to confirm the curved texture of the panels. We chose additive fabrication, - where the digital model is sliced into two-dimensional layers, and then the 3D printer makes the model by adding material layer by layer (Kolarevic, 2001). The two prototypes produced where not very conclusive, probably because the scale was too small to produce a real version of the textured wall (figure 12 and 13). Consequently this proved that a real scale prototype using the correct method of fabrication was needed.

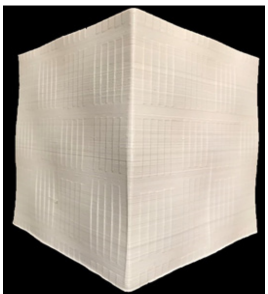
Figure 12 | 3D prototype

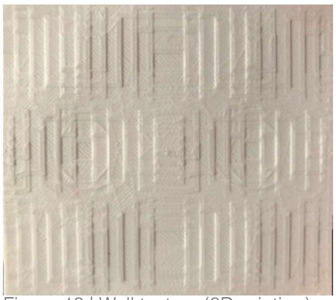
Figure 13 | Wall texture (3D printing)

The second round of prototypes involved subtractive fabrication using the CNC milling machine. In total, we made 6 prototypes each one testing different solutions of the wooden structure. The machine available used the software Aspire (CAD/CAM) to do the manufacturing. This software only receives stl files – files that translates surfaces into a mesh through a process of triangulation. Since the curved texture had a tridimensional shape, the machine did a 3D milling, composed of 3 parts: 1) the roughing where most of the material was cut out, producing rectangular sections; 2) the finishing where with more precision the machine goes through the material and refines the rectangular sections into curves and, finally, 3) the 2D cutting where the panel is separated from the material frame (used to fix the block material onto the work table). In total, the 6 prototypes fabricated were to verify several solutions: the first one was to confirm if the curved texture wall was visible to the naked eye, since in the digital model was not clear (figure 14); the second was to test the cover of the window and it's rotation system (figure 15); the third prototype was to test the dovetail wood joint (figure 16); the fourth prototype was to test the wood corner detail (figure 17); the fifth one was to test out the structure (this one was fabricated using traditional tools) (figure 18) and the final prototype was the assembly of the wall with the window cover (figure 19 and 20). In all prototypes there where several errors that came to light. The main ones where related to the behavior of the material chosen (pine) and the limitations set from the machine, concerning the fact that it converted the stl file into a bitmap image, therefore making the texture surface less accurate and with slight deviations.


Figure 14 | 1st Prototype


Figure 15 | 2nd Prototype


Figure 16 | 3rd Prototype


Figure 18 | 5th Prototype


Figure 17 | 4th Prototype

Figure 19 | 6th Prototype

Figure 20 | 6th Prototype 2

5 I DISCUSSION

5.1 | Parametric Design

Throughout the whole process there were some advantages and disadvantages of choosing the parametric design approach. Nonetheless the workflow of the approach and the questions inherent to the methodology were observed and understood.

In our perspective, the parametric design has great benefits in the quick change of the digital model as well its customization. With great ease it's possible to produce several solutions by altering the different parameters. However, it is understood that the design process always needs to take into consideration several previous information to make sure that the whole model is planned in an intelligent and efficient way. That means the information gathered beforehand, regarding the different fabrication processes, CNC machines and material, were extremely relevant in the conception of the wooden structure, since it was, for example, restricted to the measures of the work table of the CNC. Nevertheless, this early considerations and solutions established must be understood as guide lines and not defined solutions.

Most of the disadvantages that occurred during the parametric process where related to the lack of previous experience using the Grasshopper software. In establishing the parameters of the structure we have to keep in mind that some parameters have intrinsic relations, for example, one parameter defined the division of the surface in slats and the other parameter defined the volume of which slat, when you change one, you'll have to change the other immediately, or the model won't work. These small details lead to errors in the digital model, that sometimes were hard to comprehend. We were able to conclude that the user, who created the code, is the one better equipped to alter the code and identify the errors that might occur. The alteration, by a third party, might reveal to be a difficult task, since every person approaches programming in a distinctive way.

During the whole process it was obvious the shift between two thought processes, the creative thinking and the mathematical thinking. An architect that uses a parametric approach must be capable of translating creative ideas into mathematical and geometrical thoughts.

In the end, the workflow was understood. The first step is to establish requirements and then move to the parametric design that needs to gather information from several important areas (figure 21).

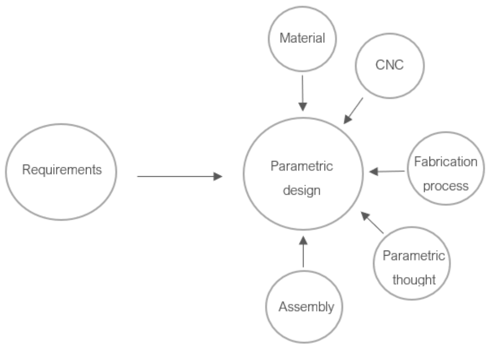

Figure 21 | Parametric design workflow

5.2 | Digital fabrication

One of the greatest advantages of digital fabrication witnessed was the gained relation between design and production. With the fabrication of several prototypes the constructive solutions were verified and consequently perfected. This way, the repetition of the fabrication was considered of great benefit to the conception of the wood structure. Subsequently, the digital model was updated through the whole fabrication process, receiving information to optimize the final product. In general since the structure was relatively simple, the perfecting of the solution didn't require must testing.

The rapid fabrication allowed to confirm and perfect solutions that were more easily tested with a physical model. For example, the cover of the window was modelled but its rotation system and fixation were only tested in the physical model.

The materials used (pine) were not the best option for the final solution but the material was used bearing in mind that the product fabricated was for the sake of prototyping and confirming solutions. Every panel fabricated got slightly warped with the milling process, particularly the last prototype. Throughout the process the small cuts and errors were also related to the heterogeneity of the pine.

The most concerning error during the whole fabrication process was due to the conversion of the digital model into a stl file, that was next translated by Aspire into a bitmap image. These two conversions caused the original digital model to lose information thus accumulating small errors. These small errors translated into unexpected occurrences in the prototypes like the example in figure x. The biggest issue with this problem was that it was not much we could do to prevent the loss of information. The best option was to ensure that Rhino converted the stl file with the higher information possible. That seemed to solved the issue in the last prototype but, in perspective, there is no way to fully comprehend the best approach to this problem.

The CNC machine available also revealed itself a bit limitative regarding the possibilities of the solutions. A lot of solutions were simplified because of constrains imposed by the CNC. Regarding the error mentioned, it would have been avoided if the CNC machine was compatible with files composed of surfaces/solids.

The workflow for this process is cyclic, since we start form the digital model to the fabrication and then go back to the digital model to perfect and correct according the errors observed in the prototypes, until the solution is optimized (figure 22).

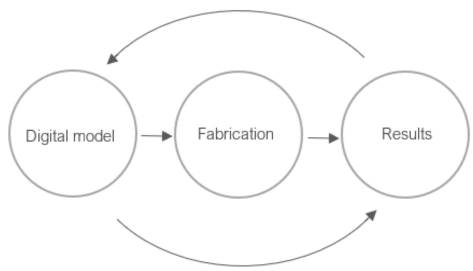

Figure 22 | Digital fabrication workflow

5.3 | Design and fabrication

In the end we concluded that the design process and fabrication process cannot be thought unconnectedly. Both complemented each other making a cyclic workflow (figure 23).

The fabrication process is extremely important to be only considered after the parametric design. The digital model must receive inputs from the fabrication process, material and CNC machine. Thus avoiding unnecessary mistakes through the design process.

The fabrication process has an intrinsic relation with the design process. Even when the workflow is regarding the fabrication process, the digital model ended up being an element that was in constant revision and development. During the fabrication of the several prototypes the digital model suffered alterations to accommodate the analyses of the results.

In the present case study, it was necessary to work and comprehend, not only the field of architecture, but the field of material science, engineering, computer manufacturing, proving that the relationship between architecture and its means of production is suffering great changes and developments, thanks to the digital driven processes.

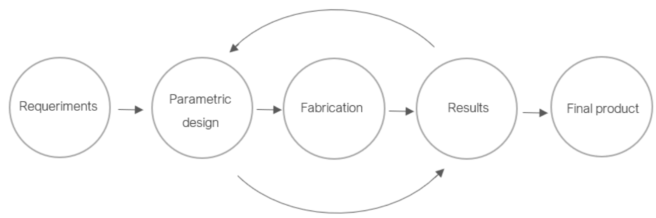

Figure 23 | Digital fabrication + design workflow

CONCLUSIONS

One of the main goals of this project was to evaluate the application of digital fabrication process in a case study related with heritage. This was accomplished with the development of a modular wooden structure, adapted to respond to the requirements found in Park and Pena Palace.

The structure was designed to receive a worker inside and to give support and information to the visitor of the palace. In way to respect the contextualization of the site the material chosen was wood since the site is considered Natural Heritage. To better respond to requirements the pre-existent ticket structures were observed and small adjustments were proposed.

Regarding the assembly and construction of the structure the main focus was to plan a simple structure that was easy to build. For that we opted for two types of fabrication a digital and a traditional. The traditional was only used in the beam wooden structure and the digital for the fabrication of the curved textured panels with joints. In the end the fabrication process of the last prototype lasted 6 hours, the final finishing with sandpapers took 1 hour and 30 minutes and 5 hours to assembly the whole wall with the window cover. Keeping in mind that it was an experimental process done with tools, that maybe were not the correct ones, in an environment not suited for this job. It is projected that the assembly time would be less after perfecting the assembly process. The foreseen time of fabrication for the whole structure is around 28 hours. Considering a cost of 20/25€/h the final cost will be around 560/700€ - without considering the material price and necessary man work to assemble the structure.

In the case of the application of a specific methodology of digital fabrication (H-CNC) for heritage, the workflow observed was identical to the workflow of a simple structure. The question regarding heritage was important in the beginning to help us identify the requirements necessary for the historical location and to better design the proposal. As soon as the fabrication process was included into the thought process the heritage aspect was intersected with other questions. Questions such as the CNC available and its limitations and potentials, the fabrication process, the structure, the assembly method among others. The historical site was important in the beginning has it would be with any project that dealt with such location, whether they are traditional or digital.

The present proposal dealt with the construction of a small structure, needed to support the visitors access to the historical palace and park, and not exactly with the restauration/construction of an historical building. Nonetheless, several advantages were identified with the application of such technologies, whether it is a project that works more intimately with heritage or not, like the case study.

There was no new workflow established or fabrication process adapted to the heritage aspect, as we seen with H-BIM. The application of a digital process, like BIM, requires more adaptation, since it's dealing with the documentation and preservation of heritage. But the inclusion of digital fabrication can reveal itself as a means to understand the historical building or site, with the help of a physical model. As we seen in the case of the Sagrada Familia, these technologies were introduced with great success regarding the efficiency of production and the reduction of costs. And they were introduced to help in the conceptualizing phase, with several study models, and in the construction phase to help and fabricate stone pieces.

The approach of a digital fabrication process (H-CNC) or the inclusion of one in different phases of a project (Sagrada Familia) doesn't require adaptation of the workflow. It does require a previous knowledge for an intelligent use of these methodologies and tools. In the end the digital fabrication was easily introduced to this specific case, with the great benefit of rapidly manufacturing prototypes to help understand the proposed solutions.

An architect that learns these digital tools, understands its workflows and can deal with the questions that come up along the process, is capable of applying this tools to different projects. The whole process was very interesting in terms of approach and in shedding light to the intimate relation between design and production. In the end these tools revealed themselves truly useful in any project regarding contemporary architecture or heritage.

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Figures:

Figure 1 - https://www.etsy.com/dk-en/listing/573522839/wood-wall-art-parametric-framed);

Figure 2 - https://architizer.com/projects/petting-farm/);

Figure 3 and 4 - BURDEK, B., GROS, J., (s.d.) Digital Wood Joints [CD-ROOM] Holanda: dds;

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