BENDSCAPE

Optimized manufacturing by incorporating tool development and machining in design

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Abstract. The abundance of computationally designed and manufactured architectural projects and pavilions in recent years has shifted the boundaries of architectural design and fabrication to a great extent. Hence, there exists a gap between the computational design and computationally controlled or informed manufacturing. This imposes additional design and production time, waste of material, and in general project costs, more specifically for non-conventional projects. The expansion of architects' computational design skills did not always require an up-to-speed knowledge of computer-aided manufacturing and expertise with material. This is maybe one of the main causes of the aforementioned gap. Moreover, experiments in architectural firms and schools are not always of the same nature. Students of architecture are not necessarily equipped with the knowledge that could be used in the real field to solve the actual computation design and making problems. This article elaborates on an academic experiment attempting to narrow this gap. The project begins with a series of subtractive wood bending experimentations. These studies then provide the foundations for developing a task-specific design and manufacturing toolkit that allows for an accelerated design and making process. To prove the concept, a group of 12 students finalized the final design in one day and delivered the final manufactured pavilion in a week.

Keywords. Subtractive Manufacturing, CNC Machining, Robotic Manufacturing, Computational Tool Developing, Material Experiment, Wood Bending, KERF Bending, Manufacturing Optimization.

1. Introduction

The boundaries of architectural design as a medium required to be built are defined by the architect's capabilities of handling complexity and imagining or representing the project before realization (Denari, 2012). Implementation of an architectural project on the other hand requires a comprehensive understanding of materials and the structural capacities of material systems. The two realms, architectural design and construction are very much entangled yet separate to a great extent. The advent of digital design

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tools and the integration of these tools with computer numerical control (CNC) tools through the latter half of the 20th century, led to a paradigm shift in architectural design and manufacturing techniques. In fact, the use of terms such as manufacturing and fabrication in the field of architecture is associated with the use of digital technologies in the building industry.

In an article in 2014, Neil Leach predicted that by the end of the decade (2020) using computation in design would prevail so much that we would no longer use terms such as digital design. The term will disappear as we can imagine any design which does not utilise digital tools needs to be specified and everything else is just design (Leach, 2014). With no need to assess whether this prediction came true or not it is obvious that almost every architectural design project today, employs digital tools or computational techniques one way or another. In the same article, Leach states “The architect/engineer no longer ‘designs’ the structure in the traditional way, but sets up a series of constraints and allows the program to search for possible solutions from which one is selected” (Leach, 2014, p.154). These constraints might be defined by spatial or functional requirements, structural stability, geometrical requirements, material properties, modes of fabrication, etc. The architect's strategy for engaging with these parameters and the design team's knowledge and experience in parametric use of the aforementioned data affect the final design, design and fabrication timeline, and project costs.

Before the engagement of CNC machines in the process of making, a certain level of expertise was required for a precise piece to be made with classical tools or with NC (numerically controlled) machines. This resulted in a noticeable distance between the maker and the designer. Architects dealt with this by involving the craftsperson in the process of making and sometimes the process of design. However, this perception of the concept was and is still somehow off. Computer-aided design (CAD) tools helped architects and designers to develop more sophisticated ideas much easier and faster. The development of more user-friendly computer-aided manufacturing (CAM) tools made it possible for architects to prepare the required machine code on their own; Which eventually enhanced the capacities of architects for making mock-ups and prototypes. Mock-ups serve as an evaluation medium for parts or the whole of an architectural project. Low-fidelity mock-ups can be made out of any material and they do not necessarily reflect the real material or structural performance of the architecture. High-fidelity mock-ups, on the other hand, are quite loyal to the final manufacturing method of the project and incorporate real materials and situations to evaluate the real performance of a given design (Burry & Burry, 2016). Architects managed to a great extent to handle issues of producing low-fidelity mock-ups on their own. However, making high-fidelity mock-ups means dealing directly with materials. Designing with materials comprises different aspects. The design of the geometry, material performance, fabrication and assembly techniques and behavioural simulation (Asensio-Villoria et al., 2014). The architect needs considerable skills with CAD and CAM software, to be able to produce the required geometry, simulate the process of machine work and generate the G-CODE, on the one hand. He/She, on the other hand, is required to have a proper understanding of the material behaviour and performance under certain operations. This is the skill, overlooked by architects, which was formerly covered by the craftsperson automatically.

The Appearance of a new branch of architectural design which engages with digital tool making, robotics, computer-aided manufacturing and ubiquitous computing, attracted open-source communities and developers from different disciplines to join the cause. These forces ended up providing an abundance of computational architectural design and manufacturing tools and software (Puckett, 2014). Although these tools are available to a great extent, it is unfortunate that in many cases they are not integrated into the process of design and manufacturing efficiently. Designers use specific tools for design disregarding many aspects of making. Then they or the manufacturing team are trying to make the whole product and constellation of ideas come together by using other tools or in some cases by using the same tools but in a different setting. This causes expensive and time-consuming manufacturing of mock-ups and eventually projects. In such a process architects have to outsource the prototyping or the making of mock-ups and this often happens at a very late stage of the design. Moreover, this causes feedback loops and from time to time enforces changes in the design according to mock-up failures. This adds up to the costs of the project. One major drawback of such a workflow is that architectural firms often hesitate to dive into unknown territories or propose innovative/experimental ideas to prevent unpredicted costs.

2. Background

The advances in computational design and making, and the abundance of published projects realized in this field suggest digital design and fabrication capable of achieving almost anything, fast, easy, and maybe for a reasonable price. However, it is clear to active designers and makers in the field that, none of the above adjectives are always true. This idea may have appeared in the first place as designers tried hard to advocate the benefits of employing the new technologies and may have found it necessary not to publish much regarding the drawbacks and the hassles involved in the process of computational design and fabrication. Nowadays, using computational techniques is not a question anymore. It is everywhere but the gap between design and making persists. Analysing the advantages and drawbacks of the following projects will help us make a stronger case for this article.

In La Voûte de LeFevre (Mcgee et al., 2013) designers were realizing a compression-only structure by employing computational design and fabrication techniques. The design of the project was informed by the structural forces and was computed with a solver-based model. The initial input of the solver model was a fixed geometry and the output of the solver was then used for preparing the fabrication files. The specific 5-axis CNC machining of the modules required the manufacturing team to generate and evaluate the toolpath for each batch of milling separately and carefully. The problem was that all the sections of this process were separate from one another. The initially fixed geometry was defined by the limits of the installation site or the requirements of the client. The calculated model then, provided fixed blocks for the fabrication team but was not able to produce a safe toolpath autonomously. At this stage, any slight change in the initial design required redoing the whole process. On the other hand, the CAM and the production team had to wait until the last moment and to make sure that everything is final. It was also possible that in the fabrication stage, one piece would not be machinable or required a change, which meant that everything to be revisited from the beginning, or, from the solving state. In this project, each flow of work informed the next cycle, but there was no consistency in the data flow. This inconsistency made it impossible for the computational design specialist to revisit and evaluate the design repeatedly and easily. It also put the project at risk of additional costs; in case some essential geometrical or machining errors happened at the very last stages of the production, it would deter the entire work.

In another example, The making team of Timberdome for the International Wood Fair Klagenfurt 2018 (Robeller et al., 2020) developed a CAD plugin to calculate the 3D polygon mesh geometry of the components. The plugin considered the thickness of the CLT plates and provided the designer with the freedom to choose the number of the sides for the polygon. Yet the whole fabrication process, toolpath generations and machining operations had to be done separately. The developed plugin for the Timberdome project was a geometrical solver and did not incorporate any structural or material properties in the form-finding process.

R2 pavilion is another advanced example which was based on geometrical optimization and attempted to be more construction-aware already at the form-finding stage. The project employed the easy-assembly potential of multi-reciprocal grid structures (Mesnil et al, 2018). The project utilized a very sophisticated computational workflow which included geometrical parameters, fabrication concerns, assembly process and structural analysis for the optimization and computation of the whole structure. The workflow included custom C# code when necessary and employed existing plugins for tasks like finite elements modelling.

The Recursionism project developed a complete toolkit to deal with the problems of design and fabrication simultaneously. The project aimed at providing a fluid workflow from the beginning of the design to the end of the fabrication. The designers and developers of the project were becoming the architects of the system and placed themselves as definers of the constraints for the system (Parsons et al, 2013). Such a workflow allowed the architects to re-invent a new project by simply changing the initial parameters and allowed the fabrication team to begin the production immediately after setting up the parameters.

Each of the above-mentioned projects dealt with various aspects of computational design and manufacturing according to the requirements of the research or based on the advancement of the ideas at the period of the project. This article demonstrates the possibilities for acquiring the skills and expertise of developing and employing computational tools in academic institutions for a material investigation and the ways of expanding the boundaries of design by utilizing these tools.

3. Method

The following project is the result of a two-semester work by the students in Machining PRAXIS in Architecture I & II, at the University of Applied Arts in Vienna's Institute of Architecture. To design with materials, it is necessary for one to understand the processes of making with materials and to understand the behaviour of materials in given situations. In this study, the students began learning the processes of 3-axis machining and developed their expertise by experimenting with wood bending techniques based on subtraction. During this process, the students became familiar with the advantages and difficulties of machining. They learned how to handle CAM operations and how to employ CNC machines to manufacture the desired piece.

The students experimented on self-developed patterns of slit or KERF cuts to bend a given piece of 15 mm plywood (Figure 1). In the course of this experiment, the students, learnt about the geometrical problems of developing a pattern for machining, restrictions of executing certain cut operations, machinic limitations, pros and cons of specific operations, material constraints and the diverging character of various types of wood vis a vis same machining operations. This experience guided them through the task for the second semester. In the second semester, the students learned the basics of robotic machining in the beginning and, followed up by experimenting with more special techniques of making. Simultaneously, they were assigned to pick from the first-semester prototypes and to develop a full-scale pavilion. The design and the realization of the installation involved several steps including developing a task-specific design and fabrication tool. The development of this tool depended on the knowledge they had gained through material behaviour tests and machining experiments during two semesters of work. In the following sections, I will elaborate more on this experiment-based knowledge that the students acquired and, the steps through which they involved their experiments in developing the respective computational design and manufacturing tools/plugins.

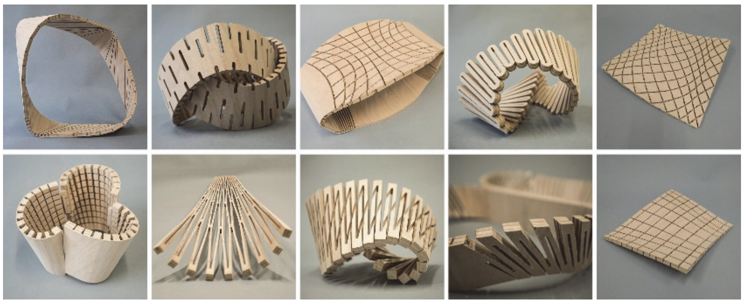

Figure 1. Prototypes of the first semester

3.1. FROM THE COMPUTER TO THE MACHINE

Employing CAM tools for generating digital manufacturing workflows and preparing ostensible simulations does not guarantee the outcome to exactly resemble the simulation. There are several geometrical and material situations to be considered while developing a digital manufacturing workflow. The main investigation of this project involves machining. The forces of the machine and the material reaction to these forces are one of the most important factors to be considered. In some cases, the section of the material is not thick enough to stick to the rest of the material during the machining operation and the section rips off the moment it is confronting external forces. (Figure 2.a). It is also important to design the machining process to prevent delamination of the stock material. One should consider the behaviour of the material, strength and elasticity and the maximum bearable load of certain sections of the respective material to design with the material. The example in Figure 2.e shows how an immediate dive into the material during the machining process caused delamination for the next step.

Another example is the specific geometry of the patterns and the order of the cuts. Evaluating different section sizes and dissipating with variables such as the milling bit diameter, depth of the cut, the number of cut steps, minimum section size, and the relations between the mentioned variables, the students found how to optimise the machining process to achieve the required results. Figure 2.b shows an example in which the geometry and the order of cuts together are causing a failed section. Figures 2.c and 2.d demonstrate a very similar but properly examined and successful section.

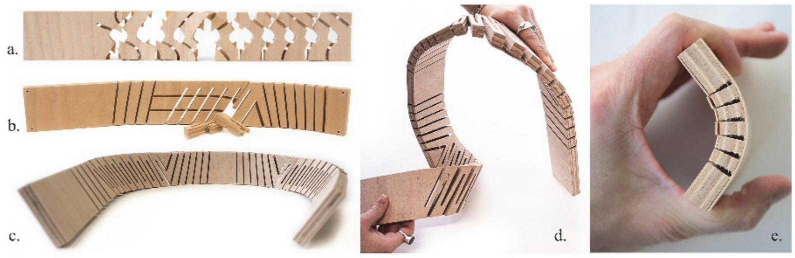

Figure 2.a. Failed sections during the machining process. b. The section failed due to inappropriate geometry and order of cuts. c, d. Similar section after editing the cut order and geometry. e. Delamination of the section

3.2. DIGITAL VERSUS MATERIAL

An important factor in designing with materials apart from the fabrication issues is parsing the material behaviour. Parsing in computer science implies building a data structure for input data. In material research, it is essential to associate computable factors with the behaviour of the material. Sometimes it involves more scientific material research and sometimes basic geometrical and mathematical models can help with decoding the behaviour of the material. In this course, one of the students tried to record the behaviour of plywood in different cut sections and built a bending calculator which produces the cut lines for the requested curvature by calculating the input data. This was the team's first attempt to connect between design, fabrication and final form. This attempt was followed in the second semester and helped students develop a more comprehensive form calculator tool with Grasshopper that helped them with the design of the final pavilion.

3.3. DESIGNING WITH THE PROTOTYPES

The students expanded their knowledge during the 4 months of the first semester and developed their initial prototypes. These prototypes provided them with many opportunities to develop a large-scale structure. To be able to digitally compare and comprehend the prototypes, the students were provided with 3d scans of the prototypes (Figure 3.a) which helped them go through the first steps of the design as fast as possible. The students developed their initial pavilion ideas by the use of these initial prototypes in teams of 2 to 3, and voted on the further development of one final idea, based on the two concepts shown in Figure 3.b. Both concepts employ the same bending principle (Figure 4.a) but they suggest different spatial configurations and joint systems.

After an intensive full-day workshop, students amalgamated their ideas to finalize a unique combination. Using the basic bending principle of the prototype presented in Figure 4.a and the spatial concept of the design presented in Figure 3.c, they developed the final conceptual model (Figure 4.b). This initial design represents a conceptual sketch based on the known factors of design and making and, the scanned and simulated elements which students produced over the first semester. At this point, the team embarked on a journey of gaining further necessary knowledge of fabrication and assessing the problems of fabrication. The following section of the article elaborates on the design and fabrication problematics of the pavilion and the situations where the development of a design and fabrication toolkit was necessary.

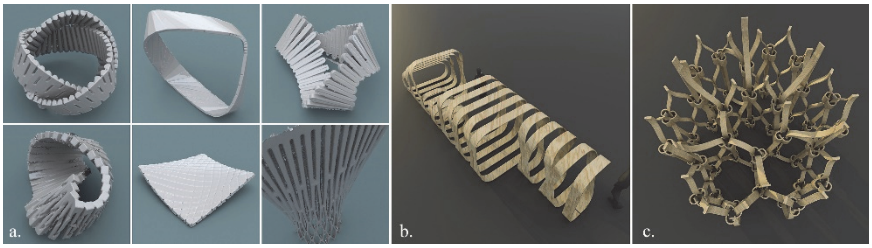

Figure 3.a. 3D scan of the prototypes. b. & c. Two of the six Initial Ideas for the pavilion based on the prototypes of the first semester experiments.

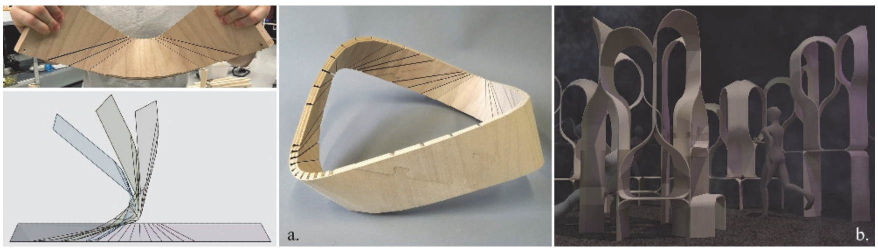

Figure 4.a. The main prototype that students chose for the further development of the idea. b. The conceptual design of the pavilion

4. The Making of The Pavilion. Exigency of a Design and Fabrication Plugin.

4.1. MAKING THE COMPUTATIONAL MODEL

One of the first requirements of realizing this pavilion, as well as many other similar projects, is to achieve a factual computational model. A model that expresses the actual behaviour of the material and is explicit in details and specific sections and joints. The idea of this project is based on one of the very straightforward yet potent prototypes of the experiment (Figure 4.a). The final shape of the bent piece is based on a few basic variables. The number of KERF cuts, their arrangement and orientation on the piece, and the freedom of axial rotation at each cut section. The depth of the cut or in other words, the thickness of the leftover layer has a direct relation with the freedom of axial rotation, as well as the strength of the whole bent piece. It is possible to gain various forms by playing around these variables. The first component developed by the students, used conventional Grasshopper components to generate forms based on these variables. They used the developed cluster with an evolutionary component to optimize the variables and reach a form, as close as possible to their initial conceptual form.

4.2. STRUCTURAL ENDURANCE

Another problem with the realization of such projects is the structural stability and endurance of the elements under certain loads. The main problem of this experiment appears around the KERF cut sections. The weakness of these sections allows the bending while it puts the material at risk of breaking. The initial experiment was not exposed to load and normal wood glue kept the sections tight enough. For the large-scale pavilion, the problem of the loads appeared to be more serious. The team experimented with different types of wood glue, including polyurethane glue. At the same time, different additional patches were tested on the section to find a final reliable solution for these sections of the pavilion. The final decision suggested a secondary bent element to be glued inside the bent area of each element (Figure 5.a). The main element and this reinforcement patch needed to have enough contact for the patch to work and to increase the endurance of the section. This added a new machining problem to the whole project. The intersection planes between the patch and the main element were not parallel with the main cut plane of the KERF cuts (Figure 5.b). To achieve such machining with a 3-axis mill one would need an unreasonable amount of time and a lot of machining power wasted on not-quite-efficient machining operations. To solve this problem, we decided to improve the machining process and involve the ABB IRB 1600 arm at the Digital Production Department of the University of Applied Arts in Vienna. Students learned the basics of robotics in a workshop and got familiar with the new problems they had to solve. Up until this moment the pavilion is composed of several modules, not necessarily repetitive and each module is a compound of two elements, the main body and the patch. The patch requires a simple 3-axis machining process while the main body requires 5-axis machining (Figure 5.e).

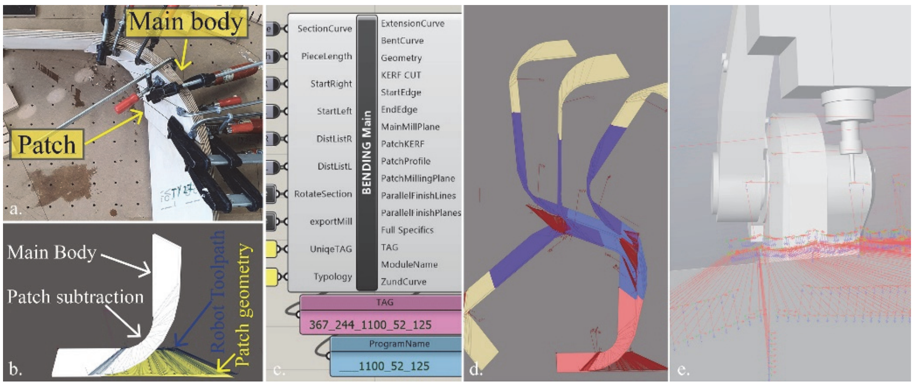

Figure 5.a. Attaching the patch to the main body. b. Essential machining information generated by the bending component. c. The developed bending component. d. Playing around with the form and the chain interaction of components made possible by the developed plugin. e. Just-in-time robotic machining simulation facilitated by the use of the developed tool.

Figure 6. The final BENDSCAPE pavilion

4.3. TOOL DEVELOPMENT

When is it necessary to develop a toolkit for a project? Isn't it adding to the existing complications of the design development? Many questions of such are asked when operating within the realm of computational design and manufacturing. In some cases, it is not necessary to develop a new toolkit and existing components and libraries of already known and used software are robust enough to handle the quandaries of computational design and manufacturing. In the case of this project, the interwoven nature of the problems together with the sequential relation of forms shouted requiring a design tool that facilitated the design process. Notwithstanding, the complicated and time-consuming process of producing machining tool-paths and tool-planes for 3-axis and robotic machining processes added up to the reason. Moreover, the final installation site and consequently the final dimensions and formation of the design were not clear up until two weeks before the installation which would have made the whole process almost impossible or insanely labour-intensive given the time frame and manufacturing limitations at the respective institute.

Using the existing shelf components of Grasshopper on a bigger scale would not have been reasonable due to the highly demanding memory and CPU requirement of these general components for a very specific task. The students developed the logic of the whole process in the first place by using existing shelf components of the Grasshopper. Subsequently, an open-source C# program was developed by the author of this article, to quicken the design sketching. (Figure 5.c). This plugin receives the aforementioned variables of each element and a rectangular wood section to start with and delivers the final bent geometry together with the output rectangular wood section to be used for the next element of the pavilion.

Using this tool allows the user to easily play with the parameters and evaluate the results on the screen (Figure 5.d) Finalize the design by turning off the calculation of fabrication information and when everything is finalized with the design, embarking on the fabrication journey is only one click away. Figure 5 shows some of the fabrication information, such as robotic machining toolpath, patch geometry, tags and the main body, as generated by the bending component.

5. Conclusion

Developing a hands-on knowledge of material experimentation alongside the use of machines and computational tools in architecture schools and academic institutions, helps the students to get familiar with these concepts at a very early stage. Developing open-source tools and open access knowledge bases from these experiments allows future projects to proceed much faster and not only accelerates the design and the fabrication workflow, but also reduces the waste of material and the overall costs of the projects. This project is one academic example that proves the possibility of the development of such knowledge and tools with the involvement of the students. It also proves the possibility of manufacturing large-scale pavilions by the aid of such computational design and manufacturing tools in a very limited timeframe. The information and the source code of this project is available at the GitHub repository of the author of this article.

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