Design of foldable interlocking 3D structures in mountboard for use in board game systems

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MASTER THESIS

Design of foldable interlocking 3D structures in mountboard for use in board game systems

Using laser cutting to explore new mechanisms in old products

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Abstract

The proliferation of commercial laser cutters has expanded the use of laser cutting technology to new markets, opening up new possibilities for small companies to innovate in their fields. This thesis aims to examine the use of laser cutting technology in the context of creating foldable 3D structures for board games and the resulting product development of these structures within a board game system.

Two cutting patterns for hinges made out of the paper-based material mountboard are researched and developed, following specifications set by the company the thesis is made in collaboration with. The hinge patterns are further implemented together with locking mechanisms in structure cutout patterns that allow different shapes of structures to be folded up from a flat plane. The structures are developed to work within a tiling grid system and exhibit properties that allow it to be used within a game board system being developed by the collaborating company.

The thesis concludes with a discussion on how the hinge and structure designs can be used in future applications as well as where further research in the subject is possible.

Keywords: product development, hinge construction, laser cutting

Sammanfattning

Den ökade tillgängligheten av kommersiella laserskärare har utvidgat användningen av laserskärningsteknik till nya marknader och öppnat upp nya möjligheter för mindre företag att finna innovativa lösningar inom sina områden. Denna examensarbeterapport ämnar att undersöka användningen av laserskärningsteknik i samband med att skapa vikbara 3D-strukturer för brädspel, och den resulterande produktutvecklingen av dessa strukturer inom ett brädspelssystem.

Två skärmönster för gångjärn gjorda av pappersbaserade materialet "mountboard" undersöks, enligt specifikationer som fastställts av företaget som rapporten är gjord i samarbete med. Gångjärnen implementeras tillsammans med en låsmekanism i olika skärmönster för strukturer, som möjliggör att strukturer i olika skepnader kan vikas upp från en plan form. Strukturerna utvecklas för att tillsammans passa in i ett rutnätssystem och sedan användas i ett spelbrädessystem som företaget utvecklar.

Rapporten avslutas med en reflektion om hur gångjärns- och strukturdesignerna kan appliceras i framtida produkter, samt var det är möjligt med ytterligare forskning inom ämnet.

Nyckelord: produktutveckling, gångjärnskonstruktion, laserskärning

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Special thanks to:

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Lund, May 2021

Tobias Widmark

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1 Introduction

As commercial laser cutting machines become more affordable, more industries are able to utilize the unique properties of the tool to create new products and designs. The benefits of fast prototyping and the digital interfacing of the tool means that, compared to contemporary methods, changes to a product's design can easily be made during development.

The degree project aims to examine the use of laser cutting to create foldable structures using mountboard, to be used in the context of a board game system. It will show the development of a hinge mechanism to facilitate folding, the application of the hinge and supplementary parts to enable structures to be deployed, and the design of the structures' layout to be compatible with a board game system's requirements. The project culminates in a set of laser cutting patterns for the company's use, with instructions on how to create new patterns using a set of hinge and structure blueprints.

The thesis is divided into five major parts; Background, Theory & Methodology, Hinge Construction, Structure Design and Discussion. The first two parts tackle the research and motivation behind the project, while the next two focus on the product development and design, as well as conveying the results. Finally, the discussion reflects on the project, shows where future research can be done.

While the degree project is primarily focused on how this research can be used in a specific board game system, the work conducted in this thesis is applicable to other products and materials as well. The hinge mechanisms, structure components and layout designs in this thesis have possible uses outside the scope of this product development.

The degree project is performed in collaboration with Shearwood Games. The company is responsible for supplying materials, specifications relating to the board game system used, and direction for how to best comply with board game design ethos. The hinge mechanism and structure design in this project are only developed so far as to fit the company's requirements; any further mechanical analysis is outside the scope of this project.

2 Background

This chapter presents the current state of board game structures, why laser cutting is being examined and the goal of this project.

2.1 Board games & board game structures

Board games (or tabletop games) in this degree report are defined as games played with the use of a play surface in the form of a marked board, along with moveable pieces and/or cards. Common examples of board games include Monopoly, Clue, Pursuit and Settlers of Catan. While the play surface has no strict definition of shape, form or material this thesis will primarily look at those made up of mountboard, a material based on compressed layered paper. These paper-based boards are often coated in varnish or laminated to reinforce them, creating a smooth surface finish that allows for extended use [1].

There is nothing new about including structures in board games; tiny plastic houses are a staple in the modern Monopoly editions, and the game Arkadia published by Ravensburger released in 2006 with small structures to add height to its board [2]. It's rarer to see structures used to represent play area however. Some examples can be observed, such as the board game Mountaineers by Massif Games which features a large pyramid mountain that extends high from the base of the board [3], but these are far and few between.

More luck can be found in the adjacent world of tabletop strategy and war games where terrain plays a larger role. These games can rely on player-built terrain or manufactured box sets to create environments, with plastic parts to be painted by the customer [4]. Since these sets are created to be used over long periods of time they can end up being problematic to store without taking up a substantial amount of space, either by being difficult or impossible to fold or take apart once set up.

This is a problem that has not gone unnoticed. There have been several attempts to tackle this issue by entrepreneurial hobbyists and many such products have been financed through crowdfunding platforms. Examples of these products will be examined in section 3.4.

2.2 Laser cutting

A laser cutter is a machine that uses its eponymous high-power laser to cut through material, being able to use computer instructions to achieve high precision, repeatable patterns and excellent finish. With the advent of commercially available laser cutters, the process of using lasers in machining has become a viable option for small companies and even individuals. Compared to other options like die-cutting, CNC milling and traditional cutting methods it is much cheaper to use laser cutting for prototypes and small-scale productions thanks to the comparatively low machine cost and ability to easily make changes [5]. These benefits are outweighed by the slow speed and long-term costs when doing larger productions, but it can be a valuable tool for entrepreneurs nonetheless. Acrylic, wood and paper-based materials are commonly used, though precautions need to be taken as the heat from the laser can create fumes and smoke that must be ventilated out [6]. As Shearwood Games only expressed interest in using a laser cutter for this project, the environmental impacts were not expressly investigated.

Most conventional laser cutters perform in a 2D plane; the laser cuts straight through the material, moving on an x-y axis (see Figure 2.1) . By alternating the power and cutting pattern most laser cutters also allow engraving into the surface of the material.

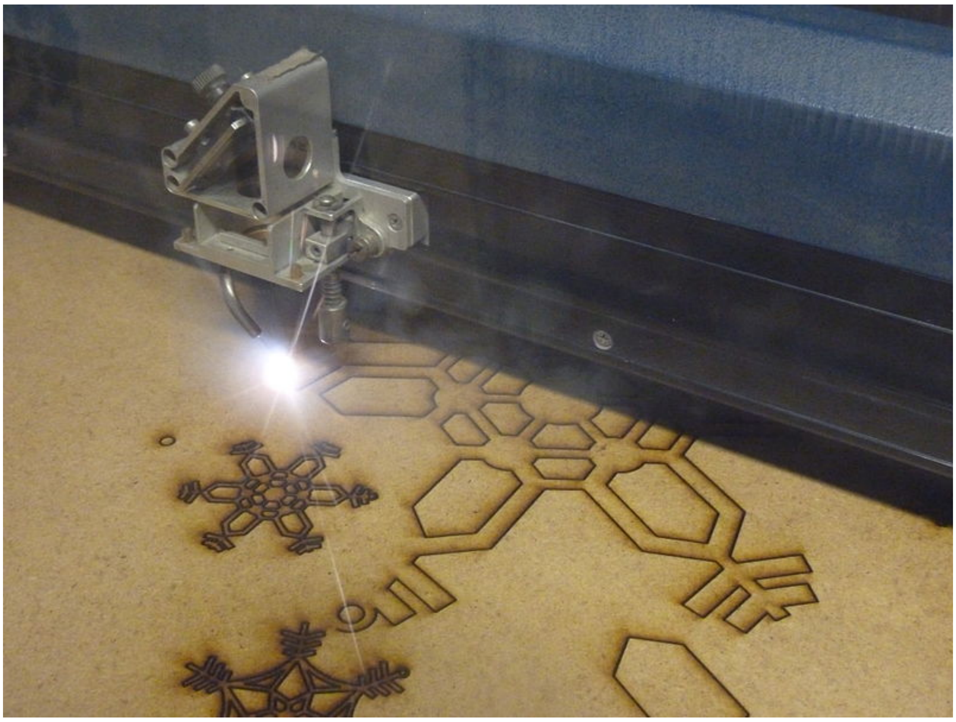

Figure 2.1 A laser cutter machine, cutting a snowflake pattern into MDF [7].

2.3 Project Phases

The project that this thesis is based upon can be divided into two distinct phases: Hinge Construction and Structure Design. The Hinge Construction phase focuses on the design and properties of the material's hinges. This includes finding an appropriate hinge pattern, determining the optimal proportions and reducing the risk of tears in the material. The Structure Design phase builds upon the work of the previous phase by examining how it can be applied in the context of a board game system being developed by Shearwood Games. This includes how the structures should fold, grid alignment and structure connection mechanisms.

3 Theory & Methodology

This chapter presents the methodology of the work done during this thesis, as well as the research the thesis is based upon.

3.1 Design Methodology

As with any product development project, the work conducted in this thesis is performed following certain design methodologies. This is done to ensure that the final result fulfills the requirements the product is set out to meet and the work is done in an efficient manner. While this project has not explicitly referenced the following methodologies the core concepts have been applied and used to guide the decision making during the design and prototype sections of the project. As the goal with the project has been to find a product that fulfills Shearwood Games' requirements most tests performed during this thesis have not been measured quantifiably, and instead decisions have been made based on observations of prototypes and feedback from the company.

The methodologies also make note of the importance of observing and testing with the end users of the product. This was done by Shearwood Games as user testing was outside the scope of this project, and any prototype created during the project was validated through them.

3.1.1 Double-Diamond Design Model

The Double-Diamond design model is named so after the "divergence and convergence" of the possibility space being considered during a design process. Initially the possibility space is widened as the core problem is examined, aiming to explore the underlying issues to see where a future solution would be the most effective. The possibility space is then constrained by focusing on a single problem statement, only to again be widened as a wide variety of solutions are considered. This concludes by singling out the favored solution, effectively forming a “double diamond” of how wide the possibility space is throughout the project timeline.

The reason why this design model is seen as effective is because it helps both free and constrain the designer; during the divergent phases, the designer is free to explore and cast a wide net of possible ideas and problem statements, while during the convergent phases the incorrect or faulty solutions are reduced until the best possible choice is determined. This keeps the designer from being distracted by previous ideas while simultaneously giving confidence that they are working on the correct problem. [8, p. 220-221]

3.1.2 Human-Centered Design Process

The Human-Centered design process aims to describe how to actually perform the steps seen in the Double-Diamond design model, represented in a more cyclical nature. It is an iterative design process; the result of one cycle acts as the starting point for a new cycle with the aim to improve based on feedback and testing. The process can be divided into four distinct parts: Observation, Idea Generation, Prototyping and Testing.

The Observation phase is primarily concerned with understanding the underlying problem that the designer is meant to solve, as well as how the eventual solution will be used/impact the user. This includes meeting, observing and talking to the people who will be affected by the solution. It is intended as a more hands-on and rapid examination compared to academic studies, bringing the designer closer to the subject at hand. While it can be likened to marketing, it is important to realize that marketing aims to figure out how to engage the user with the product and make them purchase it, while design wants to know how the user will use the product and what the core need is.

The Idea Generation phase is relatively straight-forward and, as the name suggests, is where problem solutions are created. The goal is to come up with many different ideas, with as little restraint as possible. Refining the ideas comes later, and even an idea that is impossible to implement on the surface may have helpful insights that can be applied to some solutions.

The Prototyping phase has the goal of finding out what ideas from the idea generation phase are valid enough to continue with. While the most bizarre ideas can likely be ruled out without necessarily prototyping them, many solutions can’t be validated or discarded unless some sort of simple prototype gives further insight into them. As per the definition of “prototype” it isn’t required to make a complete product; simplify where possible and simulate complex behavior using stand-in systems. The prototype is to be used in the next phase:

The Testing phase is where the prototyped idea is tested by the user and the designer evaluates whether the prototype is satisfactorily solving the user's core need through observing the tests. It is imperative that the person testing the prototype is from the group that will eventually use the product, and if possible try to have the test be performed in the correct environment as well. By observing the user interacting with the prototype in a natural way it becomes easier to discern where additional development is needed and by prompting the user to describe their experience it may give insight into problems that the designer wasn't even aware of. [8, p. 221-229]

As mentioned before, the Human-Centered design process is iterative. Once the testing phase is over, the cycle is repeated anew with new insights into the user, problem and solution. Due to this it is important that the cycle is kept short to allow for as many iterations as possible before the product is required to be completed. Sometimes it is not possible to have multiple cycles due to cost and/or time constraints, though implementing smaller iteration cycles where possible is always beneficial. [8, p. 230]

3.2 Folding patterns, mountboard or otherwise

Before any practical examination of folding mechanisms could take place, a thorough investigation of previously published research material was performed. Unfortunately, there was little information that could be found regarding the laser cutting process concerning folding mountboard or other paper-based materials, likely due to the lack of products where such a technique has been applied as well as other established methods already performing well enough. A common method of assisting in folding thick paper-based materials is die-creasing, a method which the company Tetra Pak has explored extensively in past student theses. This involves slightly breaking the material to distribute stresses in a favourable pattern, allowing a hinge to form without tearing the material [9, pp. 9-11].

Due to laser cutting being a popular choice for cutting metal sheets there are a few resources that contain information about how to cut for folding metal. These patterns are characterized by being dotted or dashed lines, either in just a single line or several lines parallel to each other [10], as seen in Figure 3.1. It is hypothesized that some of the patterns used to fold metal can be applied to mountboard as well, and can thus be used as a starting point for the practical tests in this project, as seen in section 4.2.2.

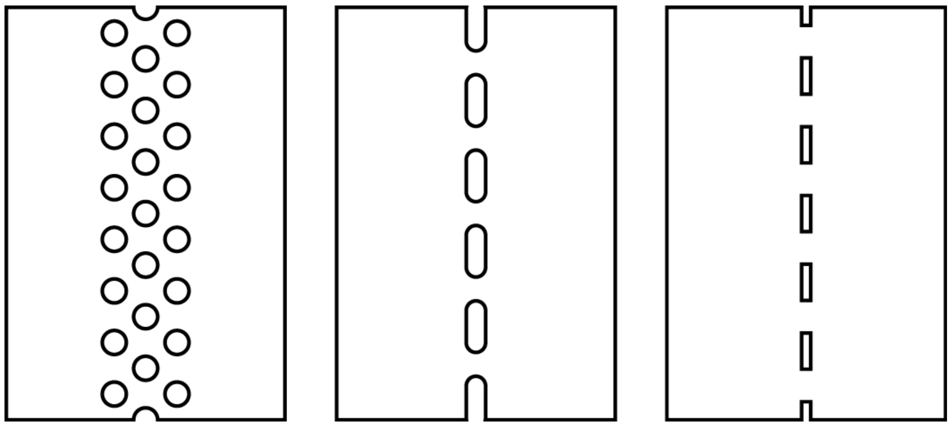

Figure 3.1 Example cutting patterns for foldable metal sheets.

3.3 Grain direction

Grain direction in paper is the phenomenon where the cellulose fibres that make up the paper pulp align in the direction of the paper machine's movement during manufacturing.

This influences the mechanical properties of the paper, providing higher stiffness in the direction of the grain and thus changing the behaviour depending on which direction the paper is folded [9, p. 9]. When the fold line is made perpendicular to the grain direction there's a higher risk of the material cracking and there's greater resistance. Therefore, it can be beneficial to fold paper parallel to the grain direction if a "clean" fold is desired [11].

Since mountboard is made up of layers of paper there's a risk that the grain direction influences the material as well. Should that be the case, it's imperative it's accounted for in the prototyping phase so that the final hinge design is not limited in its folding by the grain direction. This is further examined in section 4.2.1.

3.4 Board game properties

Since the product being developed in this project is intended to be used in combination with a board game system being developed by Shearwood Games, the company had specifications they desired to be fulfilled. Some of these specifications could not be met or had to face certain compromises during the course of the project, though they strongly informed decisions during the project process.

Grid size: The structures should incorporate a grid of squares, to be used for aligning miniatures that are to be placed on the board. The grid squares need to have dimensions of at least 25 x 25 mm to fit the miniatures.

Tiling: The grid needs to properly tile across structures. This means that two adjacent structures (for example, two rooms) need to have their interior grids line up with each other, even if the structures are of different shapes and/or sizes.

Visual Impact: Certain elements of the structure such as hinges or connective mechanisms may be deemed visually distracting since they are incongruent with the board game's setting. The visual impact of such elements should be reduced as much as possible, even if it may result in some reduction in mechanical properties. Ideally, the final hinge should have a maximum inner radius of 1.5 mm when bent 90 degrees.

Durability: The structures should be able to fold up and down at least 50 times without any major structural impact. Small scuffs and notches in the material are acceptable but should be kept to a minimum. The hinges should be able to support at least 90-degree bends, though if it's possible to enable further bending then that is appreciable. A casual user should be able to deploy a structure without accidentally destroying elements of it and the structure should be able to support its own weight even when held up in the air, folded or not.

3.5 Structure folding

It is not a new phenomenon to have a flat plane fold into a 3D structure, not even for board games. There are multiple products currently in development or on the market that employ systems that allow for such a feat, though often in relation to a strategy or wargame system. While none of the following examples use a cutting technique and instead rely on die-creasing, it can be useful to examine the various systems they've used for the overall structure. The folding mechanisms were evaluated based on watching video demonstrations, examining images and reading descriptions of the products they were implemented in. The products have been divided up into 5 different folding systems, described below. The only exception is the Flat fold, as it was derived as a conceptual idea rather than observed from an existing product.

3.5.1 Flat fold mechanism

Perhaps the most intuitive and easy to imagine, the Flat fold mechanism leaves the structure completely flat when unfolded, in the same state as it was when it got cut out of the material sheet. When deploying the structure the sides are folded up and then locked together by a locking mechanism, resulting in the final structure. This locking mechanism could for example be achieved through friction fit or by using clips. The Flat Fold mechanism requires the user to fold up every wall individually, though it does create a very flat (if large area) product when in its unfolded state.

Pros:

- Intuitive; where there is a hinge, a wall is meant to be folded up.
- As thin as possible when unfolded (the material's thickness).
- Easy to create structures all in one piece.
- Very simple to include a floor as the walls can be attached to it directly.

Cons:

- Requires a large area when unfolded.
- The locking mechanism needs to be robust to keep the walls in place.
- The final structure size is limited by how large the unfolded area is.
- Complex structures may be harder to construct, as there can't be any overlap in its unfolded state.

3.5.2 Pop-Up mechanism

Existing product(s): Upzone, Pop-Up Miniature Terrain Kit [12; 13]

Structures made with the Pop-up mechanism are deployed very quickly through a method reminiscent of a children's pop-up book, where the structure's walls are attached to a base plate being folded up, pulling the walls up along with it.

Pros:

- Very efficient; a structure is deployed through the simple action of folding up the build plate.
- Easy to use and requires very little extra input from the user.
- Allows for complex structures, possibly very complex structures.
- Depending on the structure's design the roof can be removed or be absent.

Cons:

- There's little modularity since each structure is stuck to the base plate.
- Taller structures need to have an overall symmetrical shape over the fold line, otherwise the action of folding up the build plate creates uneven forces onto the structure's material, risking breaking the structure or not having it fold up at all.
- The pop-up book aesthetic may give a childish impression.
- Can only be used with thin materials as complex structures are bound to have several layers when folded together.
- The folded structures may have an uneven or wobbly look due to material properties and the need for folding tolerances not fully deploying the structures.
- Structure sizes are limited by the base plate.

3.5.3 Thin box mechanism

Existing product(s): Acid House Terrain, Tabletop Towns, Collapsible Construction [14; 15; 16]

The thin box mechanism creates structures similarly to boxes; four sides of a cube are connected, with the top and bottoms either missing or connected to just one side. This allows the cube to be easily collapsed. Further rigidity can be made by inserting another box into the first one, resulting in the inner box acting as a stabilizer (and rooftop). It's also possible to use this method to create buildings in a manner similar to traditional box mechanisms, with flaps that fold into the structure to create rigidity.

Pros:

- Often intuitive, parts are either few or come attached where they need to go.
- Allows for large structures with simple designs.
- Feasible with thicker materials as well.

Cons:

- Does not allow for complex structures; simple box shapes seem the most efficient.
- Can be a little bit fiddly to put together.
- Requires an extra manufacturing step, connecting the box sides somehow (for example with glue).
- The roof is a requirement for the structure's rigidity.
- Can feel slightly cheap/simple in its design.

3.5.4 Thick box mechanism

Existing product(s): Mad Bob Miniatures' Folding Terrain [17]

The thick box mechanism treats the walls as solid, non-bending parts, where the hinges are separate components. The structures use a mechanism similar to the thin box mechanism for its walls to fold flat, though with hinges instead of creased paperboard. Additional floors can be stacked by slotting them into holes in the walls, with roofs simply being placed on top.

Pros:

- Intuitive to put together, requires relatively few parts for a complete building.
- Extremely rigid.

- Allows roofs to be removed or absent.
- Easy to make modular and connect buildings with.
- The thickness allows for smaller 3D details to be included.

Cons:

- Creates very thick pieces when folded down.
- Multiple manufacturing steps to create a structure.
- Hinges add to the part costs.

3.5.5 Clips

Existing product(s): Battle System modules [18; 19]

The final mechanism uses flat pieces that are connected through the use of plastic "clips", where for example an L-shaped corner of a building is made up of two walls connected with an L-shaped clip. The difference to the full flat mechanism is that the pieces that make up the structure (walls, floors, ceilings) are separate parts, not connected in material. One can also use the sturdiness of the material to connect pieces through notches, though this is likely best used for smaller structures to avoid material strain. This effectively removes hinges altogether, though the need to connect all the walls individually greatly increases set-up time.

Pros:

- Very easy to create complex structures as it does not rely on folding to the same extent as other options.
- Plastic parts could likely be created with 3D printing.
- Can easily create modular structures by stacking floors.
- Allows roofs to be removed or absent.

Cons:

- Requires much more set-up time as the parts need to be connected by hand.
- Many parts, especially for the more complex structures.
- Tiny parts can be difficult to put together.

3.6 Connective Mechanism Types

When a structure has been folded up, the intention is to be able to connect it to other structures. This would be to, for example, simulate the rooms of a spaceship, with each structure making up a room. The connective mechanism should allow for modularity when putting rooms together and a certain amount of stability, while still being easy to use. There's no need to provide strong structural support and no expectation to have the structures remain in place when they are lifted; as long as the structures can stay connected after getting bumped or moved along a flat surface the connective mechanism is sufficient.

The following types were hypothesized for the connective mechanism:

3.6.1 Mountboard Clip

This mechanism would use clips made out of mountboard to connect the walls of adjacent structures. Two notches on either side of the clip slot over the walls and keep them together. This method is primarily limited by the material properties as well as being created out of a single plane. Because of this, consideration needs to be taken regarding the 2D design of the clip.

Pros:

- Uses the same material and manufacturing method as the structures.
- Simple to attach and remove.

Cons:

- Limited by being cut out of a flat sheet.
- Thickness limited by the thickness of the mountboard.
- May risk failure due to inadequate material properties.
- Would need notches in the structures' walls to keep the walls from sliding parallel to each other.

3.6.2 3D Printed Clip

Similar to the Mountboard Clip, this mechanism would use 3D printed clips to attach the walls of the structures. This would eliminate the limits put on thickness and allow for a more complex clip. Since 3D printable plastics are often stronger than mountboard it would likely lead to a more durable clip as well. It is possible that this solution could be manufactured using injection molding as well, should it be a more cost-efficient solution compared to 3D printing.

Pros:

- More durable than mountboard solutions.
- Simple to attach and remove.
- Can have a more sophisticated design.

Cons:

- May still need notches in the structures' walls.
- Added manufacturing costs due to being made of a more complex material.
- Company is not interested in looking at injection molding solutions at this stage.

3.6.3 Wall Attachers

This mechanism would use the wall pieces of the structures and extend them, allowing them to slot into holes made in other structures' walls. Since it simply builds upon the structures that exist there would be no need for extra parts, though there may be limits depending on the available area on the structures' mountboard sheet as well as aesthetic problems.

Pros:

- Uses the same material and manufacturing method as the structures.
- Has no additional parts; are incorporated into the structures directly.

Cons:

- Might be difficult to attach the walls without some sort of locking mechanism.
- Forces the outer walls of structures to be of consistent dimensions.
- Unused attachers might protrude from the structures in an unappealing way.

4 Hinge Construction

This chapter presents the research made during this thesis in regards to developing a mountboard hinge, including methods, results and brief conclusions.

4.1 Materials & Tools

This thesis was performed using the following materials and tools:

4.1.1 2 mm Mountboard

The primary material used is a 2 mm thick Oppboga Excellent® mountboard, manufactured by Oppboga. It is a stiff material made up of several layers of paper pressed together, with a smooth but semi-matte white surface on either side. Unfortunately, no technical datasheet containing relevant properties could be acquired from the manufacturer for this thesis.

4.1.2 Zing Laser Cutter

The laser cutter used during this thesis is an Epilog Zing 16 30W supplied by Lund University. It has a cutting area of 406 x 305 mm, however, due to a misalignment in the laser's mirrors the laser performed poorly in the rightmost half of the available cutting area during this project, drastically reducing its cutting capabilities. Due to this, only the left half (203 x 305 mm) was used. The kerf created by the laser cutter was approximately 0.5 mm; since this may vary between laser cutters, the project aims to develop a design that permits variations in the kerf width. The patterns created during this project were validated by the company on their laser cutter, to ensure that the malfunctions of the Epilog Zing did not produce unusable results.

Unless otherwise stated, the power settings used for cutting lines were the following:

Table 4.1 Epilog Zing 16 30W Settings

	Value
Speed	100%
Power	90%
Frequency	1000 Hz

4.1.3 Adobe Illustrator 2020

The cutting patterns were drawn in Adobe Illustrator 2020, which was also used to interface with the laser cutter. The lines to be cut were drawn in 0.001 pt width, though for the sake of visibility they will be shown with a wider thickness in the images of this thesis.

4.1.4 Solidworks 2020

Parts of the structures' cutout pattern were easier to simulate through 3D CAD models rather than calculating by hand (as seen in section 5.2.1.2). This was done using Solidworks 2020, though it could be substituted by any other CAD program with the same capability to flatten model surfaces.

4.2 Folding Mechanism Research

4.2.1 Grain Direction Test

Since the grain direction can have an adverse effect on the folding of paper, a simple test was performed to see if the mountboard material used during this project had this property. The pattern in Figure 4.1 was cut out of a mountboard sheet:

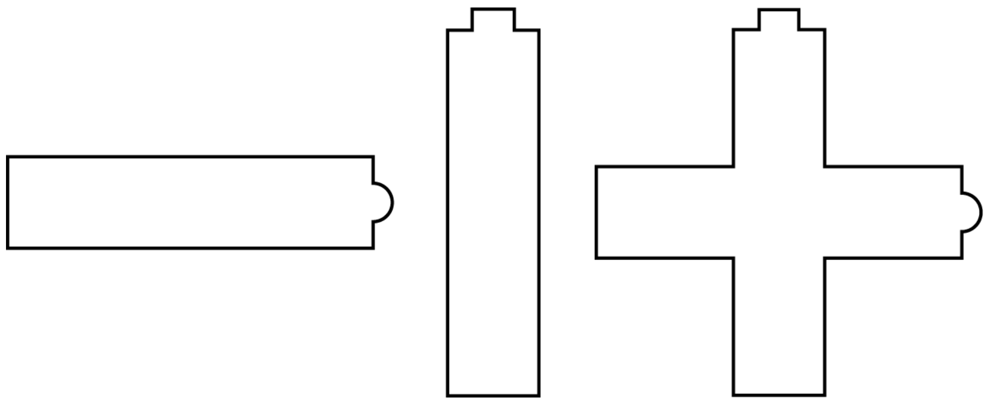

Figure 4.1 Grain direction test pieces, approximately 10 mm wide and 40 mm long.

Since the pattern features perpendicular pieces, if the material does indeed exhibit properties of grain direction one can expect more resistance when bending in one direction over the other. This ended up being true and noticeable even when bending them by hand, as when force was applied the vertical parts were rigid before suddenly snapping while the horizontal parts flexed more before gradually starting to tear.

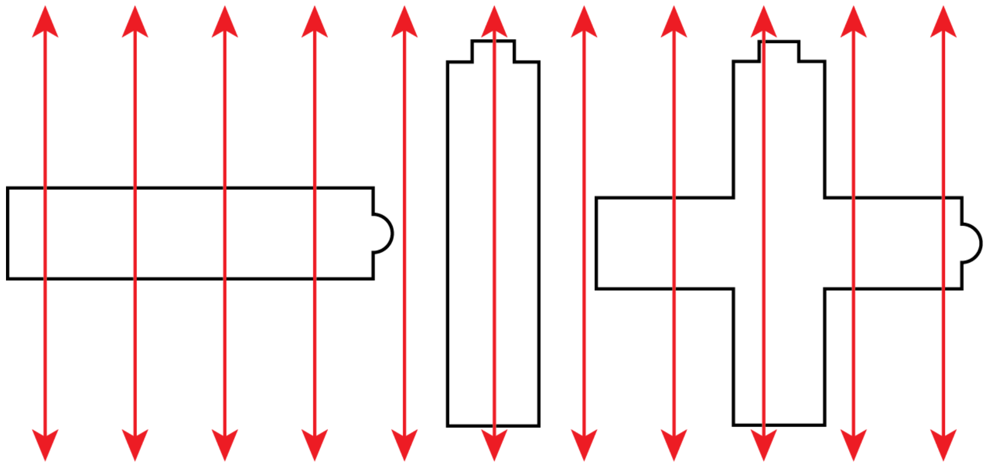

Figure 4.2 Grain direction relative to the test pieces.

Since the grain direction affects the flexibility of the material, it is important to account for it. Because folding perpendicular to the grain direction introduces the highest risk of failure, all hinges in the following sections will be made perpendicular to the grain. This is to assure that the hinges can handle the "worst-case" direction; if a hinge can manage a fold perpendicular to the grain direction, it should have no problem with a fold parallel to the grain. Note that while Figure 4.2 shows the grain direction vertically, this may not necessarily match the grain direction in other figures.

4.2.2 Initial Hinge Pattern Research

With the grain direction established and research performed on cutting patterns in other materials from section 3.2, it became possible to begin some preliminary tests to see if laser cutting mountboard could indeed be a viable method for hinge construction. An initial cutting test was performed, using patterns inspired by various metal cutting patterns featuring rows of circles and lines (see Figure 3.1 and Figure 4.3). At this point in time there was no certainty that these patterns could lead to desirable results, so this initial test was simply to try a wide variety of pattern shapes and then narrow in on potential patterns to see if any of them could be further developed into viable hinges (mirroring the divergence/convergence seen in section 3.1.1). While most of the patterns were inspired by the metal cutting patterns, there were also attempts to use straight lines with a weaker laser power to see if the cut created by the laser's kerf could work as a hinge.

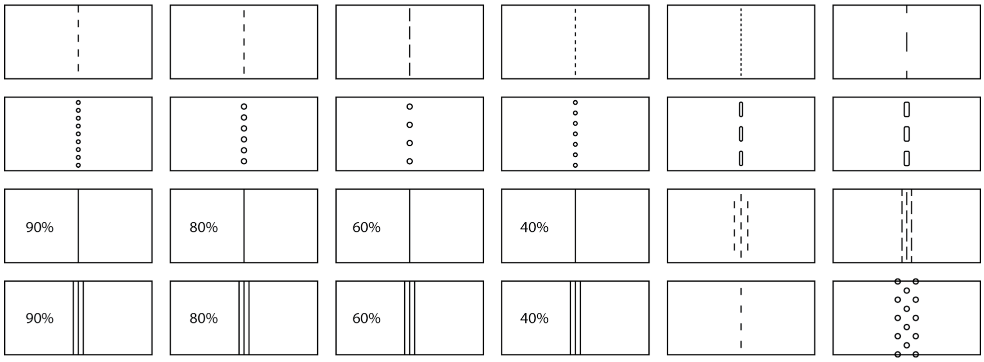

Figure 4.3 The initial cutting patterns used in the first pattern test.

The patterns were printed in the middle of a 40 x 20 mm rectangle, with the folds going perpendicular to the grain direction. The percentage values depicted in figure Figure 4.3 were not cut; instead, they indicate the power setting that was used when cutting the adjacent lines.

Unfortunately, almost all patterns proved completely unviable (Figure 4.4). Due to the many layers of paper material that make up the 2 mm mountboard they have very little elasticity, meaning that a lot of stress is introduced in the outer curve when attempting to bend the board.

Patterns that were structured in dotted single lines snapped almost immediately, the pattern only serving to provide failure points and weakening the material. The ones with multiple dashed lines fared slightly better and showed some flexibility before breaking, though the rigidness of the material meant that whenever a tear began to appear in the outer curve the hinge would eventually fail at that tear. This indicated a possible route to investigate further in the following tests.

The lines scored with a weaker cutting power proved very effective in creating clean bends when the lines were close together, looking both functional and aesthetically pleasing on the inner and outer curve. However, when even a little force was applied in the other direction the few layers that made up the uncut side proved far too weak; while this pattern could work well in a protected environment (like a display model) it was far too fragile to be interacted with (Figure 4.5).

There was also an attempt to use the laser cutter's engraving function. While it allowed for the possibility to have thicker lines that did not penetrate the paper, the amount of soot created, poor surface quality and folding difficulties meant this method showed little promise.

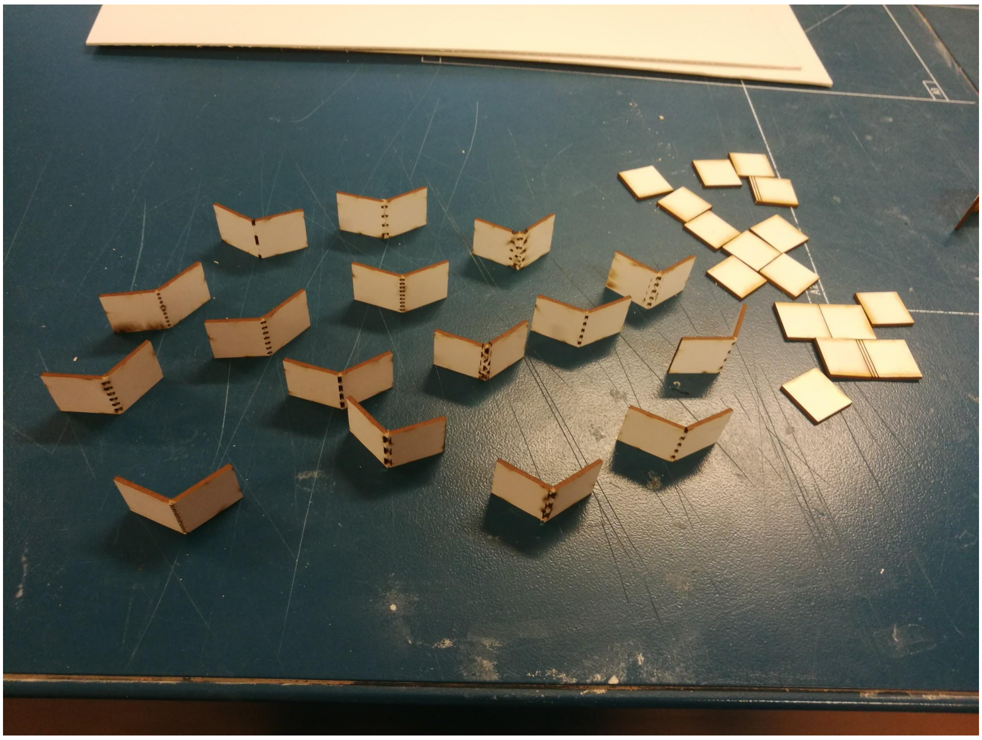

Figure 4.4 The pieces from the first pattern test, either partially or fully snapped.

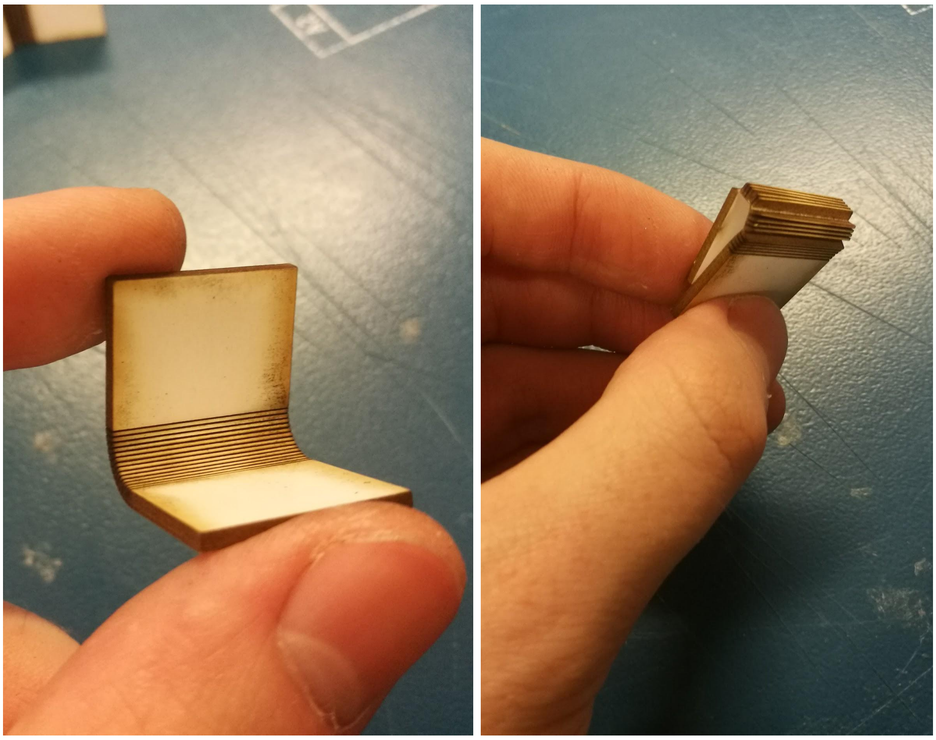

Figure 4.5 An example of having multiple lines cut into the mountboard, showing the flawed result.

As the patterns with multiple dotted lines hinted at a possible hinge solution, permutations of the patterns were created with multiple alternating lines, seen in Figure 4.6. While they all easily broke when twisted or pulled perpendicular to the pattern (Figure 4.7), their folding ability allowed for full 180 degree bends with few signs of failure. The brittleness of the patterns was hypothesized to be solvable by widening the distance between the dashed lines.

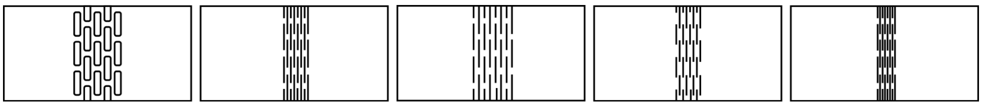

Figure 4.6 Patterns expanded upon after the first test, containing alternating patterns.

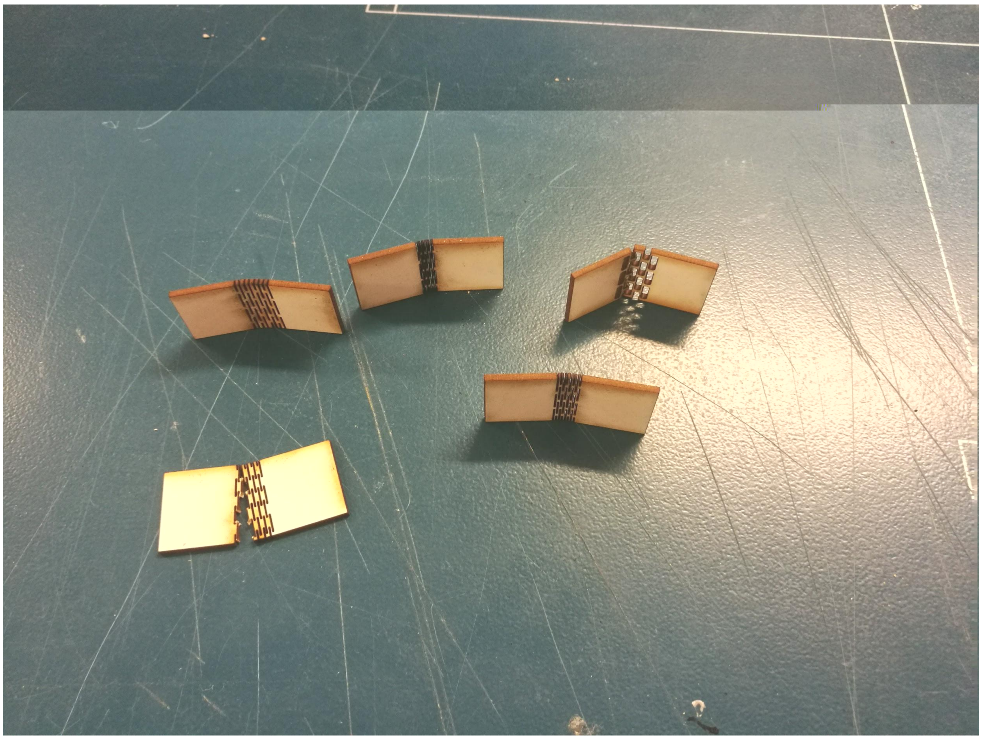

Figure 4.7 The alternating patterns from the previous tests after being bent.

The third test featured another array of alternating dashed line patterns (Figure 4.8). The key differences were how much the lines overlapped each other, the width between lines and which set of lines began at the outer edges of the hinge. From this test, it became evident that the more the lines overlapped the better; from observing how the patterns behaved when bent it appeared that the more two adjacent dashed lines overlapped the more flexible the hinge became. The hinge also seemed to perform better by having the outermost lines touch the edges of the test piece, instead of the innermost lines. Unfortunately, none of these hinges proved to function either as they were still very brittle.

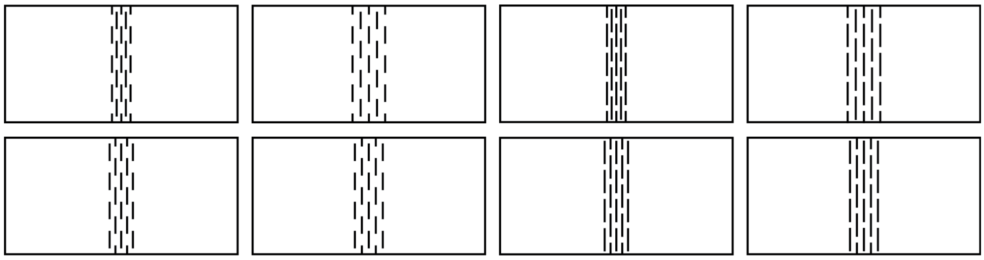

Figure 4.8 Alternating dashed lines patterns. Note that the upper row of patterns have their outermost lines touch the edge of the test piece, while the lower row has their innermost lines.

4.2.3 Living Hinges

The alternating patterns that proved successful in the initial hinge pattern research were identified to be so-called “living hinges”, a name given to a specific kind of hinge design. Their main characteristic is being part of the material that the hinge is attached to, and are often seen in plastic products like shampoo bottles and other kinds of lids [20]. While the flexibility of plastic material makes it the most common material to make living hinges out of, there have been attempts to use wooden materials like plywood as well [21]. Unlike plastics, this information is unfortunately not presented in scientific journals but are instead documented in blog posts and on company websites.

The width of the hinge section was estimated by assuming a 180-degree fold shaped like a half-circle, where the perimeter of the circle aligned with the middle of the mountboard material. Since the mountboard is 2 mm thick, that would give a circle with a 2 mm diameter. The resulting hinge would then need to be $2\pi/2$ mm wide, or approximately 3-4 mm. For a 90-degree bend, this width could be effectively halved. A graphic of this can be seen in Figure 4.9.

Figure 4.9 The diameter *d* of the hinge bend, as derived from the middle of the thickness *t* of the material.

With this knowledge the test from the previous section was further developed to include 4 cm width pieces, to allow for longer lines. The distance between the five sets of lines was 0.8 mm, resulting in a total hinge width of 3.2 mm. As it had been observed that the folding went better when the outermost lines touched the edges of the test piece, two of the patterns were tested without any middle lines (Figure 4.10).

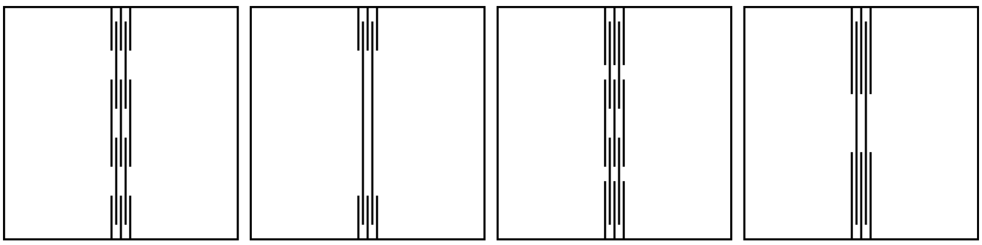

Figure 4.10 Test patterns, exhibiting longer lines and appropriate hinge width.

Here, the rightmost design excelled far more, as seen in Figure 4.11.

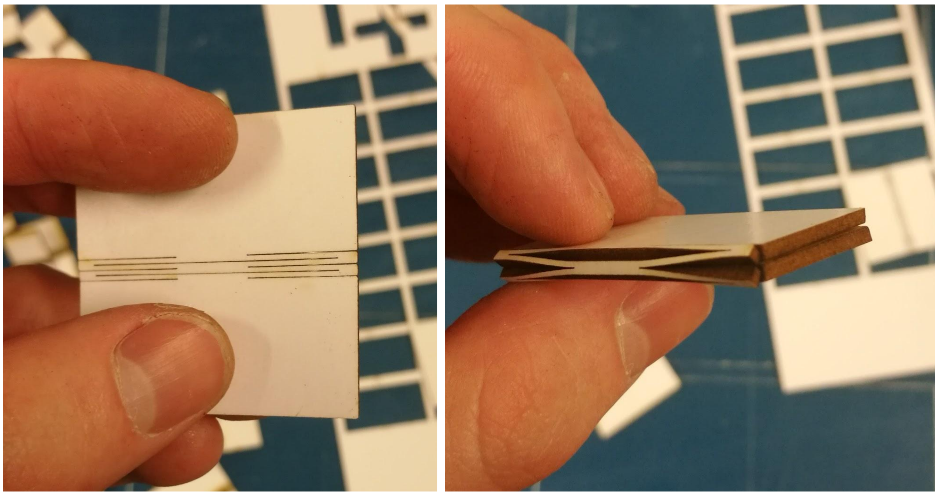

Figure 4.11 The best iteration of the hinge and how the 180-degree bend looks.

When comparing it to the other patterns it appeared the reason is the length of the rods that make up the hinge; the most successful pattern has much longer rods than any other that were tested, and the places where cracks appeared were where the rods had been shortest (Figure 4.12). Another aspect of the successful hinge was the lack of middle lines, further indicating that length and which lines touch the edges are the most important parts of a functional hinge.

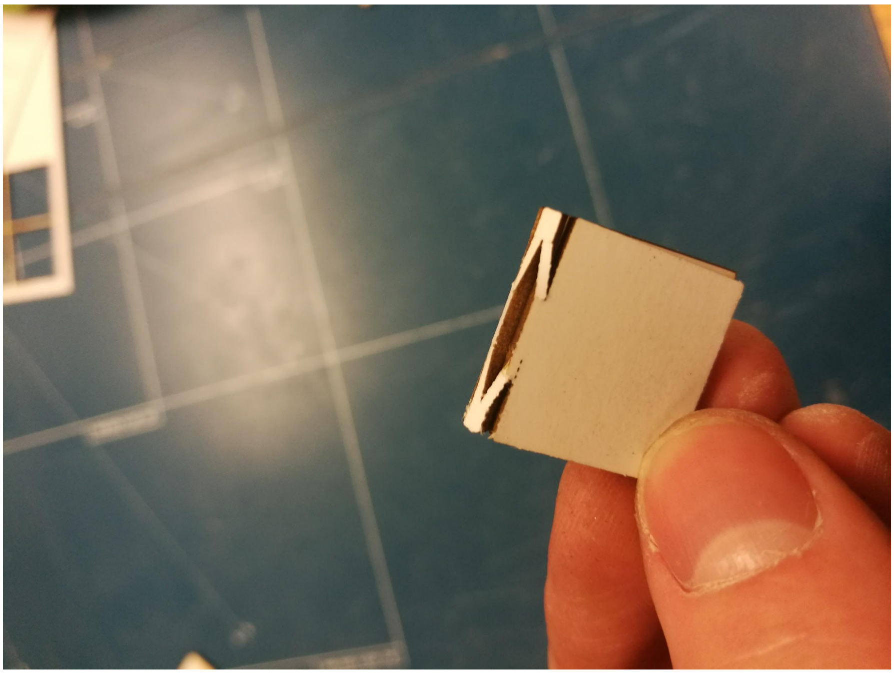

Figure 4.12 Example of a pattern with short rods, which caused visible cracks.

From the results of the previous test, the living hinge could be established as a viable hinge for this project. Two properties of the hinge were deemed as most desirable when examining the test pieces:

1) High Foldability: The hinge should require as little force as possible to be folded.
2) Low In-Plane Flexibility: The hinge should not provide a lot of flexibility perpendicular to the hinge in the plane's direction. This is to prevent deformation if the hinge is pulled on.

Based on the results of the previous tests, the patterns in Figure 4.13 were tried on 40 x 40 mm squares.

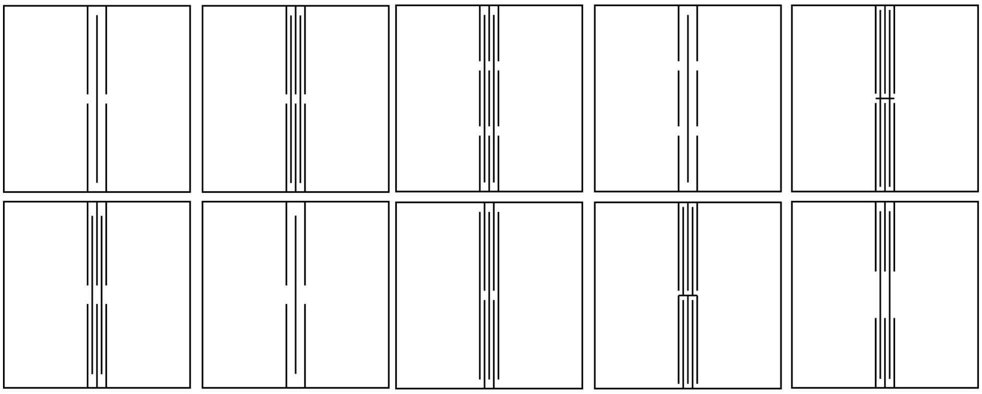

Figure 4.13 Pattern tests. The top row shows pattern 1-5, the bottom row 6-10.

Each hinge pattern is 4 mm wide; this means that the rods making up the hinge are either 1 mm or 2 mm wide depending on the number of lines in the pattern. Once cut out, the hinges were carefully bent and pulled on manually. The goal with this test was not to determine absolute mechanical properties, but rather see how the difference in pattern properties affected the hinges relative to each other. This allowed a better understanding of what parts of the pattern to optimize in later iterations. After having been examined by hand, by slowly folding the patterns to 90 degrees and then gently pulling the two sides of the patterns apart until it began to deform, the patterns were ranked by how much force was perceived to be applied, resulting in Figure 4.14.

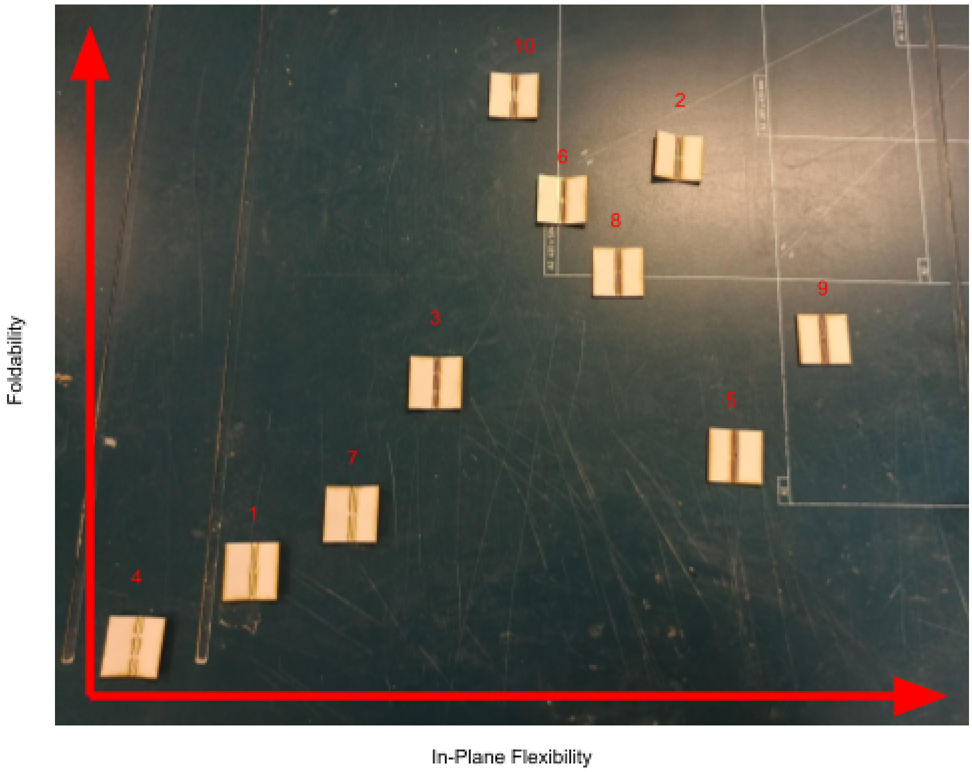

Figure 4.14 Graph of the patterns on foldability and in-plane flexibility.

Note: The graph does not depict the scale of the foldability/in-plane flexibility, just how the test pieces' properties measure up relative to each other.

The alternating **3-2 edge-middle pattern** (10, 6 and 2) had the highest foldability while having decently low in-plane flexibility. Thus, this type of pattern was chosen for further research. One thing to note is that the **2-1 edge-middle pattern** (1 and 7) had very good resistance to in-plane flexibility, though that is likely due to the width required to do a full 180-degree fold. The patterns showed much resistance to folding 180 degrees, though they did fold well up to 90 degrees. Due to the potential for a smaller inner radius this type of pattern was also chosen for further research.

4.2.4 Longer hinge improvements

Another property of interest would be the length of the hinge, to see how the patterns behave in different dimensions. A 40 x 150 mm test piece was cut out (Figure 4.15), using the 3-2 Edge-Middle pattern established in section 4.2.3. Thankfully, stretching out the pattern by elongating the middle lines did not have any noticeable impact on the hinge's properties (Figure 4.16).

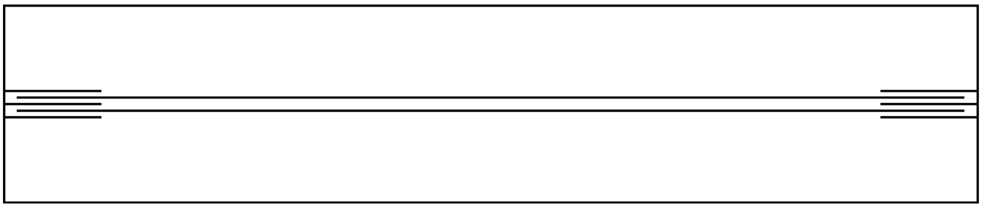

Figure 4.15 An elongated 3-2 Edge-Middle pattern.

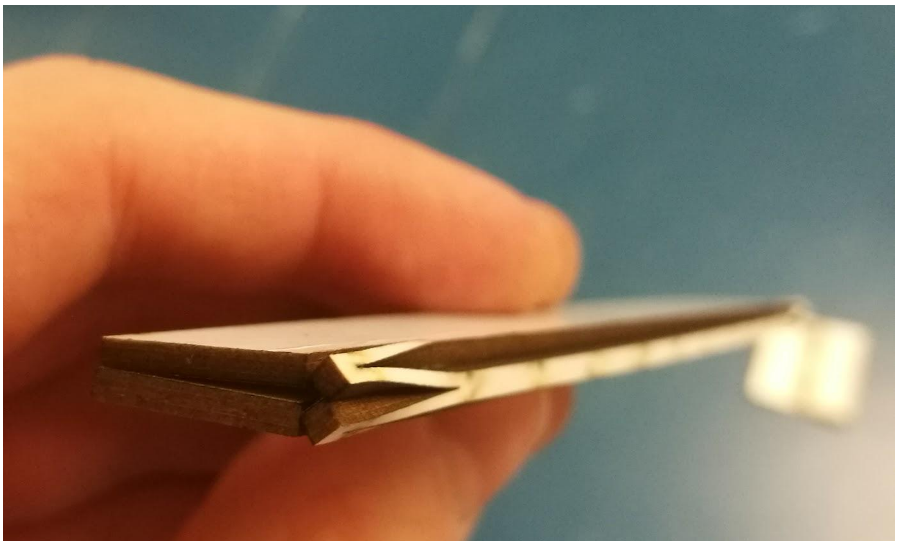

Figure 4.16 A view of the elongated pattern, with no visible tears in the hinge.

From this one can conclude that what matters is the width, length and number of the rods that extend from the edges of the hinge. Since the longer hinges do not perform any worse than the shorter hinges, there was the possibility to further improve its properties by reinforcing it along the added length.

It appears that the properties of the hinge are mainly determined by the length and thickness of the rods extending from the edges of the hinge, which will be called the "**hingerods**" (the section marked in Figure 4.17). As long as the hingerods are at a functional length there should be no problem making changes to the middle of the hinge, for example dividing the middle cuts into smaller sections, to allow for more rigidity.

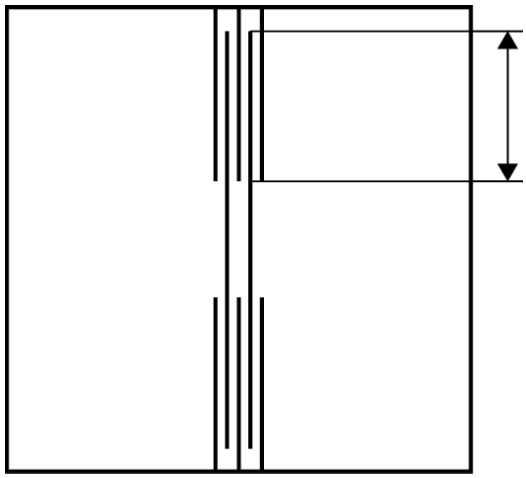

Figure 4.17 The hingerod section of the hinge.

By partitioning the middle cuts and adding more lines on the sides to compensate, the hinge can resist more in-plane flexibility (Figure 4.18). The longer the hinge, the more the middle lines can be divided, which allows for more hingerods and resistance. Of key importance is that the added hingerods are of no shorter length than the minimum viable hingerod length established for that particular hinge, as they will be bent as much as the ones on the edge and thus are at the same risk of failing.

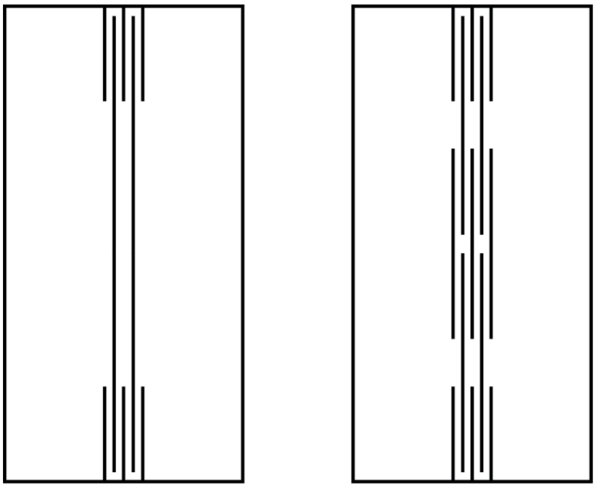

Figure 4.18 Left: A hinge with undivided middle cuts. Right: The hinge after the middle cuts have been divided and middle hingerods added.

4.2.5 3-2 Edge-Middle Hinge Inner Radius

As described in section 3.4, the company requested that the hinges should have a maximum inner radius of 1.5mm for a 90-degree bend.

When bending the hingerods one can observe that the inner radius is determined primarily by the width of the middle section of the pattern. The reason for this is that the hingerods are slightly pushed outwards due to their flexibility, while the middle sections are rigid and pressed together, see Figure 4.19.

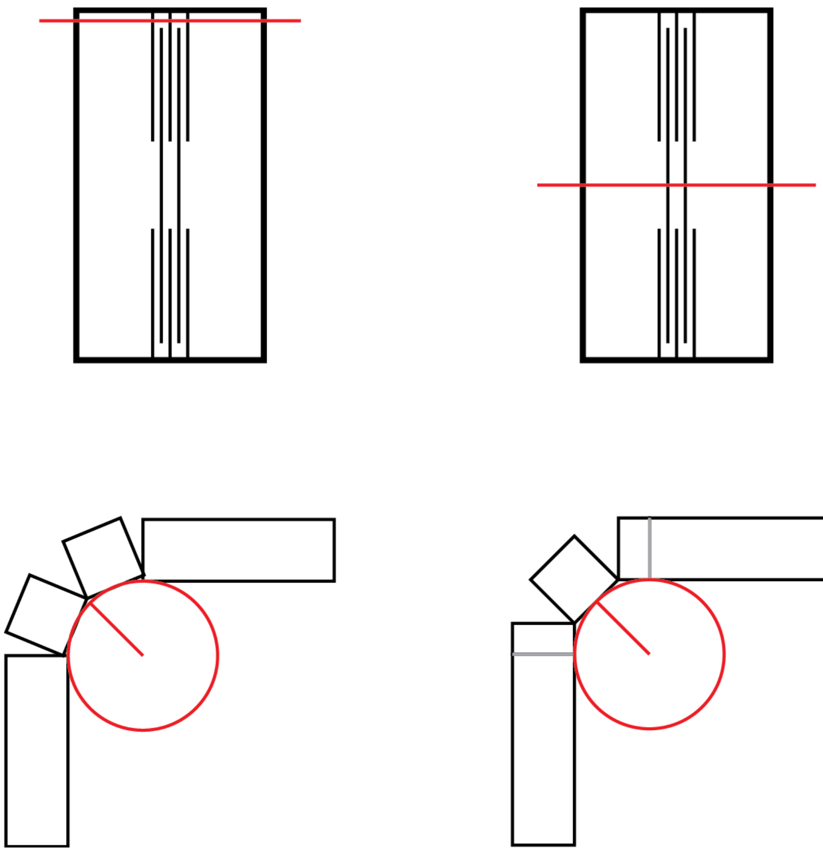

Figure 4.19 Depictions of how the radius can be determined in a 3-2 Edge-Middle pattern. Note the grey lines on the bottom right figure, depicting where the edges in the left picture are cut.

With the 3-2 Edge-Middle pattern that has been used above, one can then calculate what the inner radius will approximately be through the geometry in Figure 4.20.

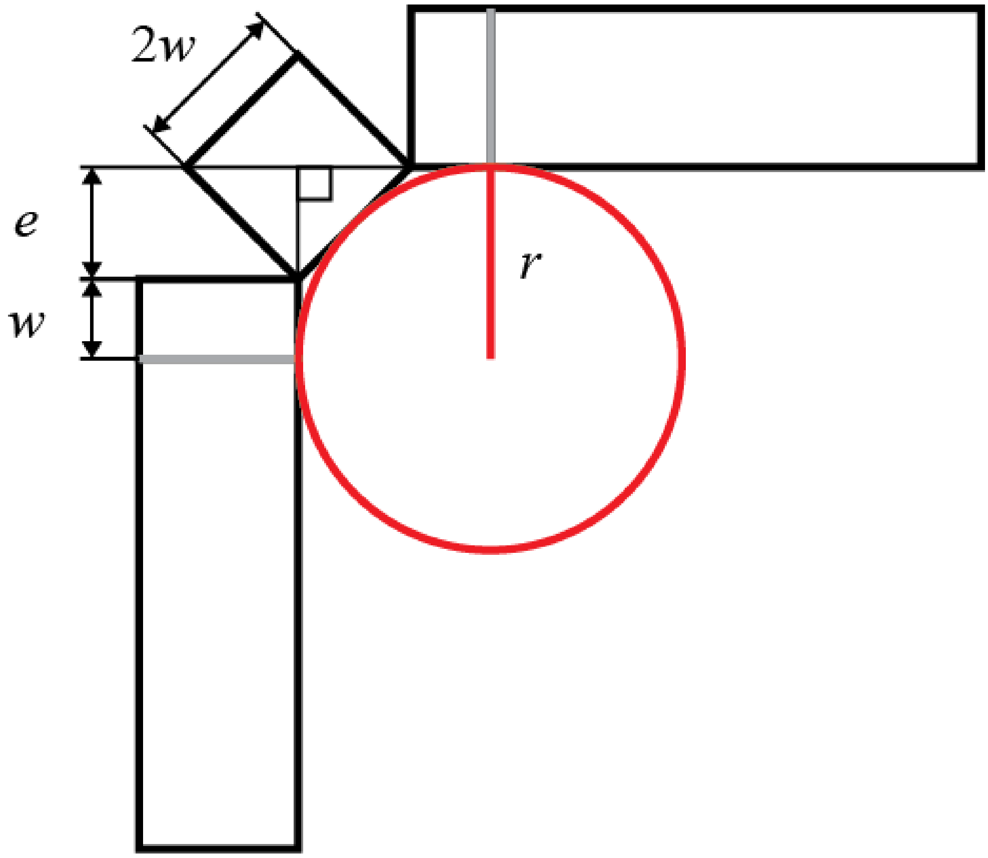

Figure 4.20 Schematic for determining the inner radius *r* for a 3-2 Edge-Middle pattern.

w = the width of the hingerods (4.1)

e = the distance the middle section adds to the radius = $\sqrt{(2w)^2/2}$ (4.2)

r = the inner radius of the corner = $w + e = w + \sqrt{(2w)^2/2}$ (4.3)

Solving for r = 1.5 mm using (4.3), the result shows that a hinge with that inner radius would need to have hingerods with the width of ≈ 0.62 mm, to a combined hinge width of ≈ 2.48 mm. This is concerning as that width is very thin for the material, making the hinge increasingly brittle.

4.2.6 2-1 Edge-Middle Hinge Inner Radius

Performing a similar analysis of the 2-1 Edge-Middle pattern geometry as the one used in section 4.2.5 (see Figure 4.19 and Figure 4.21) showed a formula that allowed for a smaller inner radius than the 3-2 Edge-Middle pattern (Figure 4.22).

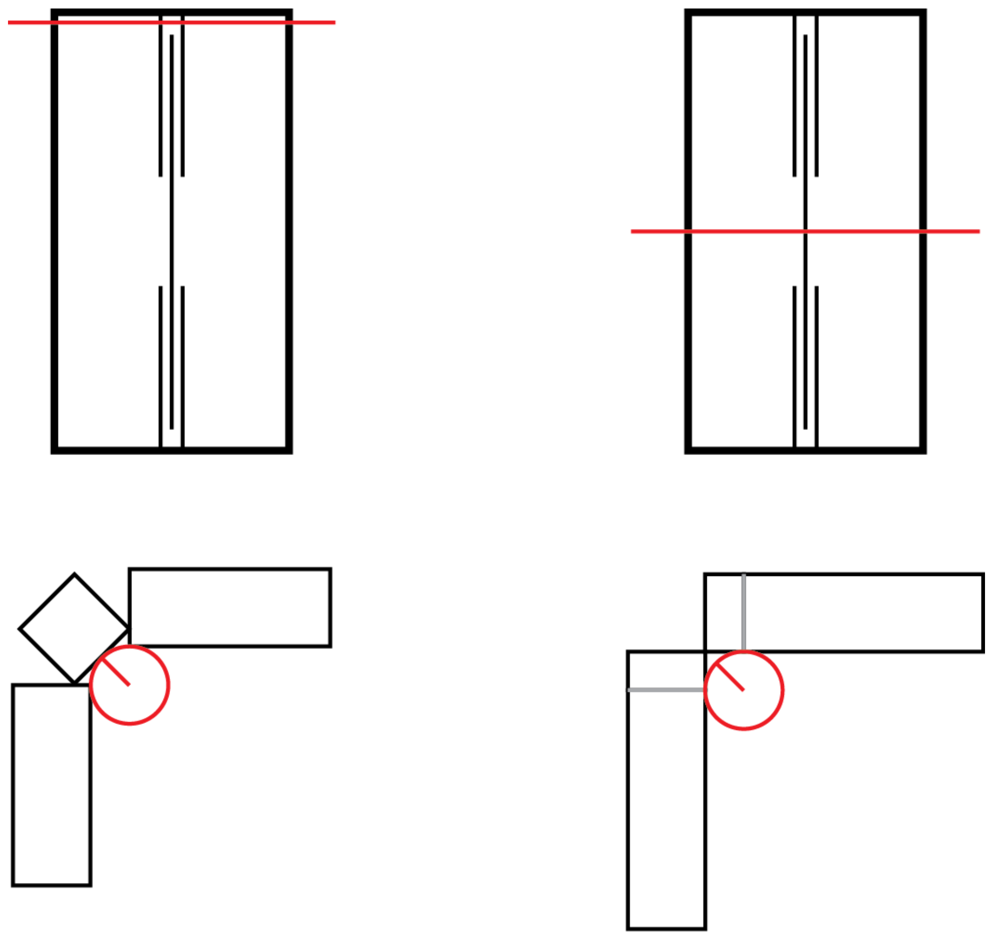

Figure 4.21 Depictions of how the radius can be determined in a 2-1 Edge-Middle pattern. Note the grey lines on the right figure, depicting where the edges in the left picture are cut.

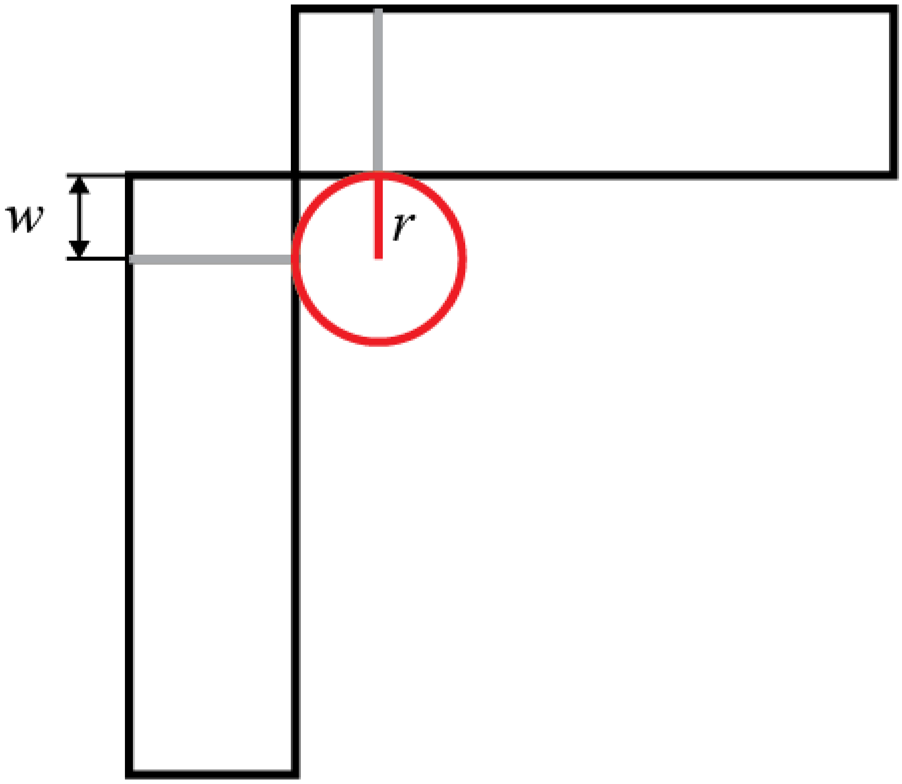

Figure 4.22 Schematic for determining the inner radius *r* for a 2-1 Edge-Middle pattern.

w = the width of the hingerods (4.4)

r = the inner radius of the corner = w (4.5)

Due to the fewer number of hingerods this pattern allows a hingerod width equal to the desired inner radius (in this case, 1.5 mm). It is important to note however that the 2-1 Edge-Middle pattern has less flexibility than the 3-2 Edge-Middle pattern, which means that the hingerods are at a higher risk of breaking from the stresses required to bend the hinge.

4.2.7 Practical 2-1 Edge-Middle pattern tests

To determine the viable parameters for the 2-1 Edge-Middle pattern, a series of tests were performed.

4.2.7.1 Hingerod Length and Thickness

Since both the hingerod's length and thickness has shown to influence the hinge's properties (as seen in section 4.2.3), finding an optimal mix between in-plane flexibility resistance and foldability could be done by testing variations in the pattern. 12 pattern variations were cut into a 25 x 25 mm square; a hingerod length of 10, 9, 8 or 7 mm, and a hingerod thickness of 0.75, 1 or 1.25 mm (see Figure 4.23). The hinges were then manually bent to a 90-degree angle and back again 50 times each.

The test showed that when a 1 mm thick pattern had a hingerod length of 8 mm or shorter, signs of tearing started to show. All 1.5 mm thick patterns failed as well (Figure 4.24). Since the 1 mm patterns had better in-plane flexibility resistance and having some margins for safety is preferable, the 10 mm length, 1 mm thickness pattern was chosen for further research.

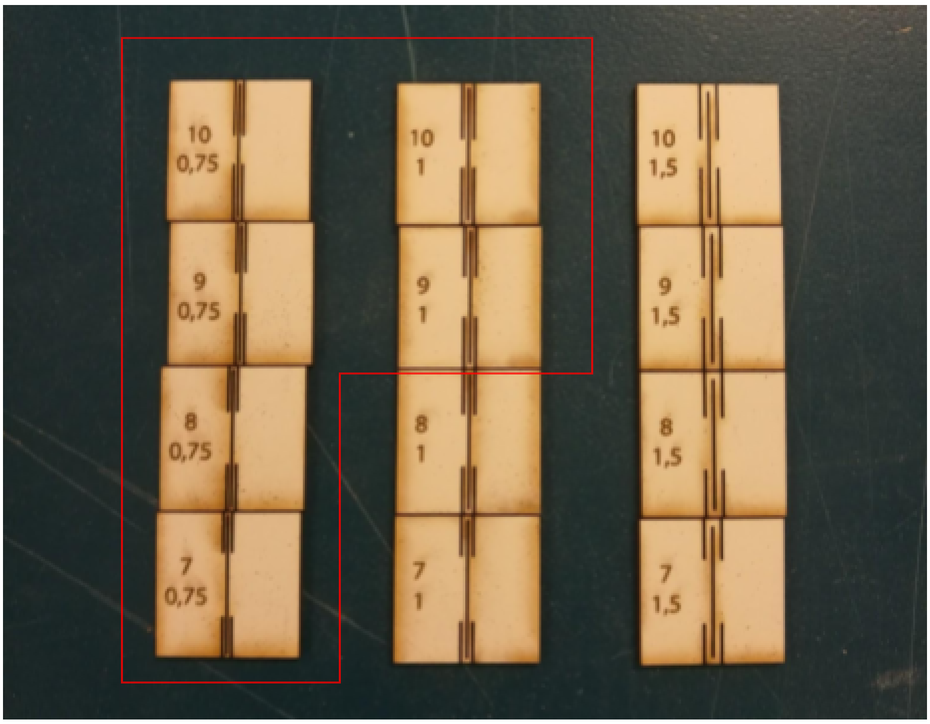

Figure 4.23 Functional hingerod variations for a 2-1 Edge-Middle pattern.

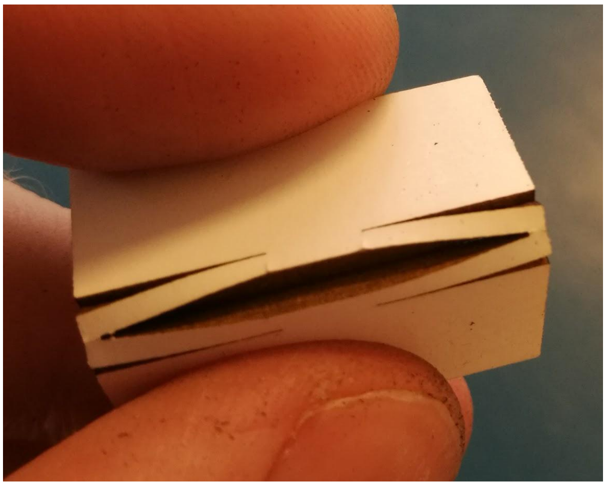

Figure 4.24 The 10 mm long, 1.5 mm thick hingerod pattern with tears starting to show.

4.2.7.2 Minimum Possible Hinge Length

Using the pattern derived from section 4.2.7.1, a test was performed to see if it was possible to make the hinge work on shorter sections (Figure 4.25). The pattern was cut out in lengths of 24, 23, 22 and 21 mm. To compensate for the shorter pattern the middle cut was made smaller.

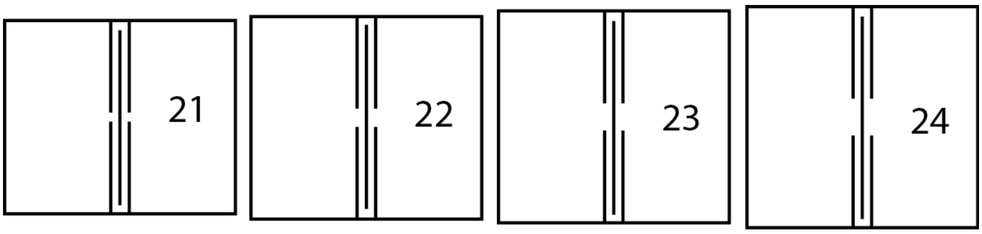

Figure 4.25 The four test pieces for minimum hinge length.

While the hinges could fold well no matter what length, the shorter they became the more another problem started to show. Below 24 mm the hinges became increasingly sensitive to twisting forces, where if torque was applied to one side of the hinge, the hinge would easily twist and break. This is not desirable, so the choice was made to use the hinges at a minimum length of 25 mm.

4.2.7.3 Hinge Elongation and Cut-To-Edge Distance

The pattern also needed to be examined for how it'd behave when repeated to create longer hinges. This was done by cutting out variations of the pattern in lengths of 50, 75, 100 mm (Figure 4.26).

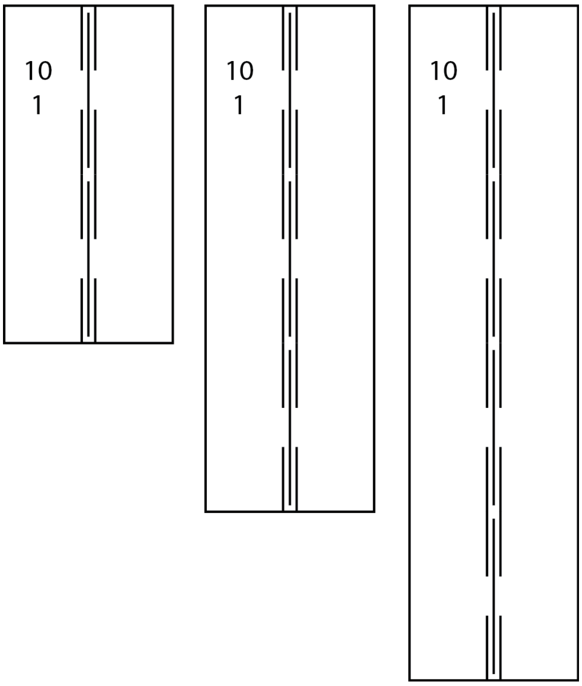

Figure 4.26 50, 75 and 100 mm versions of the 10 mm length, 1 mm thick hingerod pattern.

The hinge snapped due to the hingerods pressing together at the edges, caused by torque created from the hingerods being pulled apart during the bending action. As visualized in Figure 4.28, the stresses concentrated on the side of one hingerod, causing it to eventually snap and break.

To see if this could be solved, two variations of the 50 mm long pattern were created, to be tested along with the original. These kept the length and thickness of the hingerods, but changed the distance between the middle cuts and the edges of the hinge from the original 1 mm to either 1.5 or 0.5 mm (Figure 4.27).

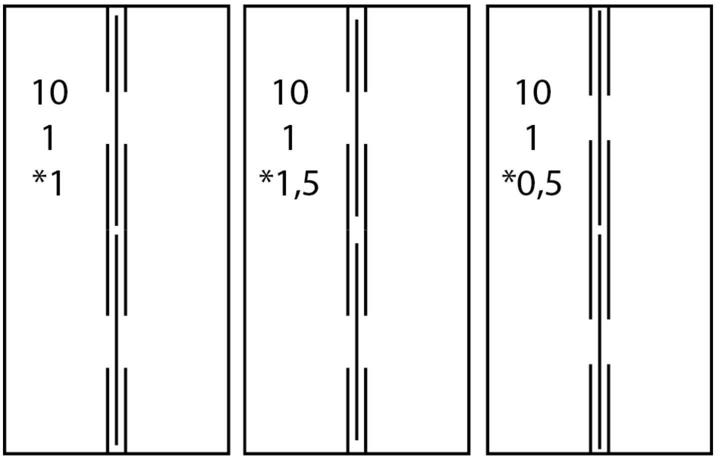

Figure 4.27 The two variations of the original design on the left.

By extending the middle cut, reducing the distance between the edge and the cut (from here-on called the "Cut-To-Edge Distance"), the place where the stresses are concentrated shifts to be along the middle cut. This means that when the hinge is folded the stresses are distributed in such a way that if the material starts to fail then the damage is confined to a small and largely unnoticeable area.

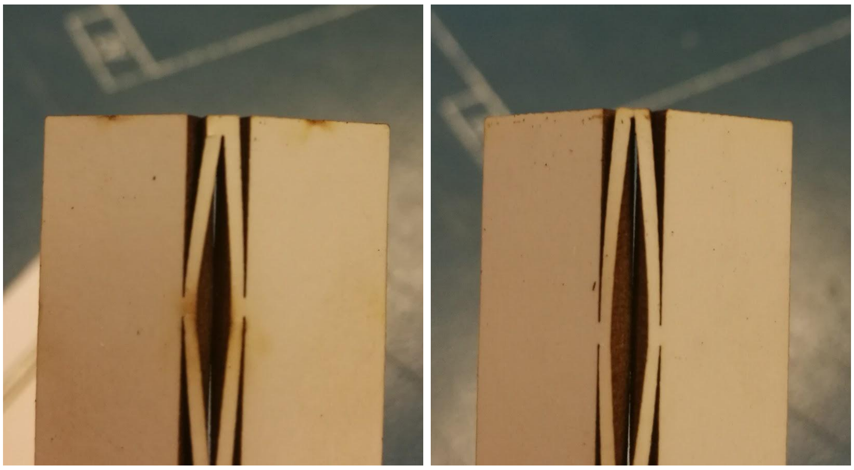

Figure 4.28 On the left, the breaking point is located horizontally on the side of the left hingerod. On the right, the smaller Cut-To-Edge Distance moves the breaking point to between the two hingerods.

4.2.8 Practical 3-2 Edge-Middle pattern tests

To determine the viable parameters for the 3-2 Edge-Middle pattern, a series of tests were performed.

4.2.8.1 Hingerod Length and Thickness

Similarly to section 4.2.7.1, a test was performed to determine the optimal length and thickness of the hingerods. Since the restriction on a minimum 1.5 mm inner radius makes 3-2 Edge-Middle pattern hingerods thinner, only the thicknesses 0.625 and 0.75 mm were tried (Figure 4.29). While 0.75 mm thick hingerods results in an inner radius of circa 1.8 mm (derived from the calculation in section 4.2.5) this was deemed an acceptable compromise should it improve the hinge's resilience. All hinges were manually folded 90 degrees 50 times each and then examined for failure points.

Both the 0.625 and 0.75 patterns fared well at a hingerod length of 8 mm and above, with the 7 mm length showing slight signs of tearing (Figure 4.30). Since the 0.625 patterns have an inner radius close to the ideal radius, the pattern of 9 mm length, 0.625 mm thickness was chosen as the best option. However, all the successful patterns exhibited high in-plane flexibility, which meant that they were relatively easy to pull apart perpendicular to the hinge line.

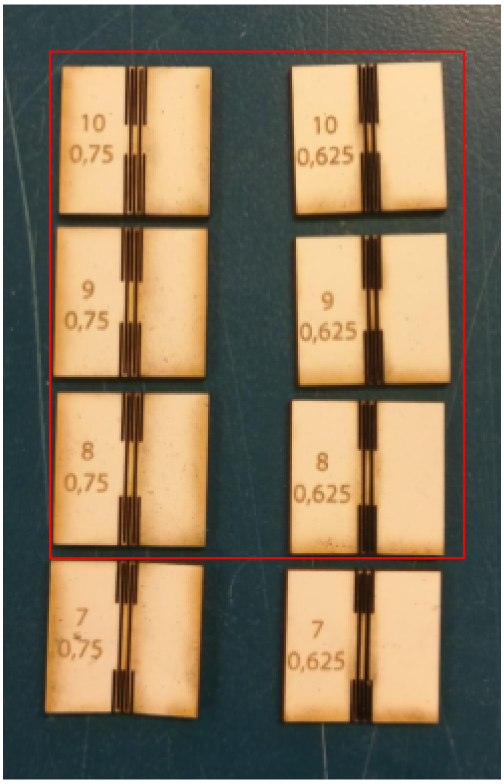

Figure 4.29 The successful patterns from the test.

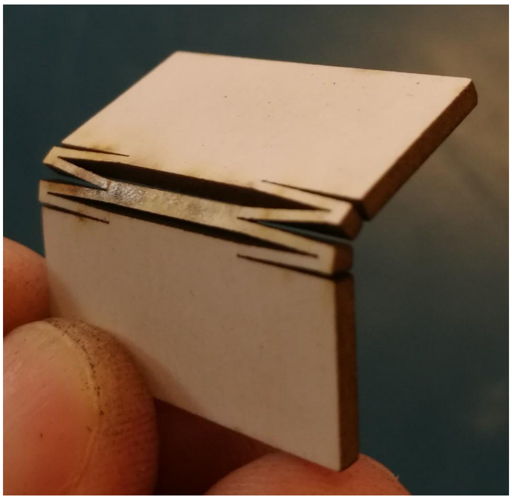

Figure 4.30 The 7 mm long, 0.75 mm thick pattern, with small tears starting to show at the ends of the hinge rod.

The successful 3-2 Edge-Middle patterns did not exhibit any problems with failure points in the way that the 2-1 Edge-Middle patterns did, which meant that there was no need for an investigation into the effect of the Cut-To-Edge Distance in these patterns. Since the length of the pattern (25 mm) closely matched that of the 2-1 Edge-Middle pattern, it was deemed to not be necessary to investigate the possibility of a smaller minimum length.

4.2.9 Hinge Pattern parameter observations

From the previously performed tests, it became clear that the different dimensions of the pattern affected the properties of the hinge in different ways. These will be detailed in the table below, with the added benefits and drawbacks that come with increasing/decreasing the dimension.

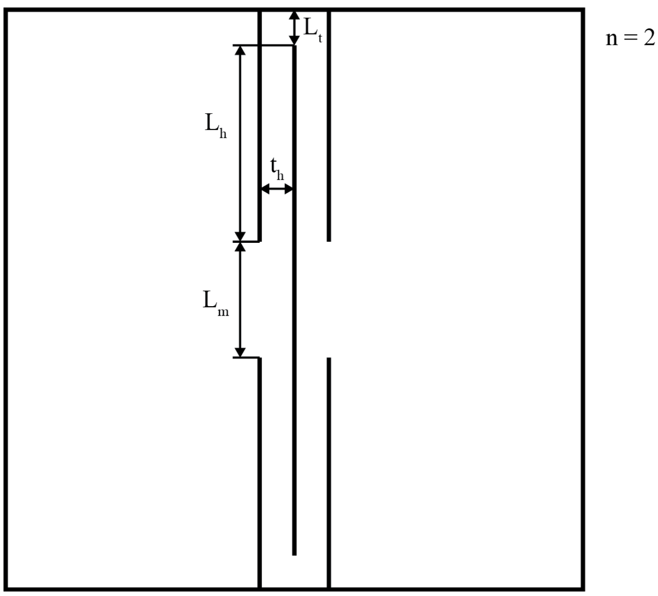

Figure 4.31 The different parameters that make up this living hinge design.

Table 4.2 Hinge Parameters, corresponding to Figure 4.31

	When increased
L_h (Hingerod Length)	Much better foldability Higher in-plane flexibility
t_h (Hingerod Thickness)	Worse foldability Much lower in-plane flexibility Higher inner radius
L_m (Middle Length)	Smaller minimum hinge length Better twist resistance
L_t (Edge-To-Cut Distance)	Changes failure point
n (Number of hingerods)	Much better foldability Much higher inner radius

4.2.10 3-2 Edge-Middle pattern, larger inner radius

Due to the high in-plane flexibility in the 3-2 Edge-Middle pattern (9 mm, 0.625 mm) an alternate variant is proposed here. The largest restriction on the patterns has been the inner radius of 1.5 mm as it limits the hingerod thickness and number of hingerods, properties that have a great influence on the in-plane flexibility. By allowing an inner radius of 3 mm, setting the hinge width to 5 mm, a pattern with high foldability yet low in-plane flexibility is created. Four variations of the 3-2 Edge-Middle pattern were tested on 25 x 25 mm square test pieces, using hinge widths of approximately 5 mm and a different number of hingerods (Figure 4.32).

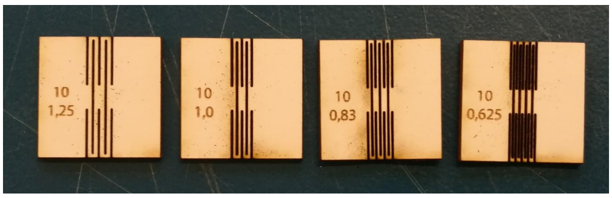

Figure 4.32 The four variations of the hinge design, using 10 mm long hingerods and variable width.

All four patterns handled being folded well, with the number of hingerods increasing foldability as expected. Similarly, the thicker hingerods exhibited lower in-plane flexibility compared to those with thinner hingerods. The 0.83 mm and

0.625 mm width patterns were easy to accidentally deform because of this, as seen in Figure 4.33.

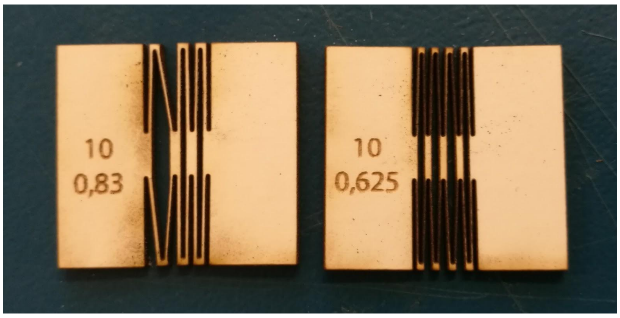

Figure 4.33 Deformations in the 0.83 mm and 0.625 mm width patterns.

As the 1.25 and 1 mm patterns were more resistant to deformations a second test was performed where the lengths of the hingerods were set to either 11, 10 or 9 mm. The hinges were manually bent to a 90-degree angle and back again 50 times each. All 6 variations seen in Figure 4.34 performed well without any visible tears and minimal differences in foldability, likely due to the added hinge width making them more resilient.

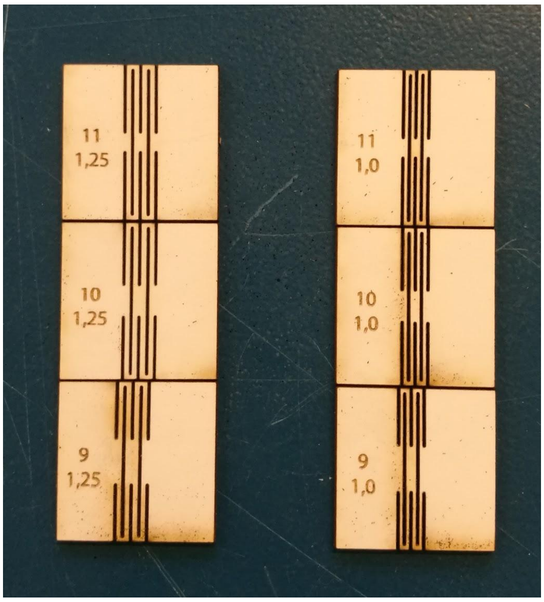

Figure 4.34 The six variations of the hinge design, of the 3-2 Edge-Middle pattern.

Ultimately the 10 mm long, 1.25 mm width pattern was chosen as the favoured design. This pattern proved itself to be the most viable hinge due to its low in-plane flexibility yet high foldability. While it has some difficulty with doing 180 degree bends it handles 90 degrees well without signs of tearing. For those reasons, this 3-2 Edge-Middle pattern (10, 1.25 mm) and the 2-1 Edge-Middle pattern (10 mm, 1 mm) were used for the next phase of the project.

5 Structure Design

This chapter presents the product development of the board game structures; how the hinges can be used to create foldable structures, how the structures are connected to each other and how the layout of the structures should be designed to fit a board game system.

5.1 Lock mechanism

The hinges created in section 4 need to be incorporated into a method that will allow the structures to be folded up. At the request of the company the mechanism that will be used is the Flat fold mechanism discussed in section 3.5.1. This mechanism requires a way to lock the walls of the structure together, which will be explored in this section.

5.1.1 Proposed lock types

Since the hinge designs proposed in previous sections showed weaknesses at smaller dimensions, it was deemed necessary to rule out any folding of the mountboard material when it came to designing the locking mechanism. Three different methods of creating a lock were prototyped, with slight variations:

5.1.1.1 Friction fit lock

The friction fit lock uses notches and nubs cut out of the mountboard, with each side of the wall having an interlocking set that when pushed together remain in place thanks to friction. This mechanism requires relatively small tolerances to ensure that the notches are not too wide and thus fails to get a grip, nor too thin, requiring too much force to make fit.

5.1.1.2 Hook lock

The hook lock has a notch, hole or other feature on one side, which a hook cut into the other side can latch on to. The hook then prevents the sides from disconnecting unless the user manually unhooks the lock. This lock requires that the hinges allow for some flexibility, as the hook needs to be lifted over the hole to hook on.

5.1.1.3 Clip lock

The clip lock uses a separate plastic part that snaps on at the top of or inside the corner created by the sides of the structure. This means that the clip can be made of a sturdier material than mountboard and enables it to hold together more complex shapes. It also means that a clip can only do the angle it is in the shape for and requires extra manufacturing costs. As seen in section 3.4.5 clips can also take a lot of time to mount if there are many of them.

5.1.2 Lock types prototyping test

Six different variations on the proposed lock types were tested based on the shapes in Figure 5.1, made up of roughly 10 x 20 mm segments. Figure 5.2 shows the 3D model of the 3D-printed clip used for the clip lock.

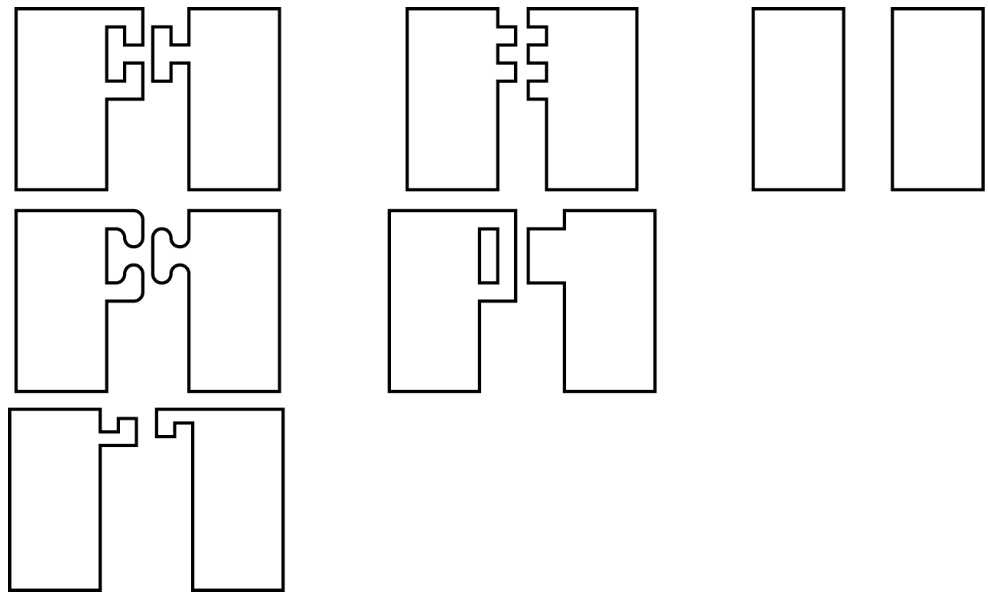

Figure 5.1 From left to right: Hook lock, friction lock and clip lock parts.

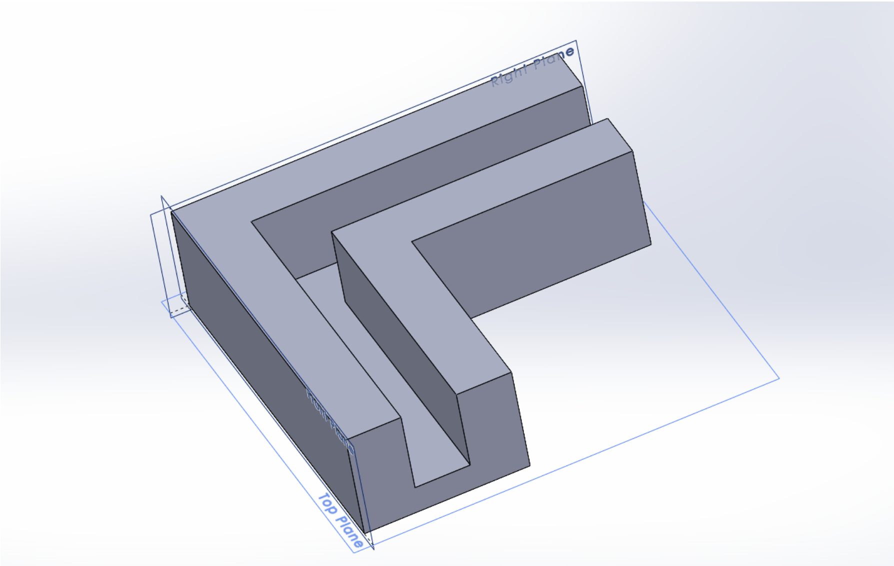

Figure 5.2 Solidworks 3D model of the clip part, to be used in 3D printing.

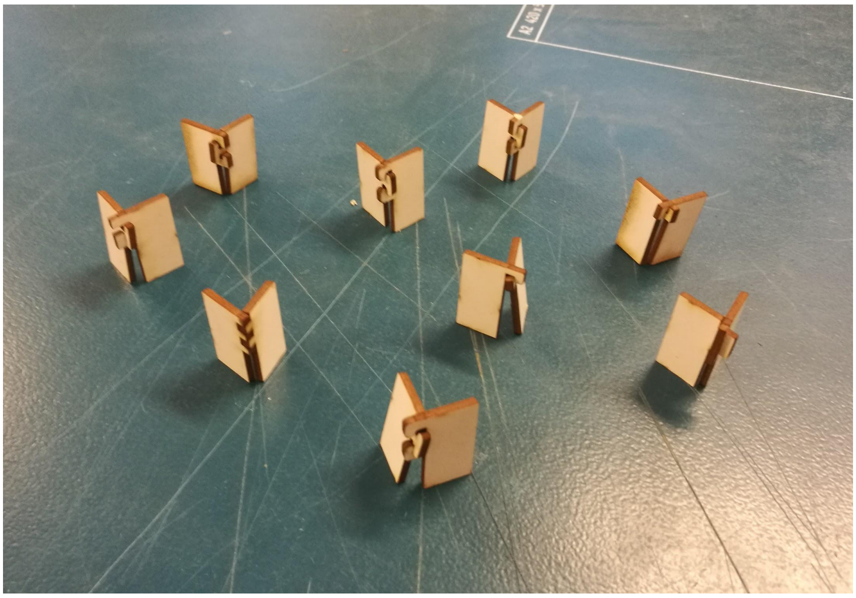

Figure 5.3 The various lock types and slight variations thereof.

The designs that proved to be the most successful were the hook locks and the clip lock; the friction locks worked but got damaged in the process, or were simply too loose. Since the clip lock requires a second component that increases the complexity of the lock, the hook lock was chosen for further research and more iterations were tested, seen in Figure 5.4.

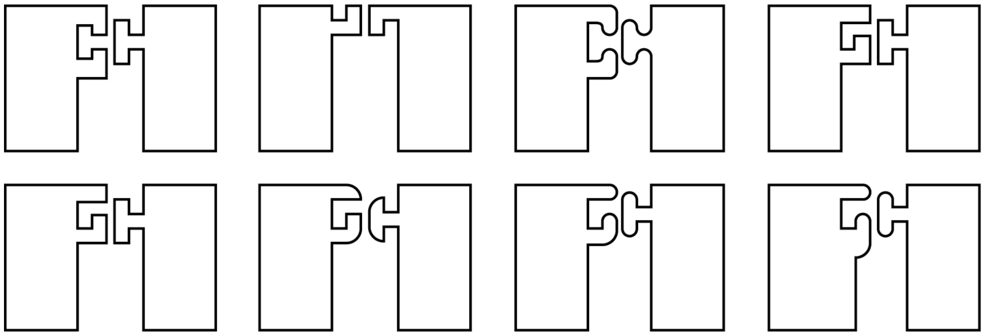

Figure 5.4 Evolution of the hook lock, left to right, top to bottom. The bottom right design is the final version.

From the initial design some improvements were made to the lock:

- The top of the hole side was removed to facilitate easier unhooking, essentially turning the “C”-shaped section into a “G”.
- The “T”-shaped section was lowered slightly so that the hook can’t unlatch on its own.
- Rounded edges were added to the ends of the “G” and “T” parts of the lock, as hard edges increased the risk of the mountboard layers separating due to wear and tear.
- The “G” side was extended outwards by 2 mm, resulting in the outer corner of the lock being flush with both sides. This only applies to 90-degree bends.

This design will from here on out be referred to as the “**GT-lock**”.

5.1.3 Lock Tolerance Improvements

As the GT-lock had been developed on a laser cutter with certain malfunctions the lock may not be as viable when cut out with other laser cutters. Due to this, some improvements could be made to the GT-lock to give it wider tolerances.

The previously established ease of use and the integrity of the hook needed to remain in the new iterations. One of the larger concerns was keeping the hook from slipping out accidentally while in use. The safest way to widen the tolerances would be to increase the depth of the G-part's lower section, to let the hook lock deeper. This would also require the T-part to be lowered to match the new depth. Another possibility would be to widen the stem of the T-part. A test was performed with four design changes in Figure 5.5, with an unchanged lock to compare against.

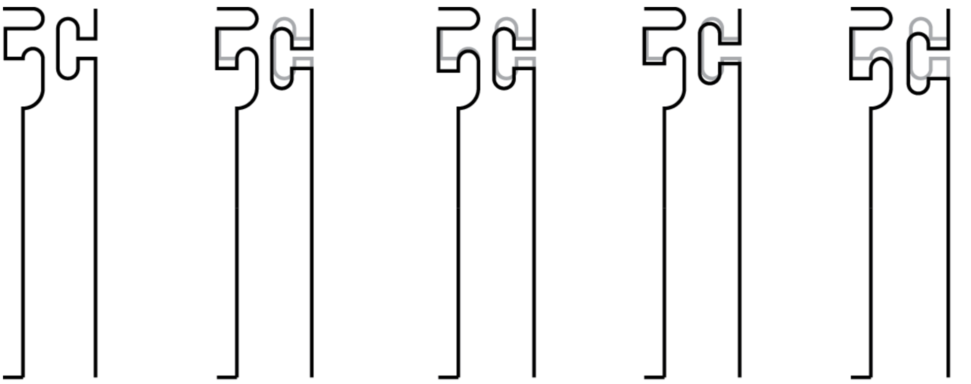

Figure 5.5 Shows variations in the GT-lock design, with the unchanged lock greyed out behind the changed versions.

All designs moved the inside of the G-part back 0.25 mm, as well as extended the stem of the T-part by the same amount. Design 1 added a 1 mm depth to the G-part's lower section, and design 2 lowered the lip of the G by 0.25 mm to give a slightly wider tolerance when inserting the hook. Design 3 only added 0.5 mm depth to the G-part, while the fourth attempted a 1 mm wider stem for the T-part combined with an added 1 mm depth to the G-part.

Design 2 proved to be the best improvement; the added tolerance helped with the ease of hooking, while the depth increase made sure to keep it in place. The hinge of the wall that contains the T-part does need to be a little bit more flexible than the previous design to allow for the hook to lift up over the G-part's lip, but this was deemed a suitably small difference. The other designs still worked well but did not provide as adequate support for the hook as design 2.

5.1.4 90-degree corners

Whether a 3-2 Edge-Middle pattern or 2-1 Edge-Middle pattern is used, gaps will form when two walls perpendicular to each other are folded up. This is caused by the inner radius of the hinges which offsets the walls away from the floor piece. To compensate, the sides of the wall pieces need to be shifted outwards 2 mm to allow the lock to connect (Figure 5.6).

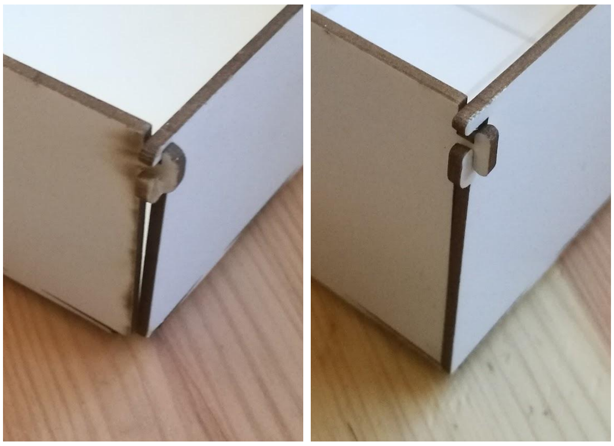

Figure 5.6 The left image shows an unmodified lock, the right image shows an extended G-part lock.

This does not fully close the gap, as the hinges themselves aren't adjusted. It results in a hole in the corner where the wall pieces meet the floor (Figure 5.8). From the observations in section 4.2.4, one can see that it should be possible to extend the hinges without having any adverse effect on the hinge properties, as long as the hingerod length isn't changed (Figure 5.7).

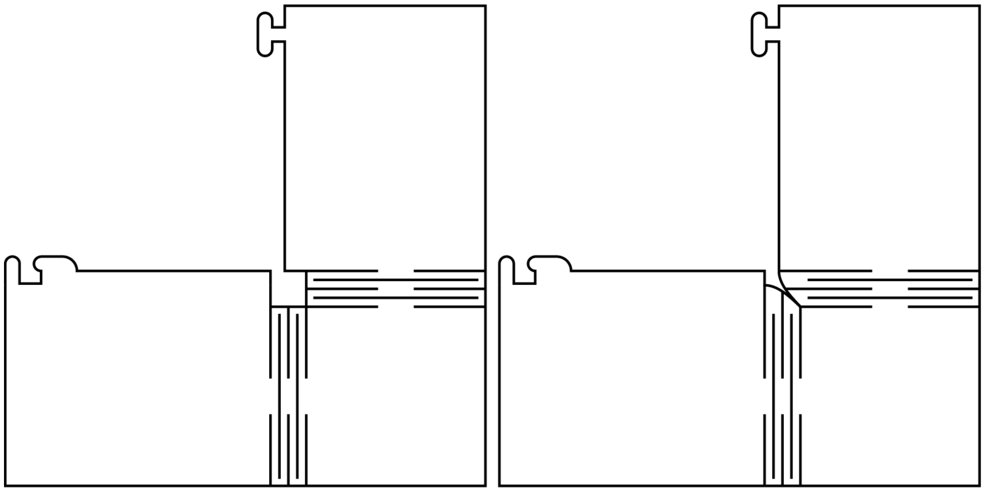

Figure 5.7 The left image shows the unextended hinges, the right image shows the hinges being extended into the corner.

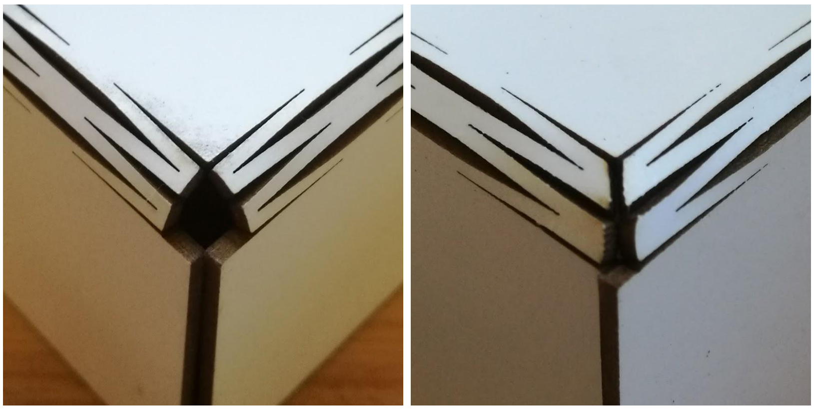

Figure 5.8 The difference the extended hinge makes when it comes to the corner.

The adjusted edge of the hinge starts at a 45-degree angle from the corner and then gently curves until it is tangent to the wall. This has the effect of extending the Edge-To-Cut distance, which needs to be taken into consideration when adding this feature.

Unfortunately due to space limitations when cutting out the structures the hinges will not have an outer corner with a sharp edge like the walls may have.

5.1.5 45-degree corners

For 45-degree corners the GT-lock required some minor changes as the difference in angle caused the G- and T-parts to approach each other differently, as seen in Figure 5.9.

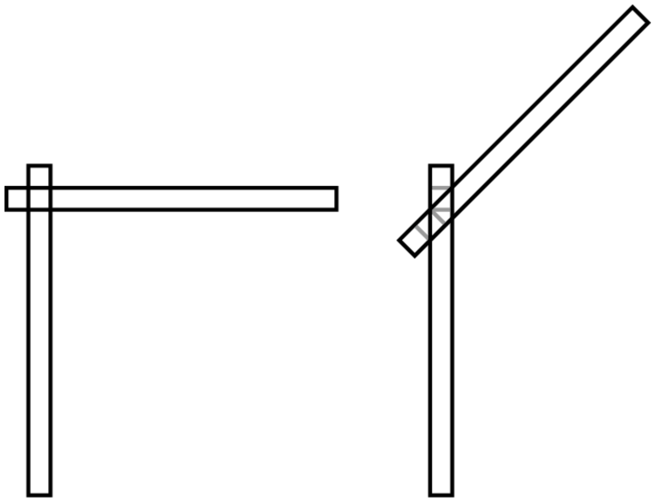

Figure 5.9 The difference in angles. The right figure's grey lines show where the walls intersect in the left figure.

As mentioned in section 5.1.2, the extension used to create a sharp corner only works with 90-degree angles. Both the G- and T-parts need to be extended since the intersection takes up a wider section of each wall, though this also means that a section below T-part will need to be removed to fit the G-part (Figure 5.10).

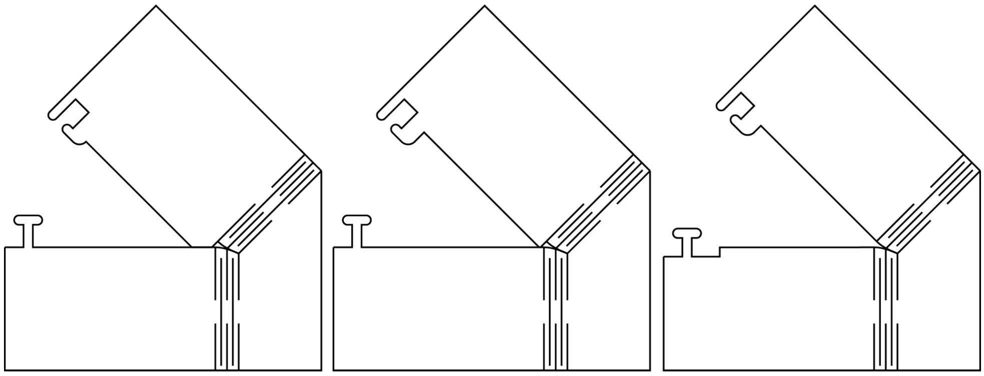

Figure 5.10 Three iterations of the 45-degree corner lock, using a 3-2 Edge-Middle hinge.

5.1.6 Final lock dimensions

The final 90-degree GT lock has the following dimensions:

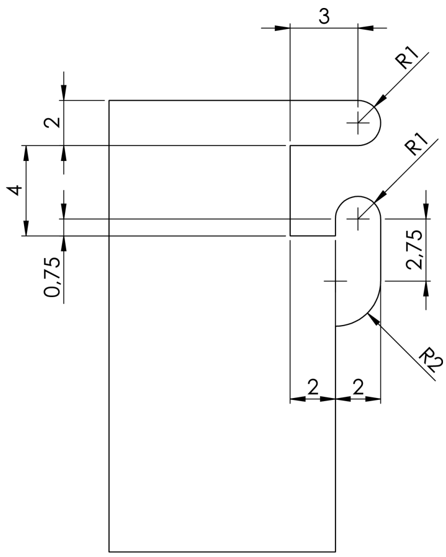

Figure 5.11 G-part lock dimensions, 90-degree corner.

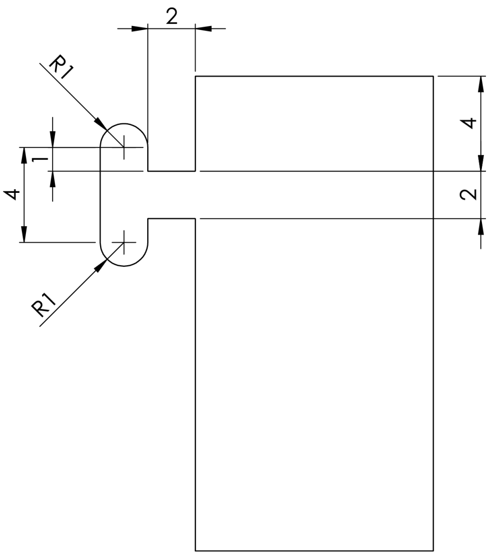

Figure 5.12 T-part lock dimensions, 90-degree corner.

The final 45-degree GT lock has the following dimensions:

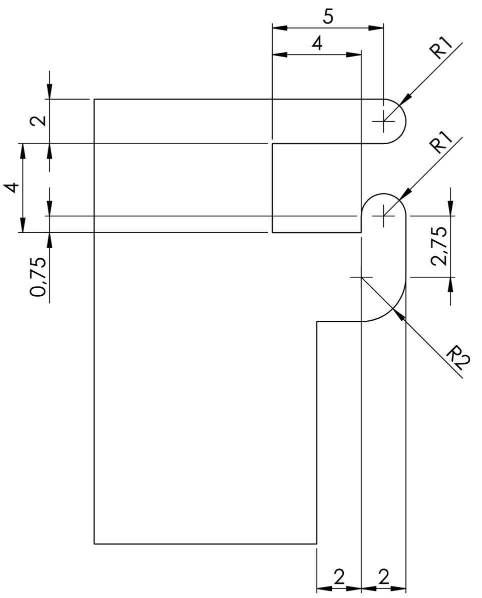

Figure 5.13 G-part lock dimensions, 45-degree corner.

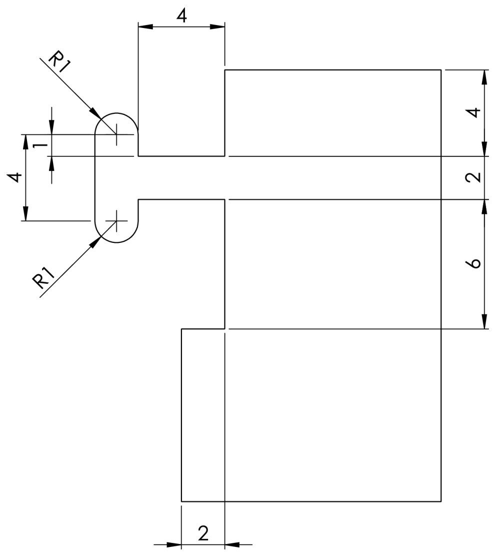

Figure 5.14 T-part lock dimensions, 45-degree corner.

5.2 Default box structure

The simplest structure to create is a square room with a floor and 4 walls (Figure 5.15). Testing this kind of room is ideal as it can serve as a reference point for developing more complex structures, and even a basic shape such as this could be applied in a board game system.

The room featured a floor section that was a multiple of 25 mm in width and length since the structures are meant to eventually tile together. This is to be able to fit in a 25 mm square grid into the room, as 25 mm is the minimum size needed to contain minifigures as requested by the company in section 3.4. The box room to be tested featured a 100 x 100 mm floor, not counting the inner radius added by the hinges. The walls were 40 mm tall measured from the table surface. The structure was folded up and down 50 times to measure how well the hinges could handle the strain in a proper structure, and also to observe any other difficulties with the design.

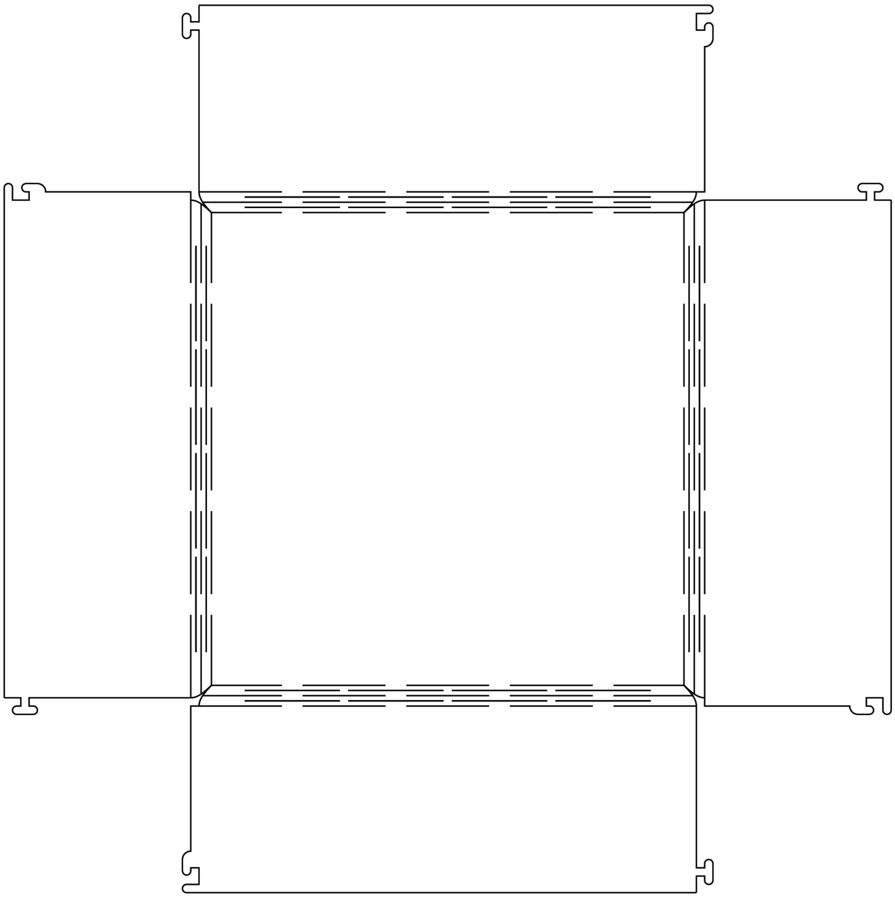

Figure 5.15 Cutting pattern for the first iteration of the default box structure.

While the room had received no structural damages, one problem was the difficulty of detaching the locking mechanism once the final wall was connected. Since the wall is detached by lifting up the T-part and then folding it down, having a G-part on the other end of the wall means the wall is hindered from folding out. This makes the unfolding process difficult as different parts need to be pulled at the same time.

The solution to this was to make sure that one wall only has one kind of GT-lock part; for example, a wall only has G-parts on either side (Figure 5.16). This resulted in the structure being much easier to set up and fold down since one wall's both locks are detached with the same movements.

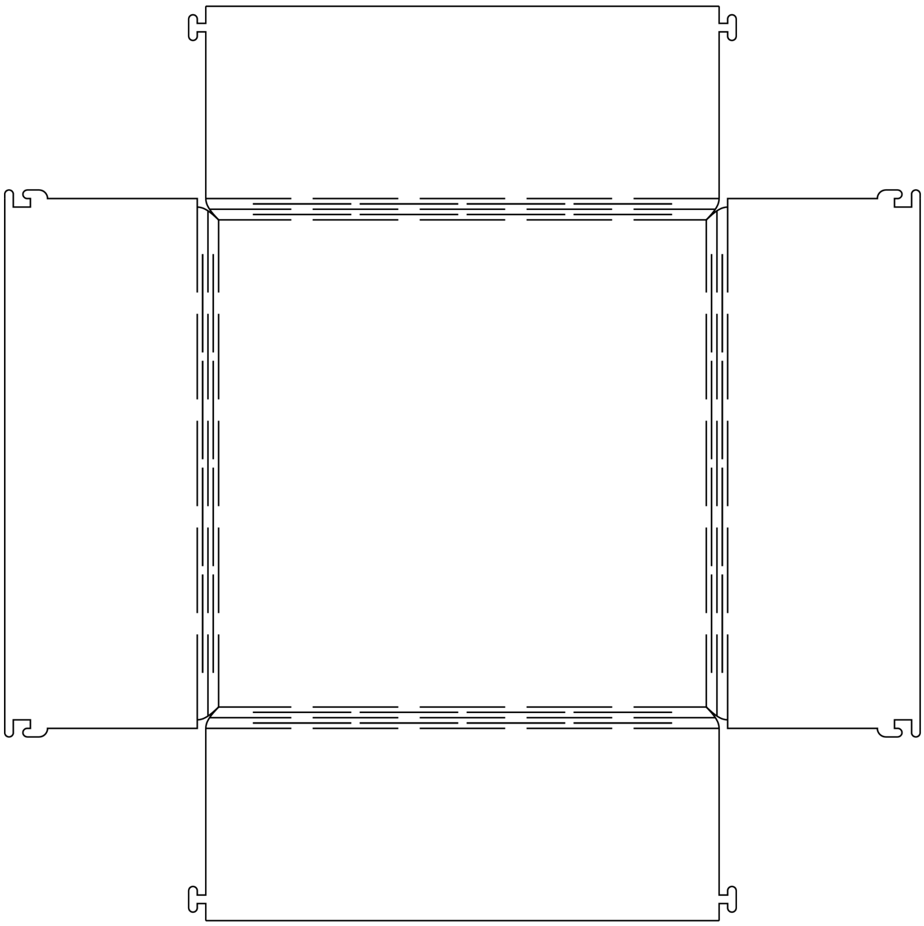

Figure 5.16 Cutting pattern for the second iteration of the default box structure.

5.2.1 Lock and hinges in more complex structures

Two structures with more complex structures were also examined at the request of the company, to determine the modularity of the hinge and lock designs. The two structures consisted of a room with a ledge, and a room with 45-degree wall sections (Figure 5.17).

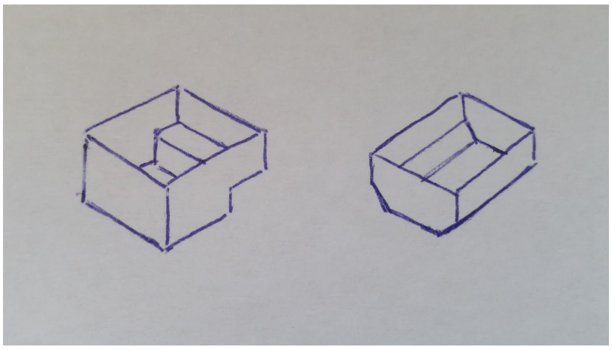

Figure 5.17 Sketch of the Ledge room and 45-degree wall room.

5.2.1.1 Ledge room

The ledge room was prototyped to a size of approximately 50 x 50 x 40 mm (Figure 5.18). When testing the first iteration of the prototype it became evident that extra support would be needed for the lower ledge wall. This added some complexity to putting the room together, however it was still a relatively simple task and deemed necessary for the structural integrity of the ledge. Another observation was how the different halves of the GT lock interacted. Since the lower ledge lock has the G-part on the ledge side, it forces the wall that the T-part is on to fold up. This makes it more difficult to attach the upper lock as the lower lock already keeps the T-part wall in place. Consideration needs to be taken to how the lock parts are positioned in the future.

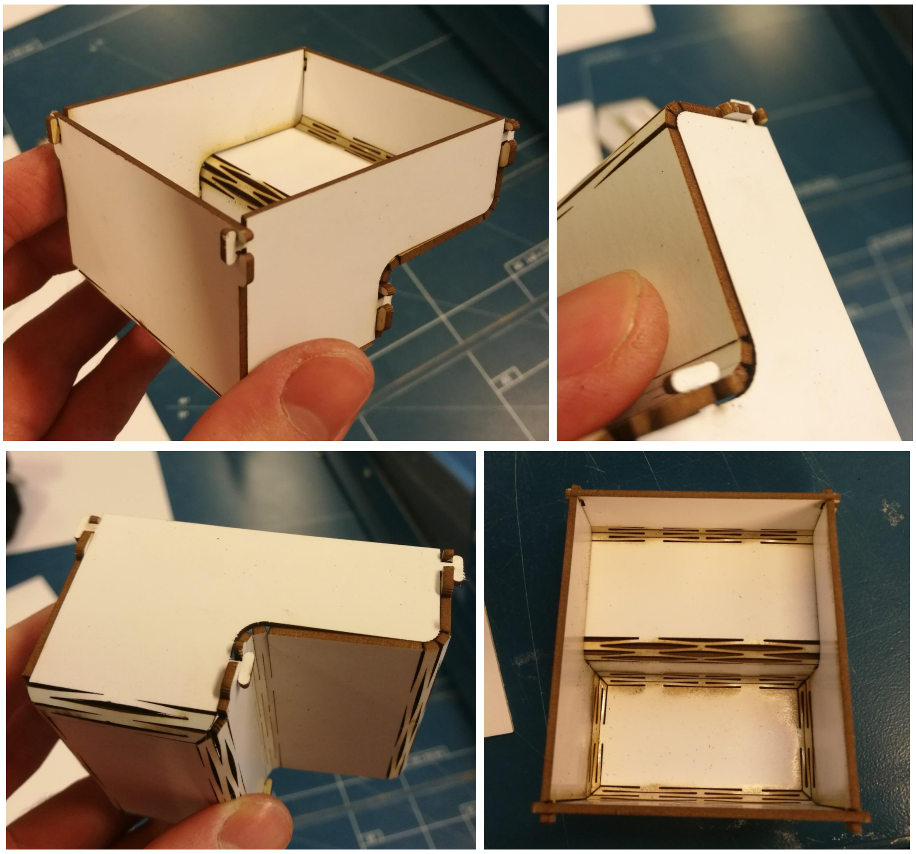

Figure 5.18 Pictures of the ledge room from different angles.

5.2.1.2 45-degree wall room

The 45-degree wall room posed some difficulties when it came to the corner of two hinges. For the 3-2 Edge-Middle pattern a 90-degree bend in the hinge creates a 3 mm inner radius, but when the hinge is only bent 45 degrees that radius ends up being about twice as large. When a 45-degree bend makes a corner with a 90-degree bend that not only means the extension to the hingerods made in section 5.1.4 needs to be changed, but the walls must account for the heights of the hinges being different.

This is further complicated by the behaviour of the hinge. As discussed in section 4.2.5, due to the hinge's inherent distortion the inner radius of the bent hinge does not match the radius calculated from the flattened width of the hinge. While the difference is no larger than a few tenths of a millimeter, for larger and more complicated structures the error can compound and create inaccuracies.

To help expedite the process the intersection between the 45-degree hinge and the 90-degree hinge was modelled in Solidworks using fillets to represent the hinges (Figure 5.19). The inner faces of the hinge could then be flattened in the program to show how they should look when cut out from a flat sheet. One important thing to note is the radius of the hinges; since Solidworks can not account for the deformation of the hinge when translating from a bent face to a flattened face, the radius of the fillets need to be set with this in mind. The required radius can be derived from the following formula:

$$r_{solid} = w_h(360/\alpha)/2\pi \qquad (5.1)$$

where

r_{solid} = the inner radius used in Solidworks.

w_h = the width of the hinge when lying flat.

α = the angle of the bend, in degrees.

Example: A 3-2 Edge-Middle pattern has a hinge width of 5 mm when lying flat, meaning a 90-degree bend must use a 3.183 mm inner radius in Solidworks. When flattening out the bend in Solidworks the resulting pattern has the correct dimensions to be used when cutting out the hinge (Figure 5.20).

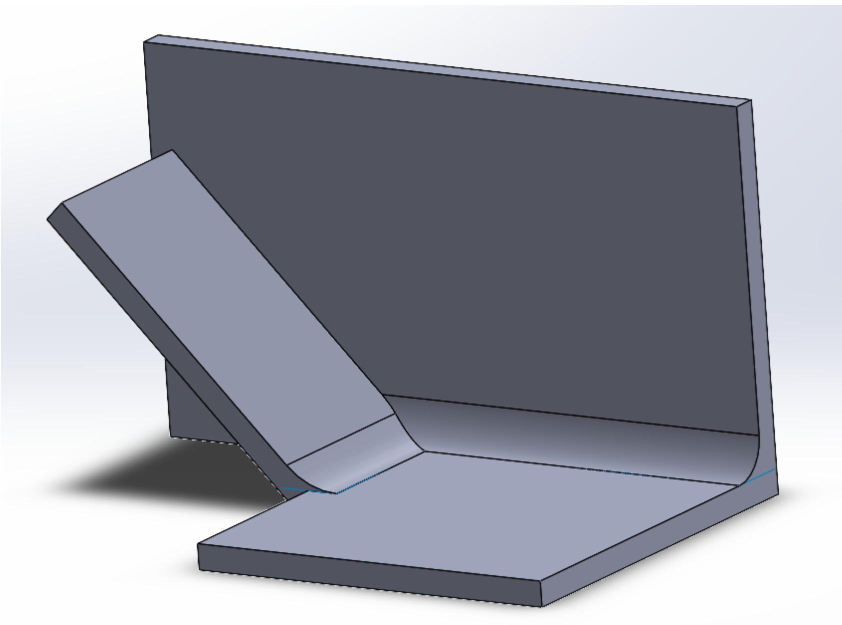

Figure 5.19 An example of a 90-degree wall interfacing with a 45-degree wall, modelled in Solidworks.

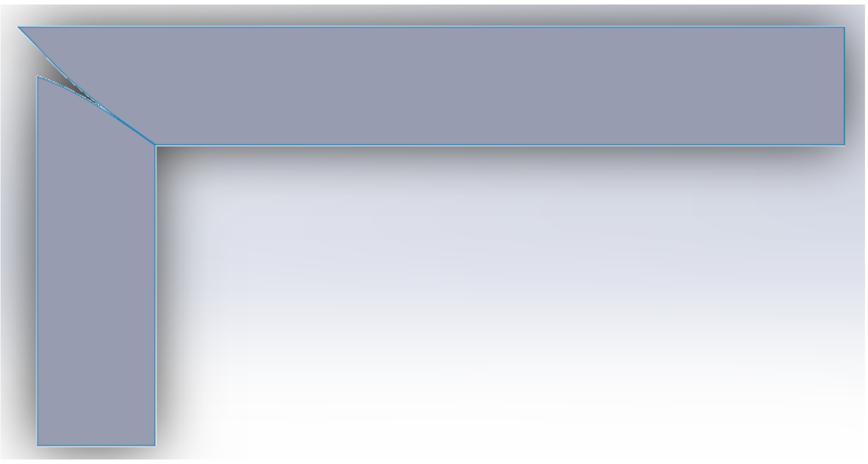

Figure 5.20 The resulting hinge sections from Figure 5.19 when flattened. Note the difference in curvature at the corner of the two walls. Due to the formula used for the CAD hinges' radius, both hinge sections are exactly 5 mm in width.

Using the curved corner for the hinge pattern as depicted in Figure 5.20, a version of the 45-degree wall room could be constructed, seen in Figure 5.21.

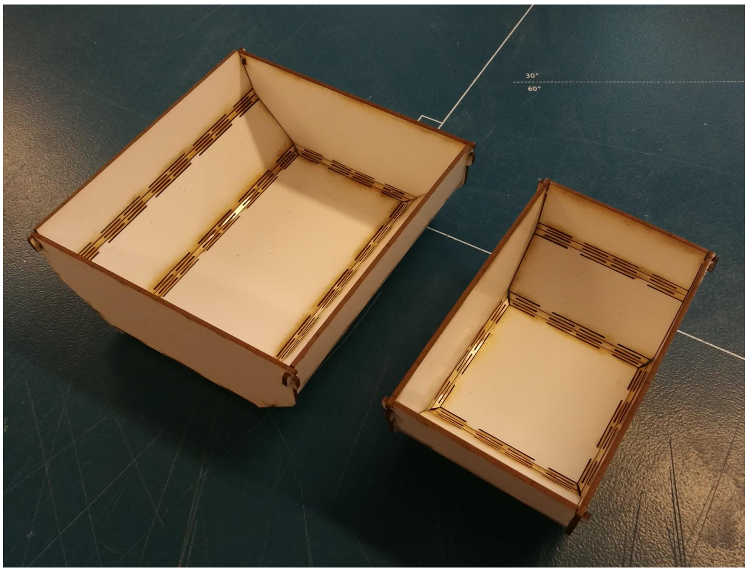

Figure 5.21 Two variations of the 45-degree wall room. The left room has the approximate dimensions of 100 x 100 x 40 mm. The right room has the approximate dimensions of 50 x 100 x 40 mm.

5.3 Connective Mechanism Research

From the connective mechanisms hypothesized in section 3.6, at the company's request the one that will be examined in this project is the Mountboard Clips type. This is primarily motivated by the manufacturing method being similar to the structures as well as the aesthetic impact of the notches is deemed to be minimal.

5.3.1 Prototype Test

When creating the prototype, a few parameters had to be considered:

1) The clips need to be made out of the same mountboard being used for the structures.
2) The structures need to be as adjacent to each other as possible, leaving little to no gap between the walls.
3) Allow for modularity. Different room types should be able to connect to each other.
4) The aesthetic impact should be reduced as much as possible.
5) A connected pair of structures should be able to sustain slight bumps and movement (as is to be expected for a board game) without disconnecting. Being able to lift the structures is not a requirement.
6) The clip needs to be easy to use, both when applying, removing and storing the clip.

By fitting the clips to align with the 25 mm grid the structures are able to connect in a consistent pattern. Due to the GT locking mechanism, the corners of the structures jut out 2 mm from the wall, making point 2 difficult to fully accomplish. With two similarly sized structures adjacent to each other that leaves a gap of 4 mm between them. If a smaller room is positioned next to the wall of a larger room only the smaller structure's lock bumps up against the other structure, meaning the gap is only 2 mm. The clip needed to take this variable gap width into account. Point 3 will be examined further in section 5.3.2.

The clip designs in Figure 5.22 were tested.

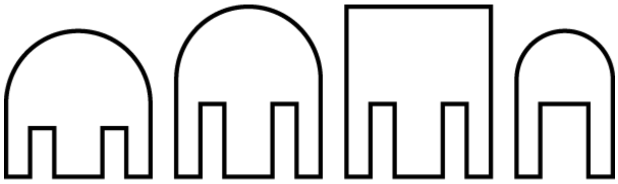

Figure 5.22 The four clip variants.

The first three clips have 2 mm notches in them, matching the thickness of the mountboard. This would allow them to slot over the room walls. They also have a 4 mm spacer between the notches, matching the widest gap possible between adjacent rooms. The fourth clip only has a 4 mm notch in the middle, to see if it'd be possible to find a way to place the room walls completely flush to each other.

The clips were attached to connect two box structures and their behaviour was examined. The fourth clip proved unusable as the walls could not be positioned in any way for it to properly connect. The other three could be attached, though it became apparent that there was a lack of rigidity when moving the structures parallel to each other; the clips would allow the structures to slide in the notches, which made it easy to move the structures out of position.

To counter this, a notch was added to each wall of the box structures. These notches were placed 25 mm apart, aligning with the middle of the squares of the 25 mm grid. By placing the clips on these notches the structures not only align properly but also resist being moved parallel.

The height of the clip created a high visual impact; to reduce this, a lower height could be used, as long as the clip is still easily accessible and doesn't create sections too thin to function properly. To ensure this a version of the square clip with the dimensions seen in Figure 5.23 was proposed.

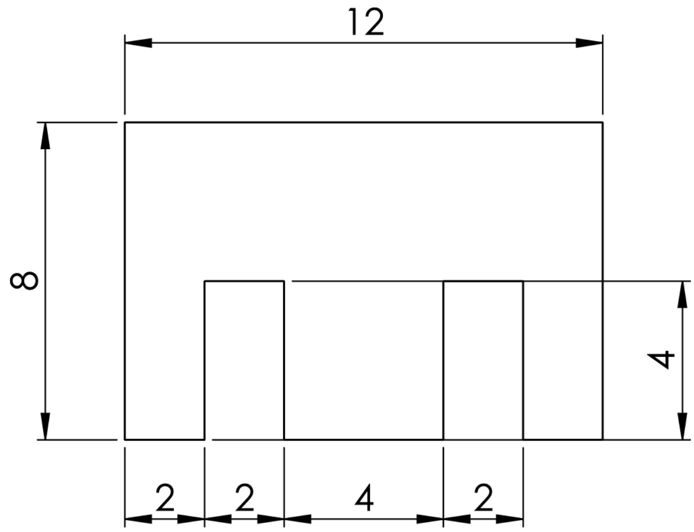

Figure 5.23 Final clip dimensions.

5.3.2 Grid difficulties

Due to the 25 mm grid used in previous sections, rooms of different sizes had alignment problems. This was because of the wall thicknesses, hinge radii and lock proportions creating discrepancies when multiple rooms of different sizes are placed next to each other. This is visualized in Figure 5.24 with the dimensions of a 3-2 Edge-Middle pattern hinge.

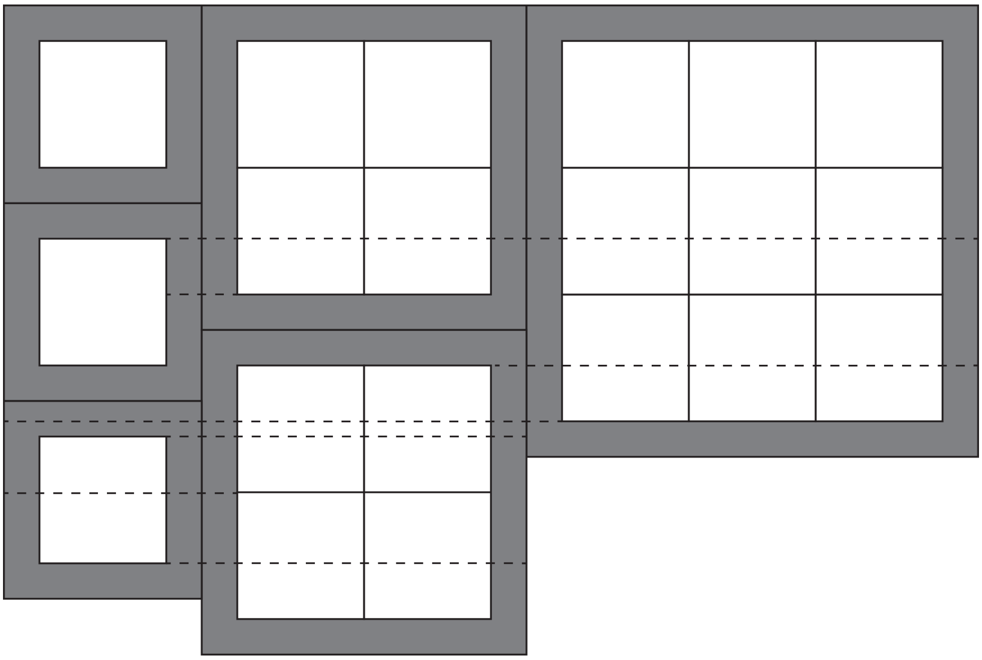

Figure 5.24 An example set-up of rooms with a 25 mm squares grid, seen from top-down. The dark grey areas show the wall boundary, the white show the available square area. Dashed lines show where the grid is misaligned.

The wall, hinge and lock combined form a total wall thickness of 7 mm for a 3-2 Edge-Middle pattern hinge, while the total wall thickness is 5 mm for a 2-1 Edge-Middle pattern hinge. Two solutions were proposed to solve this problem:

5.3.2.1 Gap grid

The gap grid spaces out the grid squares, compensating for the wall thickness by adding a gap between the squares that matches the wall thickness (Figure 5.25). This causes the squares to be aligned no matter the room size.

This method allows for small 1 square wide rooms, though due to the added thickness from the walls larger rooms waste a lot of space due to the gaps. Each square effectively takes up 39 mm of room width per square.

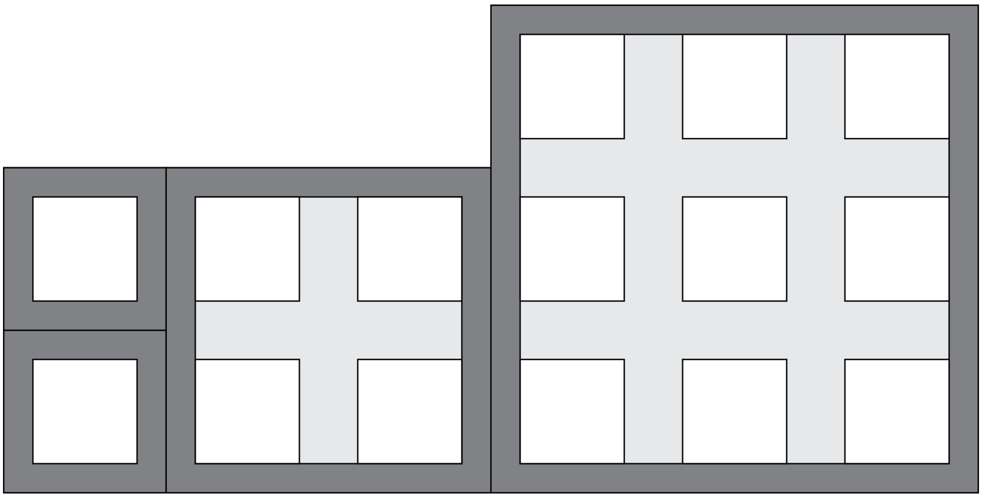

Figure 5.25 Gap grid; light grey areas mark the gaps between grid squares. Shows two 1x1, one 2x2 and one 3x3 square room.

5.3.2.2 Fill grid

The fill grid spaces out the grid tiles similar to the gap grid, but instead of leaving the area between the squares blank it expands the squares until they meet (Figure 5.26). By making the standard square size 32 mm, if a square is adjacent to a wall then the wall can take up space inside the square (effectively making the width the minimum acceptable size of 25 mm for a 7 mm wall thickness). Unfortunately, this prohibits any rooms with a width of 1 square, as a square with walls on opposite sides would only have a width of 18 mm.

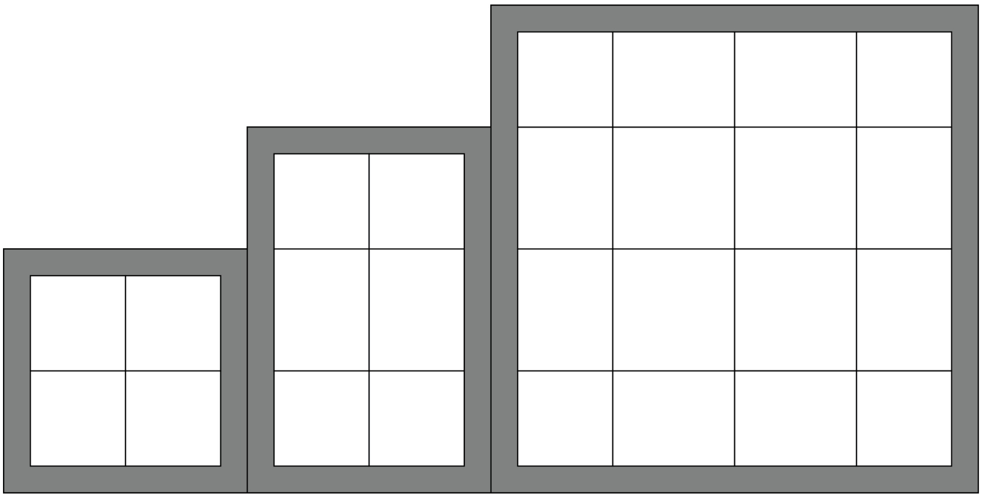

Figure 5.26 Fill grid; shows one 2x2, one 2x3 and one 4x4 square room.

The fill grid takes up much less space compared to the gap grid, allowing for more squares in roughly the same space. This is visualized in Figure 5.27, with the blue area representing the gap grid, the red area representing the fill grid and the pink area showing overlap. While the red area is slightly larger, the gap grid only allows for 15 squares while the fill grid vastly outperforms with 26 squares.

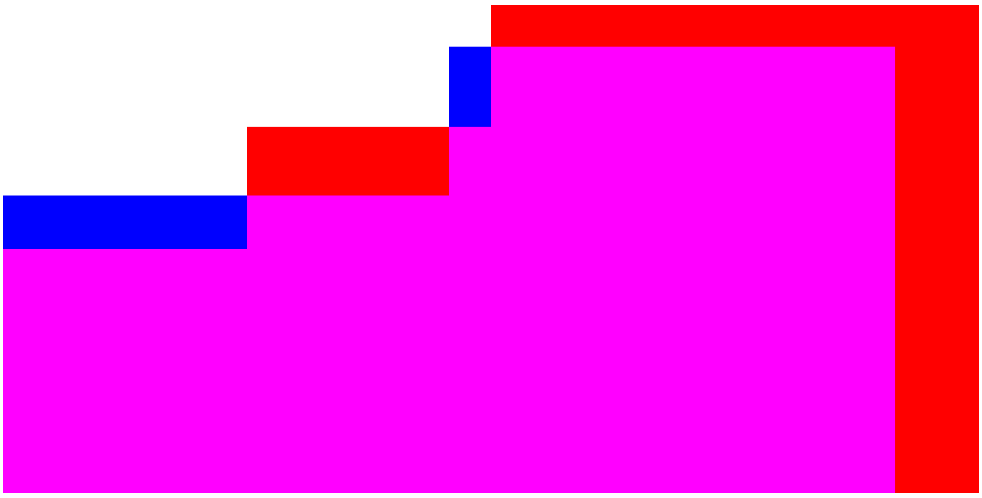

Figure 5.27 The blue area shows the gap grid, the red area shows the fill grid, the pink area shows where the two grid types overlap.

The fill grid has a slightly larger area overall in the comparison, but even if the 4x4 square room used with the fill grid is reduced to 3x4 squares it will still contain more squares than the gap grid. Since the fill grid takes up less space and provides a more aesthetically pleasing pattern, it will be used for the rest of the project.

5.3.3 Improved notch positioning

With the standard grid size being established as 32 mm with the fill grid, the rooms can be standardized to having wall widths in multiples of 32 mm, with the smallest being 64 mm (a 2x2 square room). A 2-1 Edge-Middle pattern could conceivably allow for a grid size of 30 mm since it has a thinner combined wall thickness, though this was not considered for this project.

Placing the wall notches in the middle of the 32 mm squares like before worked fine to keep the rooms together, however, to improve the strength when connecting rooms (especially when there are few points where the pieces connect) a second notch is added per square. This places a notch every 16 mm, starting 7 mm from the edge, allowing rooms to be connected in a variety of ways seamlessly (Figure

5.28). By moving the notch away from the middle of the square it will also allow for doors to be inserted in between adjacent rooms should it be desired.

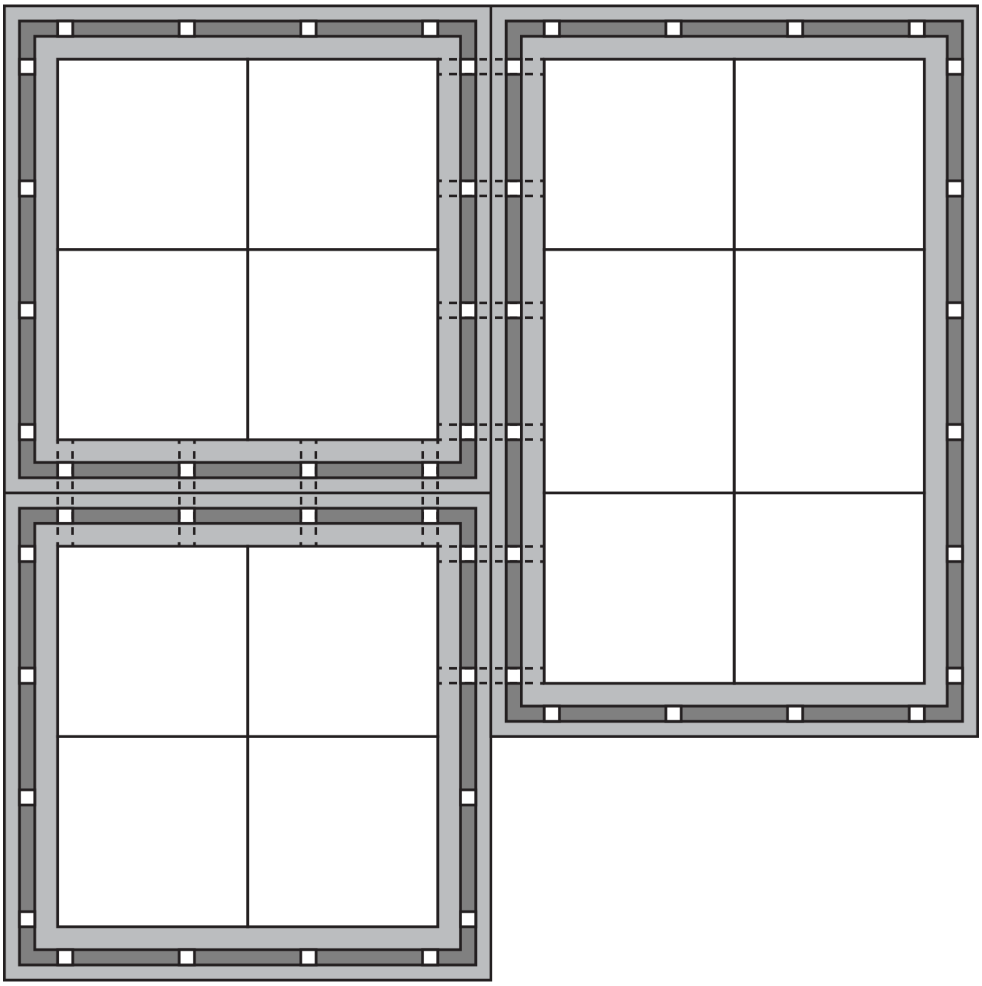

Figure 5.28 An example configuration of rooms. The small white squares show the placement of the notches. The dashed lines show where a clip can be inserted to connect the rooms.

Unfortunately having multiple notches along the wall can have a large aesthetic impact. This can be partially remedied by only having notches in specific places like doorways, should the game the rooms are being used for allow it.

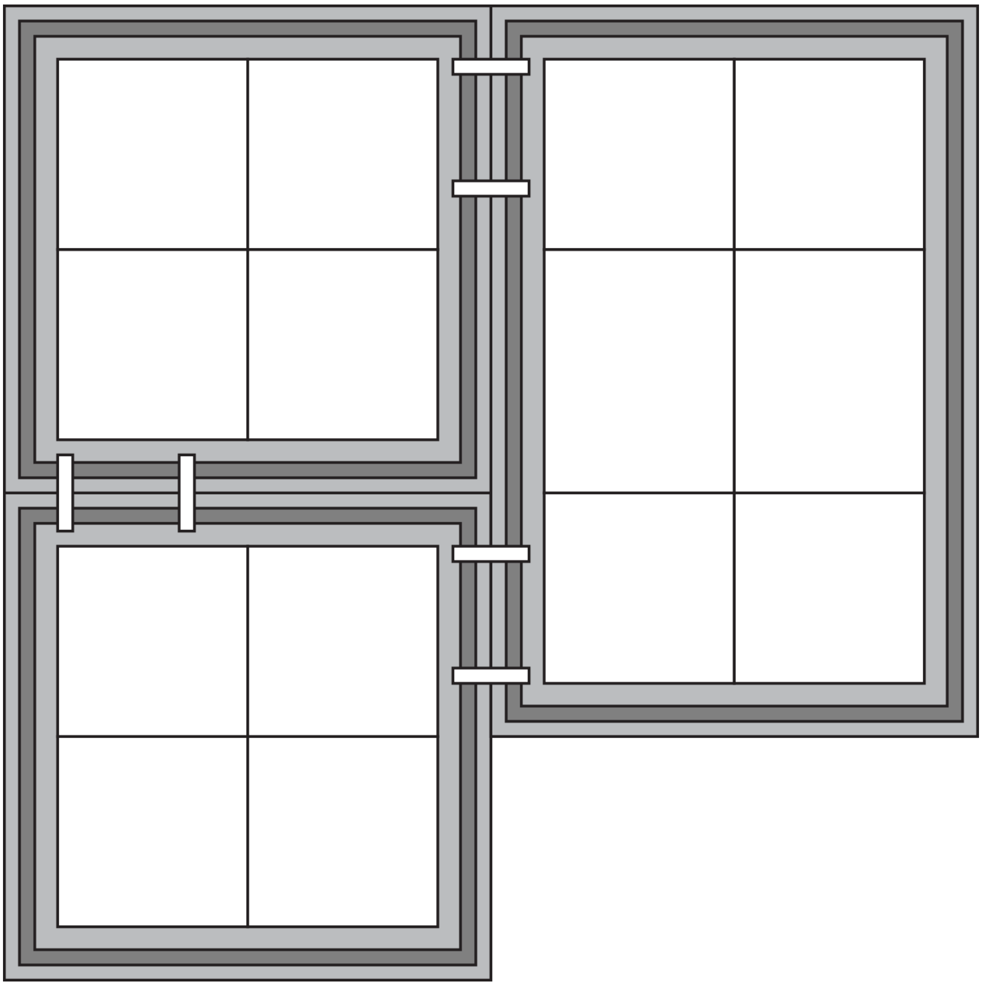

Figure 5.29 An example configuration for how the clips can be positioned, when only certain squares have notches. An example scenario would be to only put notches over doorways.

5.4 Room Layout & Design

Using the hinge and lock designs from previous sections, these can be applied to create structures relevant to the board game system being developed by Shearwood Games. The specifications of this system and the structures created for it will be described in this section.

5.4.1 Board game system specifications

The following requirements were put upon the structures of the game:

- The board game will take place on a science fiction spaceship, using multiple structures that are meant to represent the various rooms that make up the interior. The game will ship with premade spaceship layouts, with the option for players to connect structures themselves to create their own layouts.
- The structures should consist of walls and a floor, but no roof to facilitate moving figurines inside the structures.
- The 2-1 Edge-Middle hinge design is to be used for the structures.
- The structures should have a height of 50 mm when deployed.
- Rooms should range between 2 to 5 grid squares in width and length.
- Rooms should have at least two connection points, represented by doorways, where they connect together to other rooms. This is to ensure that no room has to be a dead end.
- These connection points should allow for different layouts to be created when multiple rooms are connected, and the layouts should enable circular movements through the layout i.e. a figure can exit a room through one doorway and enter it using another by moving through the layout.
- The structures must tile when connected.
- Some rooms should contain ledges and angled walls. Sections of a room that are raised should have connection points to other rooms with the same kind of raised section.
- The cutting patterns for the structures should fit on two A2 sheets, approximately 6 to 8 structures per sheet.
- Structures should be varied and have interesting shapes; not just box rooms.

5.4.2 Possible structure layouts

The biggest limitation on the room configuration is that the patterns must fit on two A2 sheets, as it restricts the size and number of rooms. To get a good idea for what layouts would be available, various square outlines based on grid size and wall height were created and positioned in different configurations (Figure 5.30 and Figure 5.31). Through this, a rough idea of the possible room sizes could be given.

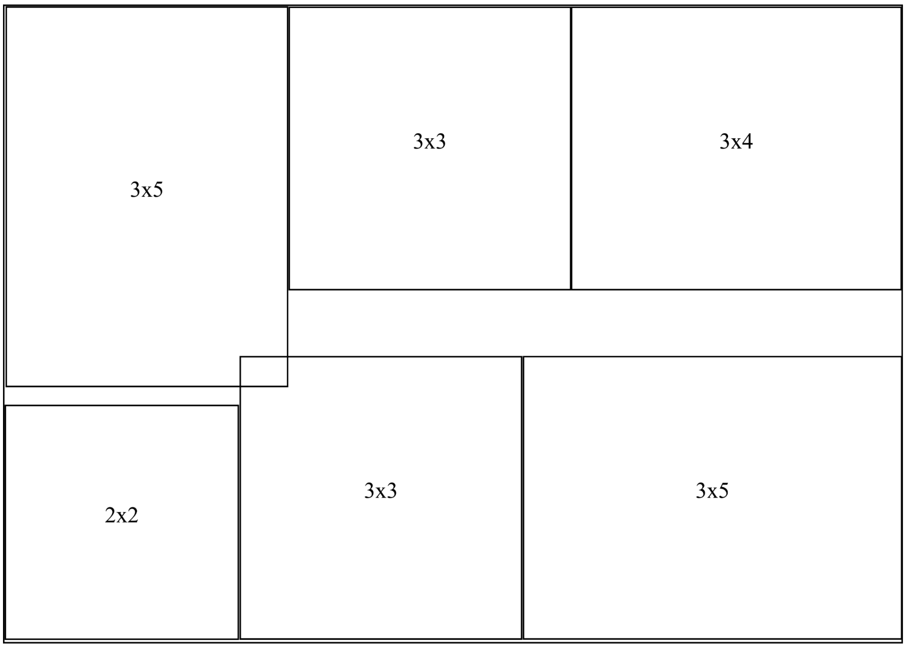

Figure 5.30 First A2 layout. The slight overlap should still be possible due to the room patterns not fully extending to the corners.

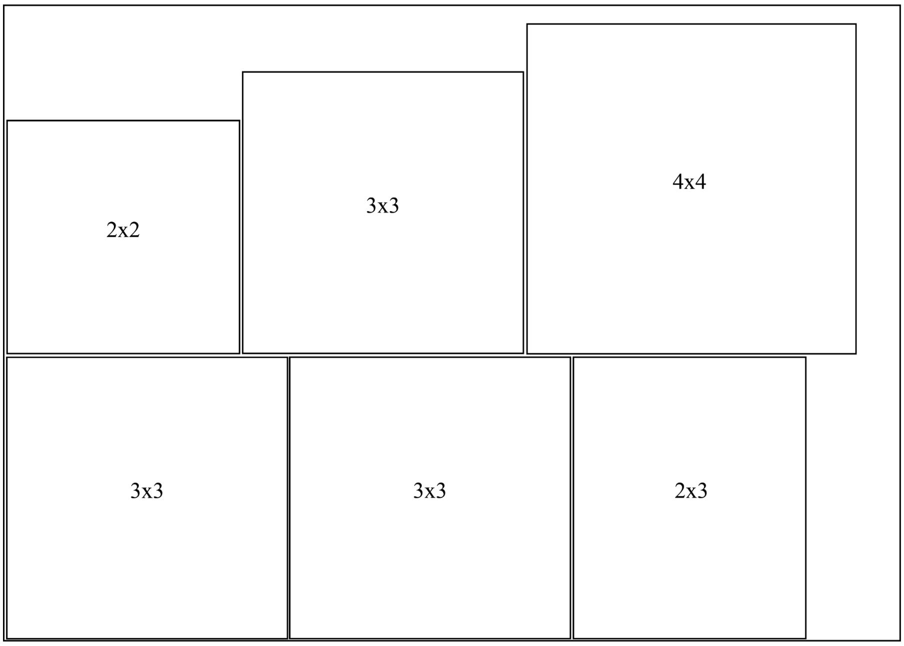

Figure 5.31 Second A2 square layout.

5.4.3 Room generation

Based on the various grid sizes able to fit on the A2 sheets, different designs of rooms were proposed. These rooms were either constructed to have an interesting shape and/or size, or to facilitate connections in the overall layout. They can be separated into the categories "**Bases**" and "**Connectors**".

5.4.3.1 Bases

The Bases rooms largely feature the 45-degree walls, ledges and 45-degree corners to create interesting shapes, and make up half of the overall rooms, see Figure 5.32.

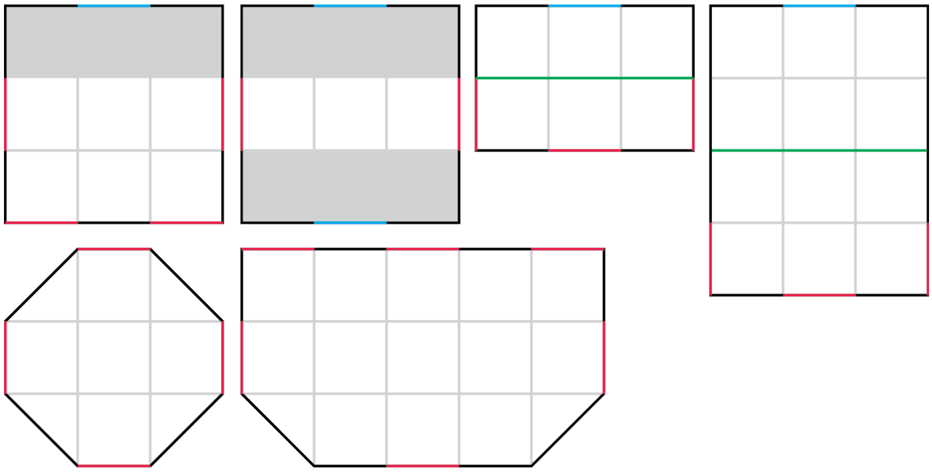

Figure 5.32 Base rooms. Red lines signify regular connection points (doorways), blue lines signify ledge-height connection points (vent shafts), grey areas signify 45-degree walls and green lines signify ledges.

To show where the rooms' connection points are, simple doorway shapes were cut out of the wall sections of the cutout pattern. Since the ledges limit the available wall height of the room, any connection points on such a wall were represented with a rectangular "ventilation shaft" cutout instead. These are visible in Figure 5.33.

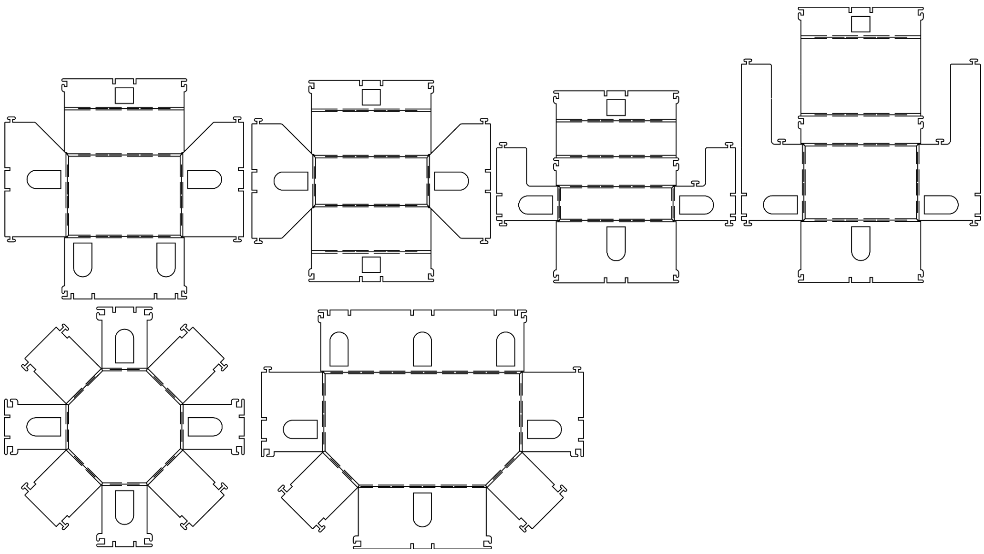

Figure 5.33 Base rooms, cutout patterns. The rooms correspond to those of Figure 5.32.

5.4.3.2 Connectors

The Connector rooms act as their name suggests; the positions of the connection points are placed to allow many configurations of rooms to fit together and increase the modularity of the layouts, see Figure 5.34. Since rooms can be rotated a single room can allow for many different connections between rooms if the connection points are carefully placed.

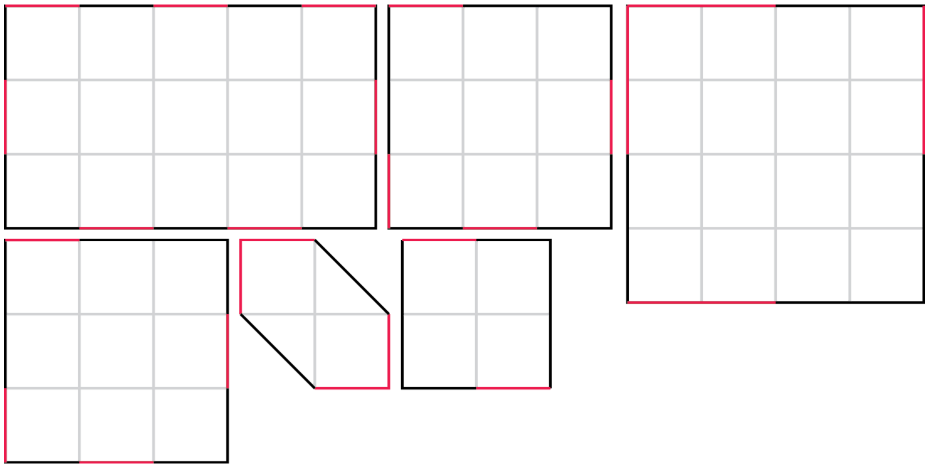

Figure 5.34 Connector rooms. Red lines signify regular connection points (doorways).

For example, this can be seen in the connection points of the 4x4 room. This room has been designed to facilitate connecting any two rooms with doorways that are perpendicular to each other. While this could be achieved by simply putting doorways along the wall at every grid square, by utilizing the fact that the room can be rotated fewer connection points need to be placed to achieve the same effect. A visualization is given in Figure 5.35; if the left and bottom walls connect to another room at one arrow, it allows for 16 possible permutations (4 different door positions on the left wall, multiplied by 4 different door positions on the bottom wall).

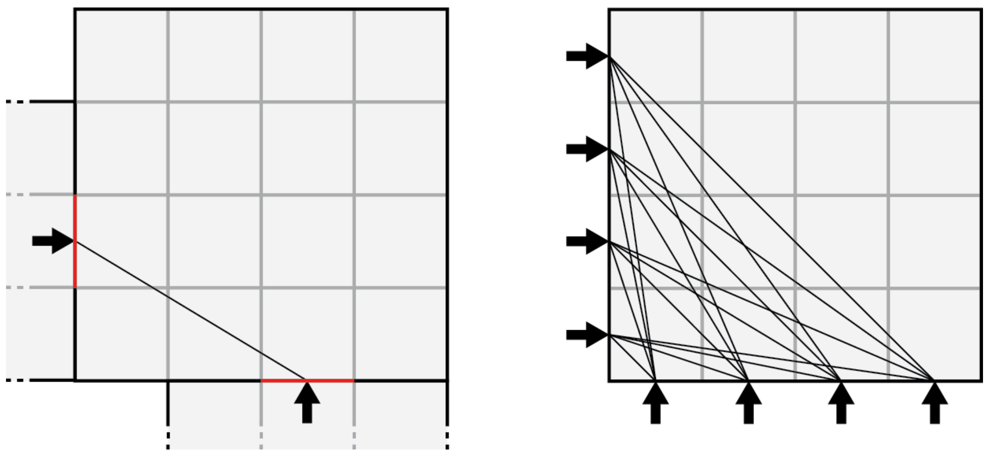

Figure 5.35 The 4x4 room. The left image shows one example scenario with two other rooms connecting to the bottom and left wall. Since there are 4 connection points on the left and bottom wall, that results in 16 possible permutations (represented by lines), as shown in the right image.

By placing two doorways on each wall in the pattern below, all 16 permutations from Figure 5.35 can be fulfilled by rotating the room, as shown in figure Figure 5.36. Doing this makes the 4x4 room very versatile, as it will allow it to fit into many different layouts.

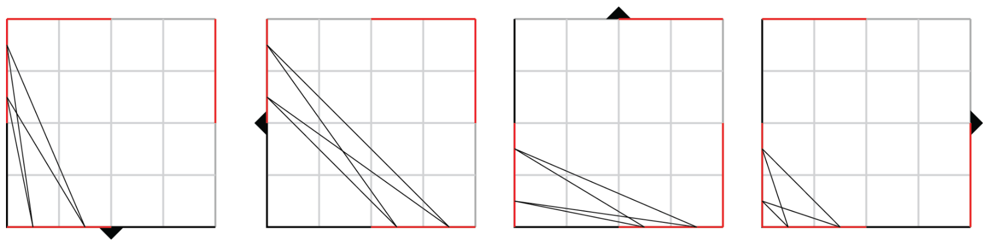

Figure 5.36 The placement of the 4x4 room's connection points/doorways (red lines) allows it to meet all 16 permutations, depending on the rotation of the room. The arrow indicates the rotation

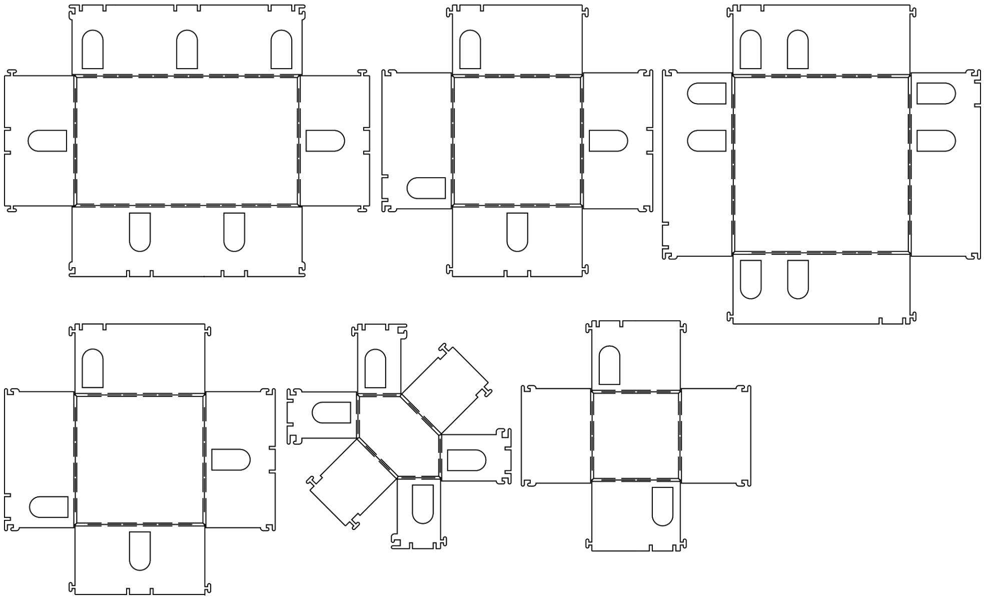

Figure 5.37 Connector rooms, cutout patterns. The rooms correspond to those of figure Figure 5.34.

5.4.4 Examples of board game layouts

While the purview of this degree project does not extend to the final board game layout, the following section contains some examples of how the structures can be combined. Figure 5.38 shows three layout examples using all 12 rooms, with the aim to provide different shapes to the layout.

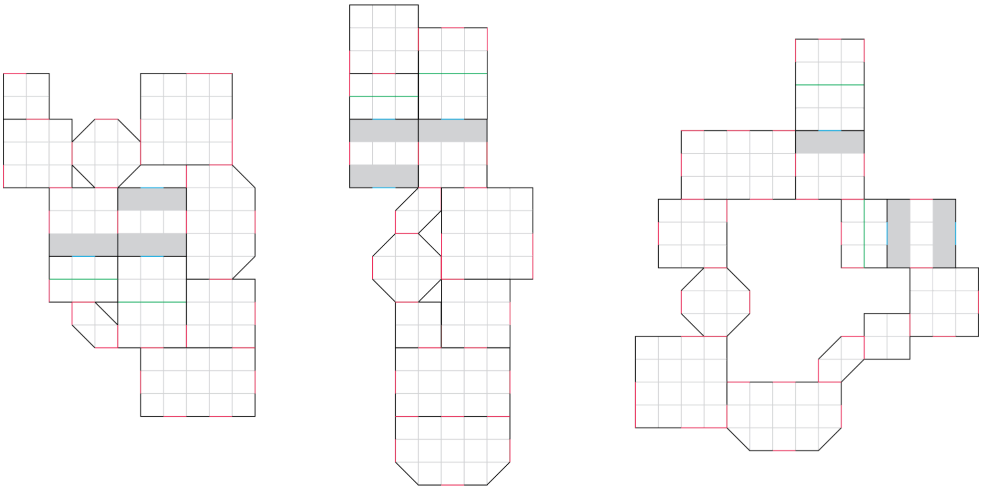

Figure 5.38 Three examples of board game layouts. The left example is concentrated with multiple pathways, the middle example is a long layout with a separated back section and the right example is a winding circle without alternate pathways.

By cutting out a selection of room samples in mountboard, this can be visualized with photos of smaller layout examples, seen in Figure 5.39 and Figure 5.40.

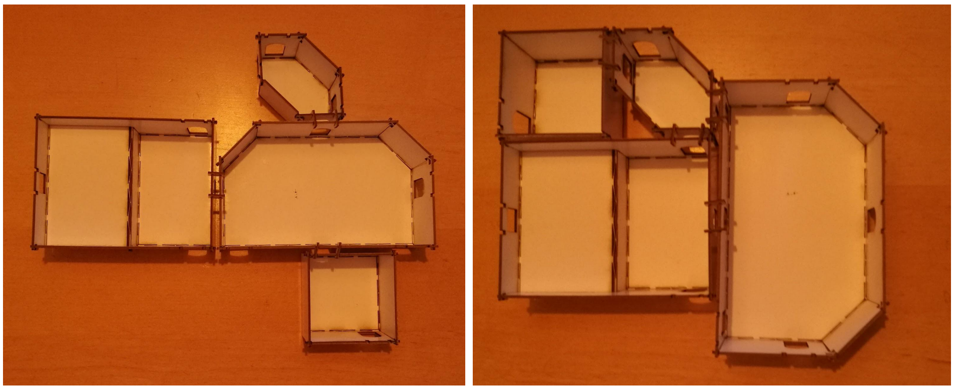

Figure 5.39 Two examples featuring some of the rooms cut out and connected physically in different layouts.

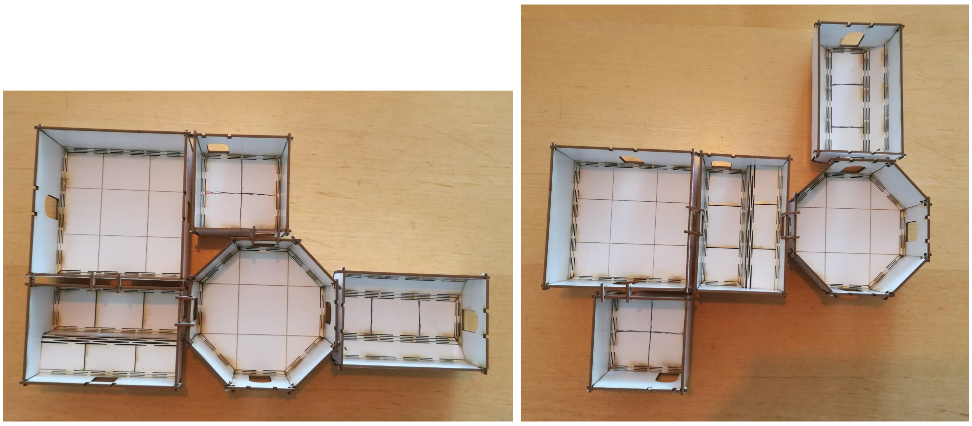

Figure 5.40 Two examples featuring another set of rooms cut out and connected physically in different layouts.

5.5 Pattern Template

At the request of the company a template for the patterns developed during this project was produced. This template features the hinges, GT-lock variations and examples that allow a designer to create their own structure patterns. It was created through Adobe Illustrator and is intended to be used with the same or similar programs.

The pattern templates also shows what parts of a pattern can have its dimensions changed and what parts can not, to allow for different heights of walls and hinge lengths. It also features rudimentary explanations for how to apply the templates, though concludes that the designer will have to make their own calculations to be certain that the structure pattern will function, due to the vast number of ways a structure can be created. This involves making sure that locks align by having them at a consistent distance from the floor part, properly extending hinge edges to meet corner profiles and ensuring that the structure follows the grid size. The template is provided to the supervisor at Shearwood Games who has intimate knowledge of the project work, and it is recommended that the company recreates it and/or provides supplementary guidance for any designer not familiar with the project work.

Of note is that the template features a wide variety of corner hinge profiles. While this degree project has examined 45-degree corners, these profiles would allow a designer to create structures with other angles as well. These profiles were created with Solidworks using the same process as described in section 5.2.1.2.

The 45-degree GT-lock pattern was provided to the company separately outside the template.

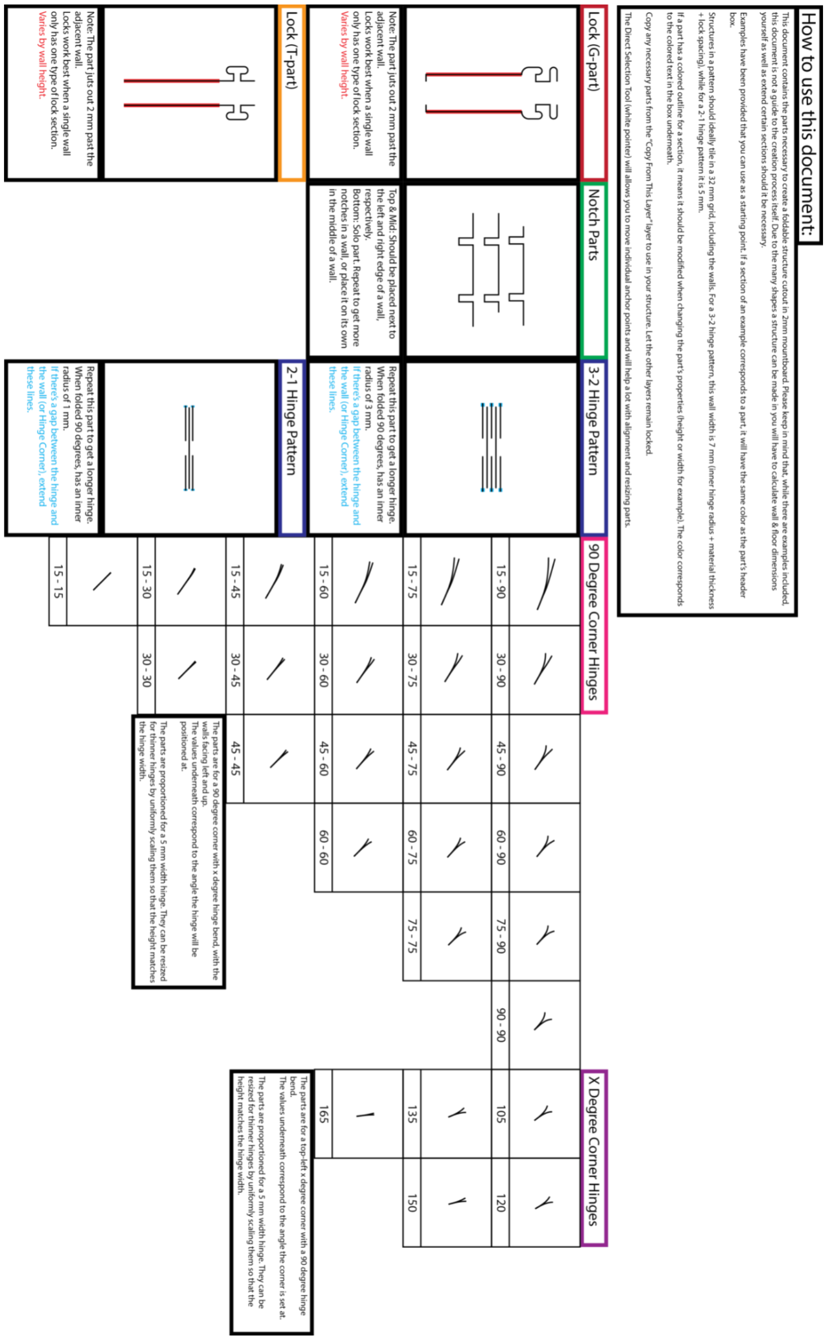

Figure 5.41 Image of the parts section of the template. The colors of the part headers correspond to the examples in Figure 5.42.

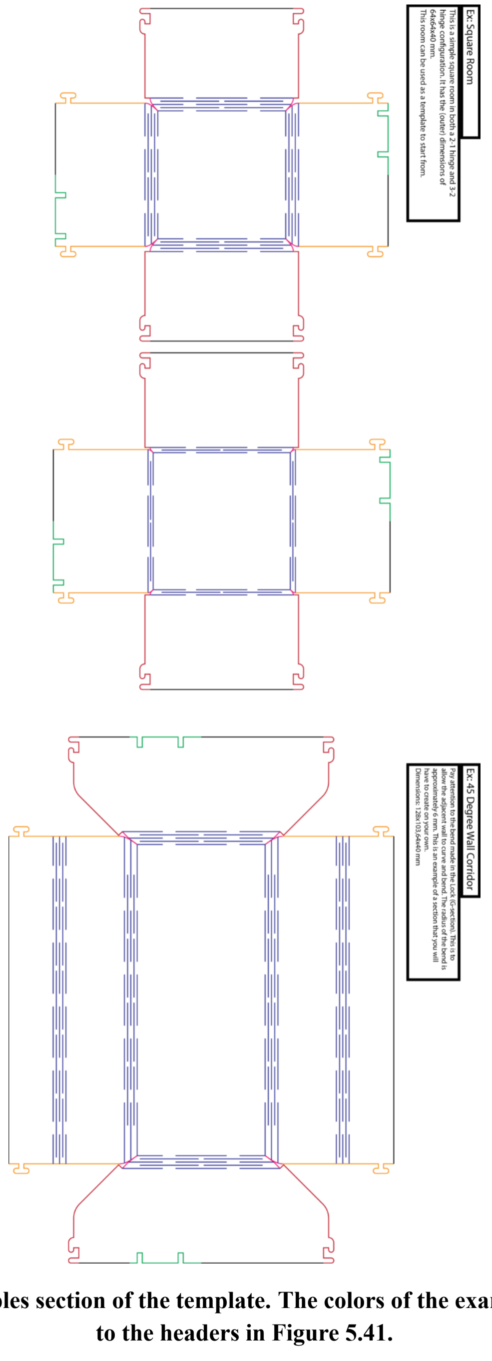

Figure 5.42 The examples section of the template. The colors of the example parts correspond to the headers in Figure 5.41.

6 Discussion

6.1 Hinge construction discussion

The development of the hinge design proved to be a success for the project and the company was very satisfied with the performance of the hinge. However, there were some problems during development that could have negatively influenced the research of the hinge.

The primary issue is the laser cutter used; due to the malfunctions of the laser cutter, not only did it limit the available cutting surface to half of what the machine should be able to perform at but it also sometimes resulted in sub-par cutting when producing the hinge tests. During each cutting session the laser cutter performed slightly worse the longer it cut, possibly causing differences between testing pieces. While any unsuccessful cut that did not fully cut through the material was discarded and not accounted for during testing, it could have created slightly different kerf widths between a piece that was cut during the start of a cutting session versus the end.

Furthermore, there is no guarantee that the performance of the laser cutter used during testing is replicable for a laser cutter being used for production. This resulted in needing to allow for a certain degree of tolerance when it came to the hinge design and for the designs to be tested by the company to confirm their validity. The thesis thus recommends that any new application of the hinge design undergoes testing to ensure that it performs suitably. Using the research conducted in this degree project it should be possible to modify the hinge design to suit new applications, particularly through the use of section 4.2.9.

The hinge design could also benefit from a more thorough mechanical analysis. This thesis did not examine it any further than the practical use case in a board game as the project required it to be applied to the product. While this allowed the company to move forward with prototyping the board game and the structure design (a vital part of finding out whether the hinge could even be applicable for a board game) it means there is a large gap of knowledge when it comes to how the hinge mechanically behaves and how it can be accurately modified to fit new applications. Ultimately the validity of the hinge design relies heavily on observed behaviour and not through mechanical analysis, and the thesis promotes the possibility of further examining its mechanical properties in a future paper.

The choice to work with two patterns, the 3-2 Edge-Middle hinge pattern and the 2-1 Edge-Middle hinge pattern, was primarily made due to the tight restrictions put on the design by the company and the material properties. The 2-1 Edge-Middle pattern was chosen in the end due to its smaller inner radius, but the development of the two patterns in tandem shows the possibility of how the hinge can be applied in other contexts where the restrictions are not as strong. The living hinge designs could very likely perform extremely well when scaled up and applied to a larger object/stronger material. The benefits of living hinges should not be understated and hopefully this project gives some insight into the application possibilities of the design.

6.2 Structure design discussion

The structure design phase similarly proved to be satisfactory to the company, and as the phase focused more intently on the product development aspect of the project it exhibited solutions to problems more specifically related to the board game system being developed. The company intends to further develop the structure design with added visual elements to incorporate the structures into their board game.

It should be observed that the hinge design could be applied to any of the structure folding mechanisms proposed in section 3.5, and the GT lock is certainly not the only viable choice for how to lock the parts of a structure together. There may be structure and lock designs that are more robust and would fit the project better, however, the pace of the project encouraged fulfilling the specifications first and foremost, so when the designs were deemed acceptable they were only further developed if a new issue arose (for example, the 45-degree corners in section 5.1.5 requiring a change to the GT lock design). While this may initially seem like a negative it also strongly indicates that the hinge and structure designs can be used in more applications other than board games as long as changes are made to accommodate them. For example, the structures could see use in architectural models or wargame terrain.

The connective mechanism was a very simple solution to the problem of connecting structures and the thesis acknowledges that it is very specific to the board game system being developed. However, as a prototype it functions as desired and should a more robust solution be necessary for the final product it is possible to find alternate designs.

It would be interesting to have developed this project with closer ties to the end user, as described in section 3.1.2. Due to the time that this project took place it became inadvisable to engage with end users, and the responsibility to validate the product with the end user became the company's responsibility. While the company could confirm whether a design was suitable or not, it became an extra layer of obscuration between the designer and user that may have impacted the final result. Additionally there was no point where the fundamental problem could be considered by the designer, as the company had already settled on laser cutting as the preferred method.

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Appendix A Project Plan

The project plan was first outlined to feature four phases to the project: Folding Mechanism Research, Connective Mechanism, Embellishments Development and Product Application, with four weeks acting as a buffer to be used for presentation preparations and if any other phase required extra time.

Overall the project was completed at a faster rate than first anticipated, both from a lack of obstacles during development and the removal of the Embellishments Development phase. The reason this phase was removed was due to a combination of factors; the added complexity could result in a needlessly advanced product, the mountboard material would ultimately not be very robust for smaller objects and there was a risk that built-in embellishment may negatively impact the visuals instead of improving them. Ït was determined that decorations could instead be included with the print of the structures. This decision was made jointly with the company.

The first two phases proceeded more or less as the schedule predicted. The Product Application phase was truncated since the first set of designs proposed were accepted by the company, and thus little time needed to be spent on feedback revision. Week 14 and 15 were needed by the company to work on their end, meaning they could be spent on writing this thesis and compiling information.

Project Phase \ Week	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Folding Mechanism Research																				
Investigate Existing Solutions																				
Test Folding Mechanisms																				
Test Locking Mechanisms																				
Create Goal Prototype																				
Connective Mechanism																				
Investigate Existing Solutions																				
Test Connective Mechanisms																				
Create Goal Prototype																				
Embellishments Development																				
Generate Embellishments Ideas																				
Test Embellishment Ideas																				
Product Application																				
Design Product																				
Feedback Revisions																				
Production & Testing																				
Final Prototype																				

Figure A.1 Planned schedule for the project and its phases.

Project Phase \ Week	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Folding Mechanism Research														
Investigate Existing Solutions														
Test Folding Mechanisms														
Test Locking Mechanisms														
Create Goal Prototype														
Connective Mechanism														
Investigate Existing Solutions														
Test Connective Mechanisms														
Create Goal Prototype														
Product Application														
Design Product														
Feedback Revisions														
Production & Testing														
Final Prototype														

Figure A.2 Actual schedule for the project.