

# Education by Design



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# Building Knowledge

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## ABSTRACT

Material characteristic and fabrication methodologies informing design processes are a growing focus of research and pedagogy. Bio-mimetics, morphogenetics or material computation theories have mostly been used as integrative tools within their teaching methods. The authors of this paper have observed that these pedagogical models are most successful when they are coupled with a practical understanding of the tools and processes that are engaged in architectural production. Without this exchange, a growing disconnect emerges between the concept and the crafted artifact, leading to unfounded speculative projections rather than true applied understanding. As such, experimentation with tools and materials is essential for students to build knowledge on the constraints and possibilities that exist within a material or manufacturing technology. This learning process is not meant to be singular – applying to one material and one fabrication process – but rather a process that is learned and then can further be applied to other design problems. However, the research and development processes are usually too extensive for students to gain in-depth understanding of the methodology - a learning experience that is beyond the scope of a single architecture studio.

Through a set of intensive fabrication workshops, carried out by the authors, a targeted pedagogical model is aimed at knowledge creation within a compressed framework. Engaging participants to a particular point in the building process - that point at which a design is materialized through fabrication processes - provides a unique platform to shift from exploratory conceptualization to technically informed hands-on implementation.

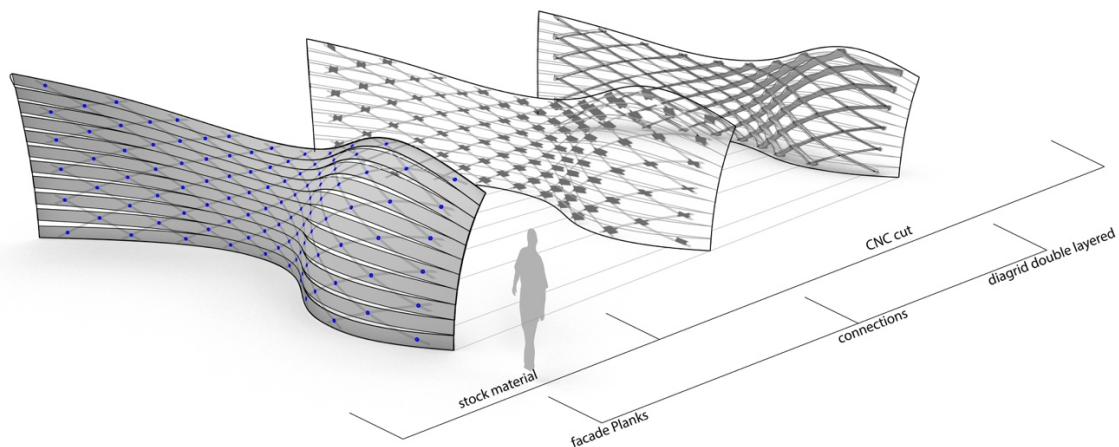


**Figure 1.** In shop fabrication of 2019 installation (left) and final outcome (right)

## INTRODUCTION

Architecture schools have always considered making as a critical dimension of learning, particularly through the use of model making as a form of representation and design iteration. However, there is a growing interest in moving beyond representation and to expand on the learning potential that exists in the process of materializing the design itself. With a growing focus on experiential learning (Kolb 2014; explearn 2019), architectural schools are finding ways to focus resources on design-build projects, digital fabrication tools, manufacturing technologies, prototype development and material research, both as a pedagogical tool but also as a source of academic research (Hinson 2007; Knippers et al. 2018; Prizeman 2005). The intention of this focus is to bridge the knowledge gap between the conception of a design idea and the new processes and technologies that may enable their execution and potential implementation in practice. This approach challenges students to consider scales of production, fabrication process selection, material performance requirements, sustainable construction, workflow optimization, as well as project management and scheduling. These are unique hands-on learning opportunities that increase the fluency of the students in the media with which they create and are essential for the changing pace of professional practice in architecture (Forbes 2017).

Understanding how materials, processes, performance requirements and economical considerations come together to facilitate a design solution can greatly improve design literacy in five fundamental ways: (1) Students learn how to translate design ideas across multiple scales – how to build a desired geometry or how to achieve a desired material effect at the object, furniture or building scale. (2) Students learn how to creatively consider and evaluate multiple fabrication approaches, materials and methods to realize a design intent. (3) Students gain an understanding of assembly and sequencing requirements – how different building components come together. (4) Students internalize the impact of material selection across multiple design stages: aesthetic and architectural considerations; budget considerations; workability of the material during fabrication; the mechanical performance within the structure itself, and how to think of material as an active participant in the design process. (5) Students consciously think about fabrication process while designing elements that must be shaped and assembled, potentially changing design outcomes but enriching the architectural process. As such, learning through making is an essential method for building knowledge that can provide a wide range of pedagogical benefits.



**Figure 2.** Workshop 2: Material and building processes and relationship to computational form

Advanced computational design processes bring added complexity to the task – the use of advanced parametrics is a developing skill in many architecture schools that can support the investigation of high levels of formal complexity and parameter inter-dependence. Learning the necessary skills to develop

parametrically controlled tectonic systems for architectural applications has become pedagogically valuable. However, due to their complexity, the outcome of these investigations is often too easily removed from concerns about materialization, component rationalization or assembly sequencing (Kolarevic 2005). As a result, there can be a great disconnect between the parametric design process, the component fabrication, and the building construction process. This disconnect has led to critique of the parametric design methods, as per Kolarevic (2005), “Their successful application requires careful articulation of a clear strategy of tectonic resolution, such that a sufficiently clear description of interdependences can be achieved; in other words, a well-defined design strategy is essential for the effective application of parametrics” (Kolarevic 2005, 26–27).

However, a closer integration between ideation and execution has emerged from several different fronts. Interest from manufacturers in optimizing product development (O’Neal 2019a; O’Neal 2019b), institutional consumers seeking to develop cost-effective customizable in-house solutions (Wittbrodt et al. 2013; Pearce, J. M. 2012), small-scale manufacturers and craftsman developing their unique IP (Rael and San Fratello 2018; Emerging Objects 2019) as well as specialized research groups (ETH, IaaC, ICD, ITKE, etc), have fostered a growing momentum to integrate design and making process at various scales.

While this growing interest provides a promising outlook, this process of integration still requires a high level of knowledge and technical skill. As a result, direct engagement with these types of projects and research is difficult for most students as it requires a significant amount of skill building, financial resources and design time. Assuming that equipment and technical support is available, the amount of skill and time it takes to complete a materially based parametric design project, and then fabricate such a project at full-scale, does not fit into a studio course framework. One solution is to fit this learning experience into an intensive 4-12 weeks summer program or a multi-semester design build project – and this has been successfully demonstrated by a number of schools including the University of Stuttgart’s ITECH program (Knippers et al. 2018), and the Architectural Association’s (AA) School of Architecture programs at Hooke Park (Prizeman 2005; Vercruysse, Mollica, and Devadass 2019)

This approach, however, is primarily afforded within the framework of research-intensive post professional or doctoral research and therefore, leaving behind most other graduate or undergraduate students. While some degrees may offer specialized electives at the graduate or undergraduate level, time constrains greatly affect the students’ capacity to experience the entire process and corresponding knowledge that comes with the design and construction of a working prototype at the building scale. This is unfortunate because it limits the number of students who truly understand the implications that these processes have in our practice as architects. This is a level of fluency with digital tools, materials and fabrication processes that will greatly benefit our students today but that is seldomly possible to teach within the current academic framework.

## **ACCELERATING AND TARGETING LEARNING OBJECTIVES**

The methodology engaged by the authors attempts to accelerate the learning process with regard to fabrication, material and machine possibilities and constraints, thus imparting to the students the understanding through a focused workshop. The workshop format allows participants to engage state of the art integrative research, carry out the entire process of the fabrication and assembly, but accelerates the process of design and coding of fabrication methodology by preparing digital tools and methods in advance. This technically supported methodology allows participants to gain valuable hands-on experience by facilitating their ability to contribute in both design, fabrication and construction.

In preparation for the workshop, a computational design framework is developed and tested, which can give participants access to key variables of material behaviour, fabrication and design intent. These pre-established tools can be prepared to have controlled simulation frameworks for multi-axis robotic kinematics, material computation form finding, finite element modelling, computational fluid dynamics or energy modelling. Thus, giving the students the opportunity to engage state-of-the-art research in an accessible and supported environment, suitable for different levels of interest and expertise. The workshops conducted by the authors utilize designs that incorporate a high level of tectonic complexity

and integrate multi-component assemblies using wood's elastic and hygroscopic properties to form shell, grid and stressed skin structures. The workshops used advanced fabrication techniques – 3D printing, laser cutting, and 3, 5 and 7 axis milling equipment, including a 6-axis industrial robot with an external linear track and a milling spindle.

One example of this process can be provided by the 2017 workshop UBC developed by the authors. The design integrates elastic bending of cedar planks to form a structurally stiffening skin over a diagrid structure. Computational form finding tools are used to rationalize a doubly curved surface using geodesic line principles that guide the positioning of the linear planks and the diagrid connection points. Assembly instructions are then also embedded within the components so that assembly can be carried out quickly. This last point was emphasized during the assembly of the diagrid (see Figure 2) as it took only 3 hours whereas the assembly of the cedar planks – an apparently simpler task (see Figure 3) - took 8 hours because the instructions for placement were not embedded in the planks and instead they had to be measured and marked for placement.

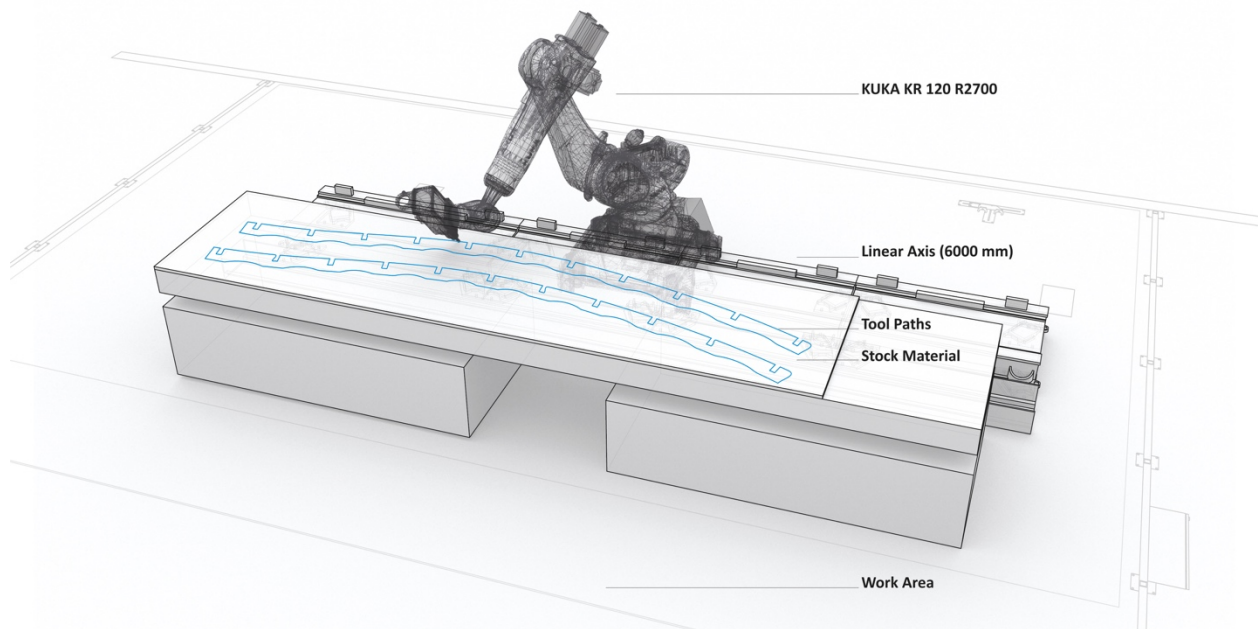


**Figure 3.** Workshop 2 assembly of diagrid (left) assembly of cedar planks (right)

The preparation for the workshops is quite extensive and carefully considered. The computational design framework always includes a form finding component, an informed assembly strategy and a flexible material system, which can be customized and adjusted during the workshop. This involves the creation of multiple associative models that address different aspects of the design, stages of fabrication, or that provide simplified examples of the geometric design development. The models have step by step documentation and can be fully modified and adapted by the participants. These models are needed for students to understand the technical limitations and affordances of each step. Furthermore, the entire design and fabrication script is fully explained in detail during the workshop and the students are encouraged to use the script to design their own version of the project. Laser cutting tools are available for rapid prototyping while teaching assistants are available to assist the instructors in providing one on one assistance with the design script.

The ability to engage with the fabrication script and, in fact, to have an example of a finalized fabrication script, is an unusual experience in an architectural education. These scripts are produced only for complex research projects and are not usually accessible to students. The script clarifies exactly how the robot is given instructions and explains to students the machine space, a concept that describes the fabrication device's range of kinetic and application-related opportunities and limitations. While many students will have this understanding in 2-axis from working with a laser cutter, or 3-axis from working with a CNC machine, an industrial robot setup with 7 or more degrees of freedom offers more opportunities and more complexity. For example, understanding the limits of the robot arm's reach, material placement, securing of material at different stages, multi-axis milling and opportunities and limitations for undercuts, all enhance a students' understanding of the machine's fabrication space and its implications for a design solution. This gained access encourages students to understand the potentials of the machines that will be fabricating their future projects so that they can design their material systems from the ground up to make fabrication efficient and straightforward and therefore, more accessible and affordable to the

projects they will engage in the future (Figure 4). Furthermore, it teaches students to engage with new fabrication technology that might enable different design and material approaches.



**Figure 4.** Understanding the machine space of a robot

Prior to the workshop, participants are encouraged to familiarize themselves with the visual scripting platform as this will enable them to get the most out of the design portion of the workshop. Students who come to the workshop with a novice understanding of visual scripting can still work on the design by manipulating parameters and some of the base geometric inputs, all using conventional 3D CAD modelling tools. Others may choose to team up with more experienced students or focus on other aspects of the process that is of more interest to them, such as structural analysis, fabrication, project management or assembly. By working with the script, the participants also learn methods of controlling an industrial robot's movement with the visual scripting platform, which offers an unusually close connection between design methodology and fabrication methodology.

After the students have experimented with the script and produced their own designs, the workshop moves to fabrication; the fabrication involves exporting files from their script, then transferring the files onto the robot setup and executing them. These steps give participants the opportunity to understand the workflow and operate the fabrication equipment hands on – under supervision. While there is little redundancy for each student (all students are encouraged to go through the process at least once), it nevertheless develops an understanding and serves to clarifying the 'black box' that is usually an industrial manufacturing process.

Assembly and construction also provide valuable learning; comprehending the staging and assembly process is a valuable part of any design build project. Since the material system is programmed with assembly instructions within the cuts – i.e. it can only be put together in one way and the angles and cuts direct the correct placement of the material – the students can recognize the value of the approach and the efficiency that it can bring to the construction process through hands-on experience.

## TEACHING FRAMEWORK

The workshop, led by the authors, has run annually for the last three years (2016-2018) and has included both practicing professionals, wood industry researchers, as well as students. Professionals include architects interested in learning the process, fabricators who are interested in engaging with new manufacturing tools, students from disciplines other than architecture such as industrial designers and engineers, as well as professors and shop staff from other universities who would like to understand the process and technologies involved.



**Figure 5.** Teaching environment of workshop classroom (left) and fabrication space (right)

The workshop has also been included as a small part of a specialized architecture studio during the last two years. The studios involved were held at the School of Architecture + Landscape Architecture (SALA) at UBC and were research studios looking at advanced digital design and robotic fabrication of wood. The students in these studios engaged in relatively complex parametric design prior to the workshop, working up to a design which would be robotically fabricated if it were to be carried out. They were otherwise unrelated to the workshop designs.

The authors have held the last two workshops during mid-term. This time frame during allows the students to gain a stronger understanding of the parametric design workflow prior to the workshop. It is also very effective at providing students with a great understanding of the equipment possibilities and limitations in relation to their studio projects. As a result, their studio projects demonstrated a higher degree of constructability, had a higher level of material awareness and had more concrete assembly sequencing strategies. Nevertheless, the workshop does encourage students to design with the fabrication process and material capabilities in mind, no matter what time in the sequence it happens.

## THE WORKSHOPS



**Figure 6.** Three pavilions in-situ



The methodology has been carried out to date in three annual workshops. Each workshop is 5 days and is focused on an experimental installation, which is fabricated and built within that time frame. The workshops build and expand on the instructor's previous fabrication expertise and research including robotic wood fabrication (Krieg and Lang 2019; Menges, Schwinn, and Krieg 2016), material informed design (Correa, Krieg, and Meyboom 2019; Correa et al. 2013; Correa Zuluaga and Menges 2015) and engineering expertise (Meyboom 2012; Neumann et al. 2015). The first workshop, led by David Correa and Oliver David Krieg with the support of Annalisa Meyboom at the Center for Advanced Wood Processing at UBC engaged wood fabrication concepts of elastic bending and hygroscopic expansion through the construction of a self-stabilizing double skin folded plate structure. The second workshop, also led by the same team engaged wood fabrication concepts of elastic bending, hygroscopic expansion and assembly through the construction of a doubly-curved diagrid stabilized at the joints by a skinning layer of linear cladding components. The third workshop, also led by the same team used elastic bending and kerfing to build a doubly curved stressed skin structure with an integrated seating element. (Figure 6)

The workshop framework is organized around 2 days of lectures and 3 days of fabrication. The first day is a full day of lectures including research context, history of robotics, a review of relevant state-of-the-art projects, digital design methods, material research theory and an introduction to the proposed project methodology. The first day has been conducted on a Saturday to encourage student and industry participation as the event does not interrupt the work week or the student's class schedule.

The second day introduces the custom script. This includes a detailed description of the components and workflow of the design script and then a similar description of the fabrication script. The second day expands on the methods through an expanded introduction to robotics and corresponding design scripts. This lecture provides a step by step illustration on the geometric rationalization, tool path generation and translation into the robotic fabrication script. This is presented through a familiar architectural software – in this case a plugin for the visual programming environment Grasshopper in the CAD program Rhinoceros. In addition, a discussion of machine space, safety and robot operation is provided. A tour of the robot is then carried out and each student can test the positioning configuration of the robot through manual control; at this point, a safety demonstration and shop tour are conducted. The students then design their own variation of the project using the material system from the script – they can modify it as much as they choose. As mentioned, the instructors and some additional TAs are brought in to support the students more directly in this phase.

The third to fifth days of the workshop are dedicated to fabrication and assembly (depending on the staging and construction sequence of the particular workshop, assembly may begin earlier or later on the second day). This work may be carried out in the shop or in the field. The first and last workshop had assembly mainly taking place in the shop with relatively little assembly in the field. This allows shelter in case of inclement weather but also allows easier access to most tools without extensive equipment requirements on site. This section of the workshop is not always possible for all participants, due to professional or academic constraints, but every effort is made to facilitate participation (i.e. people can take part for portions of the project as possible).



**Figure 7.** Workshop 2: Some prefabrication in shop and more assembly on site



**Figure 8.** Workshop 3: More prefabrication in shop and less assembly on site

## **CHALLENGES AS LEARNING MOMENTS**

Although much of the programming is completed in advance and with the knowledge, skill and experience of the instructors, the workshops are experimental research structures and as such, they are pushing the limits of what is currently possible to make with this technology. Therefore, during the workshop there are still many details to be resolved, adjusted or to be completely developed on the spot in order to respond to unforeseen circumstances. During the last three years, various unforeseen issues had been encountered in regards to equipment calibration, tolerances, assembly, and material behaviour or irregularities. These are common issues that are encountered on projects and job sites as well. The associative models make it relatively easy to adjust certain variables, however, working with very advanced robotic fabrication also bring their own set of unique challenges. The high level of precision required for the complex assemblies leads to the requirement of very tight tolerances that are required for structural performance, but at times also need to be calibrated when tolerances are too tight. The discussions regarding these challenges are extremely valuable to participants, many of which were actively involved in their successful resolution. The participants are fully engaged in the process and thereby are exposed to a wide range of learning opportunities, particularly if unexpected issues arise, allowing them again to take this back to their own design research and practice.

## **FOLLOWING UP WITH LEARNING**

One of the intentions of the workshop is to spark interest in the participants to continue further training into advanced design-to-fabrication processes and their architectural potential. This may include further training in integrative computational tools, training in wood technology and fabrication, advance joinery, or further post-professional studies in the field. For the students taking part on the workshop as part of the studio, this process is already in place, as each student can directly take the experience and knowledge from the workshop to develop a design of their own, as part of the studio curriculum. The understanding of the process, machine space, and material limitations bring a new level of understanding to their projects. In some instances, the learning may not manifest in the formal or conceptual positioning of their work but can serve to transform their understanding of detailing, constructability and assembly.

## DESIGN PROCESS APPLICABILITY

The design process and methodology presented during the workshop are focused on timber fabrication, but it provides learning outcomes that are not specific to a particular material or a particular piece of equipment. The method is intended to demonstrate a design approach that is highly informed by the process of materialization. In other words, the workshop demonstrates the role of fabrication and material engagement as a critical design component in the execution of a larger design intent. This is a learning outcome that participants can apply to other materials and other fabrication technologies in their design practice. Knowledge of tools, techniques and materials in building construction are critical to the design practice, as is the understanding that any of these aspects can undergo innovation that will change their relationship. As such, the experience is broader and engages more aspects of architectural production than may be apparent at the outset.



**Figure 9.** Working with the industrial robot

## CONCLUSION

The intensive workshop format provides an opportunity to jump to the stage in a design process where design becomes material. This critical stage can be a pedagogical tool to help participants fully understand the roles that material and fabrication have in informing the design process. The presented workshops have demonstrated the ability to incorporate advanced concepts, in a hands-on experimental environment, such as: bio-mimetics, morphogenetics, material computation theories, advanced digital fabrication workflow and machine space. This format has been presented to be uniquely positioned to provide accelerated learning experience in the advanced fabrication tool machine space, material knowledge, construction assembly sequencing, scheduling, project management and tolerances. The learning outcomes are structured towards applied knowledge that can be easily taken back to the design environment and used, not only in the design of the same material, but in other materials, with other processes and even to enrich importance of understanding material assemblies and fabrication spaces in any architectural design.

Moreover, the workshop also addresses the gap between ‘design idea’ and materialization using methods and technologies that are not commonly engaged in practice. In the case of the free-form geometries presented in this paper, this is even more critical as such geometries can either be very efficient in their functional performance and material use or exceptionally wasteful. This presents unique learning opportunities into component optimization, component nesting, material selection and use - all critical components for design practice and sustainability. Moreover, without a direct understanding of how our production technologies (new or old) engage material use, it is not possible to design sustainably, optimize the way we use resources or gain an appreciation for the amount of waste that is generated in construction. The presented workshops provide students first-hand experience in how to address these challenges directly.

Lastly, the workshops have demonstrated the ability to engage state-of-the-art wood research in a controlled pedagogical framework. The developed prototype and their installation in public setting are both, a source of pride for the workshop participants and a source of inspiration for passersby. It is not possible to quantitatively validate the impact that these workshops had on the participants but the authors are aware that several participants have moved on to undertake further studies in the fields, develop their own teaching workshops (as learning tools for their students) or have implemented advanced integrative processes within practice (Hasan, Reddy, and Tsayjacobs 2019). It is speculated that this experiential learning framework, through intensive workshops, will play a larger role in the way research and teaching institutions engage applied learning for advanced integrative technologies.

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