

A digital platform for furniture mass-customization

by

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

The aim of this project is to develop a platform that enables users to design and acquire semi-customizable furniture. Positioned between mass-produced furniture and fully custom millwork, the platform promotes user agency by allowing individuals to customize designs to better fit their space, preferences, and needs. By simplifying the design process and making it more affordable, this approach aims to bridge the gap between mass production and craft production through the concept of mass customization. The platform also addresses the following issues: limited control over furniture design, high cost barriers to custom millwork, difficulty in connecting with fabricators, and the need for furniture that can adapt over time. Additionally, it will offer intelligent design feedback to help users make informed decisions about materials, costs, and sustainability. The final product includes a digital tool that allows users to configure pre-designed units into furniture and connects them with local builders for fabrication. This approach seeks to make semi-custom furniture more accessible, engaging, and adaptable to users' evolving spaces and needs.

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Table of Contents

Author's Declaration	ii
Abstract	iii
Acknowledgments	iv
List of Figures	vii
Project Introduction	1
Part 1 Determining values	4
1.0 Section Overview:	4
1.1 Furniture Systems	4
1.2 Digital Tools	5
Part 2 Existing solutions and methods	7
2.0 Section Overview	7
2.1 Provincial Store Fixtures Ltd.	7
2.2 Allwood Carpentry Manufacturing	11
2.3 Digital Design Tools	13
Part 3 Design a New Solution	16
3.0 Section Overview	16
3.1 Overall System Plan	17
3.2 Design Software	19
3.2.1 Main Menu	19
3.2.2 Design Stage	20
3.2.3 Uploading	26
3.2.4 Modifying Existing Furniture	26
3.3 Builder Software	28
3.3.1 Accounts	28
3.3.2 Viewing Projects	28
3.3.3 Exporting Projects	28
3.4 Connecting Designers and Builders	31
3.4.1 Server Functions	31
3.4.2 External Services	32
3.5 Coding the Software	32
Part 4 Conclusion	33
4.0 Section Overview	33
4.1 Evaluating the Furniture System	33
4.1.1 Dimensional Customizability	33
4.1.2 Financial Cost	36

4.1.3 Environmental Cost	39
4.1.4 Flexibility and Adaptability	39
4.2 Evaluating the Design Tool	39
4.2.1 Ease of access	39
4.2.2 Ease of Use and Ease of Learning	39
4.2.3 Depth of User Control	40
4.2.4 Responsiveness	40
4.2.5 Visual Feedback Quality	40
4.3 Challenges Going Forward	40
4.4 Conclusion Summary	41

Part 5 Post-Defence 42

Bibliography 45

Appendix 48

A.1 Furniture system values	48
A.1.1 Furniture value: Dimensional Customizability	48
A.1.2 Furniture Value: Financial Cost	48
A.1.3 Furniture Value: Environmental Cost	48
A.1.4 Furniture value: Adaptability/flexibility	49
A.1.5 Furniture value: Construction Complexity	49
A.1.6 Furniture value: Durability	49
A.2 Digital tool values	49
A.2.1 Digital tool value: Ease of access	49
A.2.2 Digital tool value: Ease of use/Ease of learning to use	50
A.2.3 Digital tool value: Depth of user control	50
A.2.4 Digital tool value: Responsiveness	50
A.2.5 Digital tool value: Visual feedback quality	50
A.2.6 Digital tool value: Scope of Capabilities	51

B Development Timeline 52

C Existing Software Solutions 65

C.1 Ikea Kitchen Planner	65
C.2 ShelfHelp	65
C.3 String Furniture	66
C.4 Roomle - Regalsystem LINE	67
C.5 Roomle - Moebe	67
C.6 Create-A-Kitchen	68
C.7 Blum E-Services	68
C.8 SmartDraw	69
C.9 Microvellum	70
C.10 Rhino 3D	70

List of Figures

Figure 1. Example furniture configuration

Figure 2. Image of the wood storage area of Provincial Store Fixtures Ltd.

Figure 3. Image of the wood cutting area of Provincial Store Fixtures Ltd.

Figure 4. Image of ventilated spray room and drying room of Provincial Store Fixtures Ltd.

Figure 5. Image of assembly area of Provincial Store Fixtures Ltd.

Figure 6. Image of the packing and shipping are of Provincial Store Fixtures Ltd.

Figure 7. The conventional process of acquiring custom milwork

Figure 8. An alternative process of acquiring semi-custom millwork proposed by this thesis

Figure 9. Example furniture configuration

Figure 10. Diagram of the proposed system

Figure 11. Diagram showing the placement and modification of a module

Figure 12. Screenshot of the main menu options

Figure 13. Screenshot of the design stage interface

Figure 14. Diagram of an example furniture configuration, in graph representation

Figure 15. Diagram showing the graph updating as a module has its dimensions changed

Figure 16. Diagram showing the non uniform scaling process of a simple shelf

Figure 17. Diagram showing the non uniform scaling process of a corner shelf

Figure 18. Diagram showing the before (left) and after (right) of joining adjacent modules

Figure 19 Diagram showing the two snapping methods for block placement, volume method on left, distance method on right

Figure 20. Example furniture configuration

Figure 21. Screenshot of the upload interface

Figure 22. Diagram showing the components that could be reused from one design to another (red)

Figure 23. Diagram showing the components that could be reused from one design to another (red), laid out flat

Figure 24. Diagram showing the process of breaking down a module into its individual components

Figure 25. Diagram showing the removal of redundant components, and combination of vertical components

Figure 26. Example furniture, exported as an assembled model, exploded model, and individual components

Figure 27. View of unit layout using conventional mass produced furniture (top), layout using proposed custom furniture (bottom)

Figure 28. Bedroom storage volume of unit using conventional furniture

Figure 29. Walkable floor area of unit using conventional furniture

Figure 30. Furniture design used for cost analysis, also one of the example configurations

Figure 31. Diagram showing mass produced alternatives to the target design

Figure 32. Possible material transportation map interface

Figure 33. Diagram showing the optimization of the CNC mill layout

Figure 34. Detailed price breakdown for the example shelf from section 4.1.2



A digital platform
for furniture mass-customization

Project Introduction

Given the high cost of housing in many downtown centers like Toronto¹, many residents, especially renters and first-time homebuyers, often face constraints in terms of space and affordability. This situation often leads to smaller living spaces², such as apartments or condominiums, where maximizing the utility of space becomes crucial. In such environments, custom-designed furniture can provide many advantages.

Custom furniture systems can be tailored to make the most of limited space. In small apartments or condos, where every inch counts, having furniture that fits precisely can create a more functional and comfortable living environment³. When making custom furniture, the designer can choose to use more durable materials, which in the long run, can be more cost-effective than constantly replacing cheaper, mass-produced furniture⁴. Custom furniture has the additional benefit of allowing residents to express their individual styles and preferences.

However, the current process of acquiring custom furniture is not accessible to everyone; Hiring someone else to design and build it for you is prohibitively expensive for the majority of people, most do not have access to the facilities required to build furniture themselves, and many people don't have the technical (or artistic) skills required to model their ideas for a millwork facility to manufacture them.

The goal of this thesis is to create a platform that promotes user agency in the process of designing and acquiring semi-customizable millwork furniture. This platform fits somewhere in between highly accessible mass-produced furniture like Ikea, and less accessible, but highly custom, one-of-a-kind millwork. This approach, known as mass customization, refers to a business strategy that conciliates the two different business practices of mass production and craft production⁵.

The following points summarize the main problems that motivate this thesis:

- Typically people select furniture from prebuilt pieces available on the marketplace and exercise little control over the design of their furniture, resulting in them using furniture that does not quite fit in their space, using materials they don't like or that don't meet their particular needs⁶. **Therefore, the platform aims to: Give users more agency in the design of their furniture.**
- Getting custom millwork furniture has a high cost barrier, and requires both design skills and technical skills (or someone with those skills, meaning additional/increased cost)⁷. **Therefore, the platform aims to: Make custom millwork more accessible to those without the resources or skills currently required.**
- Finding a suitable fabricator for millwork projects can be difficult (for someone not already familiar with the field). **Therefore, the platform aims to: Make connecting clients with local furniture fabricators easier for both parties.**
- Furniture that originally fit well becomes less useful when needs or spaces change. Replacing the entire piece

1 "Historical Prices in Toronto." Accessed November 6, 2023. <https://www.numbeo.com/cost-of-living/city-history/in/Toronto>.

2 Government of Canada, Statistics Canada. "The Condo Market in Toronto and Vancouver: A Home, an Investment and Increasingly a Rental Property," March 17, 2023. <https://www.statcan.gc.ca/o1/en/plus/3237-con-do-market-toronto-and-vancouver-home-investment-and-increasingly-rental-property>.

3 Thøgersen, Kristoffer. "Small Spaces Need Smart Solutions," n.d.

4 Bumgardner, Matthew S., and David L. Nicholls. "Sustainable Practices in Furniture Design: A Literature Study on Customization, Biomimicry, Competitiveness, and Product Communication." *Forests* 11, no. 12 (November 28, 2020): 1277. <https://doi.org/10.3390/f11121277>.

5 Blecker, Thorsten, and Gerhard Friedrich. *Mass Customization: Challenges and Solutions*. Springer, 2006.

6 Gomes, Rute. "Designing for Unpredictable Households: Furniture Design Requests for a Flexible Use of Dwellings." In *Advances in Creativity, Innovation, Entrepreneurship and Communication of Design*, edited by Evangelos Markopoulos, Ravindra S. Goonetilleke, Amic G. Ho, and Yan Luximon, 175–84. Cham: Springer International Publishing, 2020. https://doi.org/10.1007/978-3-030-51626-0_21.

7 Banker, Rajiv D., Gordon Potter, and Roger G. Schroeder. "An Empirical Analysis of Manufacturing Cost Drivers." *Journal of Accounting & Economics*, April 1992.

of furniture is both expensive and wasteful⁸. **Therefore, the platform aims to: Make furniture that can easily be modified over time as the user's space and needs change.**

- When designing without previous knowledge and training, it can be hard to know which materials are more or less durable than others, more or less expensive, and have a greater or smaller impact on the environment. It can be hard to know how one can design in a way that makes the best use of available material dimensions and equipment bed sizes, and it can be hard to know what are the best dimensions to use for maintaining structural stability. **Therefore, the platform aims to: Make a design tool that provides intelligent feedback, advice, and statistics that let an untrained user make informed design decisions.**

The product of the thesis can be viewed in two parts: (1) A digital tool that lets users combine and configure pre-modeled units into a complete piece of furniture, and (2) a system that connects those users with builders who can manufacture the designs. By making a digital configuration tool as accessible as possible (similar to product display/configurators made by car brands⁹¹⁰, clothing brands¹¹, furniture brands¹²¹³, etc), any user can be involved in the design process, regardless of existing technical or artistic knowledge.

“Opening the design process to individuals that may become users increase the level of engagement before the object exists and, in theory, supports the development of a more personal-effective solution, thereby achieving greater symbolic significance.”¹⁴

The design of the digital tool will follow some of the general strategies outlined in the Delft Design Guide¹⁵ (using diagrams that are more legible than the actual software code, to both stay organized during development and to help describe the process in more simple terms), and use the design strategies specific to the digital settings of Steve Krug¹⁶ and Laura Kalbag¹⁷ (both of which focus on making software as easy to use and as accessible as possible). In addition to these design guides, there are countless examples of digital configurator tools used for room layout visualization¹⁸, furniture product display¹⁹²⁰, and procedural furniture design²¹²²²³²⁴. These tools, and the companies that create them²⁵, can be used to observe the established conventions and help act as a starting point for my own design explorations. Following existing conventions of similar systems is an important strategy that can be used to make a product easier to learn, and therefore more accessible.

8 Bumgardner, Matthew S., and David L. Nicholls. “Sustainable Practices in Furniture Design: A Literature Study on Customization, Biomimicry, Competitiveness, and Product Communication.” *Forests* 11, no. 12 (November 28, 2020): 1277. <https://doi.org/10.3390/f11121277>.

9 Mitsubishi Motors US. “Custom Car Builder & Vehicle Configurator | Mitsubishi Motors.” Accessed April 11, 2024. <https://www.mitsubishicars.com/configure-your-mitsubishi>.

10 “Car Configurator | MG Motor.” Accessed April 11, 2024. <https://cc.mgmotor.co.in/vehicles.html>.

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15 Boeijen, Annemiek van, Jaap Daalhuizen, J. Zijlstra, Roos van der Schoor, and Technische Universiteit Delft Faculteit van het Industrieel Ontwerpen. *Delft Design Guide: Design Methods*. Revised 2nd edition. Amsterdam: BIS Publishers, 2014.

16 Krug, Steve. *Don't Make Me Think, Revisited: A Common Sense Approach to Web Usability*. Third edition. Berkeley, Calif: New Riders, 2014.

17 Kalbag, Laura. *Accessibility for Everyone*. 1st edition. A Book Apart, 2017.

18 Ikea. “IKEA Kitchen Planner.” Accessed October 2, 2023. <https://kitchen.planner.ikea.com/ca/en/>.

19 “Build Your Own Custom-Made Shelf - String Furniture.” Accessed September 29, 2023. <https://stringfurniture.com/build-your-own?room=outdoor>.

20 “Roomle 3D Shelves Configurator.” Accessed September 29, 2023. <https://www.roomle.com/en/demos/shelves>.

21 J. L. M. Ripper, “Modelagem Geométrica Parametrizada Da Cadeira Folha (Parametric Geometric Modeling of the Chair ‘Cadeira Folha’),” in SIGRaDi’2000 - Construindo (n)o Espaço Digital (Constructing the Digital Space) [4th SIGRADI Conference Proceedings / ISBN 85-88027-02-X] Rio de Janeiro (Brazil) 25-28 September 2000, Pp. 283-285 (CUMINCAD, 2000), <https://papers.cumincad.org/cgi-bin/works/paper/7965>.

22 Barros, Mário; Duarte. “Digital Thonet: An Automated System for the Generation and Analysis of Custom-Made Chairs.” In RESPECTING FRAGILE PLACES [29th eCAADe Conference Proceedings / ISBN 978-9-4912070-1-3], University of Ljubljana, Faculty of Architecture (Slovenia) 21-24 September 2011, Pp.521-529. CUMINCAD, 2011. https://papers.cumincad.org/cgi-bin/works/paper/ecaade2011_053.

23 Barros, Mário; Duarte José. “Thonet Chairs Design Grammar: A Step Towards the Mass Customization of Furniture.” In Computer Aided Architectural Design Futures 2011 [Proceedings of the 14th International Conference on Computer Aided Architectural Design Futures / ISBN 9782874561429] Liege (Belgium) 4-8 July 2011, Pp. 181-200. CUMINCAD, 2011. https://papers.cumincad.org/cgi-bin/works/paper/cf2011_p170.

24 White, Ana. “Free, Easy to Use Woodworking Design Tool.” Shelf Help. Accessed September 29, 2023. <https://shelfhelpnow.com/pages/shelf-configurator>.

25 Albert, Ortig. “Make Your Furniture a Better Digital Experience - Roomle.” Roomle.com. Accessed August 16, 2024. <https://www.roomle.com/en/about>.

The thesis is organized into 4 parts; Part 1 aims to clearly identify the goals of the project, to clarify the objective of the final project, as well as facilitate the comparison of it to existing solutions. Part 2 involves researching existing software solutions and performing in person research of existing manufacturing methods for custom millwork. Part 3 describes the process of creating the new system for designing and acquiring custom millwork, and part 4 compares the newly created system to the existing ecosystem, using the values outlined in part 1.

Figure 1. Example furniture configuration



Part 1 Determining values

1.0 Section Overview:

Before creating the digital configuration tool and furniture manufacturing strategy, and before even looking at existing solutions, this section clearly defines the goals of the project, and creates a rubric for measuring the project's success (i.e. what would make the end result successful or not). It outlines a methodology for scoring furniture systems and digital configuration tools, while taking into account the overall goal to make custom furniture more accessible to the general public through the use of a digital platform. To meet these goals, the design tool should give the user more agency over the materials, dimensions, and configuration of their furniture, and give them the statistics they need to make informed decisions.

This section is split into two subsections: one for physical aspects of the furniture and furniture creation process, and the other for aspects of the digital configuration tools. In each of these subsections, there are several attributes that can be used to score/describe any furniture system and digital configuration tool.

Attributes of the furniture system:

1. Dimensional customizability (maximal)
2. Financial cost (minimal)
3. Environmental cost (minimal)
4. Flexibility/adaptability (maximal)
5. Construction complexity (minimal)
6. Durability (maximal)

Attributes of the digital configuration tool:

1. Ease of access (maximal)
2. Ease of use/learning (maximal)
3. Depth of user control (maximal)
4. Responsiveness (maximal)
5. Visual feedback quality (maximal)
6. Scope of capabilities (maximal)

These attributes are ranked based on how relevant they are to the goal of the project. In addition to ranking them, a methodology for measuring each one is created. With this, it will be possible to score existing solutions, as well as score our final product. (Refer to Appendix A for the complete breakdown of attributes and methodology)

1.1 Furniture Systems

While the primary focus of this thesis is the creation of a digital platform for furniture design, not the design of furniture itself, it is still important to consider what kinds of furniture the platform aims to produce, as well as the necessary transition from digital to physical. In this context, "furniture systems" can refer to both individual pieces of furniture, as well as the more general manufacturing methods associated with them.

The most important value of the furniture is the dimensional customizability. While technically all furniture can be made with custom dimensions if the dimensions are known before the manufacturing of the furniture, some designs are easier to modify than others, and some manufacturing methods require more initial investment for each new design. For example, updating a design to have different dimensions is much easier if linear components can be scaled than if freeform shapes need to be completely remodeled. Manufacturing methods like casting, which require the production of molds each time the design is changed would be considered less

customizable than a CNC mill manufacturing method that could make every iteration custom with no extra cost.

The second most important aspect of the furniture is the financial cost. Some aspects that typically determine the cost of furniture are absent in this context. The cost of the designer can be ignored - since in this context, the user is the designer. The cost of the infrastructure required to market designs and communicate with clients (showrooms, sales representatives) can also be ignored as the software acts as the interface between the clients and manufacturers. The remaining costs come from the raw materials, the manufacturing processes, the assembly of components, transportation, and installation.

The environmental impact is determined by the same factors as financial cost, although not necessarily in the same way, for example, some materials may have a greater financial cost and a lower environmental cost. Rather than trying to optimize the furniture for either financial cost or environmental costs, the software should provide the end user with enough information to let them decide for themselves.

Adaptability is important when the user's needs change, and can be accomplished in different ways. Furniture can be designed to be physically static yet functionally multi-purpose, it can be designed with moving parts that allow it to change size, or it can be designed to accommodate being disassembled and reused in a different configuration. Minimizing construction complexity is important when making a system that can be configured in many different ways.

Construction complexity should also be minimized since the end users (who are likely the people assembling the furniture) may not have workshop experience or access to tools. Finally, the durability of the furniture should be as great as possible. Not only does more durable furniture last longer, reducing financial cost and environmental costs in the long run, but more durable furniture designs are also more likely to be able to have their dimensions changed to suit a user's particular needs without becoming unstable.

1.2 Digital Tools

The following rubric can be used to score existing software solutions, and ultimately the software produced as part of this thesis. Looking closely at similar existing products can also help provide references in terms of layout conventions, and scoring them will expose which ideas work well and which do not in the context of the thesis goals.

Since the goal of the thesis revolves around making custom furniture more accessible, the software itself must also be extremely accessible. Therefore, removing barriers to access to the software is as important as the functionality of the software itself. Barriers to access can come in many forms; obviously, there is the barrier of cost - but since the software proposed will be free we can ignore this. Other barriers can be things like having to make an account to use the software, only being able to access the software on one type of device, and having to download the software. Ideally, the software should be accessible on any type of device (phone, Mac, Windows, tablet, etc), and be directly integrated into a website with no download required.

As with ease of access, it is important to maximize ease of use and ease of learning. As the target audience of the software is the general public, including non-experts, the software should be simple and intuitive, with clear instructions when necessary. The third aspect is to maximize the depth of user control. For the furniture produced to be considered "custom" or even "semi-custom," the user needs to have a significant level of control over the furniture. This also ties into the dimensional customizability value of the furniture system defined earlier.

Digital configuration tools, particularly those embedded in websites, are often frustratingly unresponsive or laggy. This is an important consideration, as it impacts the accessibility of the software as well as ease of use. The

fifth attribute is visual feedback quality; How true to life is the digital representation of the furniture, and how easy it is to read. While 2D plans and elevations are great for professionals, a rendered perspective is by far the best way to present information to a general audience. It's important to remember, however, that making a pretty picture comes second to making a responsive picture.

The final attribute to consider is the scope of capabilities. If the depth of user control measures how well the software can do one particular thing, the scope of capabilities measures how many different things the software can do. While a wide range of capabilities is generally a software strength, it may directly harm other aspects - namely ease of use. Additionally, the scope of capabilities is directly related to the amount of time required for development, which in the context of a thesis is limited. For these reasons, this value is ranked as least important.

Part 2 Existing solutions and methods

2.0 Section Overview

Having outlined the key values for furniture systems and digital tools in Section 1, Section 2 looks at existing furniture systems and digital tools to see how well they meet this project's goals.

Since individual furniture pieces' success is largely determined by their context (physical and functional), this section focuses on general fabrication processes rather than specific furniture designs.

Furniture can be categorized into custom-made and mass-produced. Furniture within these fabrication categories also generally have similar strengths and weaknesses related to each of the attributes outlined in Section 1. Most mass-produced furniture will have similar levels of dimensional customizability, financial cost, durability, etc.

To research furniture fabrication methods, several millwork manufacturers in Ontario are visited and their processes are documented. At the same time, a range of different digital tools related to the realm of furniture design are studied. This includes both the software used by professional millworkers, and the accessible configurators used by people looking to buy furniture but who have no previous software experience. Although the attributes outlined for a successful digital tool are all targeting a non-expert end user, it's important to look at how professional software works as one part of the thesis software needs to create an output for manufacturers.

2.1 Provincial Store Fixtures Ltd.

The first millwork facility I visited was Provincial Store Fixtures Ltd. As one of the largest millwork firms in Canada, they work on all sorts of projects across the country as well as in the United States. They are currently working on courthouses, hospitals, libraries, and some residential projects.

The facility is made up of several distinct sections that handle the different parts of the manufacturing process. Before entering the factory floor there are offices where general company management work and cost estimates for project bidding are done. The cost estimates are determined by the base materials, the time it will take to manufacture the furniture, and the cost of installation. The cost breakdown varies by project type but an example residential project breakdown was 30% for raw material costs, 45% for manufacturing and assembly time, and 25% for installation. The installation fee is always 25%.

The next section was the programming department. This is where they take the model or drawings from the architects and convert them to a design that can actually be built. Depending on the architect, they may only receive what the desired look is or they may receive a fully detailed model. The amount of time spent in this part of the process depends on the quantity and quality of information they receive from the architect. If the model given by the architects is fully detailed and already separated into components that can be cut by the machines, a lot of time is saved. In contrast, more vague models require the programming team to design all of the internal structure as well as figure out a way to split the millwork into components that can be cut. When I visited there were 15 people working in person with another 15 working remotely. Once the programming team is done with the model, digital instructions are sent directly to the CNC mills.

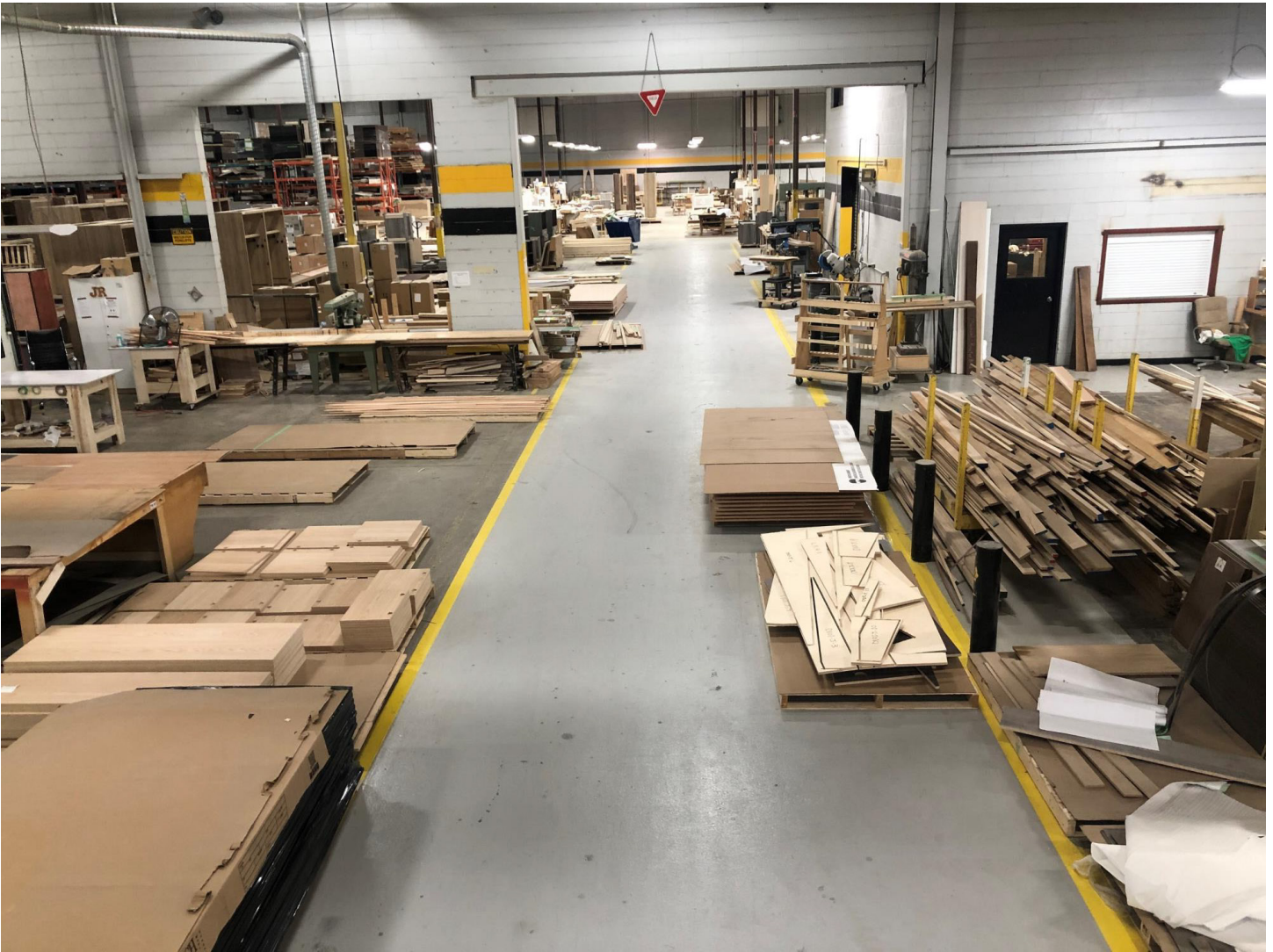


Figure 2. Image of the wood storage area of Provincial Store Fixtures Ltd.

At the front of the factory floor, they have a staging ground where prototype pieces for high-end projects can be tested by clients, at the time of my visit they still had some desks from the recently completed new Toronto courthouse.

Also near the front of the factory floor, beside the truck loading doors, is the material storage area. At any given time they keep about \$500'000 worth of wood here. This includes various composite board materials, veneer, and solid wood. Here workers load pallets with all of the materials needed for a given project, before sending them to the CNC mills.

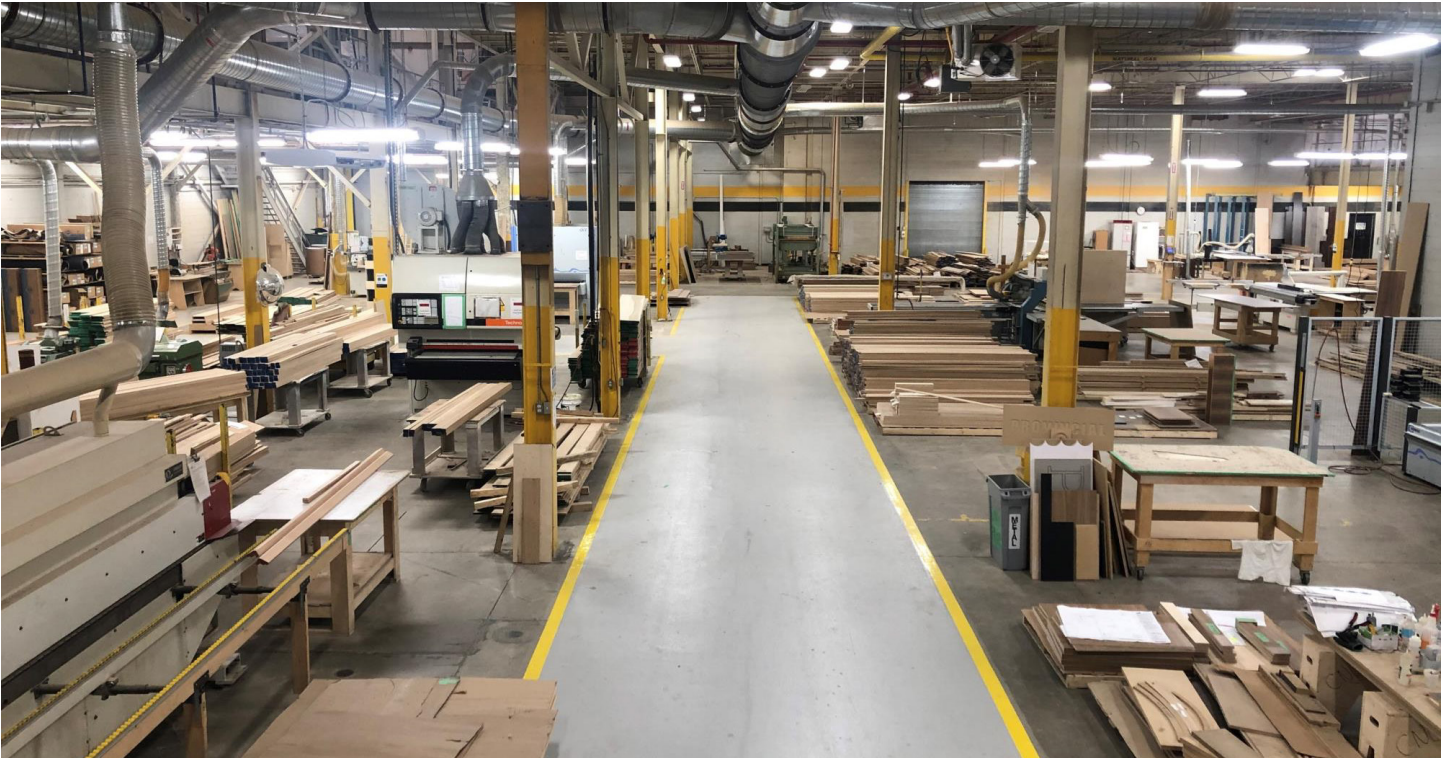


Figure 3. Image of the wood cutting area of Provincial Store Fixtures Ltd.

The facility has several large CNC mills, including one with 5 axes for more complex geometry. They also have some rarely used table saws and other manually controlled machines. The main CNC mills cut out the pieces and automatically print labels on each one, indicating where the piece needs to go and what sort of finish needs to be applied. Since the cutting and edging of panels are all automated, there were only a couple of employees transporting the cut pieces to the next area.



Figure 4. Image of ventilated spray room and drying room of Provincial Store Fixtures Ltd.

The finishes at this facility are all still done by hand. Provincial has decided not to automate this stage to be able to offer the full range of finishes to clients. Other firms in Ontario that are geared more towards mass-produced, less customizable millwork (such as what you might find in a condo tower) offer finishes at a much cheaper price but with fewer options.

The finishing is done in a room with a very advanced ventilation system. The wall along the circulation path is porous from floor to ceiling, through which there is a steady flow of air being blown. The wall opposite is also porous but air is being sucked in. The result is a constant, laminar flow of air through the entire space. This facility also has a massive insulated room that acts as a walk-in oven for drying finishes. Because the oven is so large, it's possible to either dry the pieces before assembly or dry the furniture after being fully assembled, which can lead to a more seamless result.

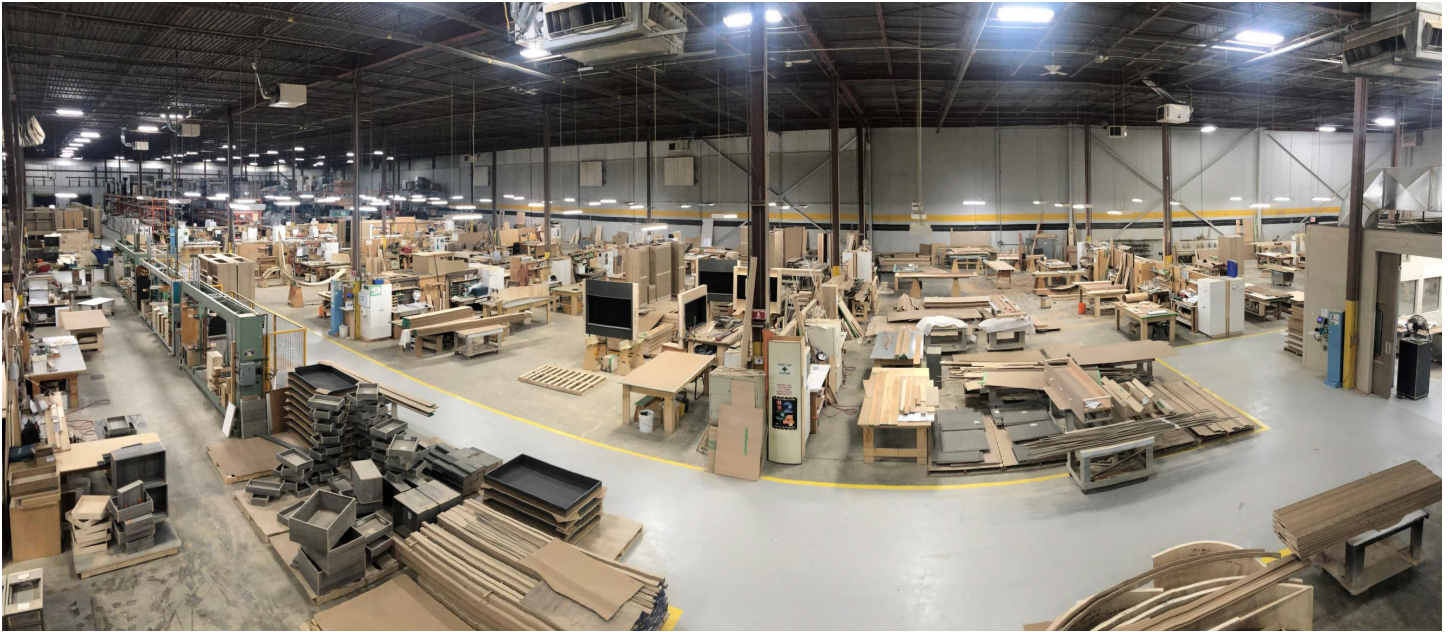


Figure 5. Image of assembly area of Provincial Store Fixtures Ltd.

By far the largest area in the facility was the assembly area. This was also where the vast majority of manual labor took place. Approximately 200 workers were doing the assembly. All of the assembly is done manually, as every project they do is unique, automating a machine to do assembly every time would be impractical. As much of the assembly as possible is done in the factory rather than on-site. The working conditions are more predictable here; they have access to more tools, and since they do projects all over North America it would be too expensive to send so many workers to the site. There are still times that they will keep the millwork separated and assemble it on-site, if for example, the assembled piece is too large to fit on a truck, or if it needs to fit through a narrow corridor or elevator.

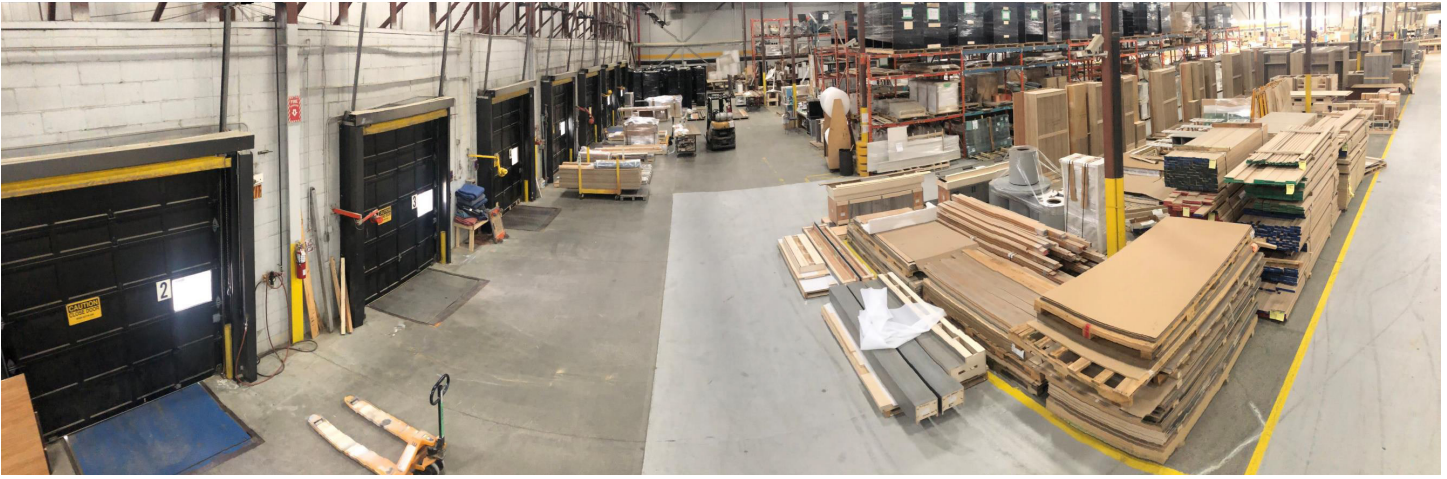


Figure 6. Image of the packing and shipping area of Provincial Store Fixtures Ltd.

Once the final pieces are assembled, they are held in a storage area, and before shipping, a visual inspection is done for quality assurance.

2.2 Allwood Carpentry Manufacturing

The next manufacturer I visited was Allwood Carpentry Manufacturing. This facility was a bit older than the one at Provincial, but for the most part, Allwood had the same pipeline, even using the same software solution. They also receive the models in the same state from the architects, model all of the required components digitally, and then send them to the CNC mills. The labor distribution was also very similar, with the vast majority of employees working on assembling the furniture from the CNC-milled components. Here I also learned that this pipeline is the same at every single custom millwork manufacturer of this scale (as shown in figure 6).

Having multiple millworkers all using more or less the same conventional pipeline is beneficial to this thesis. By making a new alternative pipeline that follows the conventional one as closely as possible (figure 7), it could be adopted by a large number of existing facilities.

One unique part of Allwood is that in addition to working with wood, they also do all of their hard-surface components in-house. They use corian, a solid surface material that can look exactly like polished stone. Conveniently they can also use the same woodworking tools on it. Since the dust created when sanding corian should not be inhaled, they do this in a separate area beside the finishing room, both of which are well-ventilated.

They used to get the hard surface done elsewhere but there could be discrepancies between what they made and what others made. I also learned that even though so many of the millwork processes are digital and automated, there is still a great deal of variance between different manufacturers. Not only are parts of the processes still done by hand, like sanding and finishing, but a lot of the natural materials can vary greatly in appearance. There is also a range of speed and craftsmanship between the different manufacturers, which also has an impact on the prices they charge.

During the tour I also learned about how they are different from factories geared towards mass production. Mass production facilities will only make casework in several predefined sizes and (unsurprisingly) in very large quantity orders. Since they make the same shapes repeatedly, they can be highly optimized and fully automated - resulting in huge cost savings. Anything that can be made in these mass production facilities can also be done at places like Allwood, but they cannot compete price-wise. They did however mention that because the mass production facilities only have one goal - to lower production cost as much as possible, they use materials that

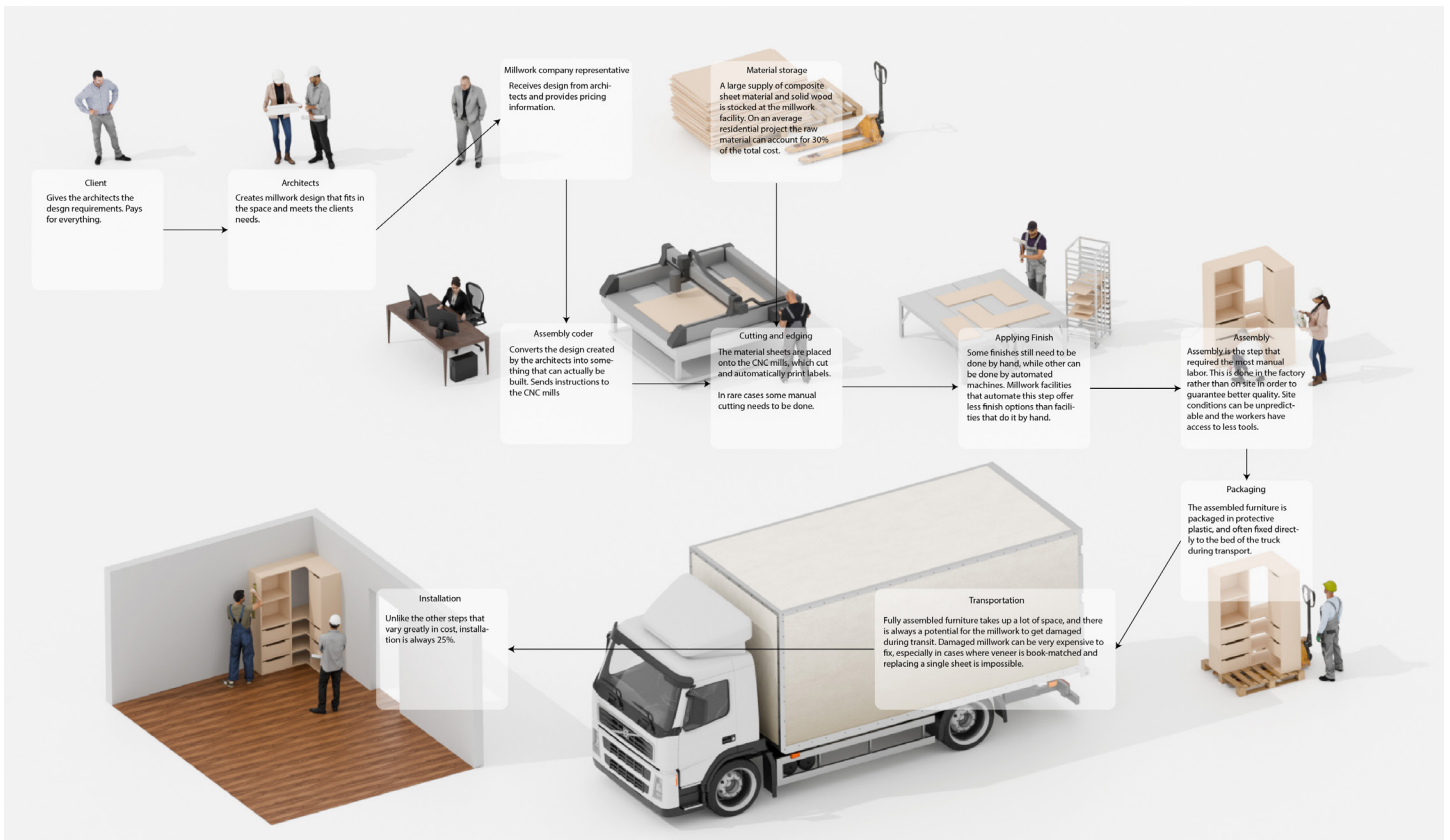


Figure 7. The conventional process of acquiring custom millwork

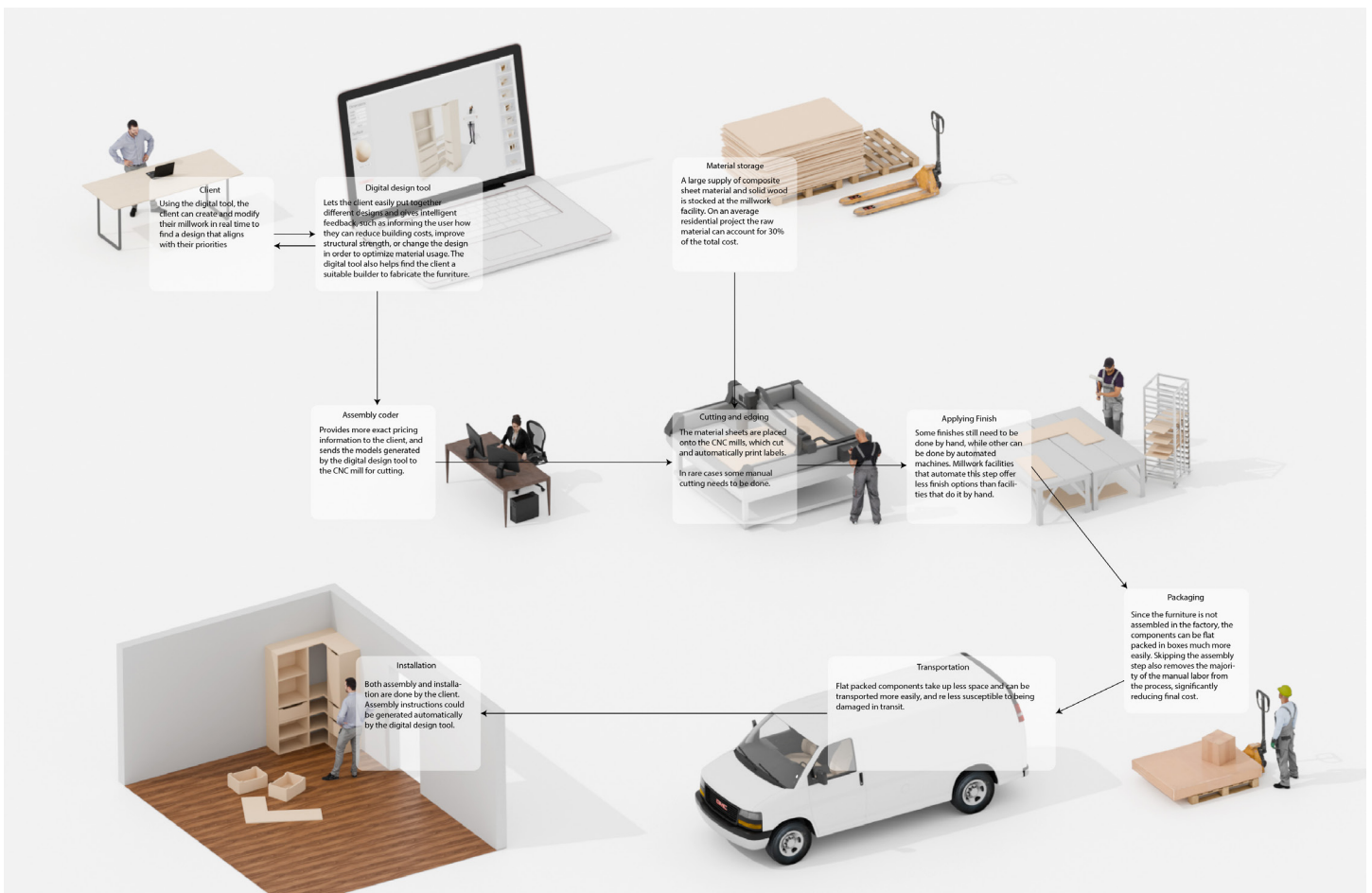


Figure 8. An alternative process of acquiring semi-custom millwork proposed by this thesis

are of much poorer quality. This results in furniture that looks just as good at first but falls apart much faster. Places like Allwood rely on their reputation for getting work, so they will spend the extra money to use more durable materials (like actual wood instead of particle board).

The range of clients that Allwood works with is similar to Provincial. They only work with architects, not directly with un-trained clients as they need a digital model or proper drawings to start fabricating. They also don't often mass-produce millwork for condos, as they can't compete with the specialized factories in terms of cost, which is the deciding factor for most developers. What's left is the work that is too small for mass production, or too unique/complex.

To summarize the values of custom millwork manufacturing, in comparison to mass production manufacturing, dimensional customizability exists for both but is much greater with custom. Financial costs are lower for mass-produced, but only when a large quantity is produced, and only when looking at initial cost, not lifetime cost. The things that drive up the cost of custom manufacturing are the setup time/work for each project, the manual labor involved in each project (primarily assembly and installation), and the unexpected hurdles that come with doing something for the first time. The environmental cost of furniture manufacturing is hard to generalize, but the resulting consumerism and frequent replacement that comes with anything mass-produced is not good for the environment. While not common, custom millwork manufacturers can make changes to furniture years after it is made, allowing it to adapt to changes in the space, while mass-produced furniture is more often made of materials that will fall apart if changes are made. Finally, while durability is not necessarily tied to whether the furniture is custom-made or mass-produced, the cost-focused nature of mass production generally leads to lower long-term durability.

2.3 Digital Design Tools

It's important to look at other existing software with similar functions before making new software. Not only will this help the new software follow existing conventions (which is very important for usability), but it will also provide possible solutions for each of the design challenges faced. By scoring the software in each value outlined in section 1, it should be possible to see correlations between the methods the software uses and the scores they receive.

While using the different software one key observation was that the smaller the scope of the software, the easier it was to learn and use. For example, comparing Blender and IKEA kitchen planner; You could use both to make a kitchen layout, but you could also use Blender to simulate a waterfall or make stop-motion animation. Both Blender and IKEA kitchen planner have very well-designed interfaces, but simply due to the differences in scope, the IKEA kitchen planner is easier to use. Because of this, it made sense to reduce the scope of the design software to only look at shelving, rather than all millwork in general. Reducing the scope would not only make the software easier to use but would also mean more time to refine the functionality being included.

As for interface conventions, the most intuitive software limited the number of buttons/options visible at a given time to only the relevant ones. It can seem counterintuitive that hiding information makes something easier to use, but as long as you show it when it is needed, the resulting experience requires much less mental effort. The same goes for things like inputting email addresses or making accounts. Just because the software has one feature that requires an account, does not mean the entire software should need an account. Asking for an address can wait for when the time comes.

Visual feedback quality and responsiveness were closely related, but visual feedback quality was not as important as anticipated. Some tools tried way too hard to make the visual representation look realistic, with material reflections and advanced lighting. The small graphical improvements were not worth the resulting laggy interface. As long as the tool had a basic 3d view, as well as a plan and elevation view that was enough.

Perhaps the most important distinction found between software usable in a larger context and software acting as a digital display case was the ability to export information to other software. An exporting feature is extremely important when designing software with a very narrow scope so that other programs can be used to expand that scope. Unfortunately, the software with less functionality lacked an export option, even when they were the ones who would benefit from it the most.

(To see the scoring breakdown and comments on each software, see Appendix C)

Figure 9. Example furniture configuration



Part 3 Design a New Solution

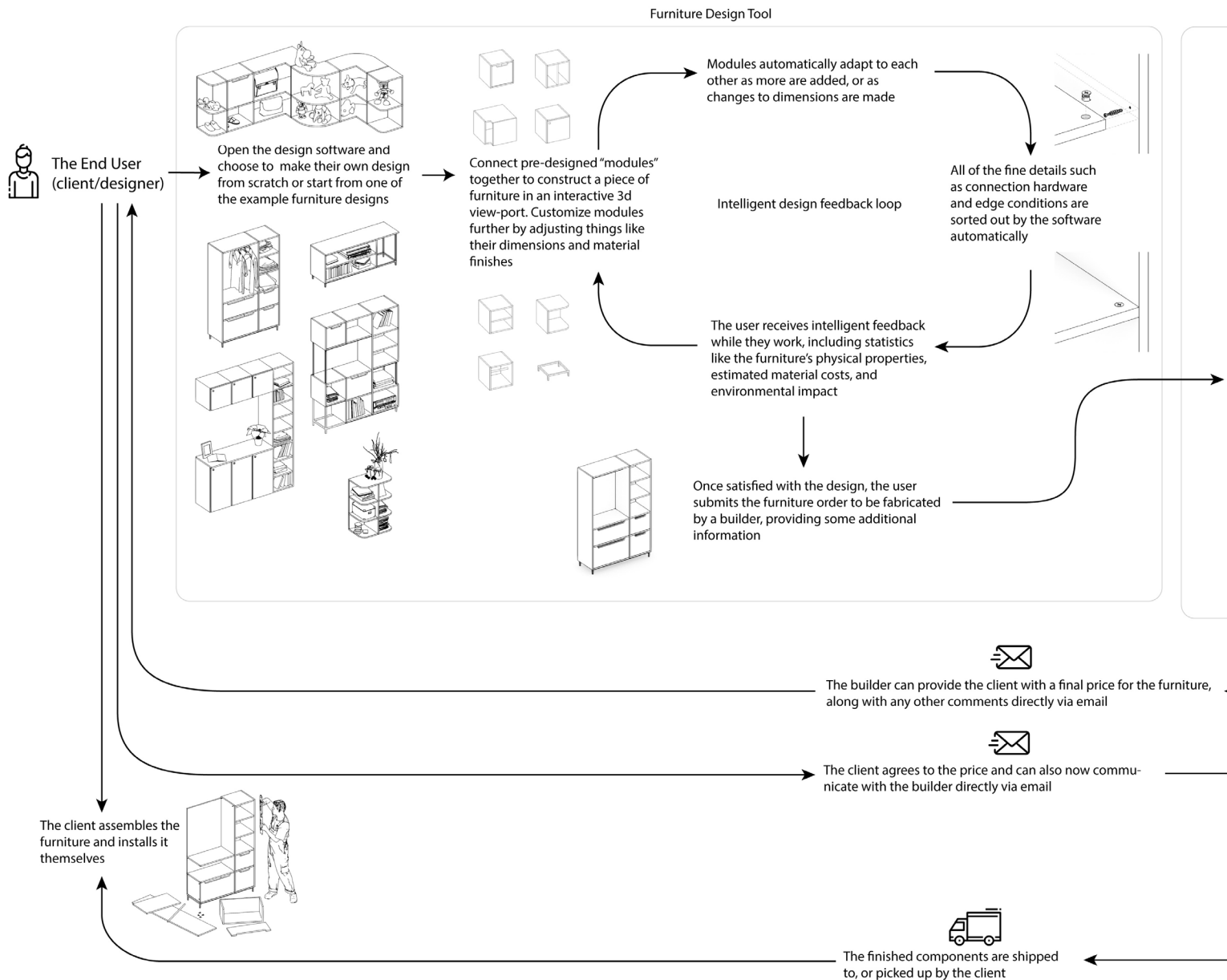
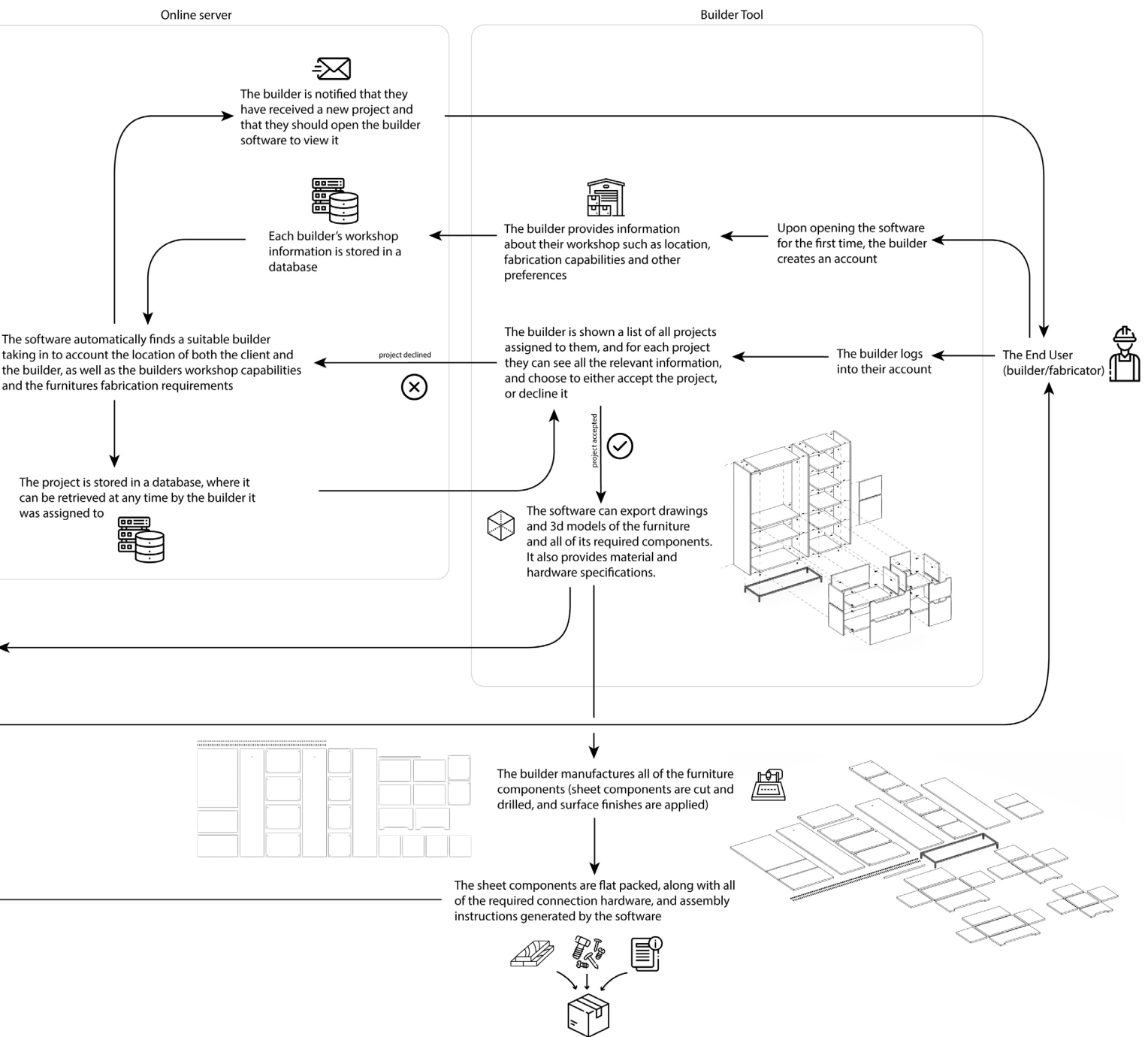


Figure 10. Diagram of the proposed system

3.0 Section Overview

This section takes what was learned from looking at the current millwork design and manufacturing pipelines and proposes a new pipeline, with the goals of being more accessible to the general public and improving users' agency regarding their furniture. This system relies heavily on a series of original computer programs designed to take into account what was learned from researching existing software in part 2. This section starts with the design of the overall system, then the conceptual design of the software within the system, and finally the production of the actual software itself.



3.1 Overall System Plan

This diagram represents how the system works as a whole. On the left-hand side, we have the end user/client. This is the person who wants to buy some custom furniture but doesn't have the necessary design skills to make it themselves or lacks the knowledge of who can build it for them. On the right-hand side of the diagram, we have the millworkers. These people have the carpentry tools and expertise for building custom furniture. The system needs to help the client create a furniture design, and connect them with an appropriate millwork company to manufacture it.

First, a piece of software is distributed to the millworkers. Upon opening the software for the first time, the millworkers create an account and provide a list of information about their workshop. This includes things like contact information, address, which materials they work with, what finishes they offer, the maximum and minimum dimensions of components they can work with, delivery range, and other preferences. This information is then sent to a server, which stores each builder's info in a database, for later use.

Once the millworkers have gotten set up with their software, different design software is then distributed to the public for people who are looking to buy furniture (these people will be referred to as clients). Upon opening the design software, clients are given the option to start with one of the example furniture projects or make their design from scratch. To modify/configure the furniture, the client connects pre-made modules (like Lego blocks) in a drag-and-drop interface.

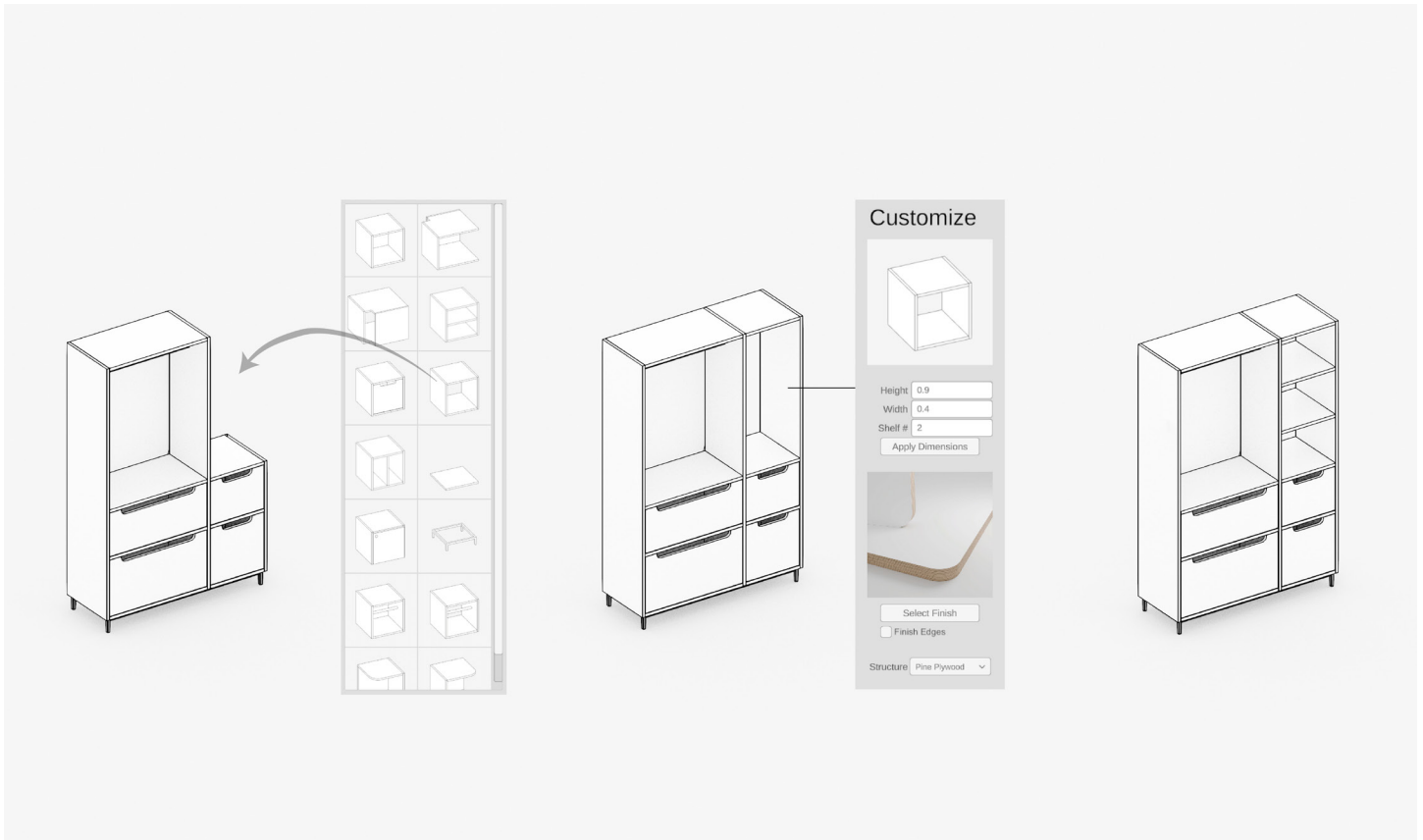


Figure 11. Diagram showing the placement and modification of a module

Once placed, modules can then be selected and further customized, by changing things like dimensions, surface finish, handle types, etc. As the user adds and modifies modules, the other modules automatically adapt and resize to fit each other. All of the fine details such as connection hardware and edge conditions are sorted out by the software automatically. While the user is working, they receive intelligent feedback from the software. In addition to a 3d view of the end product, the user is given a list of the furniture's physical properties, estimated material costs, environmental impact, and suggestions on how they can change the design to make it stronger or easier to manufacture.

Once the user is satisfied with their design, they can submit the furniture order to the server so that a builder can receive it. At this point, the user also provides additional information such as their address, contact information, additional comments, etc. Behind the scenes, the server looks through the database of millworkers to find the best match for this particular project. At the same time, it also stores the furniture project in another database for later use. When the server finds a suitable builder, it sends them an email notification telling them that they have

received a new project and to open the builder software.

When the builder opens the builder software, they can see all of the details about the new project assigned to them, and they can choose to either accept it or decline it. Should they decline the project, the server will find the next best builder and reassign the project to them. If they accept the project, they can create a price based on the specifications and 3d models provided by the software. They are also given the contact information of the client so that they can now talk to them directly and provide the final cost. When the client agrees on a price, the builder can then manufacture all of the components, and flat pack them along with the required connection hardware and a printout of the assembly instructions (generated by the software). The components are then shipped to the client who assembles the furniture themselves in a similar style to IKEA.

For the sake of simplicity, this overall plan ignores some of the more niche use cases of the system. For example, in cases where the client wants to modify a piece of furniture that has already been built, the software can take this into account and help the user design something that uses as many of the original components as possible. In cases where the client does not want to hire a millworker and wants to try building it themselves, they can also export all of the 3d models, drawings, and material specifications they would need.

3.2 Design Software

The design software is the publicly available part of the system, and as such is designed with accessibility in mind, assuming that the user has no previous experience with 3D design software. The ideal implementation would have this software embedded in a webpage for maximum accessibility, but for the sake of demonstration and to reduce the number of technical hurdles, the initial version is developed as a standalone application. For the same reason, some secondary features were removed. Unless otherwise indicated, all features mentioned in the following sections are still present and working in the proof of concept software. In the software demo itself, any unimplemented feature is highlighted in blue.

3.2.1 Main Menu

Upon opening the software, the user is greeted by a main menu with two options: create a new project, or open an existing project. Assuming this is their first time with the software, they will click “Create a new project”. The user is then given the option to either start with an example project or to start their design from scratch. Should they choose to start from an example, they will be given a list of example projects, each with a rendered preview showing what the final result looks like. If they instead choose to start from scratch, they are then asked if they want to make a wall-mounted project or a free-standing one before continuing to the design stage. If the user chooses to open an existing project, they are prompted to open the file where they saved it, before continuing to the design stage.

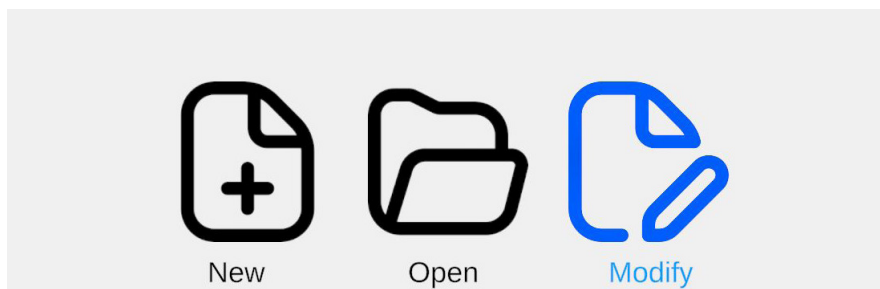


Figure 12. Screenshot of the main menu options

Ideally, a third option to modify an existing design would also be present in the main menu (figure 12), which when clicked would prompt the user to locate the file for the existing project before continuing to the design stage. This option (further discussed in section 3.2.4) was not fully implemented in the current software demo.

The main menu is designed to be as clear and concise as possible, only showing the relevant options and providing both text as well as a preview image for each option. While the user is in the main menu, the software is also connecting to the server behind the scenes to save time later on.

3.2.2 Design Stage

The design stage is by far the most complex part of the project and is the most unique aspect of it from a technical standpoint (some parts of this project like the automated emailing system or how it stores store information in databases are common practice and have probably been done by others a million times before).



Figure 13. Screenshot of the design stage interface

From the user's perspective, the design stage is very simple. The interface consists of a 3D viewport in the middle, and a list containing a collection of furniture modules on the right. The user places the modules from the collection into the viewport (via a drag-and-drop system). As the user drags new modules into the scene, they snap together forming a complete furniture configuration. To customize the furniture further, the user can click placed modules to select them. When a module is selected it gets highlighted in the 3d viewport, and a new panel appears on the left side of the screen. This selection panel lets the user customize the module by changing its dimensions, material, surface finish, number of shelves, type of handles, etc. While they work, statistics about the furniture are shown at the bottom of the screen, such as weight, cost, volume, etc. In the bottom right corner, there are standard buttons like “save as”, “open”, “settings”, “upload”, etc. The viewport navigation is made as standard as possible, right-click to orbit and scroll-wheel to zoom (right-click becomes pan when in elevation or plan view).

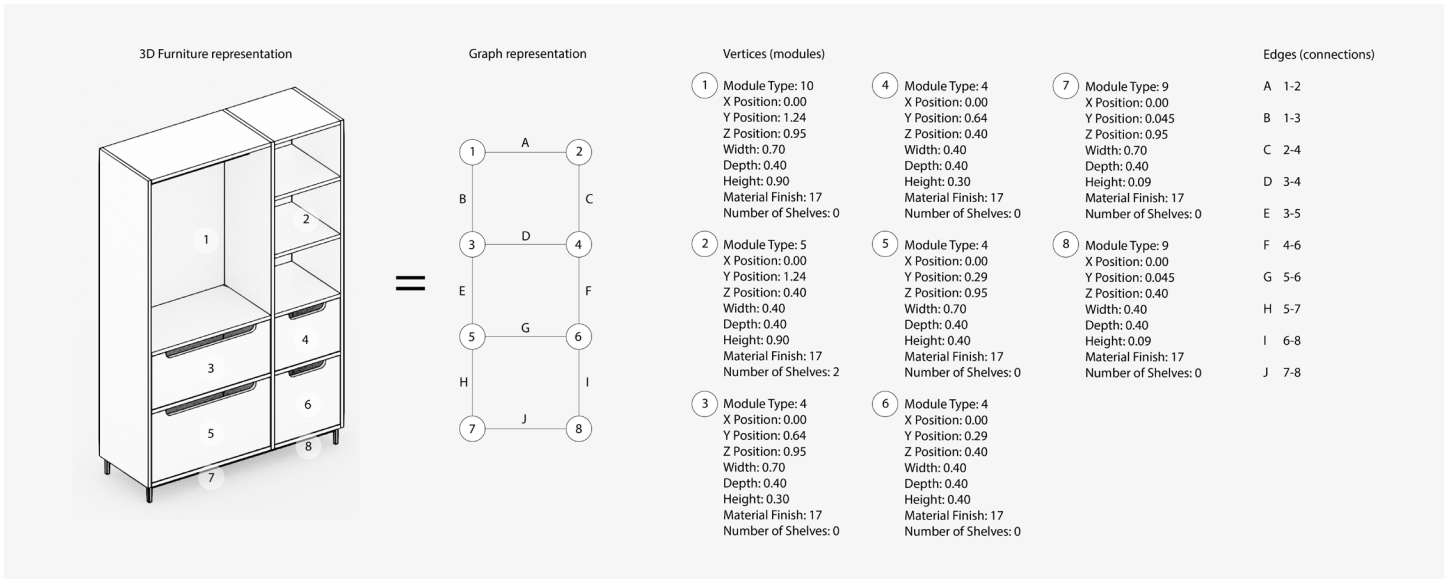


Figure 14. Diagram of an example furniture configuration, in graph representation

What happens behind the scenes is a bit more complicated. To describe how it works, first one must understand how the furniture itself is represented. While the user sees a 3D model of furniture, what the computer sees is a simple graph (figure 14), each vertex in the graph representing a module, and each edge representing a connection between modules. For each vertex (module), the program stores variables that can describe the position of that module, its dimensions, the type of module it is, etc. By using a graph structure, any configuration of modules can be represented, even ones that don't conform to a grid layout. Simplifying the furniture from a complex 3D model to just the relevant variables makes it much easier to work with (for the computer) and makes converting the furniture to and from binary for saving, loading, and sending over the internet a relatively simple process.

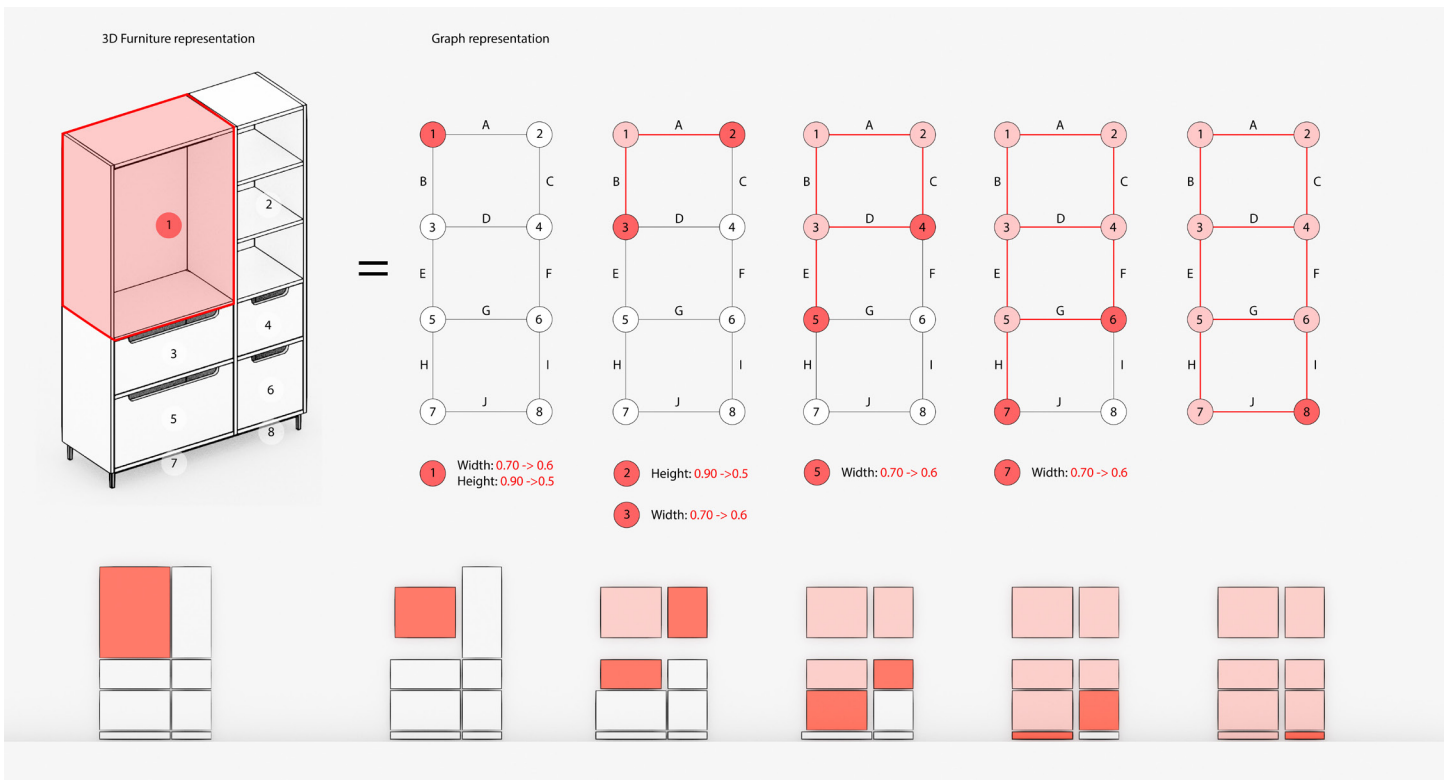


Figure 15. Diagram showing the graph updating as a module has its dimensions changed

The graph structure can also be leveraged when the user changes one module and the program needs to make the other modules adapt to this change. In this diagram (figure 15), the user has changed the dimensions of the top left module (module/vertex 1). They have made the module smaller in both width and height. Simply changing the dimensions of the selected module would make it no longer fit within the rest of the configuration. To solve this, after adjusting the dimensions of module/vertex 1, the program looks at all of the vertexes directly connected to vertex 1 (in this case vertex 2 and vertex 3) and changes their dimensions accordingly. Step by step the program traverses the graph, starting at the point of change, until all vertices have been covered. The elevation view at the bottom of the diagram shows what the furniture would look like after each step. Once all modules have the correct dimensions, the same process can be used to update their positions.

While the graph representation of the furniture is great for the computer, we still need a way to display it as a 3D model for the user to see. To do this, there is a pre-made 3D model of each module. A naive approach of simply placing the correct module 3D models at the correct positions, and then scaling them to be the correct dimensions, would be able to create a 3D model of the entire furniture configuration, but would also run into some problems.

Firstly, different parts of the models cannot be scaled in some or all directions. For example, sheet material must always remain the same thickness, and connection hardware must always stay the same size. Secondly, the resulting model would have seams in between each module and would have duplicate walls where modules meet.

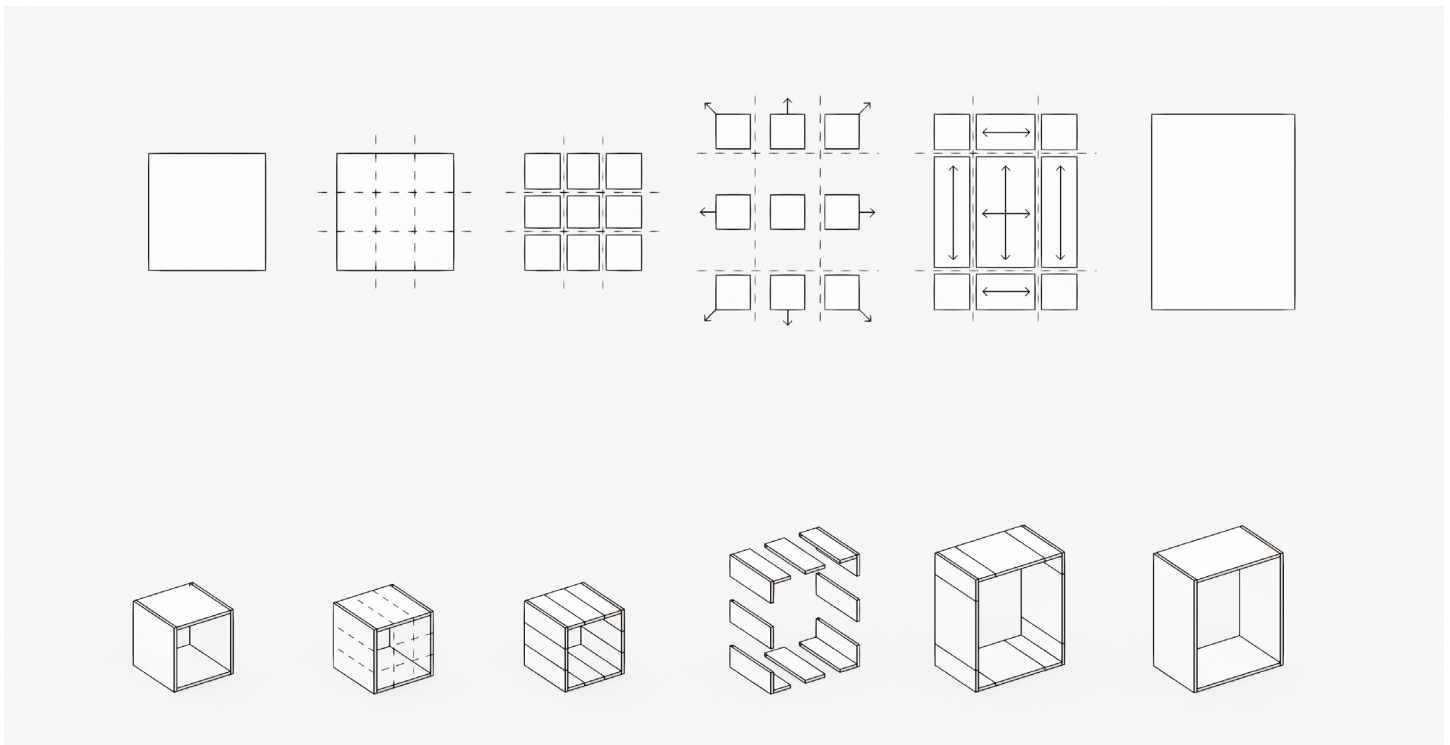


Figure 16. Diagram showing the non uniform scaling process of a simple shelf

To solve the problem of scaling limits, a special method of resizing the modules needs to be used, and some extra care needs to go into how the modules are designed. This diagram shows how a standard shelf module can be scaled without altering sheet thickness, and without scaling connection hardware. First, the model is separated into 3^x components, where x is the number of dimensions the model can be scaled in (in this case only 2 dimensions so 9 components). Next, the side and corner components are repositioned to fit the desired dimensions. The center component is scaled in both directions, the top, bottom, left, and right components are each scaled in one direction, and the corner components are not scaled at all. Finally, the components are joined back together into a new model with the correct dimensions. When modeling modules, it is important to keep

in mind which parts will be scaled in which directions. For example, connection hardware that cannot be scaled must always be positioned in the corners of modules.

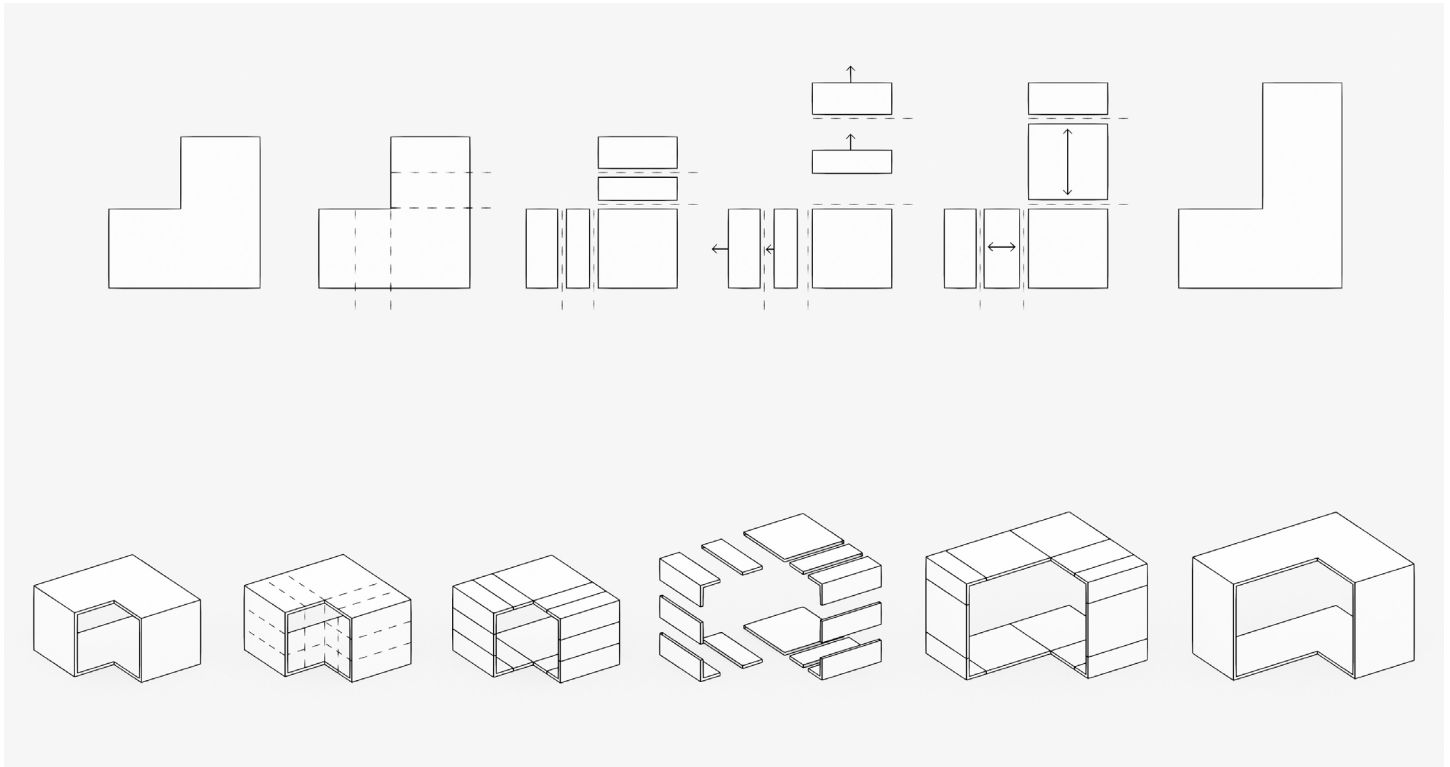


Figure 17. Diagram showing the non uniform scaling process of a corner shelf

For unusual shapes like corner pieces, a similar method is used but with a different configuration and number of components. This example corner piece is separated into 15 components. For the sake of development time, the number of dimensions was limited to width and height (depth fixed at 400mm), but the same concept would still work with additional dimensions.

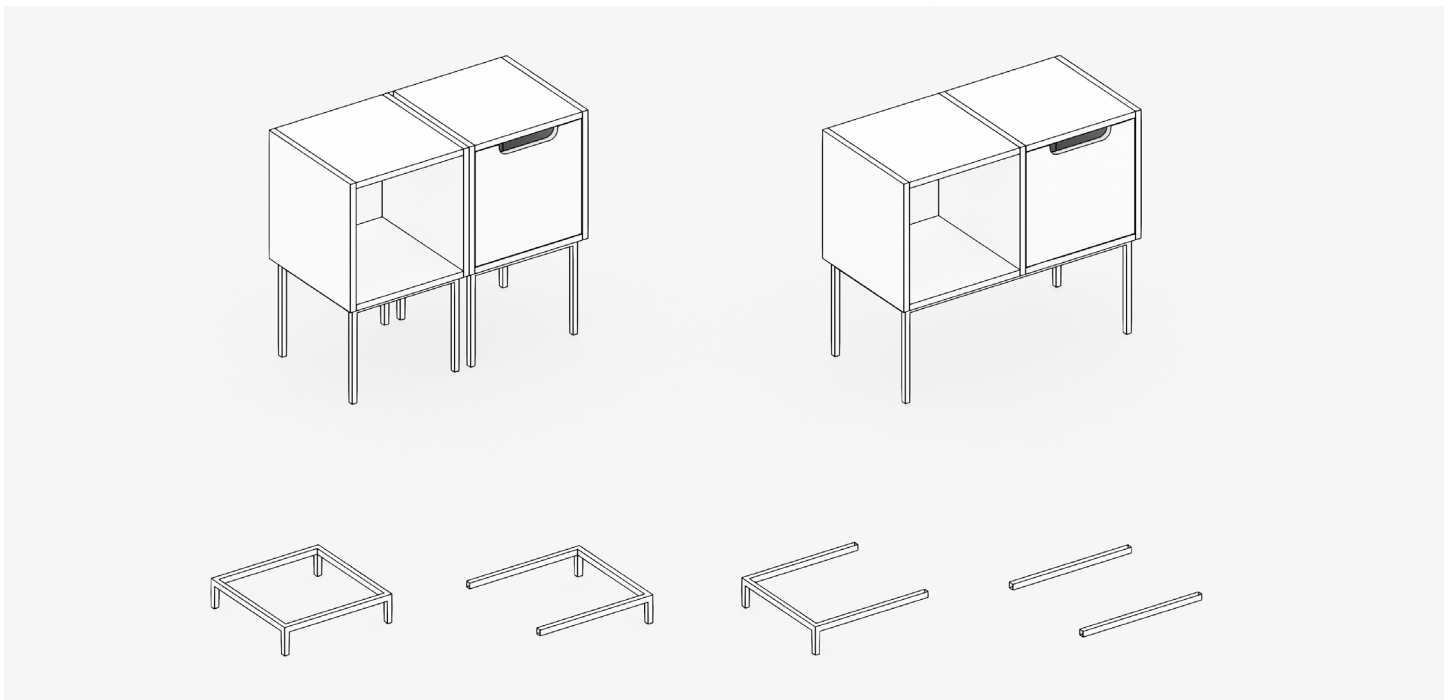


Figure 18. Diagram showing the before (left) and after (right) of joining adjacent modules

The other problem of visible seams and duplicate walls where modules meet is solved in a more brute-force method. For each edge condition, a different version of each module is modeled, the model is then chosen depending on whether or not there are adjacent modules on each side. In addition to removing double walls between modules, this also lets modules like the metal legs combine as seen in this diagram.

In addition to the 3D preview of the furniture, the design stage also gives the user information in real time about storage volume, furniture mass, material cost estimate, etc. All of these statistics can be easily generated with the information contained in the graph representation, and unique formulas written for each module type. That said, the actual final cost of the furniture is determined by several external factors - and can only be given by the manufacturers themselves. The material cost shown is also limited to the cost of the material present in the final product, ignoring all of the material that would be wasted in the manufacturing process.

In the original plan, the software also provided statistics and generated advice regarding the structural strength and buildability of the furniture, but not all of these were coded due to time constraints. In its current state, the software includes some dimension limits for structural stability, as well as the option to display the furniture center of mass. To calculate the furniture center of mass, first, the program calculates the center of mass for each individual module using a formula specific to that module type, then performs a weighted average of each module's center of mass with the module's mass as the weight. The center of mass is then displayed in the 3D viewport as a line that shows where the center of mass stands over the ground. To keep the interface as legible as possible, the center of mass (along with several other overlays) is disabled by default but can be turned on in the settings window.

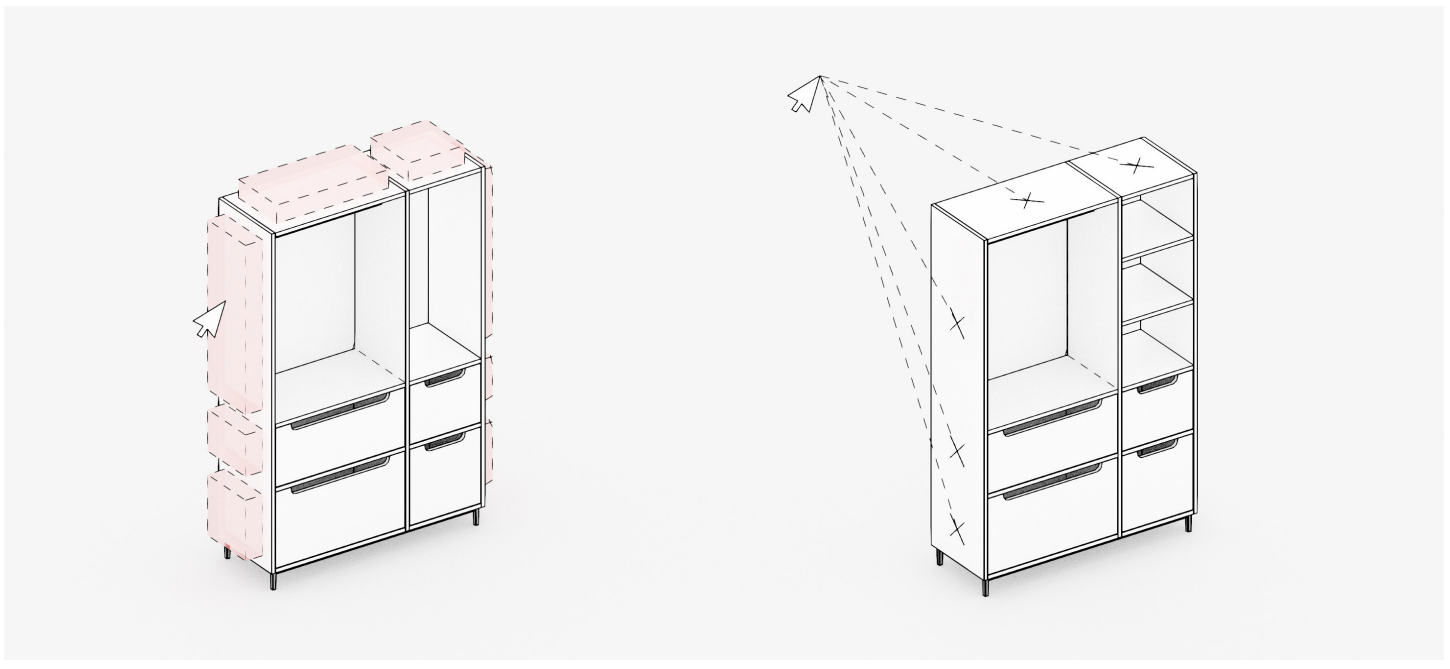


Figure 19 Diagram showing the two snapping methods for block placement, volume method on left, distance method on right

Another aspect of the design stage that the user doesn't normally think about is how the program determines when a module should snap to another as the user is dragging and dropping. This was also one aspect where getting other people besides myself to try it out was critical. My initial implementation of snapping looked great to me, and because I was the person who wrote the code I always knew exactly where to place my mouse cursor. However, it became apparent that other people were often struggling to place modules where they wanted. As a consequence, two systems for module snapping were created, one for precise module placement (which also requires precise mouse placement), and another more forgiving one. The first method involves a series of invisible volumes, one in each possible snapping location. The volumes are automatically sized to cover the

module they are associated with. When the user is dragging a module, the program checks to see if the mouse cursor is on top of one of these invisible volumes, in which case the newly placed module will snap to that position. If the mouse cursor is not on top of a volume, then method 1 fails and the program attempts method 2. Method 2 simply measures the distance from the mouse cursor to every single possible snapping point. If the closest snapping point is within a certain range, the newly placed module will snap to that point. If both methods fail then the module does not snap and will not be placed when the mouse is released.

Figure 20. Example furniture configuration



3.2.3 Uploading

When the user is satisfied with their design and would like to have it manufactured, they click the upload button and are presented with a new screen. The software generates a preview image of the furniture, along with some statistics including a cost estimate. The user is prompted to give additional information such as their address and contact information. This is also where the user can add any additional comments they would like to give directly to the manufacturers. Once done they submit, and the project is uploaded to the server. From here they can close the software; they will receive updates by email going forward.

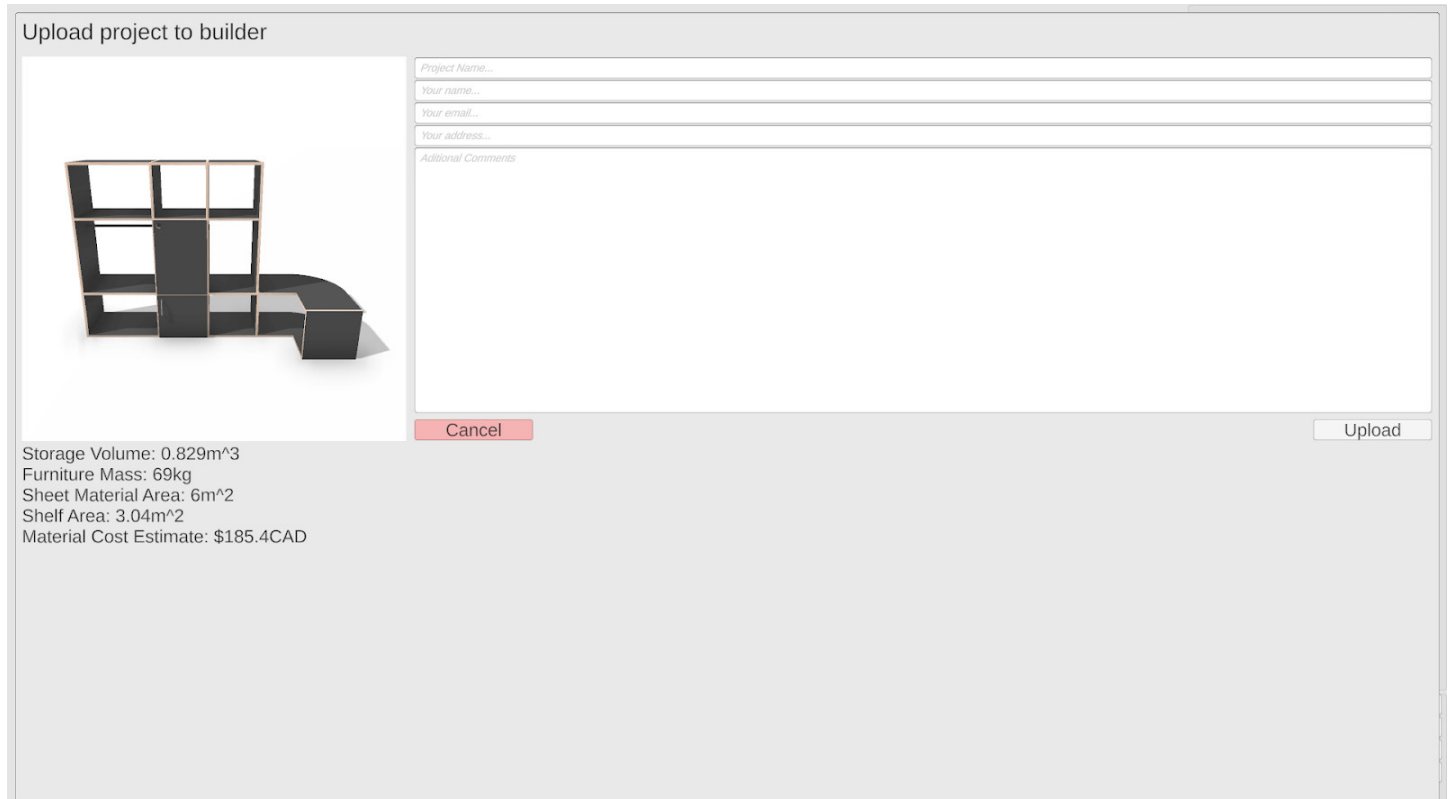


Figure 21. Screenshot of the upload interface

Since one of the software values was responsiveness, steps were taken to make everything run as fast as possible. This includes steps to remove the wait time normally associated with uploading a project to a server. First, connecting to the server is preemptively done in the background when the user is still in the main menu. Secondly, rather than sending the 3D model of the furniture, which is relatively large, the program only sends the tiny graph representation. The 3D model is regenerated from the graph on the other end. With these optimizations, uploading a project only takes a couple of milliseconds, regardless of complexity.

3.2.4 Modifying Existing Furniture

As mentioned at the end of section 3.1, along with its primary function of designing new furniture, an additional functionality (not present in the current proof of concept version of the software) could allow users to modify existing designs that have already been built (using the same system). For this to work, the user would first need to open the file for the existing furniture, and then start making a new, second configuration. While they work, the software could look at all of the components present in the existing design, and see how many of them could be reused in the new modified design.

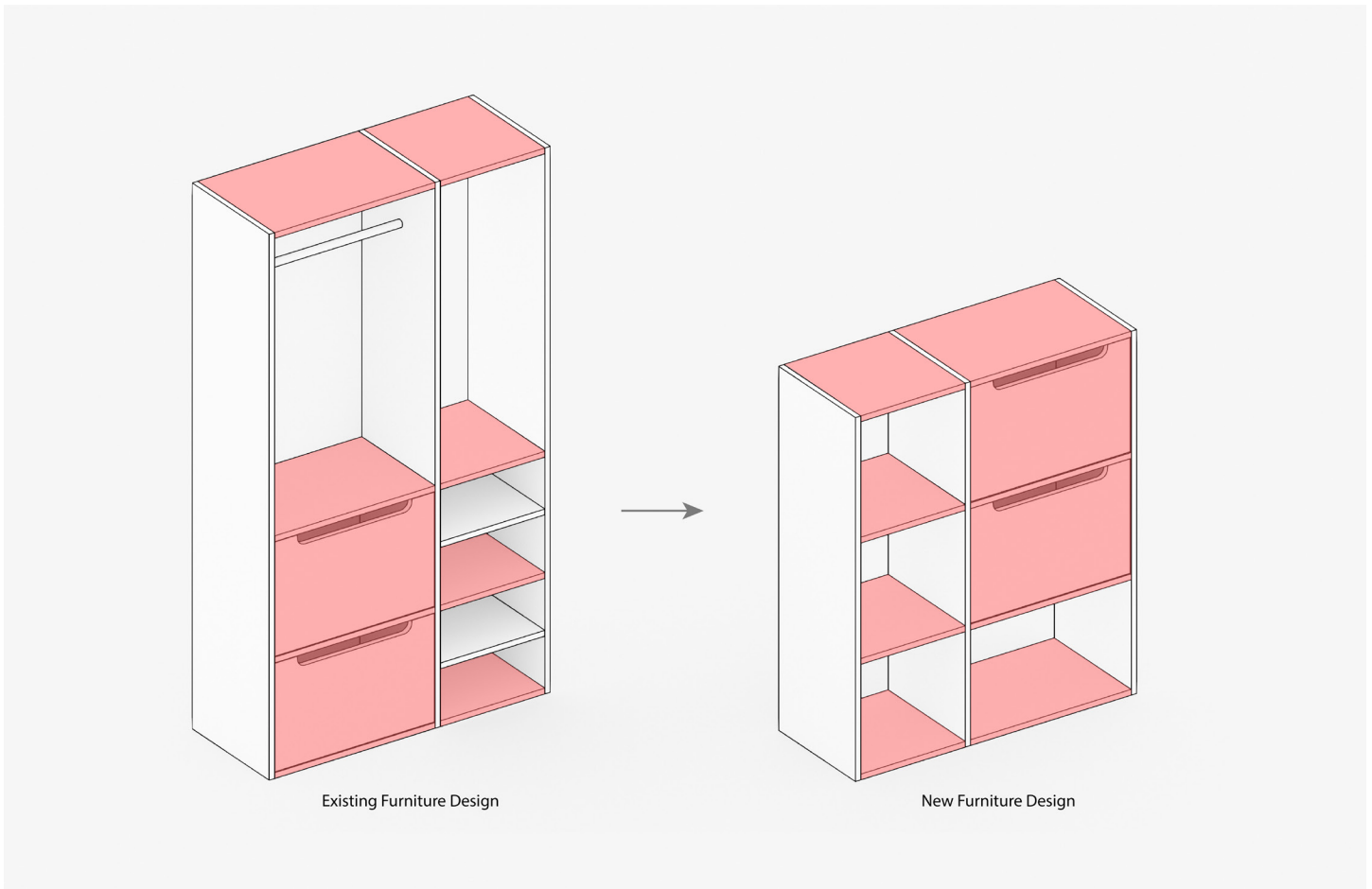


Figure 22. Diagram showing the components that could be reused from one design to another (red)

By comparing all of the components required to build the furniture (in both the existing design and the new one), the software could also suggest changes that would result in a greater amount of reuse. For example, if the existing furniture has a component that is slightly smaller but otherwise identical to a component required in the new design, the software could suggest changing the dimensions so that the smaller component would work.

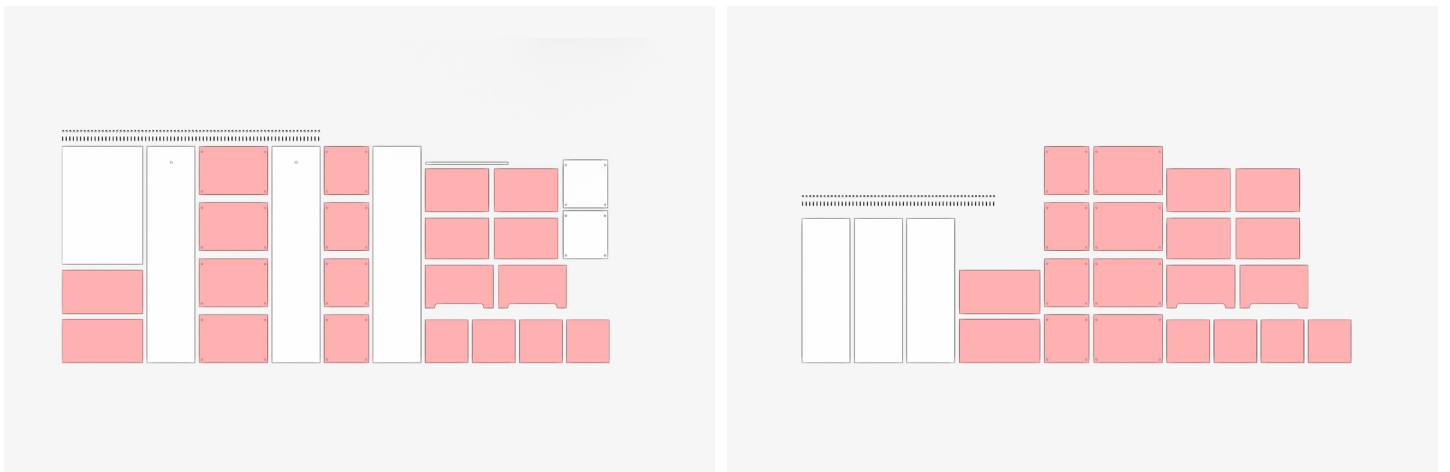


Figure 23. Diagram showing the components that could be reused from one design to another (red), laid out flat

The user would go through the same process of uploading the project to be built by a millworker, but in this case, they would only be requesting the newly needed components.

Another possibility (although impractical) is that new components that fit within the dimensions of existing components could be cut from those existing components. This would require the end user to somehow send the pieces back to the millworker to be cut from, which may be more trouble than it's worth.

3.3 Builder Software

This software is only distributed to furniture builders and manufacturers. Users of this software are referred to as “builders“. The purpose of this software is to create an easy platform for builders to receive projects, view projects, and export 3d models of all of the project's required components to their CNC/CAD software of choice to be cut.

3.3.1 Accounts

Unlike the design software, when opening this software for the first time, the builder is required to create an account. Although requiring accounts negatively impacts the ease of access value, as outlined in section 1, in this case, the system would not work without it. Additionally, since the software is only meant for manufacturers and not the general public, ease of access is less of a concern. The next step would also be considered a barrier of access, having to verify their email address. This was added because during testing I accidentally misspelled my email at one point, causing significant confusion later on. Not only does email verification prevent this from happening, but it also prevents people from creating accounts with other people's emails.

Once the account is created and the email verified, the builder is asked to fill out a list of information regarding their workshop. This includes the facility address, the range they are willing to work within, and all of their fabrication capabilities and preferences.

Fabrication capabilities refer to which sheet materials they can work with, which surface finishes they can provide, the maximum and minimum dimensions they can cut, minimum and maximum job sizes, and whether or not they can work with metal. This information is linked to their account and stored on the server. They can also be changed by the builder at any time.

3.3.2 Viewing Projects

When the builder receives a new project they get an email notification with some basic information and are prompted to open and log in to the software. Here they can see a list of all the projects assigned to them, along with the project and client information. Similar to the design tool, they can look at the project in 3d and see all of its statistics. If the builder is willing and able to build the project, they can accept it, and continue communication with the client through the email address provided. Should they decline, the server will unassign the project from them and send it to the next best option.

Viewing the project in 3D is made possible by reusing the system made for the design tool while taking away the ability to make modifications. Perhaps another version could allow the builder to make suggested modifications and send it back to the client.

3.3.3 Exporting Projects

While the option to export the furniture model and its associated information in a format legible to other software is available to both the client and builder, it is far more useful for the builder. During my field visits at millwork facilities in Ontario, I found that they already had extremely specialized software that worked directly with their machinery. Attempting to make my software capable of generating g-code and talking directly to the CNC mills would not only be a massive amount of additional work but would also be pointless - as all of the millworkers I talked to assured me they would never take on the liability of running g-code made by a third party. Instead, the builder software exports the 3D model, and 3D models of each component in a universal file format that can be read by most 3D software, including the ones already used by millworkers.

Exporting a 3D model of the furniture in its built state is pretty simple since the preview model we generated before can just be exported as is. Exporting all of the individual components (the pieces that need to be cut) requires some new steps.

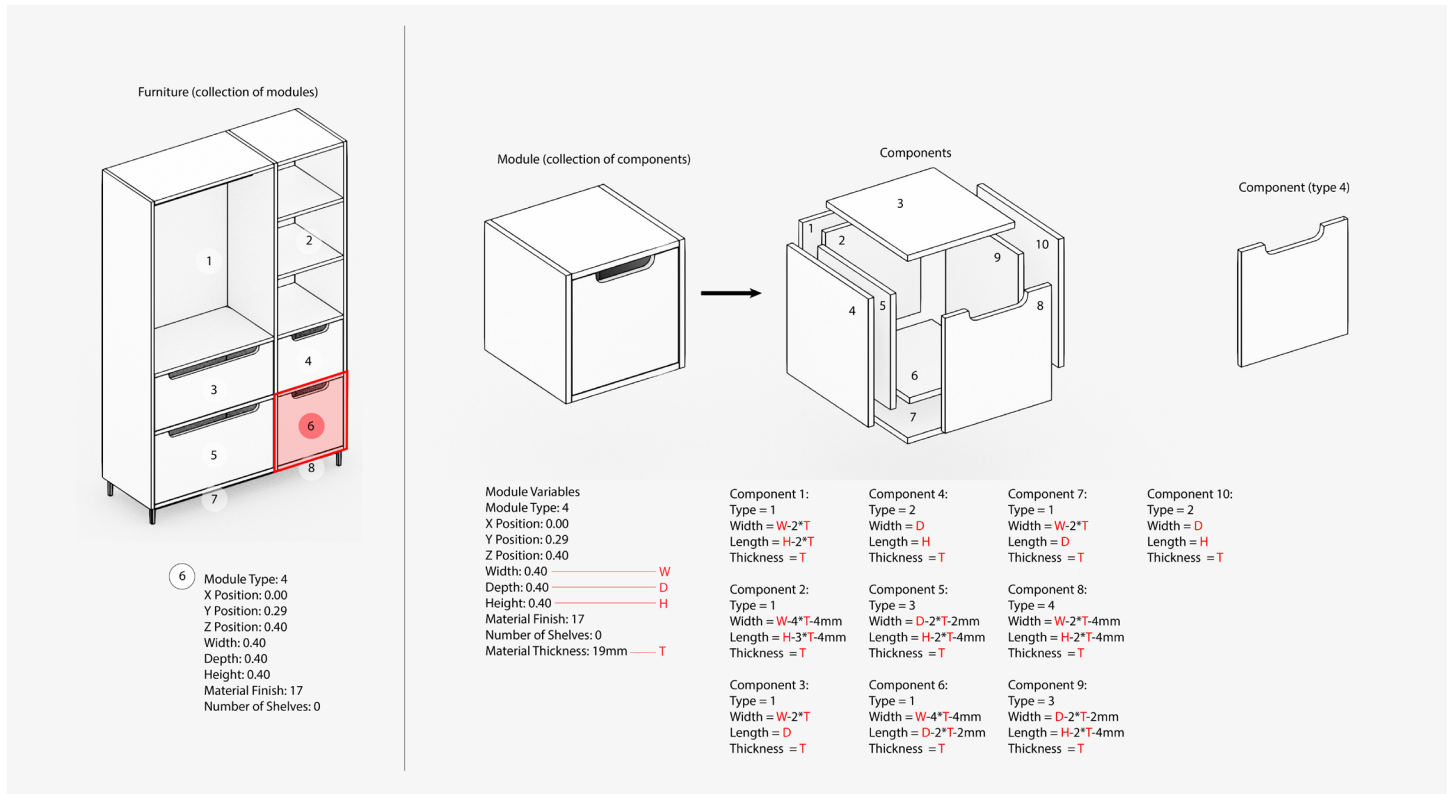


Figure 24. Diagram showing the process of breaking down a module into its individual components

Just like how the furniture can be represented as a collection of “modules”, each module can also be represented as a collection of “components”. The number of components in a module depends on the type of module, as do the formulas that determine the dimensions and types of each component. In this diagram, we can see the “drawer” module is made up of 10 sheet cut components. Each one of these components is described by a formula that takes the dimensions of the module as input variables. Things like the position of screw holes and handle cutouts are determined by the component type.

To convert an entire furniture design to the components that make it up, we can simply convert all of the modules in the furniture design to their respective components, and add them together.

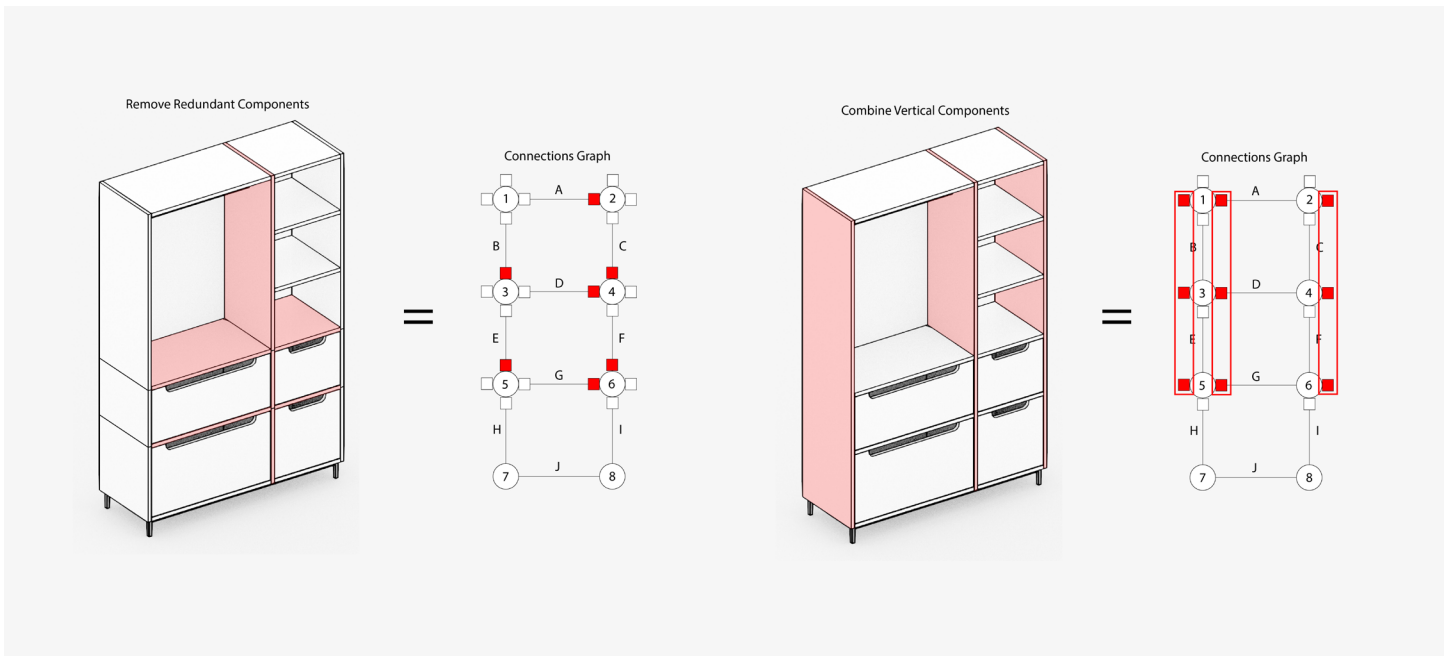


Figure 25. Diagram showing the removal of redundant components, and combination of vertical components

For furniture designs including more than one module, this creates some problems that need to be addressed. First, there will be redundant components everywhere two modules are connected that need to be removed, and secondly, continuous vertical components will need to be combined into a single piece. By examining the graph representation of the furniture, redundant components can easily be found and removed. The left of this diagram shows how one component needs to be removed for each connection (from the module below or to the left). Next, vertical components can be combined by joining them with similar vertical components on the module connected above. The generation of the individual component models is done in the same way as the individual module models, by scaling premade 3d models non-uniformly things that need to remain fixed in size are not changed.

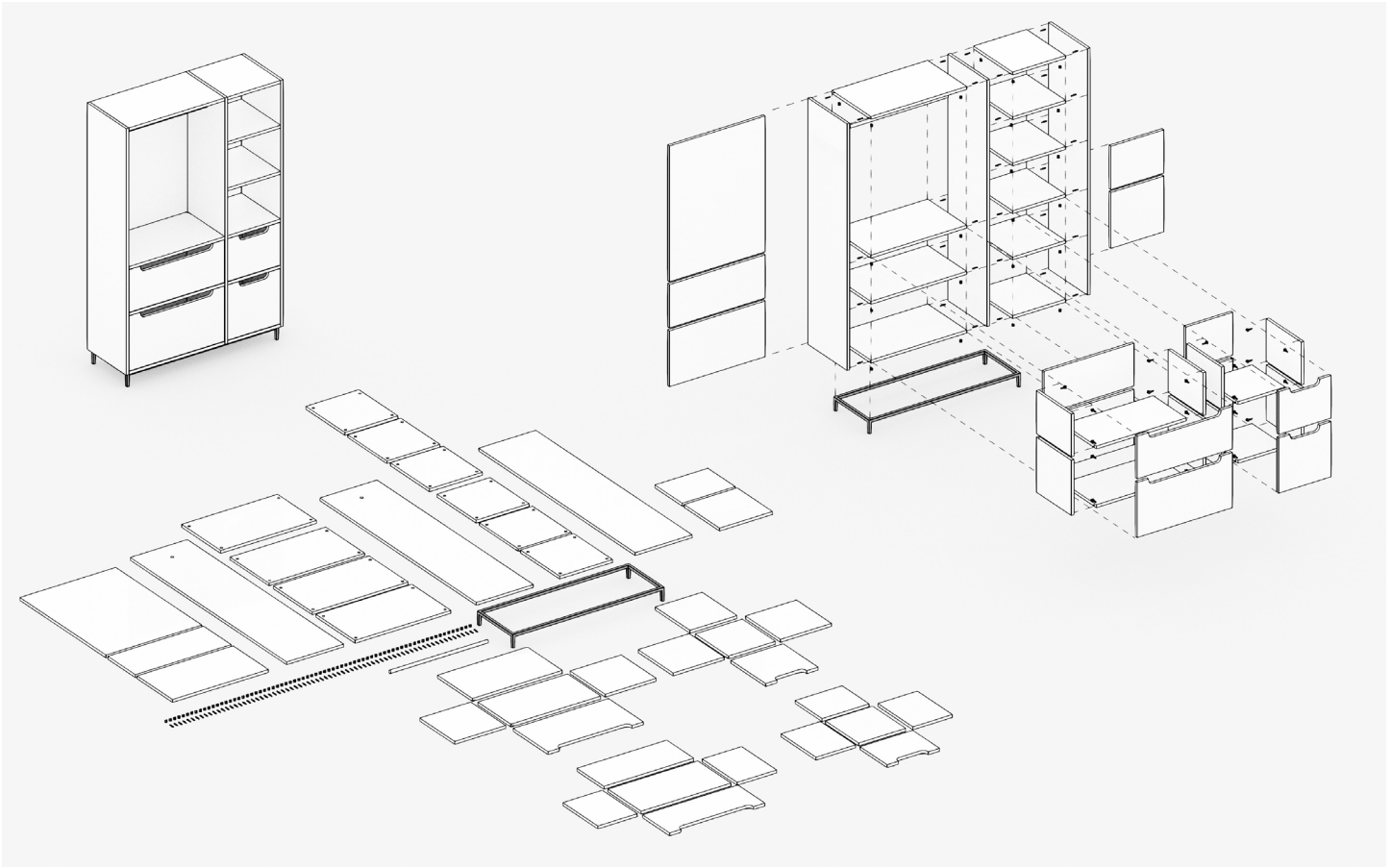


Figure 26. Example furniture, exported as an assembled model, exploded model, and individual components

In addition to a 3D model of the furniture and its components, the original plan was that the software would also export a set of automatically generated assembly instructions. While possible, it would be a thesis of its own and was not completed for this project due to time and skill limitations.

3.4 Connecting Designers and Builders

3.4.1 Server Functions

To connect the clients with the builders, an additional third program is required. This program is referred to as the server, and unlike the previous two, it is not publicly available and does not have any direct users. The server has no user interface to speak of but it still has some interesting functions that are worth mentioning. The main jobs of the server are:

- To keep a list of all builders and their information.
- To keep a list of all projects submitted by clients.
- To match projects with builders, taking into account the project's fabrication requirements, the builder's fabrication capabilities, the location of the client, the location of the builder, and the project preferences of the builder.
- To notify both builders and clients of project updates via email when needed.
- To handle other online tasks like account creation, email verification, and looking up addresses for distance calculations.
- To act as a middleman for communication between the design software and builder software

To fulfill these jobs, an instance of the server needs to be running at all times. While not currently implemented, another function the server could support would be to house a library of previously built projects for reference.

3.4.2 External Services

When assigning a project to a builder, one of the things that the server takes into account is the distance between the client's address and the builder's workshop address. To calculate a distance, the server needs to know the coordinates of both addresses. Since both the client and builder do not provide their coordinates, but rather their addresses in plain text, the server must first perform an address lookup. To do this Open Street Map's Nominatim service¹ is used.

The actual lists of builders, clients, and projects are not stored locally with the server program but are stored in a Mongo database², which itself is located in some Amazon data warehouse. This was done because, in the original plan, there would have been multiple instances of the server running at once so that an arbitrary number of builders and clients would be able to connect simultaneously. However, due to time (and skill) limitations, a much more simple server structure was developed that can only support a limited number of connections at once.

For sending emails, the server uses Google's Gmail service. The method for connecting to Gmail and sending emails used involves hardcoding my email and password directly into the server's code, which is why, unlike the design software and builder software, the server source code is not visible to the public. This less secure method of sending emails via code is also going to stop being supported by Google on September 30th, 2024³, at which point the server will be unable to send emails unless the code is updated.

3.5 Coding the Software

To produce a working prototype of the software, the Unity game engine and the C# programming language were used. The full project code, as well as downloadable versions of the software, can be found on GitHub⁴. For a full development timeline describing each update, see Appendix B.

1 "Address Lookup - Nominatim Manual." Accessed August 5, 2024. <https://nominatim.org/release-docs/develop/api/Lookup/>.

2 MongoDB. "MongoDB: The Developer Data Platform." Accessed August 5, 2024. <https://www.mongodb.com>.

3 Google Workspace Updates. "Google Less Secure Apps Support." Accessed August 16, 2024. <http://workspaceupdates.googleblog.com/2023/09/winding-down-google-sync-and-less-secure-apps-support.html>.

4 Clusia, Silas. "Silasmoth/Ourkea." C#, August 7, 2024. <https://github.com/Silasmoth/Ourkea>.

Part 4 Conclusion

4.0 Section Overview

This section evaluates the results of implementing a conceptual system into a working software prototype, acknowledging the limitations of the prototype that do not reflect the overall concept. The evaluation focuses on the working prototype, distinguishing between issues arising from the concept and those due to execution.

4.1 Evaluating the Furniture System

To evaluate the new system created in part 3, part 4 will look at each of the attributes and goals outlined in part

1. Ranked by importance, these attributes were:

Attributes of the furniture system:

1. Dimensional customizability (maximal)
2. Financial cost (minimal)
3. Environmental cost (minimal)
4. Flexibility/adaptability (maximal)
5. Construction complexity (minimal)
6. Durability (maximal)

Attributes of the digital configuration tool:

1. Ease of access (maximal)
2. Ease of use/learning (maximal)
3. Depth of user control (maximal)
4. Responsiveness (maximal)
5. Visual feedback quality (maximal)
6. Scope of capabilities (maximal)

4.1.1 Dimensional Customizability

Since the proposed furniture system is one in which each piece is made to order, the only thing limiting the final form is the range of base module designs available and the degree to which the user can alter them before manufacturing. The user can create a wide range of configurations with these modules, and control dimensions down to the millimeter. There are some limits to customization, however, that are not present in conventional custom milwork.

In its current state, the furniture system only contains rectilinear modules, so while the user can change individual dimensions, making anything with angles other than 90 degrees is not possible. The restriction to rectilinear furniture was a decision made for the sake of making a working prototype quickly, and could, in theory, be solved (for example by allowing the user to choose any angle for the corner modules). The other obvious limitation is the relatively small selection of modules that the user can currently choose from (only 18). This could also be solved in theory, as the generalized nature of the system could allow for additional modules to be added over time. Finally, the user cannot customize the depth of the furniture, which is fixed at 400mm. This too was an intentional decision taken to shorten development time and could easily be added in a future version.

To see the benefit of giving the furniture more dimensional customizability, I have taken an existing plan of a condo unit in downtown Toronto, which at the time was being used to house 3 students. By comparing the unit in its existing state (furnished with off-the-shelf products), to a layout created using furniture designed with our system (figure 24), one can measure the changes to walkable floor area (figure 25), storage volume (figure 26), and working surface area.



Figure 27. View of unit layout using conventional mass produced furniture (top), layout using proposed custom furniture (bottom)

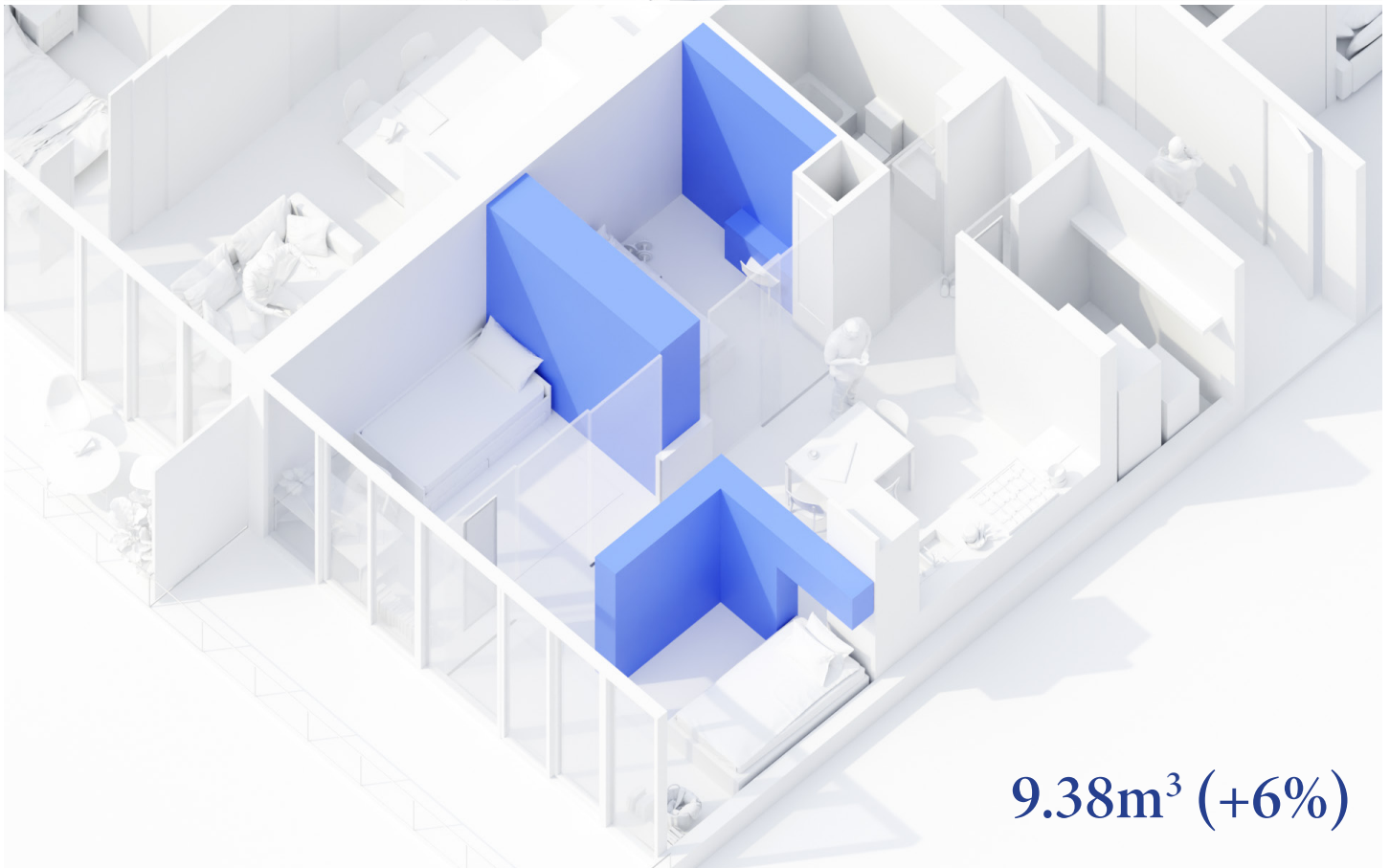
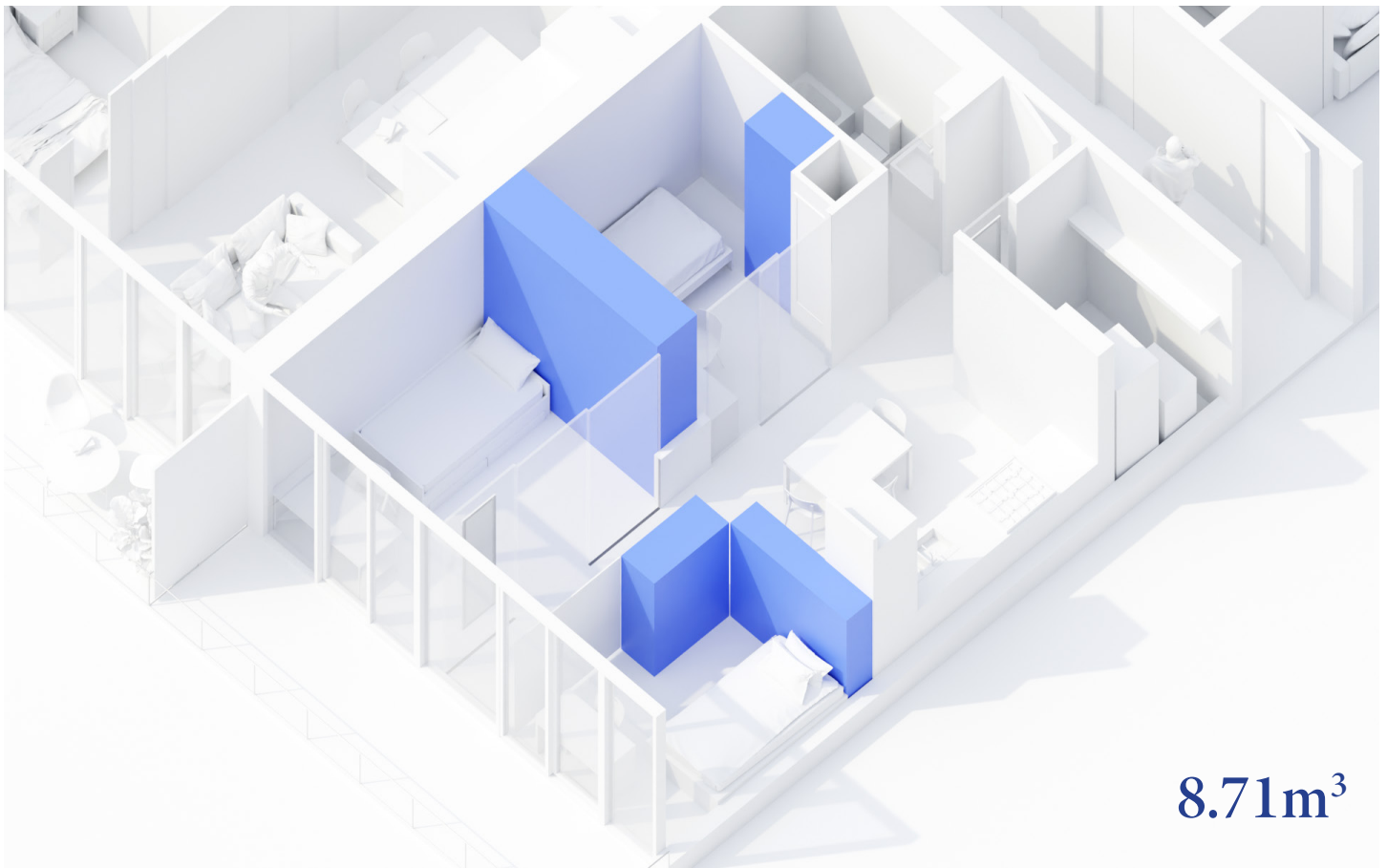


Figure 28. Bedroom storage volume of unit using conventional furniture (top) - 8.71m³, bedroom storage volume of unit using proposed custom furniture (bottom) - 9.38m³

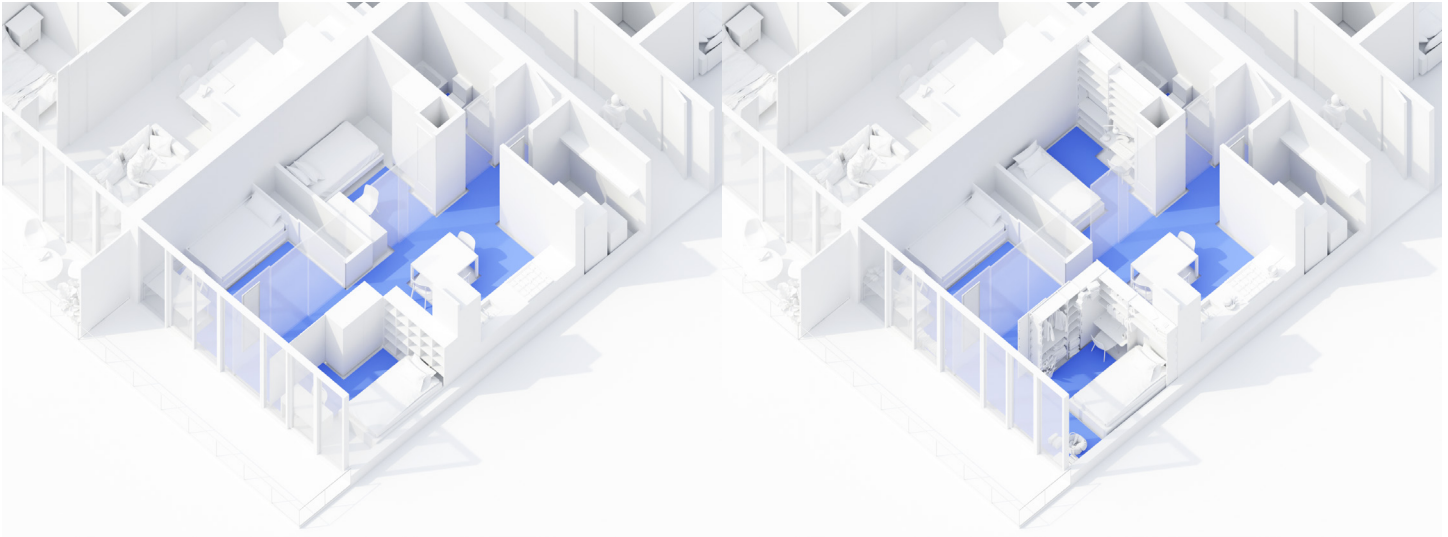


Figure 29. Walkable floor area of unit using conventional furniture (left) - 26.04m², walkable floor area of unit using proposed custom furniture (right) - 27.56m²

In addition to the aesthetic improvements, the custom furniture system offers functional benefits that can be directly measured (as outlined in Appendix A.1.1). The walkable floor area was increased from 26.04m² to 27.56m² (figure 29), an improvement of about 6%. At the same time, the volume of personal shelf storage space has gone up from 8.71m³ to 9.38m³ (figure 28), an improvement of about 7%.

4.1.2 Financial Cost

Before coming to any conclusions regarding financial cost, I would need a reference point for both mass-produced off-the-shelf furniture, custom furniture made using my system, and custom furniture acquired in the conventional method.

To get a total cost for both my system and the conventional custom millwork system, I took one of the example designs included in my software and had it priced by multiple custom millwork companies, including the manufacturers I visited in section 2.1. I chose to use the example furniture design (figure 30) that was the most generic so that the possibility of finding an off-the-shelf alternative for comparison would be greater. The quotes received were nearly identical between manufacturers. I received a conventional price for the custom design, and based on the price breakdown I could calculate an estimate for how much the custom design would cost using the proposed system:

\$2450

The price for them to manufacture, assemble, and install the furniture, as is common practice with custom millwork.

\$1200

The price for them is just to cut and finish all of the components, and have the client assemble and install the furniture themselves, as is proposed in this thesis. This is calculated by subtracting the assembly cost and installation cost.

To get a more realistic price for conventional custom millwork, we would also need to include the cost of making the drawings and models that get sent to the millwork facility, as most people would need to hire a professional for this (a cost not present in my system as the software is what generates the drawings). This means that the actual cost of acquiring custom millwork the conventional way can be (and likely is) much greater than the number shown, depending on the nature of the person buying it.



Figure 30. Furniture design used for cost analysis, also one of the example configurations

Comparing the cost of a custom design to something off-the-shelf is difficult since the main reason for doing custom in the first place is that there exists no off-the-shelf product that has quite the same attributes. I did my best to find the closest Ikea alternatives to the custom shelf design, considering appearance, dimensions, materials used, and functional qualities. This image shows the three closest alternatives I was able to come up with.

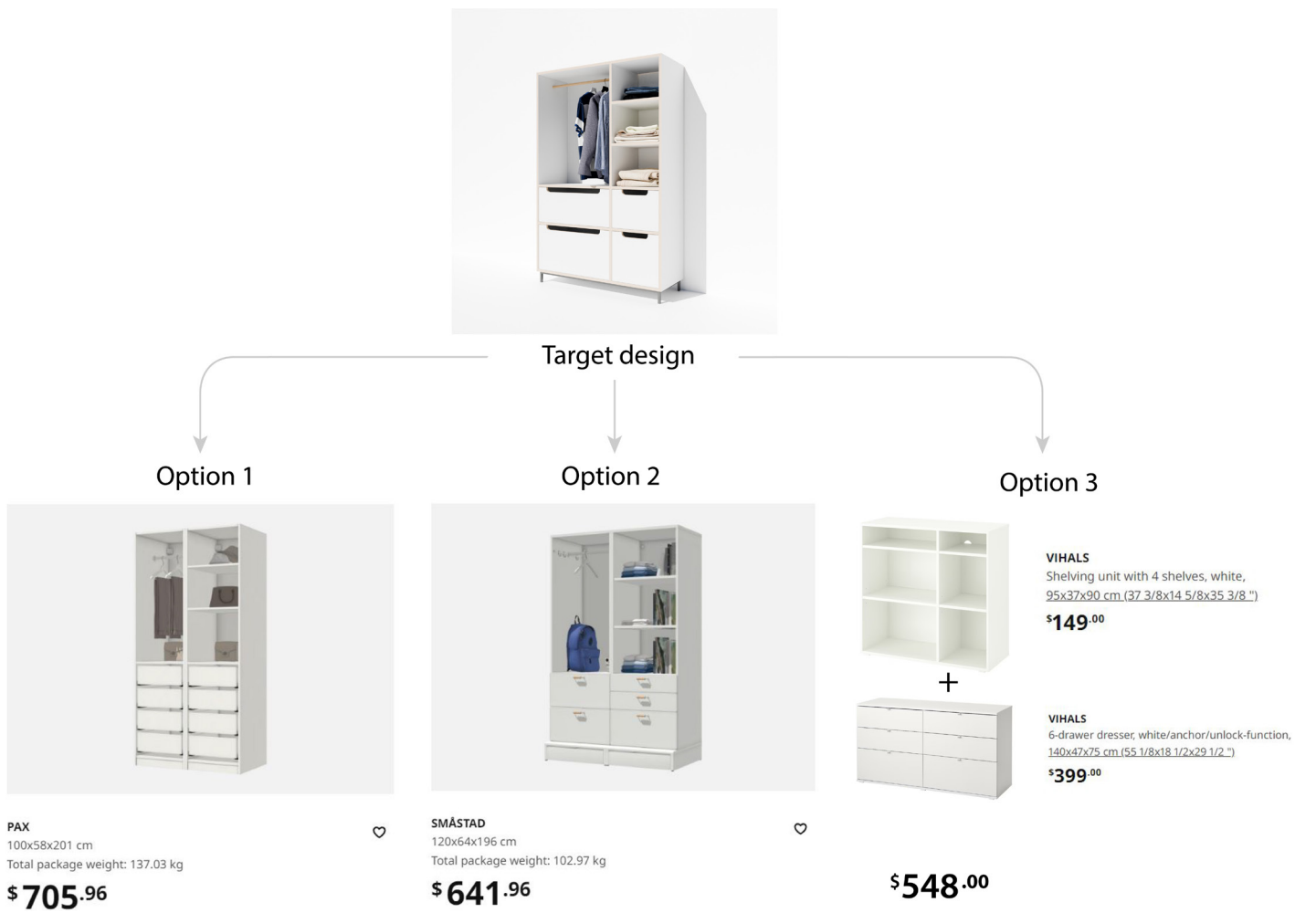


Figure 31. Diagram showing mass produced alternatives to the target design

Unfortunately, none of these options^{1 2 3 4} match the target dimensions quite right, as all mass-produced products are only available in a handful of dimensions. It is also important to note that the numbers shown do not include delivery costs (which are included in both custom furniture quotes).

As expected, at \$1200, the cost of making a shelf with the proposed system falls somewhere in between conventional custom millwork (\$2450 + design cost) and mass-produced off-the-shelf furniture available in the marketplace (\$641).

1 IKEA. "PAX Planner | Planners - IKEA*" Accessed August 16, 2024. <https://www.ikea.com/ca/en/planners/pax-planner/>.
2 IKEA. "SMÅSTAD Planner | Planners - IKEA*" Accessed August 16, 2024. <https://www.ikea.com/addon-app/storageone/smastad/web/latest/ca/en/#/>.
3 IKEA. "VIHALS 6-Drawer Dresser, White/Anchor/Unlock-Function, 140x47x75 Cm (551/8x181/2x291/2)". IKEA. Accessed August 16, 2024. <https://www.ikea.com/ca/en/p/vihals-6-drawer-dresser-white-anchor-unlock-function-30490115/>.
4 IKEA. "VIHALS Shelving Unit with 4 Shelves, White, 95x37x90 Cm (373/8x145/8x353/8)". IKEA. Accessed August 16, 2024. <https://www.ikea.com/ca/en/p/vihals-shelving-unit-with-4-shelves-white-50483289/>.

4.1.3 Environmental Cost

The environmental cost of the furniture depends on many factors including the type and amount of materials used, energy used for manufacturing and transportation, the amount of waste produced, and the end-of-life options for recycling or re-adaptation.

In the proposed system, the type of material used is chosen by the end user. This material selection could be impacted by how the software presents them. By providing the user with information about the different environmental costs of each material, the software could promote more sustainable options.

Since the proposed system utilizes a distributed network of existing manufacturers and connects end users to builders based on proximity, the transportation distances involved in this system would be lower than conventional mass-produced furniture (mass-produced furniture is predominantly manufactured overseas⁵, which in turn results in an increase in greenhouse gas emissions⁶).

One negative aspect of the proposed system in terms of environmental sustainability is the amount of waste material left over after manufacturing. This is an issue with subtractive manufacturing in general, where material is removed from a larger volume to make the final parts. Normally this issue can be partially avoided by purposefully sizing components in a manner so that they all fit nicely into the volume being subtracted from. For example, reducing the size of components slightly to fit them all on one sheet of plywood. Since in the proposed system, the end user creates their design without input from the manufacturers, this optimization would not be possible.

4.1.4 Flexibility and Adaptability

The modules in the system are designed to reuse as many parts as possible; By consistently using the connection hardware, same sheet material, and same drill hole layouts across components, furniture pieces can be disassembled and many of their components can be repurposed in new designs. This can be further supported by the digital tool, which could help the user come up with new designs that reuse as many existing components as possible (as discussed in section 3.2.4).

4.2 Evaluating the Design Tool

4.2.1 Ease of access

When looking at the factors determining ease of access in section 1.2 it would appear that the current version of the software is already very successful; The software produced from this thesis is free, can be downloaded by anyone, runs on pretty much any device, and upon opening the software users can start designing immediately without having to make an account. Unfortunately, the rubric created failed to consider that the distribution method for the software, and the public's awareness of the software can also create barriers to access.

Currently, the only way for someone to access the software is by downloading it from its GitHub page. This is not ideal, as no one searching for custom furniture would decide to look on GitHub of all places. To make matters worse, downloading apps from anything other than the App Store or Google Play is a nightmare on tablets and mobile devices. While these technical problems could be easily solved, and were only ignored due to the proof-of-concept nature of the project, the other barrier to access created by a lack of public awareness is not so easily resolved. For the system to be successful, it requires both millwork manufacturers to be aware of its existence, and the general public as well.

4.2.2 Ease of Use and Ease of Learning

To make learning the software as easy as possible, it follows conventions established by existing, similar products

5 Ringstrom, Anna. "IKEA Supply Chain Disruptions into 2022." Global News. Accessed August 12, 2024. <https://globalnews.ca/news/8265916/ikea-supply-chain-shortages-2022/>.

6 OECD. Globalisation, Transport and the Environment. OECD Publishing, 2010. 21

(as described in section 2.3). This way, if the user has already learned how to use a different piece of software, their knowledge can transfer to this one.

The software only presents relevant information at any given time, to guide the user through the process one step at a time. There is always the option to go back or undo the last action, which encourages an inexperienced user to try out all the features without fear of losing their progress.

While the idea of placing modules first, and then customizing them later is a bit unconventional, how it is done remains consistent. Making the software as consistent as possible means that once the user learns how one thing works they learn how other things work as well. A good example of consistency is the similar way in which both surface finishes, as well as handle types, are selected.

4.2.3 Depth of User Control

The depth of user control provided by the software is one aspect that is heavily limited by development time constraints and the proof-of-concept nature of this project. In its current state, the user has control over the configuration of modules, the depth and width of each module, the surface finish of each module, the sheet material used, and a couple more module-specific variables such as handle type or number of dividers.

While the depth of control is already far greater than most existing online furniture configurators (see Appendix C), there are still some additional variables that could be added. For example, the ability to change each module's depth, flip module orientations, and additional material options such as cardboard or acrylic.

4.2.4 Responsiveness

When testing the software on a range of hardware from top-of-the-line desktop computers to low-end mobile devices, the software remained highly responsive. Given the graphically simple nature of the software, this performance is unsurprising. As the program was never embedded directly into a website, a fair comparison cannot be made to the existing website-based tools, where performance was a concern.

4.2.5 Visual Feedback Quality

The software was able to match the visual feedback quality of existing furniture configurators (see Appendix C), providing both a 3D view with lighting and materials, as well as orthographic views and dimension overlays. The software's weakest point was its buttons and input fields for inputting numbers and text. This became particularly problematic when trying to use the program on devices with smaller screens like cell phones.

The scope of what the software can do is currently limited to shelving and basic tables. This is already a greater scope than several of the existing furniture configurators (see Appendix C), and increasing it further (to include chairs, benches, beds etc) could risk detracting from more important aspects such as ease of learning.

4.3 Challenges Going Forward

By trying to make something that is both highly customizable and highly accessible at the same time, the proposed system ends up having to compromise in both aspects. Because of this, it would never be able to compete with existing methods in any one of those two aspects. (it will never be as affordable or accessible as mass-produced furniture like IKEA, and it will never allow for the full customizability that comes with conventional millwork pipelines).

The final furniture design is determined by both the design of the individual modules, as well as the design of the overall configuration of these modules. Since the user configuring the modules together may not be a skilled designer, the quality of the design comes down to the person designing the modules themselves. Unfortunately, given the proof-of-concept nature of the project, there are so many limits on how the modules can be made that they end up all looking very similar.

Since the user can only place modules that are pre-designed, there is an inherent limit to what they can make. Adding modules with different styles would help, but there would need to be limits on which modules would be able to connect. Adding more and more modules and more and more rules while maintaining the simplicity and usability of the software would likely become very challenging very fast.

Should people with no furniture design experience be the ones designing their furniture, or should this be left to professional designers and carpenters? By removing the skilled professionals from the design stage a user could unknowingly make decisions that would make fabrication much harder, more expensive, or make the furniture less structurally stable. In theory, the software could guide the user and try to prevent them from making bad decisions, but only to a limited degree.

With the current system, when a user requests that their design get built, there is no guarantee that anyone will build it, and there is no system in place to tell the user why. It could be that there simply are no builders available, or they all declined the project for some reason. As an example, the user could select a combination of finishes and core materials which none of the fabricators provides.

The idea of distributed manufacturing where several independent workshops make the furniture means that there is no way to guarantee quality, consistency, fabrication speed, and delivery speed.

Since the system involves both manufacturers and clients/designers, it would also require convincing two separate user groups to actively use it.

When selecting a millworker, architects typically go through a bidding process. Not only does this keep prices competitive but also lets the architects make the final choice. Depending on the project the architect may choose a more expensive builder with a better reputation. One could argue that while the absence of this bidding stage streamlines the process for both parties, it could result in less competitive prices and a lack of choice for the end user.

4.4 Conclusion Summary

To summarize, the solution created in this thesis aims to utilize strategies present in mass produced furniture and conventional custom mill work, in order to have the pros of both while avoiding the cons. While the solution created does have its benefits it also has a series of completely new challenges not present in either existing method. As a result, the final solution ends up somewhere in the middle. Whether or not this in between approach is worthwhile ultimately depends on the end user and what they are looking for. For those looking for the cheapest solution they are better off with mass produced or used furniture, and for those who want something completely custom they are better off with conventional custom mill work. For the remainder (who may or may not exist), who are willing to spend a bit more than IKEA, or want something custom but can't afford conventional custom millwork, the proposed system would be ideal.

While there are a number of challenges present in the current solution (either due to the proof of concept implementation or due to the nature of the proposed system), I believe they could be overcome while still keeping enough of the existing benefits of the system for the project as a whole to be worthwhile.

Part 5 Post-Defence

This section covers the main points discussed during the thesis defense. The topics included potential next steps for the system, with a focus on how it relates to sustainable design; a detailed breakdown of the system's cost drivers from MCM; ideas for addressing challenges mentioned in section 4.3; and a comparison of the proposed system to craft furniture, as well as conventional millwork and mass-produced furniture.

As noted in the discussion, one of the weaker aspects of the proposed system (at least in its current state) is how it addresses the environmental impact of furniture design and manufacturing. For each limitation identified, next steps were suggested that could help solve them.

The first problem is that while the software gives the user choice about the materials and finishes they use, it does not provide them with sufficient information to make an informed decision regarding the environmental impact. One way of giving this information to the user would be to tell them the embodied energy present in each material, and to show them a map of the transportation route required for each material in their design. In the software this might look something like this:

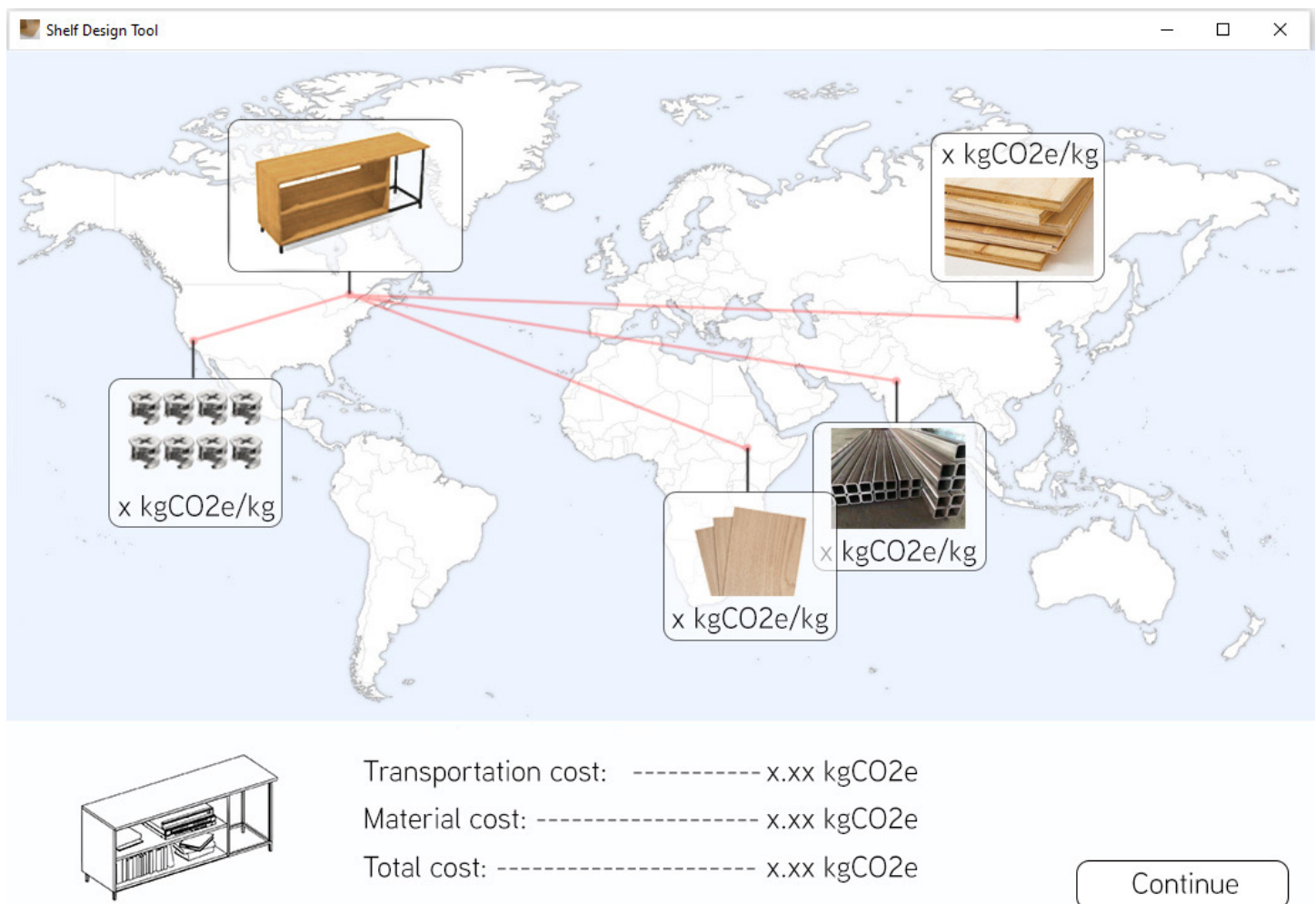


Figure 32. Possible material transportation map interface

Another problem was the waste that is created when manufacturing a small number of components. In larger systems it becomes possible to optimize fabrication, both in terms of material usage but also in terms of machine time and overhead costs. For these reasons not only is small scale fabrication more wasteful but also more expensive.

To solve this problem the software could help optimize the design of the furniture itself to use less material, as well as optimize the manufacturing process to use less materials. This would require the software to not only generate the components required to build a design, but also to create milling layouts. When generating a milling layout the software could calculate the amount of waste material created. In order to reduce waste, the software could use intelligent packing algorithms⁷, suggest alternative designs to the user, and combine multiple projects from different users to be manufactured in larger batches.

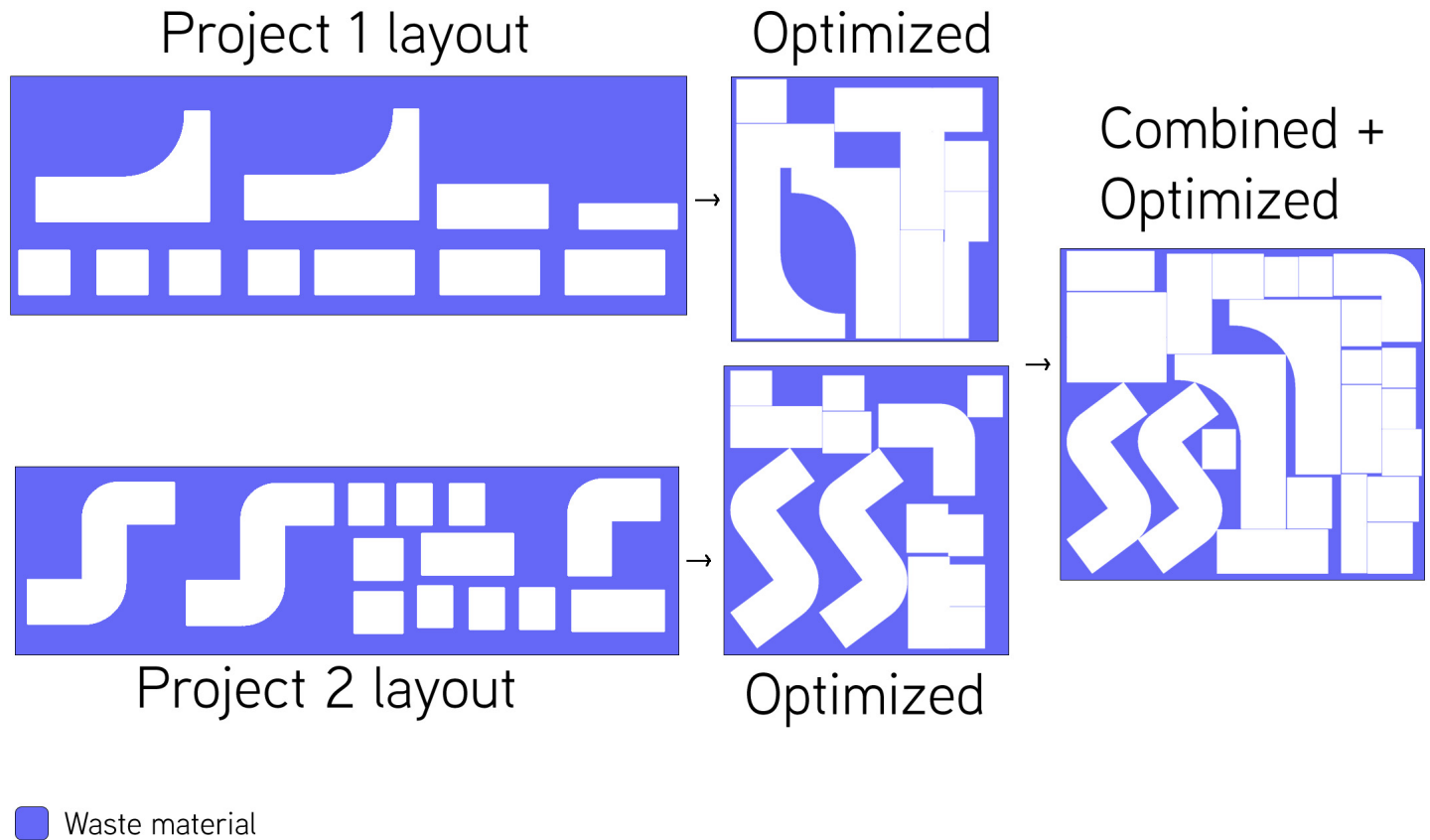


Figure 33. Diagram showing the optimization of the CNC mill layout

Another topic discussed during the defence was whether or not the proposed system could incorporate craft furniture and the benefits that come with it. If one were to associate a primary value with each furniture type, mass produced furniture would have the value of affordability or accessibility, conventional custom millwork would have the value of customizability, and craft furniture would have the value of high quality (high material quality, artistic quality and construction quality). Since the original goal of the thesis was to combine the values of mass produced furniture and conventional custom millwork, craft furniture was not considered.

One of the main takeaways from this project is that when combining the values of multiple systems there are often compromise that need to be made. While trying to incorporate the values of craft furniture into the system may provide some benefits, it would result in compromising the benefits already present.

Additional, as craft furniture relies heavily on the technical skill and craftsmanship of the person fabricating, it would be extremely difficult to automate with the use of software. Similarly, using unprocessed natural materials could make converting craft furniture to procedural modules very complicated.

⁷ Posavec, Igor. "UV-Packer." Accessed October 4, 2024. <https://docs.3d-plugin.com/uv-packer/>.

Since the software itself was the focus of the thesis, the furniture design used in the thesis was kept as simple as possible. When looking at the detailed cost breakdown provided by MCM, it became clear that the small details of the design actually have a very large impact on the cost of the system as a whole. The decision to have all of the components cut using a CNC mill, in combination with the use of cam nut connections, resulted in a lot of machining time. The cost of the CNC ended up being the largest driver of cost, even greater than the raw materials being used. To push this project further (and make it more affordable and accessible), new designs would have to be made with direct input with the manufacturers.

<u>Material</u>						
Name	Quantity	Base UoM	Unit Cost	Ext. Cost	Margin	Price
Drawer Slides	4	pairs	\$ 36.29	\$ 145.16	30%	\$188.71
3/4" Plywood	53	SF	\$ 5.00	\$ 265.00	30%	\$344.50
5/8" Plywood	12	SF	\$ 5.00	\$ 60.00	30%	\$ 78.00
1/2" Plywood	29	SF	\$ 4.80	\$ 139.20	30%	\$180.96
Cam Hardware	TBD	TBD	TBD	TBD	TBD	TBD
Coat Rod	TBD	TBD	TBD	TBD	TBD	TBD
<u>Operations</u>						
Name	Quantity	Base UoM	Unit Cost	Ext. Cost	Margin	Price
CNC	3	Hourly	\$ 130.00	\$ 390.00	30%	\$507.00
Panel Saw	1.5	Hourly	\$ 39.20	\$ 58.80	30%	\$ 76.44

Figure 34. Detailed price breakdown for the example shelf from section 4.1.2

This became even more clear when looking through the price breakdown and seeing that the design had actually been modified to use different components than what had been specified in the model; Some parts were priced as being ½ plywood instead of ¾ inch, drawer slides were added, and the material finish was changed to be something that was more durable and would hold up better in the long run.

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Appendix

A.1 Furniture system values

A.1.1 Furniture value: Dimensional Customizability

How can this value be measured: Dimensions are a key factor when choosing furniture for a space. Some furniture designs are limited to a single size, some have multiple predetermined sizes, and some can be custom-made with whatever dimensions are requested. Measuring the level of customizability of a furniture system is as simple as counting the number of size options there are, or in cases where there are infinite, by counting the number of size variables that the user can control. Dimensional customizability also leads to another related value, the use of space. Furniture can provide volume for storage and surface area for working. At the same time, furniture takes up space and, depending on the room layout can make additional space around it inaccessible. Optimal use of space can be measured by taking the newly created storage volume (or other functional statistics like working surface area, number of seats, etc) and dividing that by the total amount of area that is made inaccessible by placing the furniture there. For example, a storage shelf on a wall that goes all the way up to the ceiling would be a more optimal use of space than a storage shelf that is a couple of inches too short. Similarly, a bed that can retract to have a smaller footprint¹ when not in use has a better use of space than a bed that cannot. To measure this value one needs to look at both the furniture itself as well as the space in which it exists. Since this project does not have a specific site, To generalize, and to measure this value based purely on the furniture, one can look at how customizable the furniture is to fit in different spaces - hence why the use of space is included in the dimensional customizability value. How important is this value for the final product to be successful, and why? In this case, dimensional customizability, and therefore optimizing the use of space is one of the most important values. Optimizing the usage of space is always good practice, but it becomes more important as living spaces become smaller. It also becomes much more difficult to do with mass-produced furniture made in predefined dimensions. Additionally, the greater the customizability, of a furniture system, the greater the user agency.

A.1.2 Furniture Value: Financial Cost

How can this value be measured: The financial cost is the cost that the end user has to pay for acquiring the furniture. This is not limited to the material costs, but also the transportation costs, labor costs, and any equipment costs that result in a higher price for the end user. This not only takes into account the initial cost of acquiring the furniture but also the long-term investment costs which are affected by the durability and flexibility values.

How important is this value for the final product to be successful, and why? When making furniture for dense living spaces, cost is extremely relevant. Generally speaking, financial cost is the main force driving people to live in such dense conditions. Therefore, the furniture also needs to be as affordable as possible. Unfortunately, only using furniture that is as inexpensive as possible can make some of the other values harder to achieve. Using cheaper materials compromises durability, and buying used furniture can reduce costs but the limited selection available compromises on use of space (it is highly unlikely that one can find used furniture that will perfectly fit their new space, and older furniture is often too large to work in small spaces).

A.1.3 Furniture Value: Environmental Cost

How can this value be measured: The environmental cost of the furniture system can be measured in terms of the pollution that is produced (or sequestered) throughout the whole process of collecting, processing, and transporting the raw materials, as well as the manufacturing and transporting of the furniture². Similar to the financial cost, this not only looks at the initial environmental cost of acquiring the furniture but also the lifetime and end-of-life environmental costs. The easiest way of estimating the initial environmental cost is to look at

¹ Fuseproject. "Ori Expandable Apartments." Accessed October 1, 2023. <https://www.oriliving.com/>.

² Sandher, Paige. "From Living Room to Landfill: The Hidden Cost of Furniture Waste Choosing Sustainable Furniture." Couch Haus. Accessed February 10, 2024. <https://www.couchhaus.com/blogs/featured/from-living-room-to-landfill-the-hidden-cost-of-furniture-waste-choosing-sustainable-furniture>.

the materials the furniture is made out of and where the furniture is fabricated, wood has a very low cost while steel or aluminum has a very high cost³, and the farther away the furniture is fabricated the higher the cost. The best way to estimate the lifetime environmental cost is to look at the other values of durability and flexibility. How important is this value for the final product to be successful, and why? While not the primary goal of this project, minimizing the environmental cost of their furniture could be the most important aspect for some users, and since the goal of the project is to give users more agency in every aspect of their furniture (including environmental cost) the furniture system must address this.

A.1.4 Furniture value: Adaptability/flexibility

How can this value be measured: The adaptability/flexibility of a piece of furniture can be measured by how easy it is to be reconfigured, moved, or otherwise changed to fit a new environment or function. This is different than the initial dimensional customizability of the furniture and focuses more on reconfigurability over time. If a furniture system is unable to be modified over time, for example, because the user moves to a new space, or because a user's needs change, it needs to be replaced which leads to a greater environmental and financial cost. How important is this value for the final product to be successful, and why? Adaptability of the furniture system is important for multiple reasons. dense living conditions can be temporary or quickly changing environments, so the furniture should also be able to be reconfigured as situations change. There is also the benefit of being able to reuse the furniture (or parts of the furniture) for longer, which in turn reduces waste.

A.1.5 Furniture value: Construction Complexity

How can this value be measured: The construction complexity of a furniture system can be measured by the skills and tools required to build it, and by how much of the construction process can be automated. How important is this value for the final product to be successful, and why? Minimizing construction complexity is important for this furniture system for several reasons. In cases where the furniture is being assembled on-site, it needs to be simple enough for an average end user to put together. Minimizing construction complexity also means that the furniture is easier to take apart and repair or modify, which in turn makes the furniture more adaptable. Construction complexity also has a direct impact on manufacturing costs, as complex construction requires far more skilled labor time than simple construction which can be done more quickly and in a more automated manner.

A.1.6 Furniture value: Durability

How can this value be measured: Durability can be measured by looking at how long the furniture lasts under expected usage conditions until part of it breaks and needs to be repaired or replaced. Is the furniture strong enough to be used for alternative purposes, such as being able to sit or stand if needed? How important is this value for the final product to be successful, and why? Durability is important because it relates to the cost of the furniture. It has a direct impact on cost over time, the more often the furniture breaks, the more often it needs to be repaired or replaced. Being strong enough to support alternative functions also makes the furniture more adaptable. Unfortunately, durability is also strongly related to the material choice which in turn is directly related to the upfront financial cost. Similarly, there can also be a durability trade-off when construction is simplified. Finally, there is also a minimum durability that the furniture should have for safety reasons.

A.2 Digital tool values

A.2.1 Digital tool value: Ease of access

How can this value be measured: How easy is it for the user to access the digital tool can be measured by looking at all of the obstacles that the user must overcome before they can use the tool, as well as how easy the tool is to find in the first place. Some examples of obstacles to access could be: does the software cost money to use, does the user need to download anything, does the user need to make an account first, and how many clicks does the

³ Stede, Jan, Stefan Pauliuk, Gilang Hardadi, and Karsten Neuhoﬀ. "Carbon Pricing of Basic Materials: Incentives and Risks for the Value Chain and Consumers." *Ecological Economics* 189 (November 1, 2021): 107168. <https://doi.org/10.1016/j.ecolecon.2021.107168>.

user need to make before they can actually start using the software?

How important is this value for the final product to be successful, and why? Ease of access is the most important aspect of the digital configuration tool because it will often determine if a user will ever actually try using the tool, to begin with. Since the tool itself is meant for users with or without technical skills, accessing the tool and setting it up also needs to be possible with limited technical knowledge.

A.2.2 Digital tool value: Ease of use/Ease of learning to use

How can this value be measured: Ease of use can be measured by how long it takes a user to understand how to use the design tool, and how much effort it takes to use from then on. Several factors determine how easy something is to use, including the complexity and consistency of the software, as well as how closely the software follows established conventions.

How important is this value for the final product to be successful, and why? Making the digital tool easy to use and easy to learn is very important for this project. The goal of the project is to make something that requires very little technical experience to use. For this reason, it makes more sense to focus on feature simplification for the sake of usability rather than feature complexity for the sake of total user control.

A.2.3 Digital tool value: Depth of user control

How can this value be measured: How much control does the user have over the object they are configuring or designing? One way of measuring this is by counting the total number of possible variants that the user can create. This can range from a basic multiple-choice selection with limited predefined options to full control over exact dimensions, colors, materials, etc.

How important is this value for the final product to be successful, and why? This is extremely important for the digital tool to be successful. Particularly in terms of user control over exact object dimensions. This relates to the optimal use of space value of the furniture that the tool is being used to design. To guarantee an optimal use of space, the digital tool needs to be able to produce furniture that the user has exact control over the dimensions. The ability to input any exact dimension creates far more complexity for the software logic than offering a small selection of pre-sized modules but is critical for the success of this project. Giving the user even more control than that, over things like the connection hardware should only be considered if it can be done without affecting the ease of use/ease of learning value.

A.2.4 Digital tool value: Responsiveness

can this value be measured: Responsiveness can be measured by how quickly the software runs, particularly on slow hardware.

How important is this value for the final product to be successful, and why? Responsiveness is somewhat similar to ease of access, as unresponsive or poorly optimized software can require a more powerful computer to run properly, which can act as a barrier to users. For this reason, the software must be well-coded and optimized to be able to run on average modern hardware. Slow or unresponsive software can also be much more difficult to use, which impacts the ease of use value as well. Responsiveness can be impacted by the visual quality of what is being rendered, as well as the complexity of the tasks that the software needs to perform. Since the target audience for this software is those in dense living situations, it should be able to run on inexpensive computers.

A.2.5 Digital tool value: Visual feedback quality

How can this value be measured: This can be measured by how accurately the software portrays the final physical product.

How important is this value for the final product to be successful, and why? Visual feedback quality is somewhat important for this tool to be successful. Since the target users are those who may lack design experience, the preview needs to be a realistic representation of the final result. A 3D model that the user can look at from different angles is far more useful than a 2D elevation when it comes to previewing what the furniture will look like. Other things like accurate materials, lighting, and shadows are also good ways of improving visual feedback quality, as long as they don't create compromises when it comes to responsiveness. In addition to the realism of the preview, the amount of relevant information shown to the user can improve visual feedback quality, this can

include things like dimension lines or material statistics.

A.2.6 Digital tool value: Scope of Capabilities

How can this value be measured: This can be measured by counting the number of different tasks the software can do. For example, software that can be used to design doors and chairs has a larger scope of capabilities than software that can only design doors.

How important is this value for the final product to be successful, and why? The scope of the software does not have to be very big for this project to be a success. In general, being able to do more is good, but comes at a cost to how easy the software is to learn and how easy the software is to use. For this project ease of use is a higher priority than having a large scope of capabilities. Depth of user control is also more important than the scope of capabilities, so development time will focus on making software that can do a small number of tasks very well, instead of being able to do a large number of tasks poorly.

B Development Timeline

To keep track of my progress, and to back up all of my work online, all of the project files are stored in a GitHub repository that can be viewed by anyone

This section goes through all of the commits (each time I published changes) and briefly describe what I was doing at the time. The contents of each commit range from just a few lines of code to several hundred, depending on if I was just fixing a bug or adding a large feature.

Project Creation Silasmoth committed 7 months ago	2f80bfa			
Initial commit Silasmoth committed 7 months ago	Verified 9ac0570			

The initial commits were just me getting everything set up on GitHub and did not include any real progress. This consists of a blank unity project, with no code or assets.

Commits on Jan 31, 2024				
fixed rotation Silasmoth committed 7 months ago	41b01fe			
Improved snapping Snapping now considers adjacent modules, not just the block that it was first placed against. Also added lots of comments (to hopefully make things more clear) Silasmoth committed 7 months ago	6ad7451			
Commits on Jan 30, 2024				
Module snapping blocks now remember which other blocks they are connected to, and changing the scale of a block will adjust the position and scale of connected blocks. also did some project organization. Silasmoth committed 7 months ago	e6921a9			
Commits on Jan 28, 2024				
scroll to zoom Silasmoth committed 7 months ago	ba1365b			
furniture viewport and basic snapping Silasmoth committed 7 months ago	c6237f6			

The first part of the project I tackled was making a 3d viewport that could be navigated with a mouse and keyboard. For something to look at I also made a simple block placement and snapping system, which would just place a cube every time the user clicked. At this point, I also made the basic graph structure (described in section 3.2.2) that kept track of which cube (every module was just a cube still) was connected to other cubes. By clicking on the side of a cube it would place a cube on that side, and connect it to the cube that was clicked.

Added block deletion Added a button to delete the selected block, it clears all references to itself before being deleted, also fixed some issues with placing the corner block type. Silasmoth committed 6 months ago	b78cd81			
Block selection and modification Added a panel in the viewport that appears when a module is selected. the panel contains some input fields for changing the modules dimensions and a button to apply them and recalculate the full model. Clicking a module selects it, clicking off of a module deselects it. Silasmoth committed 6 months ago	d7d0c2d			
Added corner modules In addition to the box shaped modules there are now L shaped corner modules, this allows for the creation of assemblies that go around corners. Corners require some additional mesh components, and have two width variables, one controlling the length on each side of the angle. Silasmoth committed 6 months ago	93eef8b			

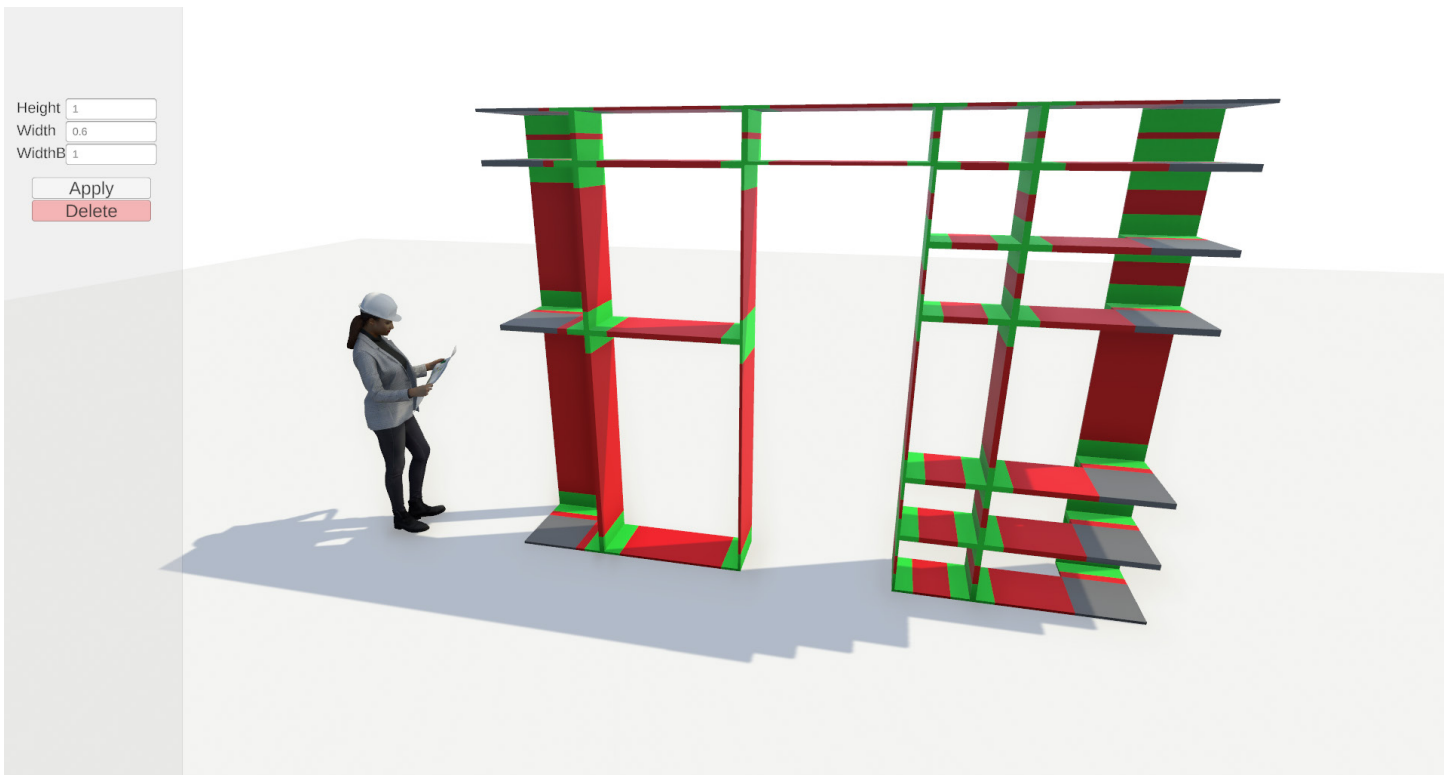


Figure 32. Screenshot of design interface early in development

Next, I added a bit of variety to the modules, replacing the cubes with very basic shelf models, including a square shelf and a corner shelf. Modules could also be selected, modified, and deleted now. Unlike the cubes, these modules could also be scaled to fit different dimensions.

Commits on Feb 7, 2024

Automatically move furniture to sit on ground

after every edit or delete, the furniture will reposition itself to be sitting on the ground, it will no longer ever be floating or sinking into the ground.

b16ea41 ...

Silasmoth committed 6 months ago

Since modules could now be deleted or resized, to prevent the furniture from floating in the air or sticking to the ground, the furniture is automatically repositioned at ground level after every change.

Commits on Feb 27, 2024

Drag and drop

Early implementation of a drag and drop system for placing modules

15fba0f ...

Silasmoth committed 6 months ago

Commits on Feb 10, 2024

block place selection

as a temporary way of choosing what block gets places you can use 1 and 0 keys. I will remove this later when I add more modules and add drag and drop placement.

b7e8b97 ...

Silasmoth committed 6 months ago

Next, I created a drag-and-drop system to let the users easily choose which module they wanted to place and where at the same time. At this point, there were still only 2 placeable modules, shelves, and corner shelves turning inwards.

Commits on Feb 29, 2024

Added reverse corner module

Silasmoth committed 6 months ago

52e75aa  <> ...

Improved drag and drop

also fixed issue where you could have two overlapping modules if you clicked perfectly in between two modules

Silasmoth committed 6 months ago

6fe956b  <> ...

More improvements to the drag-and-drop system were made, although it was still very buggy and inconsistent. I also added a reverse corner module, so now the shelf could turn both inwards and outward.

Block Dimension limits and starter block placement

There are now limits to the block dimension, and if all blocks are deleted a new starter block can be placed on the ground via drag and drop

Silasmoth committed 5 months ago

6e32171  <> ...

Support for more module types and bugfixes

Added Center module mesh component, and fixed bug where preview module would update adjacent modules during drag and drop.

Silasmoth committed 5 months ago

a6d4060  <> ...

Next were some minor changes. Another module, a shelf with a closed-back face, was added. Modules were also given some limits on their dimensions. Now when there are no modules present in the scene, the user can place one directly on the ground, after which all new modules must snap to an existing module.

Commits on Mar 4, 2024

Added model export as .fbx

Added FBX export support, as well as file browser for choosing file save location First commit where I include some code not written by myself: <https://github.com/quangdungtr/UnityStandaloneFileBrowser> and <https://github.com/KellanHiggins/AsciiFBXExporterForUnity> currently only works on windows and exports as ascii fbx type.

Silasmoth committed 5 months ago

8762488  <> ...

To make it easier to produce diagrams while I was working, I wanted to implement an export option as fast as possible. This would also be an important part of the final software.

Commits on Mar 16, 2024

Selection highlight

Silasmoth committed 5 months ago

4254f3c  <> ...

This update just made it so that the module currently clicked would be rendered in a slightly brighter color to indicate that it was selected.

Added Vertical Dividers

Silasmoth committed 5 months ago

5b68486  <> ...

Commits on Mar 16, 2024

added empty flat shelf

Silasmoth committed 5 months ago

9fc9501  <> ...

Added Drawer module

Silasmoth committed 5 months ago

c01179d  <> ...

Added horizontal dividers

added the option to add horizontal shelves to modules, and modeled a basic example shelf

Silasmoth committed 5 months ago

0f32704  <> ...

The next few updates just added some more modules, as well as the customization option to place vertical or horizontal dividers within each shelf.

Added ash and walnut surface finishes

Silasmoth committed 5 months ago

7334268   ...**fixed counter placement preview**

Silasmoth committed 5 months ago

1be0f8b   ...**Added counter and material selection options**

Added new counter module type, and added multiple material options when a module is selected, with a dropdown and a new button to apply finish to all modules

Silasmoth committed 5 months ago

6a5397b   ...**Fixed placement connection bugs**

properly updates widthB for corner modules, and checks all sides for connection when placing new blocks

Silasmoth committed 5 months ago

60e0f02   ...

Yet another module was added, this time a countertop module, and an additional customization option was added, the ability to change the surface material of each module. This was just a text dropdown menu, and the options were only: plywood, black, ash, and walnut.



Figure 33. The surface selection interface early in development

corrected MDF pricing  corrected to home depo MDF price  Silasmoth committed 5 months ago	f0f54f5   ...
Commits on Apr 1, 2024	
Improved dimension display  dimension not adjusts where the line is shown and the text alignment depending on the camera angle  Silasmoth committed 5 months ago	f8e67c3   ...
Added Core material selection and cost estimate  User can now select the furniture structure material as well as finish material. a cost estimate is also now generated in the statistics  Silasmoth committed 5 months ago	65d2604   ...
fixed bug where counters would add to shelf area twice  Silasmoth committed 5 months ago	9a2ebbf   ...
added material usage and mass statistics  Silasmoth committed 5 months ago	98de3a6   ...
fixed shelf area calculation bug  Silasmoth committed 5 months ago	e183ad0   ...
Show Dimensions and show stats  Added the ability to see furniture dimensions directly in the 3d view, can be toggle by a button in the bottom right. Also added some basic statistics, can also be toggled from a button in the bottom right.  Silasmoth committed 5 months ago	573ee9c   ...

The next batch of updates was all about calculating statistics and displaying more information to the user. These included things like area, volume, cost, and mass estimates. The cost estimate was based purely on the rough area of material used, multiplied by the cost per meter squared of the sheet material used. This cost calculation does not take into account matching costs, labor costs, transport costs, cost of material waste, or costs of finishes and hardware. It does however help provide a point of comparison when looking at different furniture configurations. This update also added the option to show dimension lines, which was repeatedly requested by testers.

Commits on Apr 2, 2024	
fixed shelves width when using single wall thickness  Silasmoth committed 5 months ago	6339704   ...
added the option to choose between double and single wall thickness  Silasmoth committed 5 months ago	35beb21   ...
material dropdown fix  Silasmoth committed 5 months ago	a4fe123   ...
Added toggle to show/hide scale figure  also made it so that blocks show on floor while dragging, rather than being hidden below  Silasmoth committed 5 months ago	89af040   ...

In addition to the dimension lines, the option to show and hide a scale figure was added to help give the user a sense of scale. At this point, I also started to work on optimizing the way modules would interact with each other, removing redundant components (as described in section 3.2.2).

Fixed Open file bugs  open file now correctly sets the material and double walls settings  Silasmoth committed 4 months ago	8296f75   ...
Added File Save and File Open  Added serializable class that can describe the full furniture system, then added code to convert the class to and from byte arrays, and finally the code to save and open the byte array files.  Silasmoth committed 4 months ago	a58ab3c   ...

The next addition was saving and loading of projects. For this, I first created an object that could store all of the information associated with the project. All this object contains is a series of arrays describing all the variables for each module in the scene (one array for positions, one for widths, one for heights, one for module types, etc) and an array of module pairs to keep track of which modules are connected. This object can then be converted to

and from byte arrays through the use of something like BinaryFormatter (which in hindsight was not a great idea as this can lead to security risks). This byte array can be saved as a binary file directly on the user's computer. The same process works in reverse for opening a file, in which case the binary is read, converted back to an object, and then the program rebuilds the scene based on the information stored in the object. This conversion of a furniture scene to a byte array will also be useful later when it comes time to send furniture projects over the internet.

fixed swing drawer material usage calculation

Silasmoth committed 4 months ago

fa133ae

<>

...

Added swing drawer module and fixed dimensions when using counter

Counter no longer creates incorrect dimension lines, and added a new module with separate handle material

Silasmoth committed 4 months ago

28cc73b

<>

...

Next, an additional module was added along with some bug fixes.

Commits on Apr 8, 2024

Added option to start from scratch or from example project

Silasmoth committed 4 months ago

c85db55

<>

...

With the added functionality of saving and loading, I could now save example projects and provide the option for users to open them rather than starting from scratch every time. I also decided to create a rendered preview for example furniture projects.

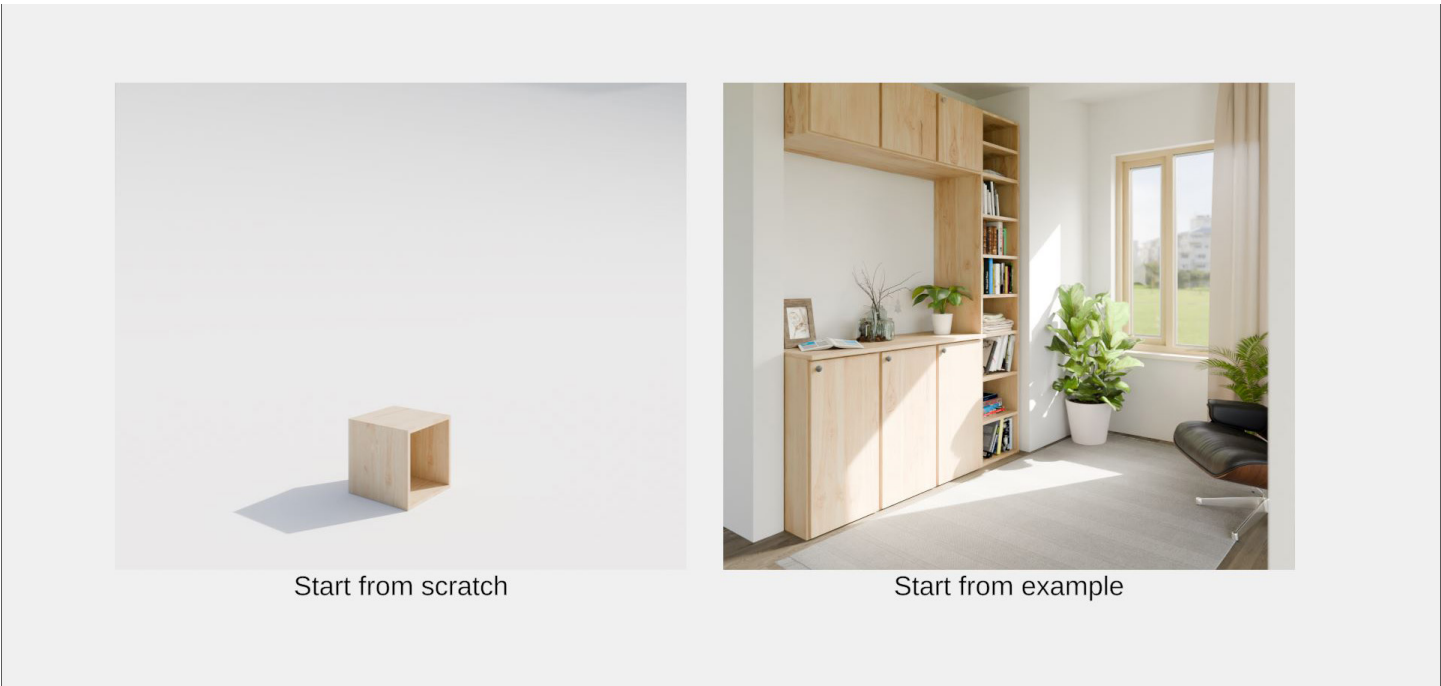


Figure 34. Start from example option

main menu UI improvements

Silasmoth committed 3 months ago

c61b316

<>

...

Create Example Shelf blank wall.png

Silasmoth committed 3 months ago

19773d5

<>

...

Commits on Apr 10, 2024

Added Wall mounted preview

Silasmoth committed 4 months ago

225fee2

<>

...

Added check to stop placing corner modules on top of non corner modules and vice versa

Silasmoth committed 4 months ago

820085d

<>

...

Next, an option was added to make the furniture project “wall mounted” or free-standing, with additional user interface improvements.

Commits on May 15, 2024	
Builder account creation code 	
All of the code required for the builder to create an account, by connecting to the server and giving them the builders email. for security passwords are hashed before being sent to the server so the server never actually knows the builders real password, only the encrypted one. also some very basic checks to make sure email is a valid email format.	2411bd9   ...
 Silasmoth committed 3 months ago	
Added code for connecting to server	c335e6f   ...
 Silasmoth committed 3 months ago	

Up to this point, I have only been working on the software from the perspective of a design tool, and have not implemented any of the online features. Here I created the code for connecting to a server program - which I also started making at the same time. I decided to make the server in a completely different project because it shared very little in terms of function with the design tool. On the other hand, the builder tool would require a lot of the same functionality as the design tool, so they are both located in one project so that they can share assets and code. This means that any improvement I make to the design tool will carry over to the builder tool and vice versa. This was also when I set up the builder account creation interface. When providing software with an email and a password, data security starts to be a concern. Users would not want their passwords stored on a server where the owner could read them. Without going into too much detail, the way I avoided this problem was by hashing the password locally in the builder tool, and only ever sending the hashed password to the server. That way, even if the account database was compromised, only the encrypted passwords would be exposed. The email addresses were not encrypted, since the server needs to know what they are for sending emails.

Commits on May 16, 2024	
basic implementation of converting furniture to individual components that can be cnc cut 	
right now its still missing things like connection holes but it does join modules together so that less cuts need to be made (if the double walls is not enabled)	817c6ed   ...
 Silasmoth committed 3 months ago	

The next update involved exporting the furniture as individual flat components that could be cut from a sheet. The process is described in section 3.3.3. There are still some missing features that I was not able to add due to time constraints, but for the sake of demonstration it more or less works.

Commits on May 17, 2024	
increased allowed message size 	
buffer is now 1024 bytes, with fragmented messages 65536 bytes	87414aa   ...
 Silasmoth committed 3 months ago	
more work uploading furniture	efe8a9f   ...
 Silasmoth committed 3 months ago	
code cleanup and prep for uploading projects to server 	
new net messages for transferring furniture projects and client information to the server. also did a bunch of code organization and cleanup with #regions	0d3be3a   ...
 Silasmoth committed 3 months ago	

Now that the program can connect to the server, I started working on the code for actually transferring projects to and from the server to both the design tool and the builder tool. I also took some time to organize my code, by writing clear comments and grouping related functions together.

fixed bug with email verification when inputting incorrect code 	
inputting the wrong email verification code would lock the program now it displays a popup and unlocks the buttons	4fe8dc7   ...
 Silasmoth committed 3 months ago	
Builder Login improvements	cb38b7c   ...
 Silasmoth committed 3 months ago	
builder login fail responses	74e6f7a   ...
 Silasmoth committed 3 months ago	

Commits on May 19, 2024

builder account creation/login, email verification

Silasmoth committed 3 months ago

05462d4   ...

For the builder account creation, I added an email verification step. Since the email would later be used for sending notifications, it's important to verify that it belongs to the user and not someone else. It also makes sure the user types in the correct email, which happened surprisingly often when testing it myself. I also added code for cases where the builder inputs incorrect information.

Commits on May 20, 2024

builder can now view projects, also added a ping to and from server every 5 seconds to prevent connection loss

Silasmoth committed 3 months ago

4ac9588   ...

UI improvements for builder

Silasmoth committed 3 months ago

5ebe4af   ...

Builders can now be assigned projects, builder app is now dark to help distinguish them

Silasmoth committed 3 months ago

3f23929   ...

Now that builders could log in, code was added for receiving projects from the server, and listing them for the builder to view. The code for viewing projects is directly shared between the builder program and the designer program, with only some editing features disabled for the builder. I also made the builder interface a darker color to make it easy to distinguish between them.

Commits on May 21, 2024

Added popup in case server was unable to locate address from information provided, both for client and builder

Silasmoth committed 3 months ago

9805880   ...

Added builder features and fixed networking bugs

Builder can now exit project view, changed to a less commonly used port (from 8999 to new port 9601), fixed ping not working when tabbed out of software, got NetworkClient singleton setup working.

Silasmoth committed 3 months ago

002b957   ...

Some more features were added to the builder interface, and fixes were made to the networking code to improve stability.

new module icons and settings menu

I also redid the example project to work with the new finishes

Silasmoth committed 2 months ago

d3eda9c   ...

Commits on Jun 3, 2024

New modules, UI improvements, and new finishes

30+ new finish options, update several modules to have proper dimensions, connections and hardware. You can now see the edge of the plywood. Finishes are now shown as a page of previews rather than a dropdown, by default material changes are applied to all modules. Improved the finish shader to support color values as well as textures, so that I dont need to store textures for every color option.

Silasmoth committed 2 months ago

4516dfe   ...

Commits on May 31, 2024

Set up material finish render file

Silasmoth committed 3 months ago

e010e82   ...

At this point, there were still very few options for surface finishes (only 3) and they did not have any previews. The modules were also shown without any connection hardware and with unresolved edge conditions. To solve this, the modules were all completely remodeled from scratch, this time including as much detail as possible, such as the screws, cam nuts, and even the plywood edge textures.

Delete module with delete key

Silasmoth committed 2 months ago

f64d9c1   ...

As requested by multiple testers, deleting a module can now be done either by selecting it and clicking the delete button on the screen or by clicking the delete key on the keyboard.

Commits on Jun 4, 2024

Improved metal legs modules, and improved customization UI

legs now change models depending on if there is another set of legs next to them, customization ui now shows icon of selected module and hides some settings that cannot be edited

45b1de1

Silasmoth committed 2 months ago

Added metal legs modules and improved module code to support more varied shapes

63aed09

Silasmoth committed 2 months ago

A new module was added for metal legs. Up until now the furniture always sat directly on the ground which looked rather odd. At this point, all of the modules were looking very boxy, and I started to improve the code to support more varied shapes.

Commits on Jun 10, 2024

Added material normal maps for relief materials

796ce7f

Silasmoth committed 2 months ago

Added remaining finish materials

4be5505

Silasmoth committed 2 months ago

Added option to finish edges, and reorganized some files

cfaad1

Silasmoth committed 2 months ago

More customization options were added for material finishes, including the option to choose if the cut edges should also be finished or left exposed. I also started to implement some surface options that had actual depth via relief patterns. These quickly became far too complicated and were causing more problems that I did not have time to fix so they were later removed. I still think that revisiting surface finishes with cut patterns would be an interesting idea worth pursuing.



Figure 35. The final material selection interface

Commits on Jun 12, 2024

Added another example project and more bugfixes

Silasmoth committed 2 months ago

35c763e   ...

Added more example modules, and fixed some bugs

Silasmoth committed 2 months ago

0d8517f   ...

4 new modules

Silasmoth committed 2 months ago

aa9b0fa   ...

For added variety, more modules were added, along with another example project and accompanying preview render.

Builders can now accept and delete accepted projects

Silasmoth committed 2 months ago

3699224   ...

Added functionality for builders to decline projects

Silasmoth committed 2 months ago

8853a49   ...

Next, the option for builders to decline projects that they had been assigned was added. This was done in conjunction with giving the server the ability to reassign projects when they were declined (see section 3.4.1).

Commits on Jun 13, 2024

Made Module snapping much easier

When placing a module it will now automatically snap to the nearest placed module within 1m

Silasmoth committed 2 months ago

1364cf6   ...

To make the drag-and-drop system more user-friendly, a more forgiving snapping system was added. Rather than having to place the mouse directly over the edge of an existing module, the user can now place their mouse in the general area and it will still work. There are still some niche cases where the drag and drop does not work as expected, but for the sake of demonstration, it works well enough. This could be improved further by letting the user choose how strong the snapping effect is.

Commits on Jun 14, 2024

Added option to show the furniture's center of mass

Silasmoth committed 2 months ago

c1b3ea1   ...

Since one of the original goals of the project was to show as much useful information to the user as possible, I wanted to include some sort of structural analysis. A full-blown structural simulation would be too complicated for the scope and time frame of this project, but a more basic stability check was possible. To tell the user if the furniture would be able to stand upright or not, it calculates the furniture's center of mass, then displays it directly in the 3d viewport along with a line going from the center of mass straight down to the ground. If the line falls within the footprint of the furniture, it would stand up by itself, otherwise it would fall over. This only takes into account the mass of the furniture itself, not any additional load caused by its contents.

Commits on Jun 17, 2024

Added scroll view for example projects

Silasmoth committed 2 months ago

0973c4c   ...

A recurring challenge I faced during development was making the user interface work with different screen resolutions and aspect ratios. Since the computer I was developing on had 4k screens, that was the original resolution I was targeting. However, since the laptop I used to present only had a 1080p screen I had to make sure it would also work at lower resolutions. To fit everything on a smaller screen, I used a lot of scroll bars.

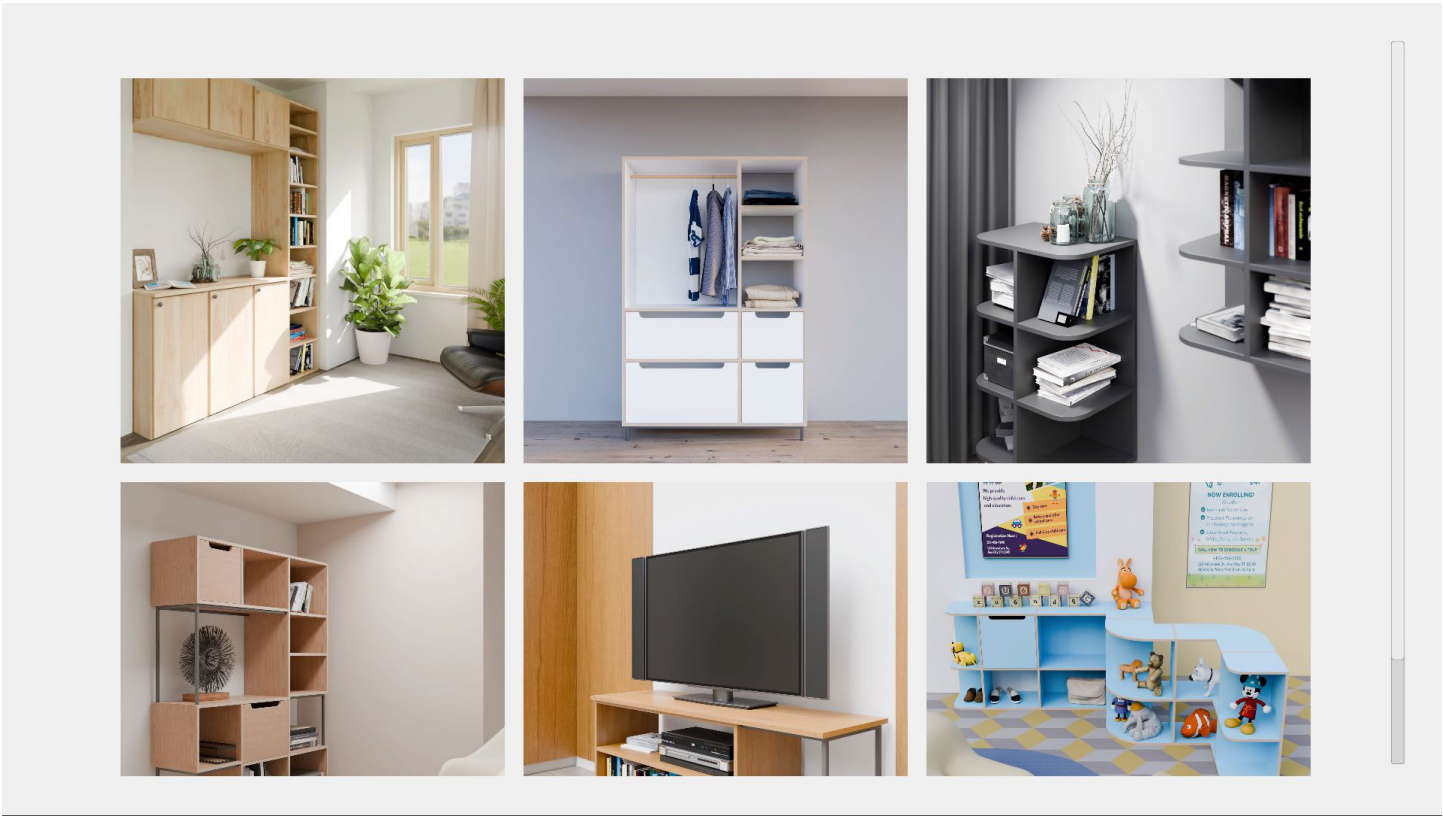


Figure 36. The example project selection interface

Commits on Jul 9, 2024

Diagrams Silasmoth committed last month	70cebff	
Revert "Corner shelf edge fix" This reverts commit fd96324 . Silasmoth committed last month	9ae263d	
Corner shelf edge fix Silasmoth committed last month	fd96324	

This update involved me trying to fix a bug that I had noticed with the shelf edges sometimes showing up as pure black instead of the plywood texture. After publishing the update I realized that I had unintentionally broken something else so it was reverted.

Commits on Jul 16, 2024

2 more handles and further UI improvements Silasmoth committed last month	d6d62a6	
fixed corner snapping issue Silasmoth committed last month	15e16fb	
UI improvements and handle customization Improved upload to builder UI, made unfinished features blue, and added the option to select a different door handle for modules that have handles Silasmoth committed last month	3279172	

Commits on Jul 12, 2024

4 new modules and several bugfixes Silasmoth committed last month	5cab37d	
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Next, I was able to properly fix the black edges problem, along with some other bugs. I also added 4 new modules. For uploading the project to the server, there is now a preview image of the project, along with all of

the generated statistics. I also added more options for choosing drawer handle types.

At this point, it was clear that there would not be enough time to complete all of the features I had originally planned. Rather than removing the unfinished features I decided to leave them in, but to make them a different color to indicate that they were not finished. This color distinction also meant that I could add buttons for “fake” options that I lacked the skills to code or had previously removed due to time limitations.

Commits on Jul 22, 2024

Added orthographic viewing options, and added another example project, and viewport camera bug fixes

you can pan and zoom in plan and elevation view, and rotating the camera is no longer impacted by screen resolution

28e53fb

Silasmoth committed last month

Although the target audience for the software was people without technical modeling skills or previous design experience, most of the people who tested it were fellow architecture students and architects. For the sake of those users, as well as the builders, I decided to add the option to view the project in an orthographic plan and elevation view, in addition to the 3D preview. While adding these other viewing modes I noticed that my previous mouse control system was impacted by screen resolution - when moving the mouse on a screen with twice the resolution, the model would spin twice as fast. This was far more noticeable when using the mouse to pan in orthographic view, so I took the time to fix it.

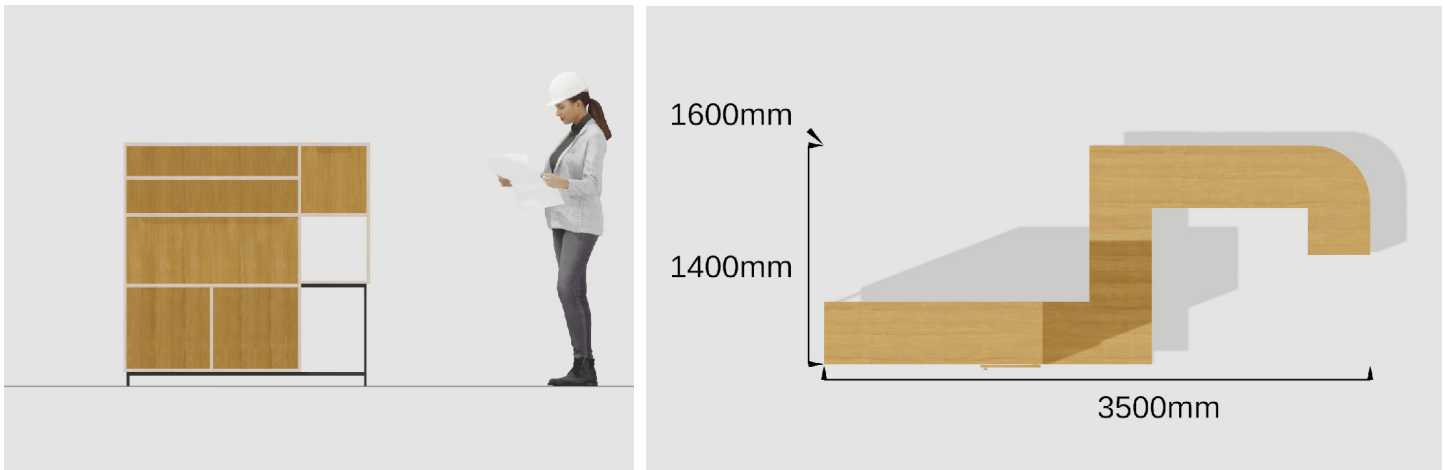


Figure 37. Elevation and plan view modes

Commits on Aug 6, 2024

Added touch control support, and added automatic recentering

Silasmoth committed last week

9de584c

Up until this point all development and testing were being done on a Windows computer, but for the sake of accessibility (which was one of the key software values determined in section 1.2 and expanded upon in Appendix A.2.1), and for the sake of circulating a demo in person I decided to make versions of the software that could also run on Mac, Android, and IOS. Porting the software to Apple computers was fairly straightforward; Unity makes it easy to switch platforms at any time in development, although some specific features that involved saving and loading files would need to be rewritten, as file structures are done differently with Apple. Getting the software to run on mobile devices was more complicated because the entire interface and viewport movement would need to be rewritten with touch controls in mind. Both Android and IOS also have their unique file structure so loading and saving would need to be rewritten for each of them as well.

Saving and loading files was used in several parts of the software but for the sake of demonstration, I decided that the most important part was when opening example projects. To keep the example projects working without having to recode the entire file saving/loading system 3 times for Mac, Android, and IOS I took the shortcut of

simply pasting the entire binary representation of each example project directly into the code itself. In the long run, this is really bad practice but for the sake of creating some working demos, it's good enough.

As for adding touch controls, luckily I only had to add them once since both Android and IOS work the same way in that regard. For orbiting the camera I went with a single-finger swipe, and a two-finger pinch for zooming in and out. Selecting modules is done by tapping them with one finger. Unfortunately, the interface I made was meant for larger screens, so while the software does work on mobile phones, it looks a lot better on tablets. This update also added several improvements that had been requested by testers, including the option to automatically recenter the furniture in the center of the screen, and the option to change the surface finish of each module individually.

 Commits on Aug 7, 2024

Added undo system and other UI improvements

 Silasmoth committed last week

4e45d45   ...

After some testing of the software on a tablet by myself and others I found that making mistakes was far more common than on a desktop computer. All the buttons were made slightly larger to help prevent missed inputs, and an undo/redo system was added for when mistakes do happen. The undo system was also added to the desktop versions with the standard ctrl z shortcut.

C Existing Software Solutions

This section includes existing software solutions that share similarities to mine in terms of functions or target audiences. I collected information on each one, relating to the attributes outlined in section 1.2. For each program, I took note of particularly successful features that I could implement into my solution, as well as any problems I found while using them.

C.1 Ikea Kitchen Planner

Ease of access: This is a free program, which is available directly in a browser⁴ and only requires an account when saving a design. As it is online an internet connection is required to use. This software is extremely accessible.

Ease of use: This software is extremely intuitive and takes no time to learn. The main features for ease of use are: drag and drop modules directly into the room, drag modules after being placed, automatically snap modules together, automatically snap modules to the floor and wall, multiple mouse buttons work for viewport navigation (left-click, right-click, middle mouse).

Depth of user control: The user has full control over the base room shape, but the furniture modules are not customizable in any way and are limited to the Ikea catalog. Because of this, the software does not add any real customization capabilities compared to just going to the store and buying the components off the shelf.

Responsiveness: I found there was always a slight input lag, but overall smooth and responsive movement, on a relatively high-end laptop (the same laptop was used for all testing, CPU: i7-8750H, GPU: GTX 1070, mem: 16 GB DDR4).

Visual feedback quality: Offers both 2D view and 3D view with flat materials and basic directional lighting. No AR view. A dimensioned line drawing can be exported at the end.

Scope of Capabilities: Modeling capabilities are limited to using preset components, no 3D model export capability, no 3D model import capability, plan and elevation line drawing export, no CNC mill gcode generation, exact pricing provided, no material usage display, includes component list, and can produce low-quality renders.

Other notes: This relatively new creation by Ikea is an interactive web-based design tool for creating kitchen layouts using furniture from the IKEA catalog. It has an intuitive 3D viewport and lets the user input room dimensions at the beginning of the process. The act of moving and rotating objects is super easy, and it has built-in snapping. One drawback is that since it uses the preset Ikea catalog, rather than having a few editable furniture pieces, it has a massive catalog of preset furniture. This means that there is a multi-step dropdown menu hiding the furniture component pictures. I think it would be a lot more fun to use if there was no menu and there was a smaller selection of components easily visible.

C.2 ShelfHelp

Ease of access: This is a free program, which is available directly in a browser⁵ and does not require any account. As it is online an internet connection is required to use. This software is extremely accessible.

Ease of use: This software is extremely intuitive and takes no time to learn. The main features for ease of use are: changing dimensions directly in the 3d view without having to type in a specific number, starting with an already completed shelf to show its capabilities, showing dimensions directly in the viewport, allowing you to switch

⁴ Ikea. "IKEA Kitchen Planner." Accessed October 2, 2023. <https://kitchen.planner.ikea.com/ca/en/>.

⁵ White, Ana. "Free, Easy to Use Woodworking Design Tool." Shelf Help. Accessed September 29, 2023. <https://shelfhelpnow.com/pages/shelf-configurator>.

between shelf types after placing them (door or no door).

Depth of user control: The user has no control over the room, but has full control over the exact dimensions of the furniture, except depth where there are 3 fixed options. The shelf types themselves are extremely limited.

Responsiveness: This program was perfectly responsive and had very smooth movement.

Visual feedback quality: Offers 3D view with flat materials and basic directional lighting but no 2D view. No AR view. An optional back wall can be shown for wall-mounted shelves.

Scope of Capabilities: Modeling capabilities are limited to adding and removing dividers and shelves to a rectangular layout, no 3D model export capability, no 3D model import capability, plan and elevation line drawing export, no CNC mill gcode generation, no pricing estimates provided, material usage stats are provided, includes a component list with dimensions and quantities, and can produce low-quality renders.

Other notes: This site is in many ways the closest to what I would like to create. Using an interactive tool, the user defines the shelf dimensions they want and then orders the components. It's very simple and easy to use, (although a bit limited in what is possible), and I would argue the best part is that besides offering to sell you the pieces, you can also download the design yourself for free and build it without having to pay. That said, I was unable to download my design so that feature may no longer work. The site is also no longer accepting orders at the moment.

C.3 String Furniture

Ease of access: This is a free program, which is available directly in a browser⁶ and only requires an account when saving a design. As it is online an internet connection is required to use. This software is extremely accessible.

Ease of use: This software is fairly intuitive and only takes a bit of time to learn. The main features for ease of use are drag-and-drop modules into place and a fixed view that always shows the entire project.

Depth of user control: The user can only place modules in certain predetermined grid positions, and the modules can only be customized through a selection of material finish.

Responsiveness: This program was quite responsive except for a noticeable 1-second lag after placement of every module.

Visual feedback quality: This program only offers a fixed diagonal view of the project with no perspective. The materials are flat and there is no lighting. There is no AR view but there are photographs of example configurations.

Scope of Capabilities: Modeling capabilities are limited to placing modules in positions on a grid, with only 2 dimension options, no 3D model export capability, no 3D model import capability, 3d view export, no CNC mill gcode generation, exact pricing provided, material usage stats are not provided, includes component list, and cannot produce renders.

Other notes: This design tool is for the wall-mounted String System furniture kit. To use the tool the user must drag and drop components in a certain order, which could be communicated more clearly. The diversity of shelf types is quite impressive and makes the system useful in many situations. The bay dimensions are fixed, and all of the components must be purchased from the company

⁶ "Build Your Own Custom-Made Shelf - String Furniture." Accessed September 29, 2023. <https://stringfurniture.com/build-your-own?room=outdoor>.

C.4 Roomle - Regalsystem LINE

Ease of access: This is a free program, which is available directly in a browser⁷ and only requires an account when saving a design. As it is online an internet connection is required to use. This software is extremely accessible.

Ease of use: This software is fairly intuitive and only takes a bit of time to learn. The main features for ease of use are: starts with a complete example to start and show off capabilities, shows a preview image of all possible material finishes, uses icons for clean UI, with text that only appears when hovering over a button to clarify what it does, toggle option for showing measurements directly in 3d viewport and option for full screen.

Depth of user control: The user can only place modules in certain positions, and the modules can only be customized through a selection of material finish.

Responsiveness: This program was very laggy, to the point where it made placing modules inconsistent.

Visual feedback quality: This program only offers a 3d view, which has basic materials, ambient lighting effects, and reflections. This program also provides the option to view the furniture in AR, although getting it to work was a bit frustrating.

Scope of Capabilities: Modeling capabilities are limited to placing modules in predetermined positions with no module customization options, no 3D model export capability, no 3D model import capability, 3d view export, no CNC mill gcode generation, exact pricing provided, material usage stats are not provided, includes component list, and can produce low-quality renders.

Other notes: This company specializes in making product viewers and configurators. Many of the configurators I found were developed by this company. They also create augmented reality solutions that allow customers to view products through their mobile cameras. As a company that exclusively makes these types of tools, they have refined their interfaces to be extremely user-friendly and robust.

C.5 Roomle - Moebe

Ease of access: This is a free program, which is available directly in a browser⁸ and lets users save designs as a link without having to create an account. As it is online an internet connection is required to use. This software is extremely accessible.

Ease of use: This software is fairly intuitive and only takes a bit of time to learn. The main features for ease of use are: starts with a complete example to start and show off capabilities, shows a preview image of all possible material finishes, uses icons for clean UI, with text that only appears when hovering over a button to clarify what it does, toggle option for showing measurements directly in 3d viewport and option for full screen.

Depth of user control: The user can only place modules in certain positions, and the modules can only be customized through a selection of material finish.

Responsiveness: This program was very laggy, to the point where it made placing modules inconsistent.

Visual feedback quality: This program only offers a 3d view, which has basic materials, ambient lighting effects, and reflections. This program also provides the option to view the furniture in AR, although getting it to work was a bit frustrating.

Scope of Capabilities: Modeling capabilities are limited to placing modules in predetermined positions with no

⁷ "Roomle 3D Shelves Configurator." Accessed September 29, 2023. <https://www.roomle.com/en/demos/shelves>.

⁸ moebe.dk. "Build Your Own | MOEBE Shelving System." Accessed September 29, 2023. <https://moebe.dk/pages/configurator>.

module customization options, no 3D model export capability, no 3D model import capability, 3d view export, no CNC mill gcode generation, showed “calculating pricing” but never actually did, material usage stats are not provided, includes component list, and can produce low-quality renders.

Other notes: Moebe is a Danish furniture designer who makes extremely elegant and minimalistic furniture. Their design tool (created by Roomle) is equally as minimalistic. The tool is somewhat limited in what can be changed, for example, the shelves snap to predefined increments, and the bay sizes are fixed.

C.6 Create-A-Kitchen

Ease of access: This is a free program, which is available directly in a browser⁹ and only requires an account when saving a design. As it is online an internet connection is required to use. This software is extremely accessible.

Ease of use: This software is extremely intuitive and takes no time to learn. At its core it does everything the same as the Ikea kitchen planner: the main features for ease of use are: drag and drop modules directly into the room, drag modules after being placed, automatically snap modules together, automatically snap modules to the floor and wall, multiple mouse buttons work for viewport navigation (left-click, right-click, middle mouse). What separates this from the Ikea kitchen planner is the option to automatically generate a layout based on a room floor plan.

Depth of user control: The user has full control over the base room shape, but the furniture modules are not customizable in any way and are limited to the cabinets.com catalog.

Responsiveness: I found there was always a slight input lag, but overall smooth and responsive movement. The automatic layout generator took a few seconds to complete.

Visual feedback quality: Offers both 2D view and 3D view with flat materials and basic directional lighting. No AR view. A dimensioned line drawing can be exported at the end.

Scope of Capabilities: Modeling capabilities are limited to using preset components, no 3D model export capability, no 3D model import capability, plan and elevation line drawing export, no CNC mill gcode generation, exact pricing provided, no material usage display, includes component list, and can produce low-quality renders.

Other notes: This tool looks pretty much identical to the IKEA kitchen planner, so I am positive it was made by the same developer. It uses the same floorplan drawing tool that the IKEA kitchen planner uses. The tools differ in that some of the features are not working correctly in this tool, both the pricing calculator and the component list would not load. One thing that this tool has that the IKEA kitchen planner doesn't is an automatic furniture layout generator. It takes the base floor plan that you draw and tries to fill it with kitchen cabinets and appliances. It even generates a couple of different options. When I changed the floor plan to something different than the default rectangular one it starts with the results were less successful. It cannot generate anything that works with angled walls.

C.7 Blum E-Services

Ease of access: Although this is a free service, which is available directly in a browser¹⁰, it requires an account to use which takes a couple of minutes to set up. As it is online an internet connection is required to use. This software is somewhat accessible.

Ease of use: Compared to the other furniture configurators examined so far this one is much more complicated.

⁹ “Create-A-Kitchen” Accessed August 10, 2024. <https://www.cabinets.com/createkitchen/blank-slate>.

¹⁰ “Blum E-SERVICES.” Accessed August 10, 2024. <https://e-services.blum.com/main/#>.

That said it is still far easier to learn than typical standalone software. The main ease-of-use feature is that the user drags and drops panels rather than full modules. This allows for much greater control at the cost of slower modeling speed.

Depth of user control: Not only does the user have full control over all of the dimensions, but they can also control the hardware and finishes.

Responsiveness: The viewport was very responsive, but lags for a second every time an update or change is made.

Visual feedback quality: Offers both 2D view and 3D view but no material previews or lighting. No AR view. A dimensioned line drawing can be exported at the end. A very cool feature was the ability to show an exploded view that separates all components.

Scope of Capabilities: Modeling capabilities are very in-depth and include not only dimensions but hardware and materials, 3D models of both the hardware as well as the entire furniture can be exported, and 3D models can be imported but only from their own file type, plan, and elevation line drawing export, CNC mill gcode generation, no pricing provided, material usage display, includes component list, and cannot produce renders.

Other notes: This tool was very powerful and is the first free in-browser tool I could find that had the option to export the furniture model in a format that I could then import into my 3d application of choice. I could see this as being useful from an architect's point of view as a fast way to model more custom millwork. Normally when I do interiors I find myself using pre-modeled furniture, or when I do model anything custom I skip over a lot of the finer details. One downside to this tool is that although it's free you have to go through a lengthy account creation process and sign in every time you want to use it. An account makes it easier to do cloud saves but I think the way other tools did it where you only had to make an account at the time of saving was better, and even better than that are the times when the "save" function just gives you a link straight to your design.

C.8 SmartDraw

Ease of access: This is a free in-browser¹¹ program, and does not require an account or a download to use. As it is online an internet connection is required to use. This software is very accessible.

Ease of use: This is one of the easiest tools to use and takes no time to learn. It has two features that make it easy to learn: drag and drop items onto the canvas and scale items directly on the canvas.

Depth of user control: The user can only place images of shelves together and scale the images, the tool is completely 2d.

Responsiveness: The viewport was very responsive, although this should be expected from such a simple tool.

Visual feedback quality: Only offers a 2D view, with the option to export the 2d image. No other information is generated.

Scope of Capabilities: The least capable program I tested, this software only lets you drag and drop 2D images together onto a canvas. The images can be scaled but they are stretched uniformly resulting in inconsistent material widths and dimensions.

Other notes: This was the easiest tool to use for creating a shelving design but also the least useful, it's only 2d and all you can do is drag around some premade images and stretch them. the images are not set up using a 9 tile system so they get distorted when stretched. There are also no good measurement tools.

11 "SmartDraw." Accessed August 10, 2024. <https://app.smartdraw.com/editor.aspx?templateId=c8e1ed05-1ba9-43e9-808b-ddc1f802a461&flags=128>.

C.9 Microvellum

Ease of access: This is the first paid software I looked at, the pricing of which was easily found, requiring one to contact their sales team. A license to use this software costs tens of thousands of dollars, but a free 30-day free trial is available. The software is run locally and requires an account to use. This software is extremely un-accessible

Ease of use: Using this software requires extensive 3D and 2D modeling experience, which most people will not have. One usability benefit of this software is that it is a package that can handle all aspects of the millwork pipeline.

Depth of user control: The user has complete control over every single detail, every aspect of the design can be completely custom and has no limitations.

Responsiveness: I was unable to test the software on my computer due to its inaccessible nature, but the minimum specs given on their website¹² are not particularly demanding and would be able to run on my testing laptop.

Visual feedback quality: This software offers both 2D and 3D views, as well as fully rendered views, wireframe views, and individual component views.

Scope of Capabilities: This program can be used to model pretty much anything, can export 3D models, import 3D models, Export 2D drawings, generate CNC mill gcode for components, provide pricing information, provide material usage, create component lists, and create high-quality renders.

Other notes: Microvellum was the software package that both millwork facilities that I visited used. I was unable to find exact pricing on their website, but I did find one person online saying that the cost of all the modules was around \$30'000. Microvellum can handle all aspects of the millwork process including pricing, modeling, rendering, and factory floor management. The only time when purchasing it would make sense would be for large millwork facilities, like the ones I visited. I was able to see the software in action during my visit to Provincial, and from what I saw it looked very similar to AutoCAD, with some extra functionality specific to woodworking. There are other very similar programs from different developers such as Cabinet Vision Pro but they all share the same challenges of high complexity and high cost.

C.10 Rhino 3D

Ease of access: This software is paid and can range in price from \$200-\$1000 depending on if the user is a student or not¹³. This software works offline but requires an account to use. This software is accessible to anyone involved in the field of design, but not very accessible to the general public.

Ease of use: Using this software requires extensive 3D and 2D modeling experience, which most people will not have. The software does follow 3D modeling software conventions, so it's easy to learn if you already have experience with other modeling programs.

Depth of user control: The user has complete control over every single detail, every aspect of the design can be completely custom and has no limitations.

Responsiveness: This software is very responsive, unless the viewport is set to raytraced or if the design is exceptionally complicated.

¹² "Microvellum Production System Requirements." Accessed August 10, 2024. <https://community.microvellum.com/portal/en/kb/articles/microvellum-production-system-requirements>.

¹³ "Rhino - Rhinoceros 3D." Accessed August 10, 2024. <https://www.rhino3d.com/>.

Visual feedback quality: This software offers both 2D and 3D views, as well as fully rendered views, wireframe views, and individual component views.

Scope of Capabilities: This program can be used to model pretty much anything, can export 3D models, import 3D models, Export 2D drawings, generate CNC mill gcode for components with free add-ons, does not provide pricing information, can provide material usage with a bit of manual work, cannot directly create component lists, and can create high-quality renders.

Other notes: While Microvellum was an industry-standard software for use by millworkers, Rhino is an industry-standard software used by architects. The scope of capabilities is way greater than what this thesis is aiming for, but to integrate with existing industry standards it's important to make sure that my software can export in a way that they can import. There are other very similar programs from different developers such as Blender, 3DsMax, and Solidworks which differ in price but are otherwise pretty similar so I decided not to include them.