Defining Sustainability Through Bentwood Lamination

Christopher Scott Taylor

Thesis submitted to the faculty of Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of:

Master of Science in Architecture

Mitzi Vernon
Committee Chair

Jim Bassett
Committee Member

Noah Reiten
Committee Member

Akshay Sharma
Committee Member

School of Architecture + Design
College of Architecture and Urban Studies
Blacksburg, Virginia
August 27, 2014

Keywords: sustainability, bentwood lamination, woodwork, furniture

Copyright 2015, Christopher Taylor
What does sustainability mean with respect to furniture design and fabrication? How has technology created – and subsequently clouded – opportunities for new thinking? This body of work explores these broader questions and, more specifically, the efficiencies of bending wood. Historical precedents will guide a distillation of established bentwood technologies, which in turn will generate a more sustainable operation. The framework of this operation revolves around a minimalist approach to design coupled with an increased focus on product longevity – the paramount sustainable attribute. Additionally, an investigation of suitable alternatives to the most common – and highly toxic – adhesives is necessary. Beyond secondary research the primary research will utilize small-scale models to minimize material waste while examining the appropriateness of new processes. These studies will emulate the sculptural plywood experiments of Alvar Aalto and Charles and Ray Eames. The final manufacturing process will make use of these study models with the intent of generating a modular system of interchangeable formwork to customize sustainably produced pieces. Final deliverables include the tangible studies along with full-scale designs utilizing modular formwork and a research component documenting the potential for a more comprehensive definition of sustainability with regards to furniture.
### CONTENTS

<table>
<thead>
<tr>
<th>Page</th>
<th>Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>iii</td>
<td>Abstract</td>
</tr>
<tr>
<td>vi</td>
<td>List of Figures</td>
</tr>
<tr>
<td>xi</td>
<td>Preface</td>
</tr>
<tr>
<td>001</td>
<td>Essay 1</td>
</tr>
<tr>
<td>003</td>
<td>Artifact 1</td>
</tr>
<tr>
<td>004</td>
<td>Turntable Commission</td>
</tr>
<tr>
<td>008</td>
<td>Stretcher Geometry</td>
</tr>
<tr>
<td>010</td>
<td>Model/Full-Scale Relationship</td>
</tr>
<tr>
<td>014</td>
<td>Lamination Process</td>
</tr>
<tr>
<td>016</td>
<td>Aluminum Stem Design</td>
</tr>
<tr>
<td>018</td>
<td>First Gen Build</td>
</tr>
<tr>
<td>020</td>
<td>Second Gen Build</td>
</tr>
<tr>
<td>022</td>
<td>Third Gen Alterations</td>
</tr>
<tr>
<td>024</td>
<td>Bentwood Stretcher Family</td>
</tr>
<tr>
<td>031</td>
<td>Essay 2</td>
</tr>
<tr>
<td>033</td>
<td>Research</td>
</tr>
<tr>
<td>034</td>
<td>Research Components</td>
</tr>
<tr>
<td>036</td>
<td>Sustainable Furniture</td>
</tr>
<tr>
<td>038</td>
<td>Disposable Design</td>
</tr>
<tr>
<td>040</td>
<td>Invest in Longevity</td>
</tr>
<tr>
<td>042</td>
<td>Bentwood Process: Milling</td>
</tr>
<tr>
<td>044</td>
<td>Bentwood Process: Steaming</td>
</tr>
<tr>
<td>046</td>
<td>Bentwood Process: Laminating</td>
</tr>
<tr>
<td>048</td>
<td>Plywood</td>
</tr>
<tr>
<td>050</td>
<td>Logging vs. Resawing Veneer</td>
</tr>
<tr>
<td>052</td>
<td>Adhesive Technology</td>
</tr>
<tr>
<td>055</td>
<td>Research</td>
</tr>
<tr>
<td>056</td>
<td>Structural Capabilities</td>
</tr>
<tr>
<td>058</td>
<td>Material Influencing Form</td>
</tr>
<tr>
<td>062</td>
<td>Formwork Construction</td>
</tr>
<tr>
<td>064</td>
<td>Press Method: F/M Formwork</td>
</tr>
<tr>
<td>066</td>
<td>Press Method: Vacuum Bag</td>
</tr>
<tr>
<td>068</td>
<td>Mitigating Adhesive Use</td>
</tr>
<tr>
<td>070</td>
<td>Lamination Studies</td>
</tr>
<tr>
<td>079</td>
<td>Essay 3</td>
</tr>
<tr>
<td>083</td>
<td>Artifact 2</td>
</tr>
<tr>
<td>084</td>
<td>Bentwood Stool</td>
</tr>
<tr>
<td>086</td>
<td>Design Inspiration</td>
</tr>
<tr>
<td>088</td>
<td>Leg Base Design</td>
</tr>
<tr>
<td>090</td>
<td>Laminate Thickness</td>
</tr>
<tr>
<td>092</td>
<td>Formwork Construction</td>
</tr>
<tr>
<td>094</td>
<td>Aluminum Neck</td>
</tr>
<tr>
<td>096</td>
<td>Seat Contour</td>
</tr>
<tr>
<td>098</td>
<td>Seat Contour Mock-Ups</td>
</tr>
<tr>
<td>102</td>
<td>Seat Perimeter Construction</td>
</tr>
<tr>
<td>104</td>
<td>Final Build</td>
</tr>
<tr>
<td>106</td>
<td>Excessive Formwork</td>
</tr>
<tr>
<td>109</td>
<td>Essay 4</td>
</tr>
<tr>
<td>113</td>
<td>Artifact 3</td>
</tr>
<tr>
<td>114</td>
<td>Waste Reduction Tool</td>
</tr>
<tr>
<td>116</td>
<td>Kerfed Formwork</td>
</tr>
<tr>
<td>118</td>
<td>Adjustable Tool Concepts</td>
</tr>
<tr>
<td>120</td>
<td>Adjustable Formwork</td>
</tr>
<tr>
<td>122</td>
<td>Template Formwork</td>
</tr>
<tr>
<td>124</td>
<td>Third Gen Model</td>
</tr>
<tr>
<td>126</td>
<td>Removable Node Studies</td>
</tr>
<tr>
<td>128</td>
<td>Fourth Gen Model</td>
</tr>
<tr>
<td>131</td>
<td>Artifact 4</td>
</tr>
<tr>
<td>132</td>
<td>FORM: Line-Plane-Solid Exhibit</td>
</tr>
<tr>
<td>134</td>
<td>Laminating Complex Curves</td>
</tr>
<tr>
<td>136</td>
<td>Free-Form Conceptualization</td>
</tr>
<tr>
<td>138</td>
<td>Custom Vacuum Press Bags</td>
</tr>
<tr>
<td>140</td>
<td>Multidimensional Form Studies</td>
</tr>
<tr>
<td>142</td>
<td>Securing Mechanism</td>
</tr>
<tr>
<td>144</td>
<td>Modular Track System</td>
</tr>
<tr>
<td>146</td>
<td>Small-Scale Prototype</td>
</tr>
<tr>
<td>148</td>
<td>Subsequent Study</td>
</tr>
<tr>
<td>150</td>
<td>Bibliography</td>
</tr>
</tbody>
</table>
All images are property of the author.

[1] Small-scale models of previous orthogonal designs, p. x-xi
[2] Illustration of tools used for each mode of drawing, p. xii
[3] Bentwood stretcher formwork, p. 003
[4] Initial sketches and iterative third-scale models of the turntable, p. 004-005
[5] Series of second generation third-scale models of the turntable, p. 006-007
[6] Small-scale model of the bentwood structure, p. 007
[7] Third generation model series investigating aluminum leg designs, p. 007
[8] Diagram of the bentwood structure’s geometric construction, p. 008-009
[10] Full-scale formwork of the bentwood stretcher, p. 011
[11] Plan and elevation diagrams of clamp pressure dispersion (red cones) on initial formwork, p. 012
[12] Plan and elevation diagrams of clamp pressure dispersion (red cones) on model-scale formwork, p. 013
[14] Squared stock marked with triangle to help with subsequent sequencing, p. 014
[15] Band-sawing individual laminates oversized, p. 014
[16] Removing band-saw marks with the planer results in finished laminates - process material waste: 40%, p. 014
[17] Layout of tools and materials prior to glue-up, p. 015
[18] Glued laminates clamped within formwork, p. 015
[19] Plan and elevation diagrams of both aluminum stem designs, p. 016
[20] Isometric diagram of stem insertion into bentwood stretcher base, p. 017
[21] Abstract illustration expressing the stem designs, p. 017
[22] First generation turntable in use during an exhibit; birch + birch plywood, p. 018
[23] Plan and elevation diagrams of the first generation turntable, p. 019
[25] Explored isometric diagram of the second generation turntable, p. 021
[26] Elevation diagrams of design modifications from second to third generation builds, p. 022-023
[27] Third-scale models of potential side table legs, p. 024
[28] Hand-shaping full-scale legs, p. 024
[29] Hand-shaping slight contour to stretcher form, p. 024
[30] Third-scale models adapting bentwood stretcher to coffe table proportions, p. 025
[31] Pedestal stand using modified bentwood construction without aluminum stem; walnut + aluminum + glass, p. 026
[32] Full-scale side table combining modified bentwood stretcher with turned legs; walnut + glass, p. 026
[33] Plan and elevation diagrams of the full-scale side table, p. 027
[34] Standing height turntable with second gen aluminum stem (detail image); walnut + aluminum + acrylic, p. 028
[35] Plan and elevation diagrams of the full-scale standing height turntable, p. 029
[36] Illustration of trees affected by strong coastal winds, p. 030
[37] Posters used during the first thesis presentation, p. 033
[38] Series of small-scale chair studies created during the research phase, p. 034-35
[39] Logo collage of some of the more prominent sustainability certification bodies for furniture, p. 036-37
[40] Illustration commenting on the difficulty of assembling flat pack furniture, p. 038
[41] Image highlighting the beneficial space-saving aspect of flat pack design, p. 039
[42] Image displaying the primary building materials of flat pack design - reconstituted waste products, p. 039
[43] Table displaying average lifespans of select domestic tree species, p. 040
[44] Illustration of furniture longevity, p. 040-041
[45] Illustration of the milling process showing structural weaknesses of contoured parts, p. 042
[46] Curved part marked on a solid stock, p. 043
[47] Curved part milled from solid stock, p. 043
[48] Illustration of the steaming process showing heavy spring back of a dried component, p. 043
[49] Process setup with PVC steaming chamber and steam generator, p. 045
[50] Illustration of the laminating process using a two part form and multiple clamps, p. 046
[51] Process setup with formwork, laminates, and clamps, p. 047
[52] Context image of bent plywood construction and detail of industrial visual aesthetic, p. 048
[53] Context image of bent laminatation and detail of harmonious visual aesthetic, p. 048
[54] Illustration of the grain orientation of successive layers of both plywood and lamination, p. 049
[55] Illustration of the veneer logging process slicing thin sheets of wood, p. 050
[56] Small collection of sequential veneers cut using the veneer logging process, p. 050
[57] Rough sawn lumber prior to resawing, p. 051
[58] Image showing blade thickness with respect to veneer thickness during resaw process, p. 051
[59] Collection of resawn veneers juxtaposed to a board of its original thickness, p. 051
[60] Image highlighting appropriate protective gear and currently available adhesives, p. 052-053
[61] Compound bent lamination study, p. 054-055
[62] Full-scale diagram demonstrating the observed bending capabilities of walnut, p. 056-057
[63] Illustration of the observed influence of manual pressure on different leverage points, p. 058
[64] Image documenting material-governed curvatures produced through manual pressure, p. 059
[65] Image documenting material-governed curvatures produced through manual pressure, p. 059
[66] Image documenting material-governed curvatures produced through manual pressure, p. 059
[67] Image documenting the resulting curvatures concept, p. 007
[68] Using hands to explore the multidimensional capabilities of a walnut veneer strip, p. 060-061
[69] Milling of formwork using the solid construction technique, p. 062
[70] Surfacing of formwork using the solid construction technique, p. 062
[71] Illustration of the essential parts of framed formwork construction, p. 062
[72] Process image of the planning stage of framed formwork, p. 063
[73] Process image of the contouring stage of framed formwork, p. 063
[74] Process image of the assembly stage of framed formwork, p. 063
[75] Process image of a pressed laminating using fe/male framed formwork, p. 064
[76] Image demonstrating over-surfacing of solid formwork and the resulting pressure dead zones, p. 065
[77] Image demonstrating over-surfacing of solid formwork and the resulting pressure dead zones, p. 065
[78] Process image of vacuum bag pressing veneers onto a one piece formwork, p. 066
[79] Vacuum press setup with rolled 4’x8’ bag and vacuum pump, p. 067
[80] Initial attempt at a variable equation to determine appropriate laminate thickness, p. 068
[81] Context and detail photo highlighting the adhesive of a laminated study with excessive veneer layers, p. 069
[82] Two-dimensional, tapered lamination base holding a multidimensional component; cherry + basswood, p. 070
[83] Multidimensional lamination; walnut, p. 070
[84] Two-dimensional, tapered lamination base holding a multidimensional component; poplar + basswood, p. 071
[85] Two-dimensional lamination exploring mitered assembly; mahogany, p. 072
[86] Two-dimensional, tapered lamination base holding a multidimensional component; ash + walnut, p. 073
[87] Two-dimensional, tapered lamination exploring tight radii; walnut, p. 073
[88] Series of multidimensional form explorations; birch plywood + walnut, p. 074-075
[89] Two-dimensional lamination exploring converging/diverging elements; ash + walnut, p. 074
[90] Two-dimensional, tapered lamination exploring converging/diverging elements; mahogany + basswood, p. 075
[91] Two-dimensional, tapered lamination exploring intersections; mahogany + basswood, p. 076-077
[92] Two-dimensional, tapered lamination exploring an interior section; walnut, p. 076-077
[93] Two-dimensional, tapered lamination exploring intersections and connections; cherry + walnut, p. 077
[94] Illustration of infinitely capable tools: hands, p. 080
[95] Bent lamination stool legs, p. 083
[96] Small-scale seating study models, p. 084-085
[97] Illustration of traditional joinery used in furniture construction, p. 085
[98] Two tapered lamination studies juxtaposed, p. 086
[99] Small-scale stool model focusing on the legs derived from the tapered laminations, p. 087
[100] Orthogonal concept isometric of the offset legs rotated about the center of the 14” circle, p. 088
[101] Concept plan of the offset legs rotated about the center of the 14” circle, p. 089
[102] Orthogonal concept of the offset legs rotated into the same plane, p. 089
[103] Illustration of the smallest radius for each stool leg, p. 090
[104] Illustrated collage of the LaserCAM laser and cut file, p. 092
[105] Assembled formwork component, p. 092
[106] Exploded isometric diagram of the formwork assembly, p. 092
[107] Clamped fe/male formwork with glued lamination, p. 093
[108] Detail image of saturated laminates compressed within the formwork, p. 093
[109] Elevation and plan diagrams of the aluminum neck components, p. 094
[110] Detail image of aluminum neck securing the stool legs, p. 094
[111] Isometric diagram illustrating proposed component alterations, p. 095
[112] Isolated aluminum neck components, p. 095
[113] Construction diagram of the initial linear flow form, p. 096
[114] Initial flow form extrusion creating a planar surface, p. 096
[115] Addition of a second flow form derived from the initial flow form, p. 096
[116] Custom planer sled alongside a clamped seat section, p. 098
[117] Laminated seat section iterations, p. 098
[118] Testing the effectiveness of the seat section contour, p. 099
[119] Final contoured seat section and the lamination study behind the inspiration, p. 100-101
The study documented in this book initially arose out of a desire to challenge my skills as a woodworker. As the safe and easy solution, orthogonal designs previously dominated my work, but the introduction of wood bending changed that. Bentwood techniques offered an opportunity to expand my design vocabulary with more organic form. Specifically, bentwood lamination transformed my understanding of wood capability while simultaneously raising concerns about sustainability. These issues triggered what would become an in-depth study of the complexities surrounding sustainability and its relevance to bentwood technologies.

In this book, six sections – two research and four artifact – highlight pivotal moments during the thesis study. Each section builds upon prior sections in a sequential manner, though they could stand independent of one another. Preceding specific sections are four essays concerning drawing, material, craft, and sustainability. These essays contain personal thoughts and concerns that emerged while observing and interacting with students, professors, and professionals over the course of the study.
Drawings are a type of non-verbal communication used to express design intentions. This silent discourse manifests itself in three modes: analog, digital and tactile. All three play an integral role in telling a complete story: analog hand sketches provide quick ideation; digital computer models provide immediate three-dimensional feedback; and tactile models provide physical information.

Exclusion or dependence upon any single facet can prove detrimental, and the comparative ease of the analog and digital can make physical models seem expendable. However, the tactile drawing has indispensable value offering knowledge perceptible only by touch.

Physical construction serves to counterbalance analog and digital modes by integrating reality with the abstract. Combining various levels of fidelity at different scales provides an opportunity to evaluate specific details and potential construction techniques. Paper sketch models provide quick conceptualization. Low fidelity full-scale mockups give a semblance of proportion and scale. Accurate small-scale presentation models offer analysis of process and construction. Designing without this knowledge is akin to a chef cooking without properly understanding his/her ingredients.

Ultimately, the physical form should provide a unique perspective to the design development. The benefits are negligible when the tactile becomes a precious object. This holds true for all modes of drawing. The seductive nature of glamour sketches, renders, or physical models may prevent the critical assessment necessary to advance an idea. Two-dimensional representation in either analog or digital form can mask deficiencies or unresolved areas by focusing on elements in isolation, and excessive attention to detail of the tactile form can create three-dimensional representations that are more precious than the idea they represent.

This does not negate the value of workmanship. Drawings lacking sufficient polish poorly communicate ideas. A carefully penned sketch, detailed render or well-crafted model has the capacity of enhancing strong elements. However, because ideas are constantly evolving, it is counterproductive to consider any drawing as finite. They are more of a snapshot in time of the current discourse. Therefore, at what point does workmanship become embellishment? Where is the balance of time between proper execution and iteration? By pen, mouse, or blade, these three modes of silent communication should tell the story, and resist being the story.
Artifact One: Bentwood Stretcher
The thesis exploration originated from a commission for a rotational pedestal to display student form studies at standing eye-level offering the audience a complete viewing experience. All design concepts focused on enhancing the form studies and minimizing the turntable's visual impact. Distilling the base structure to its essentials – three legs – fed the iterative use of stretchers consisting of equilateral triangles. As ideation progressed, the tectonic members developed a curvilinear interpretation that drove all subsequent designs and ultimately unveiled an unfamiliar concept – bentwood lamination.

[04] Initial sketches and iterative third-scale models of the turntable
The curvilinear interpretation of the initial ideation spawned a second generation of iterative models focusing on construction and form possibilities. Questions regarding proportions, assembly, and disassembly of the taller turntable surfaced. Additional small-scale models investigated a more compact, tabletop version that ultimately led to the creation of full-scale units. However, the visual mass that accompanied the plywood legs and top overwhelmed the student form studies. A subsequent generation of models further refined the turntables by replacing the bulky elements with visually lighter components. This series of models investigated aluminum legs in conjunction with an acrylic top and provided the inspiration for a second full-scale build. A reduced visual presence of the turntable helped refocus attention on the form studies.

[05] Series of second generation third-scale models of the turntable [06] Small-scale model of the bentwood structure concept [07] Third generation model series investigating aluminum leg designs
The next step used basic geometry to construct a stretcher form outline that took into account two project requirements: platform diameter and central support (aluminum stem p. 016-017). Following is a breakdown of the geometric process. [one] Determine the diameter of the aluminum stem mechanism and the top platform, and draw their corresponding circles. [two] Inscribe an equilateral triangle using the larger circle. [three] Bisect each triangle vertex with a line segment that stretches to the opposite side of the larger circle. Mark the intersection of that line segment with the smaller circle. [four] Create a circle that is tangent at three points: the previous intersection point and the adjacent line segments to that point. [five] Remove the unnecessary parts of each circle. Connect the resulting arcs to their corresponding flats. [six] Offset the form – outside – the necessary thickness to generate the intended geometry.

[08] Diagram of the bentwood structure’s geometric construction
The primary reason for the constructed models on the preceding pages was to create a tactile dialogue with the clients. However, models serve another purpose of equal importance: process analysis. Evaluating construction techniques at a smaller scale provides a baseline that can guide or influence processes at full-scale. Reduced-scale trial runs also mitigate potential process waste seen at full-scale. It is important to work at an appropriate scale – small but large enough for joinery and detail work – and simulate exact techniques. Creation of the bentwood model stretchers followed this technique by mimicking the full-scale lamination process, which involved pressing thin sheets together and ripping the resulting form into thirds.

Model / Full-Scale Relationship

The primary reason for the constructed models on the preceding pages was to create a tactile dialogue with the clients. However, models serve another purpose of equal importance: process analysis. Evaluating construction techniques at a smaller scale provides a baseline that can guide or influence processes at full-scale. Reduced-scale trial runs also mitigate potential process waste seen at full-scale. It is important to work at an appropriate scale – small but large enough for joinery and detail work – and simulate exact techniques. Creation of the bentwood model stretchers followed this technique by mimicking the full-scale lamination process, which involved pressing thin sheets together and ripping the resulting form into thirds.
The following diagrams illustrate how insight gained during model making is a guiding—not absolute—principle. Proper context is important in understanding the correlation between multiple scales; not everything scales in a linear fashion. Accordingly, full-scale mockups are invaluable as a way to assess processes schemed at a smaller scale. In this case, increasing model formwork to actual size produced issues initially unrealized. Standard bar clamps provided abundant pressure when used at small-scale but offered inadequate pressure when fully scaled. Pressure distribution at full-scale concentrated along the perimeter, pulling the edges tight, and creating an interior belly. Although slight, this produced dissimilar members when sliced into thirds. Augmenting pressure distribution with cauls and heavy-duty clamps only marginally reduced the noticeable inaccuracies. Ultimately, adopting a thinner formwork that pressed the stretchers individually yielded accurate results.

Defining Sustainability Through Bentwood Lamination Artifact One: Bentwood Stretcher

Figure 11. Plan and elevation diagrams of clamp pressure dispersion (red cones) on initial formwork
Figure 12. Plan and elevation diagrams of clamp pressure dispersion (red cones) on model-scale formwork
Figure 13. Individual stretcher formwork
Defining Sustainability Through Bentwood Lamination

Artifact One: Bentwood Stretcher

Figure 14. Squared stock marked with triangle to help with subsequent sequencing

Figure 15. Bandsawing individual laminates oversized

Figure 16. Removing bandsaw marks with the planer results in finished laminates - process material waste: 40%

Figure 17. Layout of tools and materials prior to glue-up

Figure 18. Glued laminates clamped within formwork

Lamination Process

The primary function of the stem structure was to stabilize and revolve a raised platform. A lack of commercially available options specific to the stretcher form necessitated a unique design combining existing and custom hardware. Visually buried amongst the structural mass, the original custom stem design had an industrial, mass-produced motif; the slotted base housed a press-fit shaft bearing that captured the top platform. As the overall turntable evolved, the stem structure took on greater visual presence, which compelled more elegant design. As such, iteration led to a revolving curvilinear element that produced a rotational flow form. The new base also employed cam-style flanges that fit into milled slots allowing the stretcher form to maintain its overall simplicity.

[22] First generation turntable in use during an exhibit; birch + birch plywood [23] Plan and elevation diagrams of the first generation turntable.
Figure 24. Second generation turntable fully assembled and disassembled; birch + aluminum + acrylic. Figure 25. Exploded isometric diagram of the second generation turntable.

Defining Sustainability Through Bentwood Lamination

Second Gen Build
Third Gen Alterations

1. Edge banding to mask machined acrylic perimeter
2. Thumb guide to revolve platform without disturbing acrylic surface
3. Machined cap threads into base without auxiliary bolts
4. Aluminum stem flows outward creating an elegant form
5. Stem base rotates into place using cam-style mechanism
6. Gentle arc across stretchers creates additional visual complexity
7. Edge sliced perpendicular to curve tangency to create directionality
8. Aluminum legs shortened and moved inward

Figure 26.

[26] Elevation diagrams of design modifications from second to third generation builds
What alternative applications could the bentwood stretcher serve? Would the bentwood concept translate into larger pieces of furniture? These questions led to the exploration of an expanded design family that utilized and modified the original bentwood stretcher. A series of models and full-scale builds studying the cohesion of traditional leg design with bentwood construction followed. Taking the investigation a step further and adapting the stretcher to coffee table proportions produced numerous design solutions. This moment signified the formal designation of thesis study – a desire to thoroughly understand the practicality and processes involved with bentwood lamination solutions.

Bentwood Stretcher Family

Defining Sustainability Through Bentwood Lamination Artifact One: Bentwood Stretcher

Figure 31. Pedestal stand using modified bentwood structure without the aluminum stem; walnut + aluminum + glass
Figure 32. Full-scale side table combining modified bentwood stretcher with turned legs; walnut + glass
Figure 33. Plan and elevation diagrams of the full-scale side table
[34] Standing height turntable with second gen aluminum stem (detail image); walnut + aluminum + acrylic

[35] Plan and elevation diagrams of the full-scale standing height turntable
We gravitate towards wood because of its inherent natural order. It is distinct among other common building materials: metals, plastics, composites, etc. Yet wood is often manipulated in a manner counter to its intrinsic properties.

Every tree is a sentient organism and subsequently continues to exhibit its inherent animate characteristics long after it is logged. Wood is a material living beyond death. Nonetheless, boards are resawn and dried in order to mitigate the natural tendency of wood movement. As designers, we ferret through piles of these boards in search of the visually pristine. The boards bearing greatest semblance to the once imposing tree – those twisted, bowed and cupped – are labeled as defective and cast aside.

Through advances in technology over the past century, discarded boards destined for the scrapheap are now cannibalized and reconstituted with various adhesives to give designers a more stable, rectilinear alternative. But at what point is human ingenuity harmful to the creative process? A plank composed of sawdust and glue – although ecologically sound in some respects – has no resemblance to the warmth and natural beauty observed in the original organism.

Instead of butchering and dissecting a tree to extract flawless planks - or fabricating uniform alternatives - why not let the organism’s natural behavior influence design form and construction? Curvilinear components have a greater association with the tree’s pre-harvested irregular form, and incorporating these organic elements prompts a more dynamic design.

Ubiquitous examples already exist as Mother Nature often contorts her creations through an assortment of weather phenomena: frozen precipitation, strong coastal winds, etc. She demonstrates the extreme bending capabilities of wood by forcing trees to adapt varying methods of survival. The tree’s complex microscopic structure creates an elastic resistance that permits adaptability, which survives until advanced decomposition. This phenomenon allows logged lumber to bend and maintain fairness until catastrophic failure.

This body of work examines how the organic nature of tree maturation influences and guides the aesthetics of fair form. The capabilities and limitations of bentwood processes are explored as a primary construction method. An analysis of the techniques serves to discern a boundary between technological assistance and interference. At what point does creative manipulation become inappropriate or harmful to the material?
Research Components

The following sections detail secondary and primary research components. In the context of this study, research also includes preexisting knowledge relevant to the thesis. As such, the secondary studies section combines prior knowledge gained from other individuals with observations of current issues concerning sustainability and bentwood lamination (the bibliography in the back of this book highlights works supporting and influencing these opinions). Conversely, the primary studies section comprises tactile experiments involving construction processes and techniques, which led to the creation of a series of small-scale lamination studies shown at the end of this section.

[38] Series of small-scale chair studies created during the research phase
Sustainability is a familiar yet often misunderstood term. Lacking a universally applied or accepted definition causes confusion primarily among consumers. Most people correlate responsible environmental behavior with the word, but the lack of a comprehensive definition allows marketing executives to manipulate the meaning in order to mislead consumers. Companies can tout a single environmentally sound attribute while ignoring the unsustainable practices of the rest of their business. As such, the proliferation of greenwashing has helped to destroy the very essence of sustainability. In an effort to combat misleading advertising, numerous organizations established their own sustainability guidelines. Yet, the problem seems to have worsened as certification agencies have effectively created an a la carte menu for sustainability and allowed unsustainable practices to continue so long as companies meet other, less demanding, requirements. The complexities inherent in sustainability make it difficult to distill a checklist. Still, the dialogue initiated by certification agencies is a positive step. But is a tighter definition of sustainability necessary? If small portions of a product are unsustainable, are the rest of the sustainable claims ultimately negated? This line of inquiry was fundamental in pushing the thesis to examine potentially unsustainable bentwood lamination issues: veneer logging, manufacturing techniques, and adhesive technology.

Sustainable Furniture

Sustainability is a familiar yet often misunderstood term. Lacking a universally applied or accepted definition causes confusion primarily among consumers. Most people correlate responsible environmental behavior with the word, but the lack of a comprehensive definition allows marketing executives to manipulate the meaning in order to mislead consumers. Companies can tout a single environmentally sound attribute while ignoring the unsustainable practices of the rest of their business. As such, the proliferation of greenwashing has helped to destroy the very essence of sustainability. In an effort to combat misleading advertising, numerous organizations established their own sustainability guidelines. Yet, the problem seems to have worsened as certification agencies have effectively created an a la carte menu for sustainability and allowed unsustainable practices to continue so long as companies meet other, less demanding, requirements. The complexities inherent in sustainability make it difficult to distill a checklist. Still, the dialogue initiated by certification agencies is a positive step. But is a tighter definition of sustainability necessary? If small portions of a product are unsustainable, are the rest of the sustainable claims ultimately negated? This line of inquiry was fundamental in pushing the thesis to examine potentially unsustainable bentwood lamination issues: veneer logging, manufacturing techniques, and adhesive technology.

[39] Logo collage of some of the more prominent sustainability certification bodies for furniture
In an effort to entice customers, furniture companies are increasingly touting sustainable operations. The use of recycled/reconstituted materials in conjunction with space-saving transportation methods creates the very real appearance of sustainability. However, these ecological attributes are short lived when encouraging the attitude of disposable furniture. For instance, flat pack design leads to an initially reduced carbon footprint while decreasing transportation and storage costs. But flat packing disregards quality construction and forces unskilled consumers into deciphering confusing instruction manuals. Combining this with substandard materials abbreviates an already short furniture lifespan. Claims of sustainability are more about profitability than ecology. Cheap resources and transportation methods – championed as environmentally sound – drop price points; as accessibility to the masses grows, so do profit margins. However, the availability of inexpensive products fosters a disposable attitude towards furniture.
Despite how lightly we tread upon this earth, we impact our environmental surroundings. Manufacturing and technological advances that serve to alleviate problems often exacerbate environmental situations in unforeseen ways. This project examines how to increase product longevity, the paramount sustainable characteristic. In this context, longevity is considered equal parts durability — a product’s survival despite moderate abuse — and aesthetics — an overall lasting appeal. Both attributes seek to lift the lifespan of furniture from disposable into heirloom. As a potential rule of thumb, furniture pieces built from harvested lumber should exist as long as it takes to regrow another tree of same species and maturity. A wholesale investment in longevity would diminish disposable furniture while pushing a higher design standard.

<table>
<thead>
<tr>
<th>Species</th>
<th>Years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basswood</td>
<td>100</td>
</tr>
<tr>
<td>Beech</td>
<td>300</td>
</tr>
<tr>
<td>Black Cherry</td>
<td>100</td>
</tr>
<tr>
<td>Black Locust</td>
<td>60</td>
</tr>
<tr>
<td>Black Walnut</td>
<td>150</td>
</tr>
<tr>
<td>Chestnut</td>
<td>100</td>
</tr>
<tr>
<td>Elm</td>
<td>175</td>
</tr>
<tr>
<td>Gray Birch</td>
<td>50</td>
</tr>
<tr>
<td>Mockernut Hickory</td>
<td>200</td>
</tr>
<tr>
<td>Poplar</td>
<td>60</td>
</tr>
<tr>
<td>Red Maple</td>
<td>130</td>
</tr>
<tr>
<td>Red Oak</td>
<td>200</td>
</tr>
<tr>
<td>Redwood</td>
<td>1250</td>
</tr>
<tr>
<td>Sassafras</td>
<td>100</td>
</tr>
<tr>
<td>Western Red Cedar</td>
<td>1000</td>
</tr>
<tr>
<td>White Ash</td>
<td>260</td>
</tr>
</tbody>
</table>

Source: Tree Life History Strategies

Figure 43. Table displaying average lifespans of select domestic tree species

[43] Table displaying average lifespans of select domestic tree species [44] Illustration of furniture longevity
Although technically not “bentwood,” milling hardwood with a bandsaw is the quickest and easiest method when creating curved components. Parts take only minutes to cut and surface smooth. However, milling curves is not without drawbacks. Even though blade depth dictates potential contours, grain pattern ultimately should guide the curvature. Resulting parts maintain their overall strength so long as the contour closely approximates the existing grain pattern. Not coordinating the two will create areas of weakness as the grain pattern approaches perpendicularity with the curve. Beyond structural issues, milling tight curves produces wasteful – non-orthogonal – scraps. Taking the issues of excess waste and structural integrity into account, milling curved components beyond a gentle arc yields issues that outweigh the time saved.
Steam bending as a method lies on the opposite end of the time spectrum. Steaming wood relaxes its internal structure and substantially increases its pliability. Steaming times range anywhere from a few minutes to multiple hours depending on species, thickness, and environmental conditions. Bending and securing around a form until thoroughly dry follows the steaming process. Generally, the piece maintains its original strength once dried because it experiences no material loss. Yet, steam bending’s primary advantage – nominal waste – is matched by its biggest limitation: springback. If not initially considered, springback can completely alter the anticipated form. Steam bent designs should therefore employ additional fastening to prevent gradual movement over time.
The third bentwood technique, laminating, provides an alternative to structural and springback issues and offers design possibilities unattainable by milling or steaming. Bentwood lamination uses adhesive to bond multiple layers of thin wood in contoured forms. The combination of wood and adhesive produces a stronger bond than the original log and is much less prone to movement once set. But high toxicity is a consequence of rigid adhesion; handling laminate glue requires proper protective gear. In addition, certain veneer fabrication techniques yield significant waste. Ultimately, the design versatility of lamination warranted exploring ways to diminish these drawbacks.
The difference between bent plywood and bentwood lamination deserves attention because people often use the terms interchangeably. Although they both consist of laminated veneers, their construction methods differ in one small, yet critical, facet: grain orientation. Successive plywood layers rotate 90 degrees as a way to enhance stability. Rotating the veneers produces a distinct pattern of alternating light (edge grain) and dark (end grain) layers. Conversely, bent lamination has a completely different visual aesthetic. Grain orientation is directionally consistent throughout the piece, which gives the appearance of an unaltered form. Bent plywood visually conveys an industrial motif while bentwood lamination presents a purer and more elegant surface.

Plywood | Lamination

The difference between bent plywood and bentwood lamination deserves attention because people often use the terms interchangeably. Although they both consist of laminated veneers, their construction methods differ in one small, yet critical, facet: grain orientation. Successive plywood layers rotate 90 degrees as a way to enhance stability. Rotating the veneers produces a distinct pattern of alternating light (edge grain) and dark (end grain) layers. Conversely, bent lamination has a completely different visual aesthetic. Grain orientation is directionally consistent throughout the piece, which gives the appearance of an unaltered form. Bent plywood visually conveys an industrial motif while bentwood lamination presents a purer and more elegant surface.
Veneer production occurs through two main processes: logging and resawing. In the former, sawmills use a large knife to slice paper-thin sheets out of harvested logs, producing effectively no waste. Pre-determined standards established to maximize yield and profits dictate these sheet thicknesses. Current technology – and to a certain degree, demand – prevents sawmills from resawing special thickness veneers any larger than 1/8 inch. Degradation of material and tooling occur beyond this dimension. If design stipulates a veneer thickness greater than that commercially available, the maker must create his/her own slices. This requires resawing rough-sawn lumber using the bandsaw. Unlike the knife of veneer logging, the bandsaw blade removes material with each cut. As such, design dictating numerous thin layers will result in an excessive amount of waste. Ideally, a new process would combine the flexibility of resawing with the efficiency of veneer logging.
The single most important component in any bentwood lamination is the adhesive. Advances in chemistry over the past century have pushed ever-increasing alternatives onto the market. Quick set, long set, low tack, high strength – countless options exist for almost every gluing need. Standard yellow (PVA) glue – used in the majority of woodworking applications – exhibits the most versatility with essentially no toxicity. Yet, yellow glue lacks the rigidity necessary for lamination because of its elastic, water-based formula. Unfortunately, the most effective lamination glues are ureaformaldehyde (UF) based and highly toxic. Proper protective gear – goggles, gloves, and a respirator – is imperative. Even though UF adhesives are a great detriment, they should not deter the exploration of bentwood lamination. Instead, increased dialogue should push adhesive technology towards a more benign alternative.
Structural Capabilities

Wood species have finite bending radii depending on numerous interconnected variables: type of cut, drying process, thickness, and grain orientation, to name a few. Manual processes control or influence the majority of these variables. However, the ultimate determining factor for bending radius is a tree’s microscopic construction. Oversimplifying, the internal makeup consists of cellulose fibers and lignin. The lignin acts as an adhesive, holding the vertical cellulose structure together like a bundle of straws. The density of these cellulose fibers essentially dictates elasticity. Of the common domestic hardwoods, black walnut has the lowest density and highest natural bending tolerance.

[62] Full-scale diagram demonstrating the observed bending capabilities of walnut
This section deals with the manipulation of individual veneers to explore inherent material possibilities, which allowed the material to directly influence and denote the extents of its capabilities; a creative exploration of form without dictated function. Wood excels at expressing form because of its pliability. When manipulated, the tight structural configuration creates an elastic resistance that produces the tensile force necessary for fair curvatures. This section of studies explored the resistance of two-dimensional manipulation: a secured position creating a leverage point allowing the free end to bend with the grain. Adjusting the many variables — species, thickness, pressure, leverage point, etc. — produced a catalog of two-dimensional bends. These initial forms became the basic elements of the majority of lamination experiments seen in this section.

[63] Illustration of the observed influence of manual pressure on different leverage points [64-66] Images documenting material-governed curvatures produced through varying degrees of manual pressure [67] Image documenting the resulting curvatures of Figures 64-66
Multidimensional exploration influenced the other collection of lamination experiments. Dynamic movement – human hands – replaced *static leverage points* allowing complex linear forms to accompany simple wrist movements. Absence of a controlling dimension permitted the material to contort itself in unpredictable ways. The effortlessness of the process also enabled rapid development and analysis of a flurry of concepts. Yet, ease of conceptualization did not translate into ease of lamination as form complexity proved tough to dissect.

[68] Using hands to explore the multidimensional capabilities of a walnut veneer strip
To realize the material explorations as laminations, a method of compressing the veneers together was necessary. This step used supplementary tools – formwork – requiring a modest time investment for both design and construction. Additionally, a discriminating sense of touch was ideal, as fair laminations demand fair formwork; surface imperfections tend to translate onto the laminated piece. Frame and solid construction are the two main formwork fabrication techniques, each with their own benefits. Solid construction delivers the most stability but often requires a large amount of material. Conversely, framed construction markedly reduces material use but commands additional design and planning time. The lamination studies of this section explored both fabrication methods and how they functioned with the following press methods.
The formwork press method consists of two parts – female (negative) and male (positive) – that sandwich veneers into shape. Curvature layout is the most crucial aspect of this method as the curves for both halves are not the same. Instead, the curve of one side offsets the total thickness of the veneers to create the supplemental curve. Precise layout and construction is necessary to avoid pressure dead zones – voids between laminate and formwork – that lead to irregularities (thicker glue lines, gaps) in the resulting piece. Additionally, forethought regarding pressing the formwork is important. Formwork needs a significant amount of force to fuse the veneers together. Traditionally, clamps – fixtures of every woodworking shop – supply this pressure. However, clamp configuration needs planning beforehand to prevent potential space conflicts during glue-up.
Flat panel veneer work commonly utilizes the vacuum press method, but bentwood lamination also makes use of it. For bentwood construction, the vacuum press method consists of only a single formwork element, usually male. With the formwork and veneers sealed inside the bag, a vacuum pump evacuates the air and creates omnidirectional atmospheric pressure – roughly 14.7 pounds per square inch. The resulting force drives the lamination into the formwork allowing it to set. This force is sufficient for simple contours but struggles to support complex forms or thick laminations. Instances of uneven pressure and bridging increase along with form complexity. Moreover, because the predominant use of commercially available bags is for flat panels, even small bags dwarf bentwood formwork. Besides being cumbersome, excess bag material also causes nonuniform pressure if left unmanaged.

Figure 78. Process image of vacuum bag pressing veneers onto a one piece formwork. Figure 79. Vacuum press setup with rolled 4’x8’ bag and vacuum pump.
Initial attempt at a variable equation to determine appropriate laminate thickness

<table>
<thead>
<tr>
<th>Walnut</th>
<th>(t_s)</th>
<th>(o_s)</th>
<th>(r_s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\frac{1}{16})</td>
<td>1 ¾</td>
<td>0.0179</td>
<td></td>
</tr>
<tr>
<td>(\frac{1}{8})</td>
<td>3 ½</td>
<td>0.0179</td>
<td></td>
</tr>
<tr>
<td>(\frac{1}{4})</td>
<td>7</td>
<td>0.0179</td>
<td></td>
</tr>
<tr>
<td>(\frac{1}{2})</td>
<td>14</td>
<td>0.0179</td>
<td></td>
</tr>
</tbody>
</table>

Species bending ratio \(r_s\) = \(\frac{\text{species laminate thickness (}t_s\text{)}}{\text{tightest observed bending radius (}o_s\text{)}}\)

Part laminate thickness \(t_p\) = \(\frac{\text{total part thickness (}h_p\text{)}}{\text{total part layers (}l_p\text{)}}\)

Part bending ratio \(r_p\) = \(\frac{\text{part laminate thickness (}t_p\text{)}}{\text{part bending radius (}o_p\text{)}}\)

\[ r_p = \frac{h_p}{l_p 	imes o_p} = \frac{h_p}{l_p 	imes o_p} \]

Part efficiency percentage \(e_p\) = \(\frac{\text{part laminate thickness (}t_p\text{)}}{r_s \times \text{part bending radius (}o_p\text{)}}\)

\[ e_p = \frac{h_p}{l_p 	imes o_p \times r_s} \]

Mitigating Adhesive Use

Adhesive technology was a primary focus during the exploratory phase. As noted in the previous section, there are no viable alternatives to the current, toxic lamination glues. Therefore, it was important to mitigate the use of adhesives through a proper understanding of the interrelated design elements: species, bending radius, veneer thickness, overall thickness, and adhesive. For instance, using a relatively inflexible species for a tight bend dictated the use of thinner layers, which in turn, required more glue. Using a more pliable species enabled thicker layers and less glue. This basic example illustrates the importance of designing with all elements in mind. Ideally, there would be an equation to determine an appropriate ratio of the material elements.

\[ \text{more efficient part as } e_p \text{ approaches 1} \]
\[ \text{perfect part efficiency: } e_p = 1 \]
\[ \text{failed part: } e_p > 1 \]
Defining Sustainability Through Bentwood Lamination Research: Primary Studies

The following small-scale (less than 12”) lamination form studies explore the experimentation illustrated in the preceding research section: structural capabilities, material influencing form, formwork construction, press methods, and mitigating adhesive use.

(Laminate: Figure 82) Two-dimensional, tapered lamination base holding a multidimensional component; cherry + basswood (Figure 83) Multidimensional lamination; walnut (Figure 84) Two-dimensional, tapered lamination base holding a multidimensional component; poplar + basswood

Lamination Studies
Defining Sustainability Through Bentwood Lamination Research: Primary Studies

[85] Two-dimensional lamination exploring mitered assembly; mahogany

[86] Two-dimensional, tapered lamination base holding a multidimensional component; ash + walnut

[87] Two-dimensional, tapered lamination exploring tight radii; walnut
[88] Series of multidimensional form explorations; birch plywood + walnut

[89] Two-dimensional lamination exploring assembly configurations of similar elements; ash

[90] Two-dimensional, tapered lamination exploring converging/diverging elements; mahogany + basswood
[91] Two-dimensional, tapered lamination exploring intersections; mahogany + basswood [92] Two-dimensional, tapered lamination exploring a diverging interior section; walnut [93] Two-dimensional, tapered lamination exploring intersections and connections; cherry + walnut
Craft: (noun) skill in carrying out one’s work, especially manual skill.
Skill: (noun) the ability to do something well; expertise.

The word “craft” originates from the Old English word, cræft, meaning “strength, skill.” Craft later evolved to stipulate “skill in making things by hand” during the Arts and Crafts Movement of the late nineteenth century. This differentiation occurred as a way to distinguish handmade from the burgeoning mechanization of the Industrial Revolution. However, a century of technological innovation has slowly eroded that definition to incorporate more digitally based products. Is this a bastardization of the word, or simply a shift in its evolutionary meaning?

People mistakenly assume skill is a prerequisite for craft. However, craft is less about the application of acquired skill and more about an investment of time. A meticulous temperament and patience are essential to execute craft. Skill, on the other hand, builds on experience and repetition; it is rarely innate. Skill primarily serves as a catalyst that expedites quality craft. An individual can produce excellent craft while lacking abundant skill.

Nevertheless, many refuse to yield the paramount resource: time. A fast-paced, “time is money,” society rooted in mass consumption demands immediacy. We face ever-increasing expedience at an early age and rarely afford ourselves an opportunity to explore and iterate, let alone develop proficiency. This pace drives the ambition for accelerated results, and technological solutions are often the answer. Digital processes often replace skill as the catalyst of quality craft.

Digital tools can be effective, but technology is only as intelligent as its architect. We easily become complacent with software capability. If the machine is incapable of a process, students often assume they are also incapable because of the machine’s perceived omnipotence. What follows is a design modified to fit within the machine’s parameters. This submission constrains creativity and funnels people down a path where digital technology is the only approach. Accordingly, mass production in the digital age is eclipsing the slower human hand of craft.

Digital technology can enable quicker iteration of conceptual ideas, but this assistance becomes dependence if not given a proper context. One must understand why technology is beneficial, and that requires exploring materials and processes through a hands-on approach. Manual operations require time investment, but human hands offer infinitely more dimensions of exploration than the boundaries imposed by tech-
Technology. Amplifying knowledge learned during this exploration is the potential risk of sacrificing accumulated progress. Knowledge is more intimately grasped with the looming prospect of failure as the onus is placed on the individual utilizing the tool, whereas inputting commands often removes responsibility from the detached individual. Often when technological processes falter the reason is not always apparent, or the technology is to blame simply by default. Hands-on experimentation provides immediate feedback and allows a higher degree of variable adjustment on the fly. Human senses will always be the greatest tool an individual has in pursuing quality craft.

Digital technology has a place in the world of craftsmanship. It is a vital part of every designer’s tool palette. However, it is just that: a tool. It serves to enhance—not replace—our understanding of quality craft. As with every tool, discretion is necessary. Digital methods may appear as the easy choice, but generations of people can overlook potential manual alternatives and ultimately limit themselves further down the line. An understanding of our own manual capacity for craft is essential for us to ever know there is a better alternative. Technology cannot become a mask for our own incompetence.
This portion of the study served to investigate the application of bentwood lamination as structure. Is it a viable alternative—or supplement—to traditional furniture joinery? How does the inherent strength of curved geometries or additional adhesive compare to the staples of joinery (mortise and tenon, lap, bridle)? Can curvilinear components rival the dependability of millennia-old construction techniques? Using traditional methods, full-scale test joints and small-scale seating studies assessed these questions. The design, construction and analysis of these models provided a baseline of quality for all subsequent bentwood concepts.

Figure 96. Small-scale seating study models
Figure 97. Illustration of traditional joinery used in furniture construction
Design Inspiration

The bentwood concept that is the basis for the rest of this section originated during the primary research phase. However, what is important to note here is not so much the idea but the idea’s conception. Before fully constructing any piece, time is given to the playful assembly of individual parts. This tinkering can generate stronger ideas, highlight weaknesses or produce abstract constructs that inspire subsequent concepts. The latter occurred with the haphazard juxtaposition of two tapered lamination studies. The created form prompted a series of iterative line sketches and small-scale models that eventually led to the bentwood stool design shown in this section.

[98] Two tapered lamination studies juxtaposed. [99] Small-scale stool model focusing on the legs derived from the tapered laminations.
A 14” diameter circle is the basic construction element for this design. This measurement is an observed average of generic seating surfaces on many common stools and helped place each leg in a specific location. The centerline of the initial leg foot resides along the perimeter with two subsequent legs offset to the inside and outside of this first leg. In its closed configuration, all three legs nest together for easier shipping and storage. Ultimately, this concept challenges preconceived notions of flat pack design.

Figure 100. Figure 101. Figure 102.

Leg Base Design

[100] Orthogonal concept isometric of the offset legs rotated about the center of the 14” circle. [101] Concept plan of the offset legs rotated about the center of the 14” circle. [102] Orthogonal concept elevation of the offset legs rotated into the same plane.
Evolving from the lamination studies highlighted a few pages back, the stool legs flow along a tapered path from a 2” thick vertical base into a 1” thick horizontal support. In order to maintain a fair form, the taper extends into the curve of each leg. As such, this project offered the opportunity to test the bending capability of varying laminate thickness along a specific radius. Each leg had a unique interior radius determined by its base construction placement and the overall seating height of 18”. Knowledge illustrated in Figure 62 (walnut’s ability to bend at a constant material thickness) served as the starting point for tapered dry-bend trials. The experimentation created a limit of no larger than a taper from 1/4” to 1/8”; everything thicker resulted in consistent bending failure. However, this bounding laminate thickness was still vulnerable to occasional failure, and the loss of any laminate would disturb grain continuity. Decreasing laminate thickness would alleviate bending failure yet necessitate more laminates and adhesive. Instead of incorporating more glue, an increase in pliability came through saturating the individual laminates with warm water. Soaking entailed the expense of additional drying time but was worth the saved glue.

[103] Illustration of the smallest radius for each stool leg
The relatively thick bentwood legs required the robust nature of solid construction formwork, and cheap plywood sheets (2’ x 4’ x ½”) were the ideal choice for creating this mass. Five profiles for each of the six formwork components (3 female and 3 male) were necessary to reach the layered thickness. Manipulating the orientations of the thirty profiles led to an efficient arrangement using three sheets. Inputting each sheet configuration into a CAD/CAM program allowed the LaserCAMM to rough out the profiles. The layers were then stacked, fastened together, and surfaced smooth.

Subsequent reflection questioned the order of the overall design process: why was formwork construction not considered when determining the laminate thickness? If the formwork has to be excessively thick, maybe concessions are necessary elsewhere. Thinner laminates would have increased the amount of glue, but it also would have reduced the amount of necessary formwork material. Initially understanding the consequences of these decisions could have produced a more well-rounded design.
Transforming the tapered laminations into usable stool legs necessitated a central support. This support required a sturdy, lightweight, and simple design; but it primarily had to control leg rotation about the central axis. With nothing commercially available, the solution was to fabricate custom hardware. The design consisted of shouldered aluminum rods threaded into each other through a milled hole in the laminated legs. Each aluminum ‘tenon’ press fit into its corresponding laminated ‘mortise.’ The aluminum components then thread together using the legs as levers.

Although initially secure, continued use loosened the friction fit allowing the legs to rotate irrespective of the aluminum components. Subsequent iterations will circumvent this issue by milling square, rather than cylindrical, tenons (Figure 111).

[109] Elevation and plan diagrams of the aluminum neck components
[110] Detail image of aluminum neck securing the stool legs
[111] Isometric diagram illustrating proposed component alterations
[112] Isolated aluminum neck components
The seat design is a basic manipulation of a section. The initial contour of the seat, a section, derives from the human body. This natural curvature influences the positioning of strategic control points with adjustments made based upon the bending capabilities of the wood species. Extrusion of the resulting section creates a planar flow form. Removal of a circular/triangular shape gives the surface a simulated undevelopable appearance. The addition of a second section along the centerline influences directionality while alleviating the displeasing central glue line.

Figure 113. Construction diagram of the initial linear flow form
Figure 114. Initial flow form extrusion creating a planar surface
Figure 115. Addition of a second flow form derived from the initial flow form

Seat Contour
For the laminated seat to match the intended contour, each individual laminate required slight thickness adjustments, using a custom planer sled shimmed at locations mirroring the control points of Figure 113 on the previous page. The shims are thin – a heavy 1/32” – but lift the appropriate areas closer to the planer blades, removing just enough material. Widening, shortening, or simply moving the shims allowed for fine-tuning. When clamped against a flat, thick base, the cumulative laminated effect created an undulating top surface. Realizing the specific contour took multiple iterations, but even with the contour matched, the flat plane of the underside created an overall static form dissimilar to the more dynamic base.

Seat Contour Mock-Ups

[116] Custom planer sled alongside a clamped seat section
[117] Laminated seat section iterations
[118] Testing the effectiveness of the seat section contour
Securing the aluminum neck plate to a flat surface was the original idea and the simplest solution. However, it seemed perverse that ease of construction would supersede overall aesthetic. Form eventually took precedence as another lamination study (Figure 91) furnished inspiration. Translating the designed seat contour into formwork produced the final mock-up and resulting seat.

[119] Final contoured seat section and the lamination study behind the inspiration
At first, a circular seat appears logical because of its importance in the organization of the legs, and it grounds the piece. However, it conflicts with the base structure feeling like the safe and uncreative solution. Having the legs guide a triangular form is more appropriate for the current context. The direction and extent of the legs map the location of the vertices creating both equilateral and scalene triangles. Pulling each resulting side – perpendicular to its midpoint – equidistant provides a varying array of surface areas. The equilateral forms ground the piece through regularity but also provide a more cohesive relationship overall, while the scalene forms create an interesting dialogue through an irregular balance.

Figure 120. Illustration of overlaid equilateral triangles representing the seating surface
Figure 121. Illustration of overlaid scalene triangles representing the seating surface
Figure 122. Construction process diagram of a scalene triangle seating surface
Figure 123. Final contoured seat with a milled equilateral triangle

Seat Perimeter Construction
Defining Sustainability Through Bentwood Lamination

Figure 124. Bent lamination stool final build

Figure 125. Plan and elevation diagrams of the full-scale stool

Final Build

[124] Bent lamination stool final build [125] Plan and elevation diagrams of the full-scale stool
The move from handheld sculptures back into full-size furniture fostered a more meticulous analysis of the lamination process. It also brought about a shift in thinking. At this point, concern over the sustainability of process waste started to take precedence. The amount of formwork material needed in this section quadrupled the actual leg material. If these legs were intended for mass-production, formwork material would be moot; however, the scope of this study focuses on limited-run processes. The excessive amount of formwork bordered on grotesque. Around this same time, a question arose regarding the value of fabricating a wholly unique tool. That simple question spawned a deep contemplation that would shape the rest of this study.

[126] Excessive formwork used to create the three leg laminations
Sustainability is a common – and overused – word in our design lexicon. But what does it really mean? There is no universally applied or accepted definition. Possibly the most cited description comes from the United Nations’ Bruntland report in 1987, which interprets sustainability as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs.” A search across any number of sources yields similar equivocal descriptions about responsible environmental interactions. The definitions are inherently vague, and the ambiguity permits its application across a wide array of practices and processes. But what if sustainability will always be more abstract than concrete? Maybe there is no definitive answer because there never should be. In our rapidly developing world, today’s efficiency often becomes tomorrow’s wastefulness. As such, sustainability’s present loose interpretation will evolve as technologies and process develop. Perhaps sustainability is less a prescribed set of rules and more an intrinsic reminder to constantly evaluate practices; it is more recognition than checklist. From this perspective, sustainability is not something to attain. Rather, it is a stimulus to continually search for better ways to interact with our surrounding environment. This includes finding ways to make even the most harmful processes marginally better.

With this as the framework, this study uses bentwood lamination to examine four areas overdue for new thinking: production, adhesives, logging, and pressing.

The first area of evaluation concerns mass production, which has become both ally and adversary of ecologically sound design. The search to fabricate using the greatest possible efficiencies reduces resource consumption, manufacturing waste, transportation effects, etc. The greater the efficiency, the lower the cost to the consumer. However, this ultimately creates an inverse relationship with value: preciousness decreases as efficiencies increase. The sustainability gains initially realized are lost as consumers view products as expendable. Mass production effectively creates mass waste. An alternative to this method is limited run production. Here, the output is significantly reduced with higher operating costs passed onto the consumer. The customer may not be able to look beyond increased expense, but the initial investment undertaken is repaid through longevity.

Longevity may be the paramount characteristic associated with environmentally conscious furniture. Longevity is equal parts sound construction and lasting aesthetics. The former provides durability, yet recognizes the need for occasional maintenance. The latter offers original design that outlasts fleeting trends. Both attributes seek to lift the lifespan of furniture from disposable into heirloom. If that lifespan requires a quantifi-
able number, tree maturity needs consideration. When a tree is harvested, the piece(s) built from that lumber should exist as long as it takes to regrow another tree of same species and maturity. This is only a suggested starting point to encourage generational furniture, as the extremes at either end of the growth spectrum will complicate matters.

Adhesive technology is another area in critical need of rethinking. Currently, dependability brings toxicity, whereas environmentally safe alternatives carry issues of pliability and creep. We must push the adhesive industry to create nontoxic solutions that mate both rigidity and strength. However, in the absence of preferable alternatives, mitigating extraneous adhesive in bent lamination construction is essential. Understanding the bending capabilities of wood laminates provides such an avenue. Thinner laminates bend easier but necessitate more layers—and adhesive—to reach a specified thickness. The solution requires identifying the maximum thickness at which the laminates are just able to conform to a given radius. It is possible to develop a formula that provides this ideal laminate thickness given part width, species, and curve equation.

In creating laminates—or veneers—sawmills generate paper-thin sheets of wood through a slicing technique—think massive block of cheese—that produces virtually no waste. These sheets are cut to predetermined standards established to maximize yield—and profits. Current technology—and to a certain degree, demand—prevents sawmills from resawing “special thickness veneers” any thicker than 1/8 inch. Degradation of material and tooling occur beyond this dimension. If design stipulates a laminate thickness greater than that commercially available, the maker must create his/her own slices. This requires bandsawing, which produces sawdust—waste. Although the sawmill standards are sensible from an economic standpoint, they unintentionally place constraints upon ecology and creativity. A bent lamination maker should not have to choose between unnecessary adhesive or increased waste. Ideally, the maker would have a custom milling operation for each design. In this respect, concept and material would then work in tandem throughout the design process with minimal restrictions.

Lastly, there are opportunities to invent new ways of pressing laminates together. Traditionally, laminates are pressed into positive and/or negative formwork using ample pressure. It is tough to justify auxiliary resources—and their subsequent waste—unless high volumes of the part are necessary. Integrating a single form across multiple designs is advantageous, though limiting. Preferably, the solution would accommodate a higher level of flexibility, via a dynamic apparatus. Wood’s elastic resistance allows for a sustained state of stress with minimal outside force. Instead of a pressing tool, it becomes a system meant to maintain structure through the drying process. Combining this natural resistance with a way to maintain tension has the potential to reduce input waste by a significant amount.

The search to reimagine and uncover latent approaches in furniture construction provided an opportunity to redefine sustainability with respect to bentwood lamination; but the complexity and constantly evolving nature of human life prevent that definition from having lasting substance. However, even though sustainability will never have a singular meaning, it is imperative it remains in our vocabulary as a way to challenge design and fabrication. Ideally, the use of “sustainable” will move away from describing and more towards evaluating. In this manner, the abstract concept of sustainability provides a continual stimulus for change instead of a complacent feeling of accomplishment.
ARTIFACT THREE
Lamination Press Tool
Research and experimentation can be wasteful as it is tough to gauge excess without knowing what is essential. As familiarity grows so too does efficiency. Increased resourcefulness, in turn, leads to a more economical solution. At this point in the thesis investigation, the collection of formwork heavily outweighed the produced furniture and tactile studies. Due to the one-off nature of the furniture and studies, a lack of adaptability doomed the formwork to a landfill. Accordingly, reducing process waste took on an importance that superseded other sustainable issues – adhesive toxicity, veneer generation – in part because of its individual manageability; no chemistry degree or massive machinery required. Subsequently, the thesis investigation shifted from analytically proposing actions to actual solution implementation: the creation of a tool that systemized bentwood furniture formwork and alleviated the process waste seen with limited-run production.

Waste Reduction Tool

Defining Sustainability Through Bentwood Lamination Artifact Three: Lamination Press Tool

Collection of wood and off-the-shelf hardware primarily used to construct subsequent tool designs.
The first attempt at systemizing formwork involved an established technique: kerfing. Saw blades create a slot, called a kerf, when cutting material, and the systematic slotting of this material—traditionally medium density fiberboard (MDF)—is kerfing. Number, width, and spacing of the slots determine the overall curvature; tighter curves have more slots spaced closer together while broader curves have fewer slots spaced further apart. Applying this technique to formwork design requires deconstructing the curvature's component radii and applying them to a kerfing equation. Although kerfed formwork offers an alternate—and more systematic—construction technique, it provided no modularity and marginal adaptability beyond its initial use. Foremost, kerfed formwork hardly reduced construction material volume, which led to the same excess waste issues as before.

Kerf spacing for a curve at a 7” radius.

\[ \angle aa = 10.305^\circ \]
\[ \angle aa \text{ bisected} = 5.153^\circ \]
\[ \angle ab = 90^\circ \]
\[ \angle bc = 180^\circ - \angle aa \text{ bisected} - \angle ab = 84.847^\circ \]
\[ \angle br = 90^\circ \]
\[ r = \text{desired radius} = 7” \]

\[ \tan(\angle bc) = \frac{\text{opposite } r}{\text{adjacent } b} \]

\[ \tan(84.847^\circ) = \frac{7}{b} \]

\[ b = 0.631” \]

\[ 2b = \text{kerf spacing} = 1.263” \]
A second attempt at systematizing formwork emphasized adjustability: how could a base format tool allow for infinite possibilities? Inspiration came from the simple mechanisms of children’s toys: pin art and an abacus. Clamping studies followed imitating the movements of the toys’ linear arrays. Observations influenced subsequent illustrations dealing with linear clamping systems. The concepts focused on defining formwork as a series of points instead of as a solid mass. Expressing form as a series of movable points—or nodes—expanded functionality beyond the initial curvature.

Illustrations of concepts focused on defining formwork as a series of points. Influential children’s toys: an abacus and pin art.
Illustrated concepts became small-scale physical models through the use of off-the-shelf materials; carriage bolts fed into threaded inserts that resided in a walnut frame. Additionally, flexible aluminum strips helped capture and protect the lamination. Simple rotation of individual bolts enabled minute and instantaneous adjustment while approximating form. However, it proved tough to accurately replicate previous curvatures once removed from its original position.

[135] Initial miniature sketch model showing basic proof of concept [136] Small-scale tool iteration one with multiple orientations
The issue of accurate repeatability required a solution that would permit interchangeable elements. For the second model iteration, tracks holding templates replaced the bottom row of carriage bolts. This template-based system used small dowels to span between each template to reduce overall material usage. Model iteration two also investigated the application of lateral pressure to more complex laminations. Although still conceptual, the model tool revealed design issues concerning the connection between the bolts and threaded inserts; the insert’s relatively large tolerance combined with the long bolts created a pivot point.

Template Formwork

The issue of accurate repeatability required a solution that would permit interchangeable elements. For the second model iteration, tracks holding templates replaced the bottom row of carriage bolts. This template-based system used small dowels to span between each template to reduce overall material usage. Model iteration two also investigated the application of lateral pressure to more complex laminations. Although still conceptual, the model tool revealed design issues concerning the connection between the bolts and threaded inserts; the insert’s relatively large tolerance combined with the long bolts created a pivot point.
A third iteration addressed the pivot point problem by increasing the overall scale and thickening the base structure. This provided a more substantial guide for the bolt and alleviated the pivot point issue. However, the scale increase ultimately emphasized the importance of bolt diameter and spacing as both elements worked together to dictate the tool’s capabilities. Tighter curves required densely packed, small diameter bolts while broader curves required the opposite. Having multiple arrays seemed counterproductive, so the focus shifted to the variability of each bolt head – or node.

[142] Third generation model of the tool [143] Process image tightening the nuts to secure the lamination
Removable node attachments became the focal point to avoid switching out bolts for each unique lamination. Multiple series of node attachments would serve to better approximate a higher percentage of curves and provide more life to the overall tool than a singular, fixed bolt head. As such, node studies explored the value of various geometric shapes – rectangular prisms, cylinders, spheres, and ellipsoids. Increasing pressure dispersion with a larger surface area was the main goal. However, even with densely packed nodes, intermittent areas lacked sufficient pressure causing irregularities along glue lines. This observation led to the use of thicker substrates to disperse the pressure between nodes and laminates, which rectified the issue of uneven glue lines.

[144] Cylindrical nodes extruded for wider laminations
[145] Collection of three distinct sizes of spherical nodes
[146] Node study focusing on how to contain veneers with different side walls
[147] Pivoting rectilinear node study
Using the observations of previous iterations as a guide, fourth generation models focused on the modularity of the tool. Having multiples of the same design provided an opportunity to assess the functionality of reorienting and connecting tools together. Subsequent combinations morphed linear forms of previous iterations into planar and complex curvatures. With modularity and adaptability accounted for, the next step involved translating the wood mockups into a full-size steel prototype. However, the original goal emphasized a reduction in formwork waste, but the new focus drifted towards clamp substitution. In essence, the overall concept provided a minimal solution to the issue of formwork waste.

[148] Tool iteration four using spherical nodes [149]
[150] Diagram of tool modularity: complex, planar, and linear orientations
[151] Construction image of tool iteration four
131130

Free-Form Press Tool

Artifact Four: Free-Form Press Tool
Coinciding with the thesis study was another project, the FORM: Line-Plane-Solid Exhibit, that featured over 200 form studies and products from 90 students during a three-year span, 2012-2014. Although my primary involvement concentrated on the design and construction of the exhibit architecture, I was asked to design a distinct bentwood lamination feature: a three dimensional interpretation linking the main form typologies – line, plane, and solid. With the thesis lamination press tool at an impasse, this commission revealed a new approach to the multidimensional studies first introduced during my primary research phase.

[146] FORM: Line-Plane-Solid Exhibit [147] Concept illustration of the initial bentwood lamination feature
Drawing inspiration from the prior multidimensional studies, elastic resistance dictated the exhibit feature’s form. The initial linear element was a thin strip that transitioned from vertical to horizontal as it fed into the planar element with a simple 90-degree rotation. Capturing this flow form entailed securing one end of the strip, rotating the opposite end perpendicular, and securing that end in place. Fixing the curve in this manner provided a baseline where a bevel gauge could approximate tangential planes at set intervals. Subsequently, a series of ribs milled to the appropriate angles filled the negative space underneath the curve. The end result created a ribbed formwork that resembled a three-dimensional curve stitch, and because of its density, sheathing substrates were unnecessary. As such, lamination involved only a few strategic clamps holding the veneers directly against the ribs.

Laminating Complex Curves

[155] Initial linear form held in tension
[156] Bevel gauge approximating tangential planes
[157] Ribbed formwork supporting the curve
[158] Clamped veneers against the formwork
[159] Final linear lamination feature
Forming the complex curve of the initial exhibit element was tedious, but it sparked an idea for a more appropriate waste-reducing tool. The beginning step in analyzing the complex curve – capturing the form – served to influence the conceptualization of a lamination press without formwork. Assumption: the veneer’s elastic resistance keeps sufficient tension when manipulated and needs a minimal amount of pressure to adhere the veneers together – pressure that a vacuum bag supplies. To test the premise, a poplar jig with angled blocks – calculated to produce the same bentwood stretcher in Artifact One – held the veneers in position while atmospheric pressure compressed them together. Inspection of the free-form part against previously laminated fe/male formwork components revealed no discernable differences. Though overbuilt, the poplar jig and vacuum press produced an identical form, but fabricated with significantly less formwork.

[160] Testing free-form lamination with the vacuum press method [161] Poplar Jig used to secure the appropriate bentwood stretcher form [162] Fe/male formwork used to press previous bentwood stretchers
As documented in the Primary Studies section, commercially available vacuum bags cater to flat panel veneer work. These bags are inherently large and not conducive to smaller bentwood parts. However, certain retailers offer vinyl or polyurethane bag fabrication kits for the “do-it-yourself” crowd. Though more expensive, polyurethane is the ideal choice for complex bentwood laminations as it provides far greater flexibility, durability, and puncture resistance. Typically, fusing polyurethane sheets together require a radio frequency (RF) welder to create an airtight seam, but individuals can also join the sheets with special contact cement. Lacking access to the proper technology, the adhesive method was the only solution. This method was tough to accurately master and yielded many subpar bags. The few serviceable results lacked a completely airtight seam but enabled the proof of concept test on the prior page. Ideally, for a successful free-form press tool, a commercial vendor would supply RF-welded bags. Similar to sockets in a socket wrench set, the tube-like vacuum bags would come in multiple widths as part of a larger set.

[163] Components of custom polyurethane vacuum bags
With a working proof of concept for free-form lamination, the next step was to define the process as a repeatable system. Similar to the studies done during the primary research phase, material studies focused more specifically on how to appropriately capture multidimensional form. A series of rectilinear constructs demonstrated how planes, angles, and proximity influenced resulting curvature. Additionally, moving the material into position – and how it responded – garnered special attention. These observations influenced the evolution of a subsequent securing mechanism for the free-form tool concept.

Multidimensional Form Studies

[164] Orthogonal frame used to explore multidimensional material properties [165-168] Rectilinear elements used to explore multidimensional material properties
The securing mechanism became the primary component in this free-form lamination tool with the most important aspect being its responsibility of capturing form as opposed to applying pressure. Because the veneers needed room to move when manipulated, the mechanism had to restrict – but not fully inhibit – movement. As such, various securing concepts – wedging, pinning, clamping – were considered during the ideation phase. Ultimately, a cylindrical compression clamp successfully permitted veneer movement and left the bag material unaltered. With the mode of securing determined, the focus shifted towards maximizing versatility. Allowing the mechanism freedom of rotation along two axes helped achieve this flexibility, though increased its complexity.

Securing Mechanism

The securing mechanism became the primary component in this free-form lamination tool with the most important aspect being its responsibility of capturing form as opposed to applying pressure. Because the veneers needed room to move when manipulated, the mechanism had to restrict – but not fully inhibit – movement. As such, various securing concepts – wedging, pinning, clamping – were considered during the ideation phase. Ultimately, a cylindrical compression clamp successfully permitted veneer movement and left the bag material unaltered. With the mode of securing determined, the focus shifted towards maximizing versatility. Allowing the mechanism freedom of rotation along two axes helped achieve this flexibility, though increased its complexity.
A track system developed alongside the securing mechanism, and as the mechanism grew in complexity, the track system simplified. Originally conceived as an orthogonal frame similar to Figure 164, the modularity of linear tracks replaced the frame concept; tracks varying in length offered far greater versatility and overall simplicity than a fixed-frame system. For example, because of the securing mechanism’s mobility, a single track could handle any orientation between consecutive points [Figure 172]. When multiple tracks are necessary, a circular joint connector would then link each length of track together [Figure 173]. This connector would permit sufficient range of motion, two-dimensionally, but a future iteration of this joint would ideally allow three-dimensional construction.

[172] Illustration of the securing mechanism’s versatility with respect to the track system [173] Illustration of the circular joint connector’s track thickness dictating the angle of rotation [174] Sketch models exploring track rotation and movement
Small-Scale Prototype

[175] Close-up shot of the free-form press tool securing a complex curve [176-178] Iterations of the cylindrical securing mechanisms used for the free-form press tool
[179] Overall image of the free-form press tool

Figure 175.

Figure 176.

Figure 177.

Figure 178.

Figure 179.
Subsequent Study

Though the thesis study outlined in this book had to conclude within the timeframe defined by Virginia Tech, this study will continue well beyond its academic life. The future phase will focus on a more dynamic securing mechanism as the small-scale free-form tool concept transitions into a full-scale metal prototype. A successful full-scale build will produce a sturdy – yet lightweight – modular tool that can hold multidimensional furniture laminations for repeatable results. Additionally, it is vital to seek a vendor that can produce custom polyurethane vacuum bags to work in unison with the free-form tool.

Ideally, this method would encourage smaller woodworking shops to experiment with more organic components and let function follow the beauty of wood’s intrinsic properties. However, the ultimate goal of this continued study is to sustain a dialogue about the constantly evolving nature of sustainability, and how all processes and techniques should see regular inspection as technologies develop.
BIBLIOGRAPHY


