folding wood

- Investigating architectural opportunities of folded plate principles in timber structures.

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Tutor: Jonas Lundberg and Jonas Runberger
Examiner: Kengo Skorick

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ABSTRACT

The concept of the folded plate has existed within the field of architecture and engineering for close to a century. However, one seldom encounters folded plate structures in the built environment. In theory, the folded plate is an efficient way of enclosing large volumes using a relatively small amount of material. Neverth-eless, in architectural design, there seems to be a multitude of challenges that prevents this theory from becoming reality.

This thesis investigates how the folded plate principles can be pushed beyond perfectly symmetrical shapes to gain spatial values. Aspects such as inclusion of apertures, space division and shell construction are discussed on a conceptual level. Moreover, this thesis looks at the use of Cross Laminated Timber (CLT) in folded plate structures and how these can be designed using digital design tools.

The work departs from existing literature and built examples and uses a combination of physical and digital modeling to further explore the folded plate as a structural and architectural concept. Fundamental principles found in origami are used to initiate the discussion on folded geometry. To contextualize findings and ideas derived from this research and to suggest an expanded use of folded plates, a design proposal for a public building in central Gothenburg was produced.

Finally, conclusions drawn from the research done relating to asymmetry as well as additional aspects are presented. The practical and architectural significance of design choices made in the final proposal are discussed in relation to knowledge gained from this research.

Keywords:

Folded plate structures, cross laminated timber, origami, apertures, digital design tools

STUDENT BACKGROUND

2016-2019 Bachelor Degree in Architecture & Engineering, Chalmers Tekniska Högskola

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Matter, Space, Structure II
Matter, Space Structure III

Courses::

Sustainable Development and the design professions
Design and Communication Tools
Hybrid Practice

CONTENT

INTRODUCTION

INTRODUCTION

BACKGROUND

POINT OF DEPARTURE

With the advancements made in regards to design tools, fabrication methods and material research, there is an increase in what is possible to design and construct. In parallel, designers and contractors are facing increasing demands in respect to social, ecological, economical and environmental aspects. Hence, these advancements entail not only an opportunity but an obligation to think critically about how buildings are designed and constructed in order for these demands to be met. The initial standpoint taken in this thesis is that one way of doing this is through thoughtful combination of material and geometry.

EXPLORATION

Folded plate structures can be a way of creating large volumes with minimal use of material as well as avoiding disruptive pillars within that volume. (Stitic & Weinand, 2015). The necessary geometries to achieve these large spans provides an aesthetic opportunity - the folded shapes can be visually expressive while also telling the structural story. (Falk et al., 2012). This thesis looks into the topic of folded plate structures and how this concept could be further developed and adopted into large scale buildings using timber as the primary material.

AIM

Although arguments can be made for these structures to be considered more frequently, it is still uncommon to encounter them in the built environment. This thesis discusses potential reasons behind this and looks at possible ways to overcome these when designing and constructing folded plate structures using timber. Furthermore, this thesis elaborates through design exploration, on possible ways of making folded plate structures more fulfilling as architecture. This is done through working with specific challenges such as internal space division in relation to the structural system and its attached structural and spatial implications. As the main objective, a design proposal for a public building implementing folded plate principles while taking into account above mentioned challenges was produced.

RESEARCH QUESTIONS

The research questions in this thesis relate to one main challenge. Namely to produce architecturally relevant designs through use of folded plate principles using timber as the main material. To dissect this rather wide question, the following more specific sub-questions are expressed:

- How can asymmetry be used consciously in a folded plate structure to create a variation of internal spaces?

-How can practical aspects such as shell construction, joinery, apertures and cladding be addressed in the design of folded plate structures in timber?

METHOD

The methodology of the project work could be divided into a number of different parts. As these parts are all interconnected, their presence in the design and research process have varied throughout the entirety of the thesis.

REFERENCING

To guide the work and to create a foundation of knowledge about the field of folded plate structures, written and built references has been used throughout the entirety of the thesis. The built references are projects both in wood and in other materials to broaden the understanding of the structural concept and its applications. The scope of both the built and written references was initially kept somewhat wide in order to allow for inspiration to come from several directions. Ultimately however, a more specific set of references and examples was collected and evaluated, focusing on the specific challenges of this project.

EXEMPLIFICATION

To put the research and any new findings into a relevant architectural context, the design work revolved around making a proposal for a building in an urban setting. A site in Gothenburg was selected. The specific site was chosen to provide reasonable boundary conditions that could help in designing a relevant proposal of a chosen typology. The decided building typology was itself motivated by the discussion on the specific benefits and opportunities of the structural concept as well as the urban context in which the proposal is situated. In choosing a specific building typology, the aim was to be able to more carefully work with the structural concept in relation to specific architectural needs.

CONCEPTUAL MODELING

Small conceptual models have been used to investigate structural behaviors and possibilities of different configurations of the folded plate in the early stages of design. These include models in paper and cardboard. Especially interesting was the discussion of spaces created by the different models, the deployability of the models as well as the early stage incorporation of asymmetry and apertures in the folded geometry.

DIGITAL MODELING AND FABRICATION

In designing, the early concepts were brought into the digital realm through Rhino and Grasshopper. Grasshopper was an important tool in building parametric models to iterate through possible designs of the structure. Existing open source scripts looking at folded plate structures and their fabrication were also used to gain understanding of practical difficulties when designing for fabrication.

THEORY AND DELIMITATIONS

THEORY

The theoretical basis for this thesis is constituted by a number of especially relevant books and research papers. Tragsysteme (Structure Systems) by Heino Engel has been a fundamental reference for looking at and comparing different options of folded plate systems. Both theoretical and practical work done by Yves Weinand, Hani Buri and Christopher Robeller has been of great value to learn about the implementation of CLT in folded plate structures as well as the relationship between folded plate structures and principles found in origami.

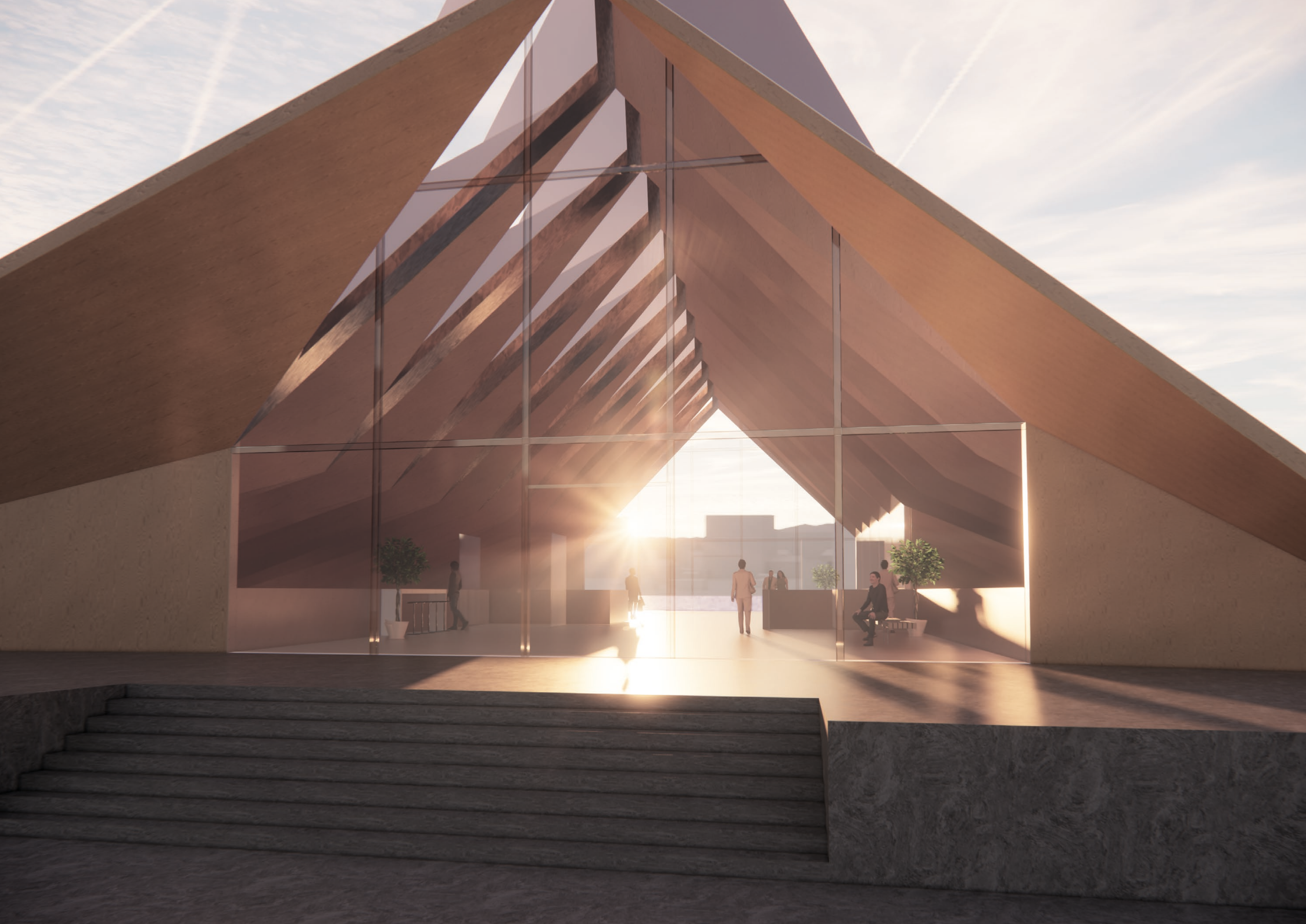
DELIMITATIONS

This thesis focuses mainly on the discussion of the architectural implications and adoption of folded plate principles. This is explored through conceptual structural design but an in depth structural analysis and dimensioning of the final proposal is not included in the work.

Furthermore, the building proposal in this thesis is an elaborated vision of how folded plates can be used in combination with CLT. Technical details of joinery/assembly, window attachment and climatic shell is not developed. Rather, these aspects are discussed and illustrated on a conceptual level.

Lastly, this thesis does not include a detailed plan for execution nor does it include an elaborated estimate of overall costs of constructing a building like the one proposed here. Efforts are made however, to discuss and elect methods of design and construction consciously through researching and referencing.

DESIGN PROPOSAL



DESIGN PROPOSAL

SKEPPSBRON CULTURAL CENTRE

Skeppsbron Cultural Centre is a proposal for a new multipurpose cultural hub in central Gothenburg. The building is envisioned as part of the larger development of Älvstaden and seeks to strengthen the connection between the city and the river as well as to connect the districts of Masthuggskajen and Skeppsbron. The cultural centre contains several functions including library, performance spaces, restaurants/cafes, rehearsal rooms for dance and music as well as exhibition and conference spaces.

The folded roof structure consists of 10 arches. The peak of each arch is placed directly above a diagonally placed walkway that runs through the building. This makes for the twisting expression of the exterior and creates space for the different functions inside. The building is set on a podium which extends out from its two ends and creates a connection to the pier.

SITE

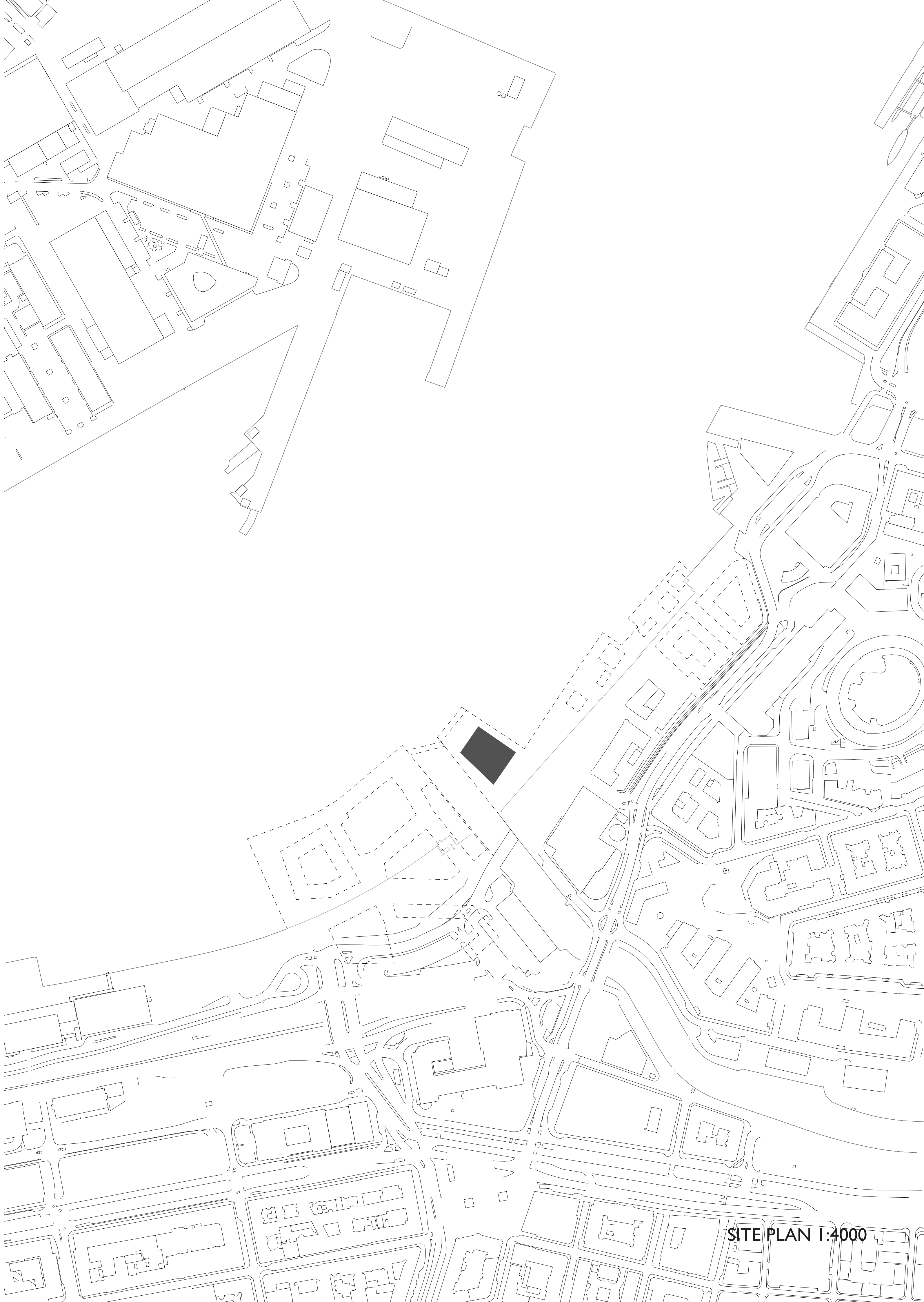
GOTHENBURG RIVER CITY

Älvstaden, (River City), is a major urban development program currently ongoing in Gothenburg. The development seeks to double the size of the city centre and create more than 25 000 new apartments and 50 000 new jobs. The ambition is to strengthen the connection to the river and improve connections between the city's different districts. (Göteborgs Stad, n.d.).

SKEPPSBRON

Skeppsbron located at Södra Älvstranden is one area that will redevloped in the years to come. Offices, shops, restaurants, a public park as well as 450 new apartments will be constructed. Furthermore, a promenade along the waterfront is going to create a strong connection to the river. (Göteborgs Stad, n.d.)

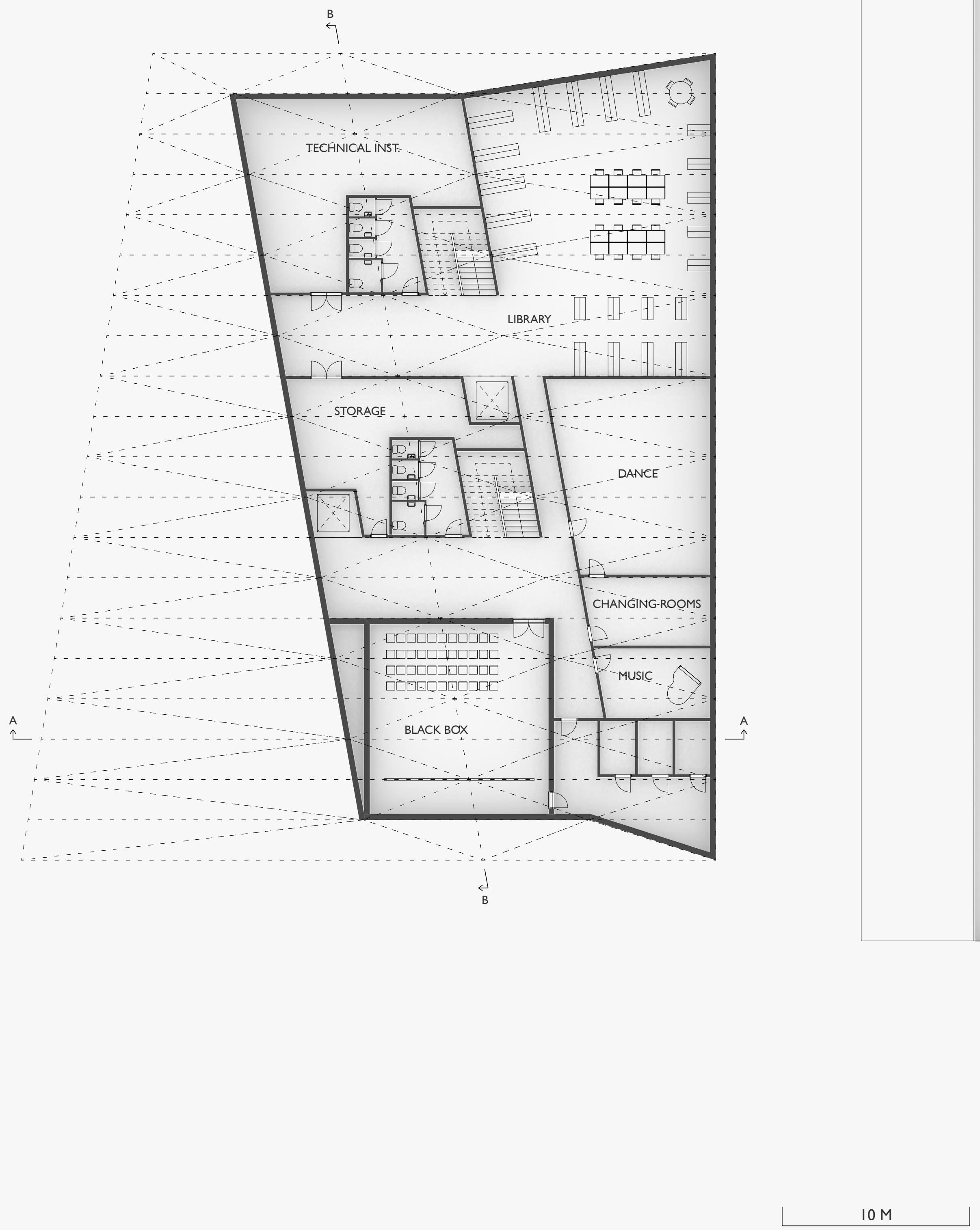
The plan for the area includes a larger public building, placed on a new pier at the southwest end of Skeppsbron. This is hence the chosen site for this design proposal. The area of masthuggskajen is also undergoing a large redevelopment. A new peninsula will be constructed adjacent to the pier of Skeppsbron. (Göteborgs Stad, n.d.). This makes possible the connection of the two areas with a footbridge creating an continuous walk from masthuggskajen all the way to the north-east end of Skeppsbron.



SITE PLAN 1:4000

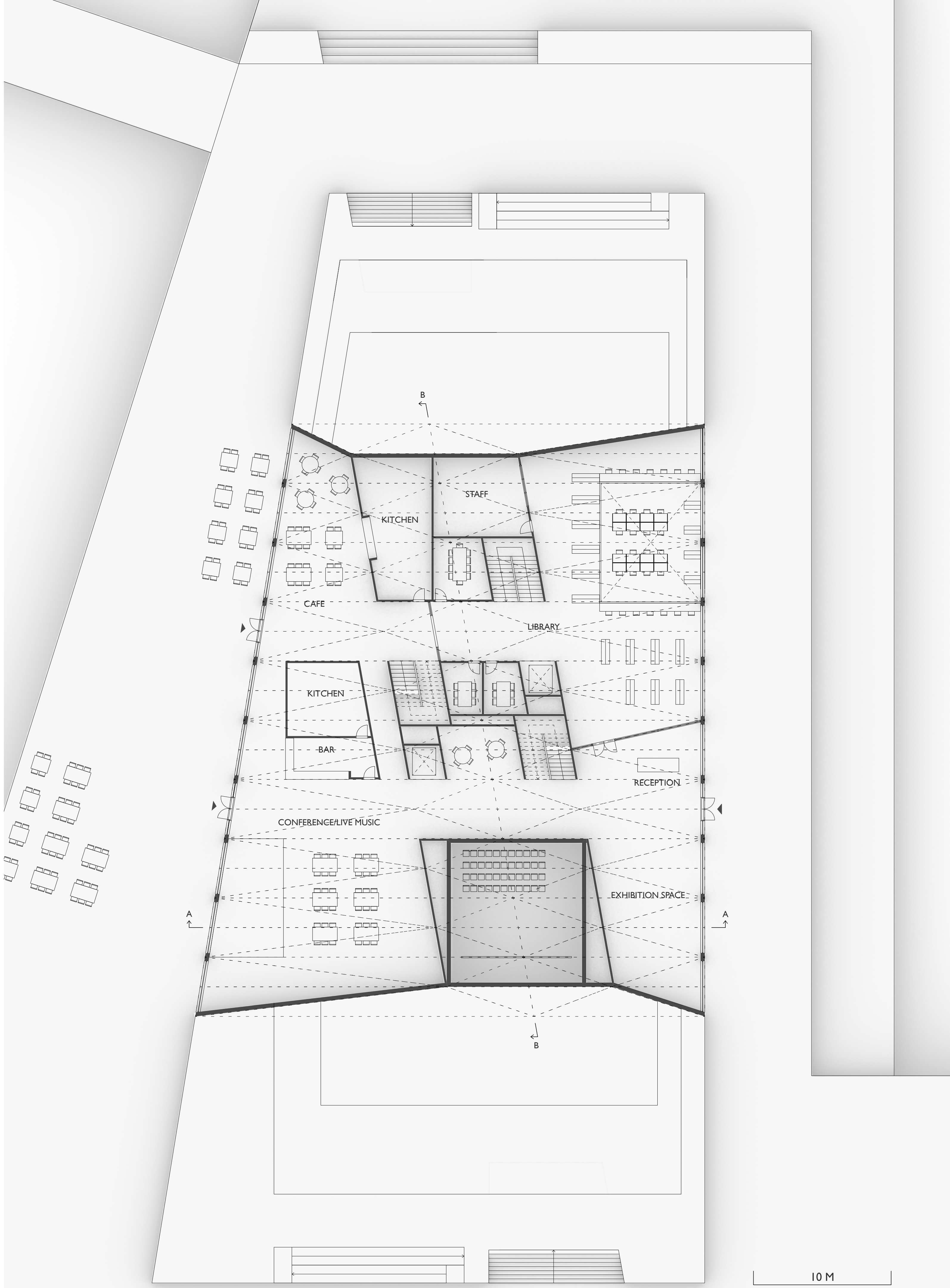
FLOOR -1

On this floor, mainly functions which do no not need daylight are placed. These include music and dance rehearsal rooms, rest rooms, changing rooms, technical and storage spaces. The entrance to the black box is also placed on this level. In addition to this, part of the library is placed here and connected visually to the ground level through a large opening in the floor above.



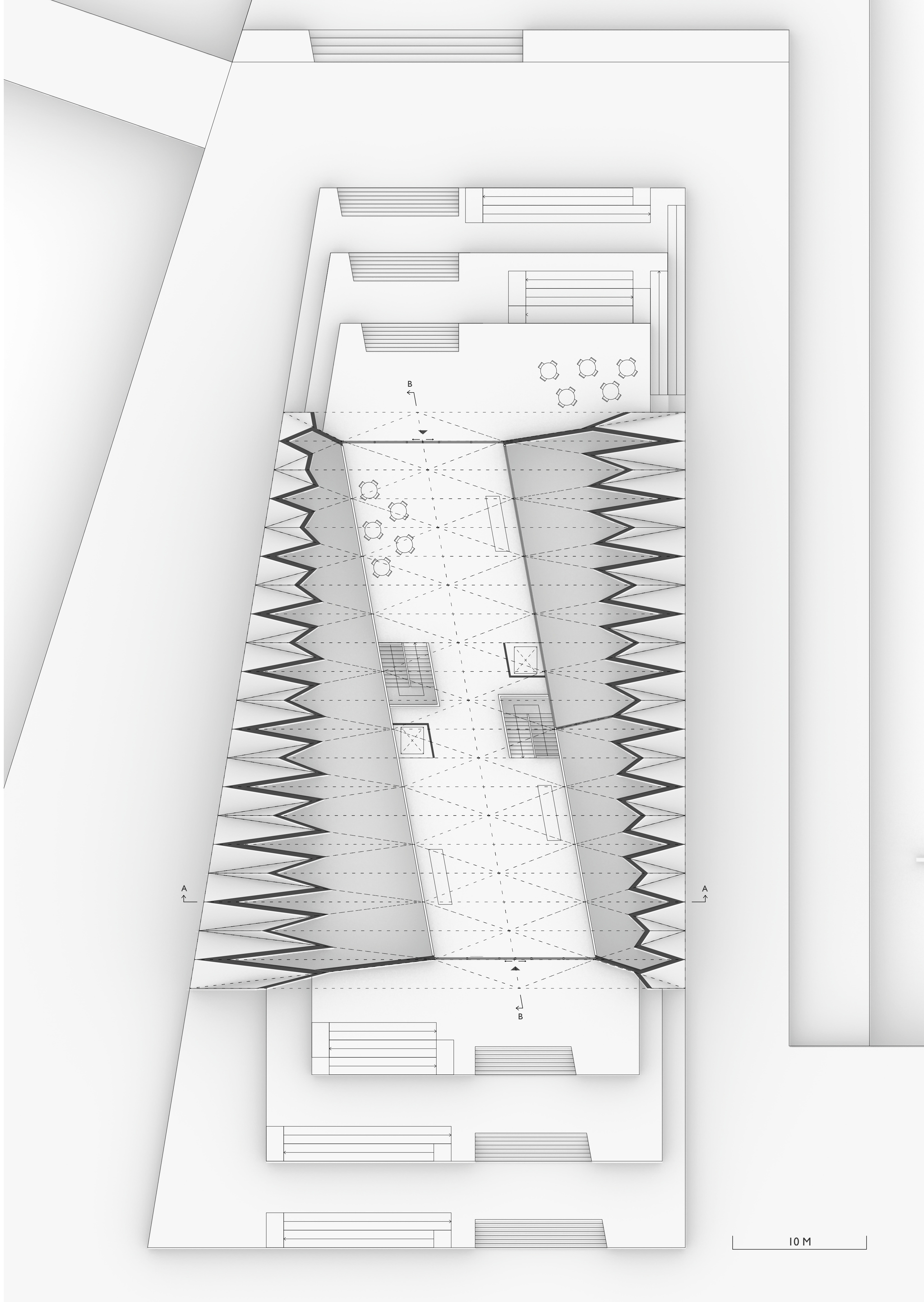
FLOOR 0

On this floor, which sits at ground level, spaces requiring daylight and less prominent physical boundaries are placed. These include reception, exhibition space, conference/performance space cafe/restaurant and bar. In addition to this, in an enclosed space at the north east corner of the building, the upper floor of the library is placed. The two sides of the podium are connected through two wide corridor spaces, creating both a physically and visually strong connection between the different functions of this floor. A number of smaller entrances to the building connects the indoor spaces to the pier outside.



FLOOR 1

On this floor, the walkway through the building is placed. It is however not only a way to pass through the building but also a space where a smaller cafe, temporary exhibitions and additional seating areas can be found. The stair wells and elevators invites visitors to enter the different spaces on the floor at ground level.

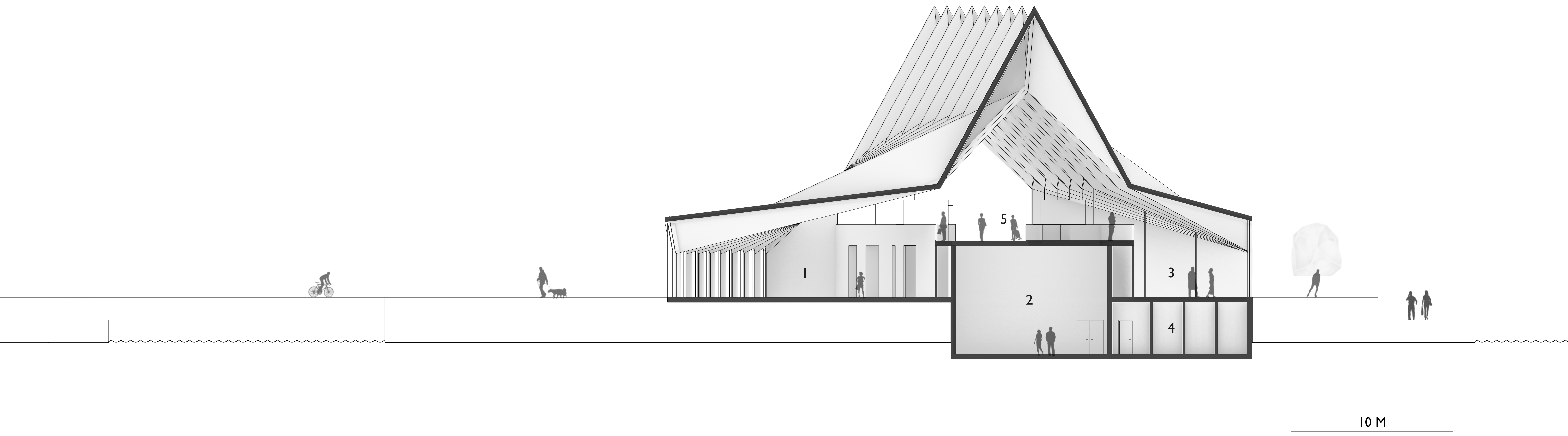


DESIGN PROPOSAL | SECTIONS

SECTION A-A

The interior space is divided into two distinct sides by the centrally placed and elevated walkway. The two sides are connected through two wide corridors which enables visitors to move between the different sides.

1. CONFERENCE/LIVE MUSIC
2. BLACK BOX
3. EXHIBITION SPACE
4. DRESSING ROOMS
5: WALKWAY

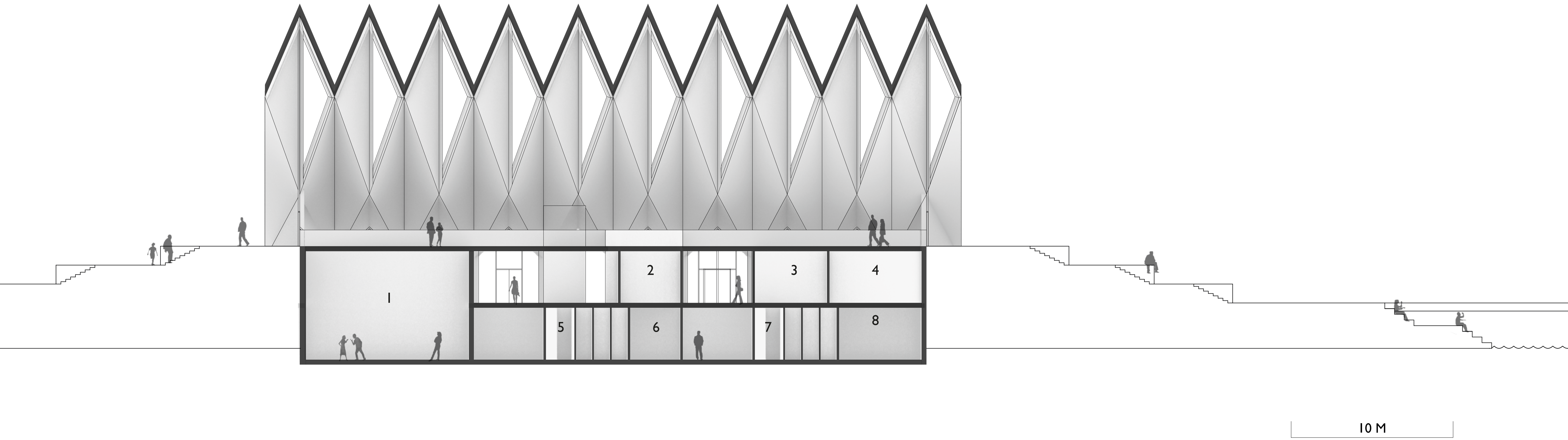


DESIGN PROPOSAL | SECTIONS

1. BLACK BOX
2. GROUP ROOM
3. MEETING ROOM
4. STAFF
5. REST ROOMS
6. STORAGE
7. REST ROOMS
8. SERVICE ROOM

SECTION B-B

The walk through the building is initiated by the external parts of the podium. Stairs and ramps lead up to the walkway in stages. This walkway is both an entrance to the cultural centre and a route through it, inviting both visitors to the cultural centre and passers by.



Physical model in 1:100. Southwest facade.

Northeast facade.

Skylights at the southwest facade.

DESIGN PROPOSAL | SECTIONS

"Peaks" of the northeast facade.

CONTEXT

THE CONCEPT OF FOLDED PLATES

INTRODUCTION

In building design, space enclosure and load transmission is always in constant discussion with one another. To be able to construct a desired space, a suitable structural system must also be developed. There are multiple ways of dealing with vertical loads in building design. The structural systems available can be categorized into a number of groups. For example: vector active, bulk active and surface active as described by Heino Engel in the book "Structure Systems". (1967).

Folded plate structures make up a sub-category of surface active structures. Through folding, sheets of material can be arranged to cover large spaces without any need of additional pillars or support systems. (Engel, 1967).

HISTORY AND ORIGIN

In construction, the concept of folded plates dates back to the early 20th century where it was first explored through use of reinforced concrete. Through greater focus on the geometry of the structural elements, less material could be used creating both more cost effective and light weight building elements. (Šekularac Et. Al. 2012). Early examples of folded structures were made in reinforced concrete through onsite construction. However, thanks to possibilities of prefabrication the complexity of assembly as well as cost could be reduced.

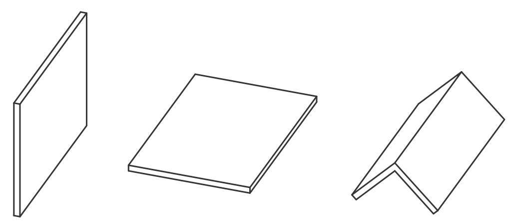
Since the early implementations made in reinforced concrete, other materials has been explored. Sheet materials made from steel, wood and glass have been used. The possible spans of structures made from such materials are however, due to limited dimensions of the individual elements, smaller than those made from reinforced concrete. (Šekularac et al., 2012).

INFORMED BY NATURE

Folded geometries can also be found in nature. For example in leaves, having a folded surface helps in making the surface rigid and strong enough to withstand external loads as well as dead weight of the leaf itself. This evolutionary form finding process creates structurally and material efficient geometries and could hence strengthen the argument for folded plates to be implemented in construction. (Trautz & Herkrath, 2009)

STRUCTURAL THEORY

To begin discussing the opportunities in implementing folded plate principles in architecture, it is important to understand its structural implications. How a surface performs both structurally and architecturally depends heavily on its orientation in relation to the acting force. If, as an example, the surface is oriented horizontally while the acting force is vertical, the surface will work through slab mechanisms. It is efficient in covering space but not as efficient in resisting deformation due to vertical loads. If both the surface and the acting force is oriented vertically however the surface is working through plate mechanisms. In this case, the surface does well to resist deformation due to vertical loads, however it is inefficient in covering space. And so, by finding an in between through using folded plates, where the surface is both working to enclose or cover space while still being efficient in resisting vertical loads these two abilities can be combined. (Engel, 1967).



(1) Plate vs slab vs folded plate.

OPPORTUNITIES IN ARCHITECTURE

Through the nature of their composition, folded plate structures can have a strong tectonic expression. The interior and exterior are largely connected and the architectural qualities and effects spawn from the structural properties of the building. Folded plate structures can take on both regular or irregular shapes, either by using repetition of similar elements or by combining uniquely shaped elements. (Falk et al., 2012).

As mentioned, using folded plates can be beneficial when covering large spans with minimal use of added supports. However, the effeciency of the load paths are partly dictated by the curvature of the global geometry and the dimensions of its constituent elements. (Falk & Von Buelow, 2011). These aspects makes the concept of folded plates less eligible for multistorey buildings and perhaps redundant where internal pillars are of no concern. Nevertheless, for some building typologies, folded plates can be an interesting option for both its structural and architectural qualities.

There is also a lot to gain from a sustainability point of view as folded plate structures can minimize material use thus being light weight options. Through design of structurally efficient geometry and by taking into account material, fabrication and construction methods aspects, folded plates could become a more commonly used concept in modern architecture. (Stitic & Weinand, 2015)

FROM THEORY TO PRACTICE

While the fundamental theory behind folded plate structures has been known for long time, it is still rather uncommon to encounter these structures in the built environment. In being both structurally efficient and visually expressive, there are certainly arguments for further exploitation of the folded plate structure as an architectural concept. However, practical obstacles found in designing and constructing these buildings seem to inhibit their expansion.

FORM FINDING

For a folded plate structure to be structurally efficient, it is important to optimize its load bearing capacity. The overall geometry of the structure in combination with proper joint design is hence of great importance. (Falk et al., 2012).

Different possible folding topologies can be seen listed in "Structure Systems". Engel (1967) emphasizes the need for discipline when designing with structural surfaces and states "Any deviation from the correct form infringes upon the economy of the mechanism and may jeopardize the functioning altogether." However, Engel also states that with sufficient understanding of the active mechanisms in a given surface active structure, opportunities for original design are plentiful.

For a thorough understanding of the structural efficiency of a specific option, combining finite element analysis methods with physical prototyping can be of great value. (Stitic, Weinand, 2015).

There is also an architectural side to the form finding process. A standpoint taken in this thesis is that folded plate principles are to little if no use unless the spaces created are not sufficiently interesting or effective for their assigned function. Hence, there is perhaps a limited amount of building typologies for which the folded plate principles are relevant. At least if intended to serve both structural and architectural purposes simultaneously.

JOINERY AND ASSEMBLY

When utilizing timber plates for folded structures, it is crucial to develop efficient joinery. The complexity of this challenge has proved to be a limiting factor in realizing folded plate structure designs in timber. For the structure to work properly, the interfaces between the individual plates need to be able to distribute the active forces to the surrounding plates without breaking. This can be done in a number of ways. If steel miter joints are used, it is necessary to use thicker timber plates due to the distance needed between the screws fastening the steel plates. If the joinery can be designed as part of the timber plate itself however, this oversizing can be avoided. In addition, this type of joinery help in aligning the plates properly so that no undesired misalignment can occur during assembly. (Stitic & Weinand, 2015).

INCLUSION OF APERTURES

In order to provide the interior of the folded structure with daylight, there needs to be places in the folded geometry where fenestration can fit. The folded structure can be designed so that the load paths do not intersect areas where fenestration is desired. Alternatively, if the window element needs to have load bearing capacity, having a rigid frame around the glass can be sufficient to make up for the removed panel of the folded structure. (Falk et al. 2012).

CLIMATIC SHELL

In order for the folded plate structure to be sufficient as a climatic shell, practical challenges including thermal buffering, solar glare, fire resistance and air tightness needs to be considered. External cladding can help in reflecting light, thus reducing internal heat gain but may result in undesired solar glare. (Falk et al., 2012).

In regards to insulation, considerations must be taken in how it is fixed to the structural system. Different options including timber studs and additional support systems to hold the insulation in place have been tested, however such solutions increases the material used and thus the weight of the overall structure. Another option is to use high density insulation connected to the underlying structure via multiple fasteners. (Falk et al., 2012). In the Theatre Vidy in Lausanne, a double timber shell made possible the use of loose flock-insulation which was a cheap alternative to using solid insulation. (Robeller et al., 2017)

A CALL FOR COMPROMISE

In discussion with Christopher Robeller, the conclusion was drawn that in order for folded plate principles to be implemented more frequently in modern architecture, a little more compromise in the design process might be needed. If strictly aiming for perfectly designed geometries in regards to structural efficiency, it can be difficult to extract architectural value from the created spaces. On the other hand, if aiming for complete freedom in terms of space design, practical problems of construction might become plentiful, rendering the design impossible to realize. And so, the way forward might be to try to find a respectful compromise, where structural and spatial ambitions converse rather than compete.

A REBIRTH MADE POSSIBLE

DIGITAL DESIGN AND FABRICATION

Due to the development of computational tools available for architectural and structural design, it is now possible to design and fabricate increasingly complex structures. Parametric design tools such as Grasshopper can be used in an iterative design process, where an initial design idea can be defined and developed through use of specific parameters. Furthermore, workflows for fabrication of these structures using CNC-tools (computer numerical control) can be set up using the very same digital tools.

In recent years, several projects exploring this realm have been realized. Novel technology allows not only for new ways of designing freely but also for optimization of aspects such as economy, production and overall environmental impact of the project in question. Furthermore, by an increase in digital tools and media, architects and designers can maintain a closer connection to the work and thus have more influence over both the design and fabrication processes. (Pintos, P. 2021).

In the context of folded plates, different topologies for folded plate structures can be defined, controlled and explored using parametric tools such as Grasshopper. In work done by Yves Weinand, Christopher Robeller and others, these tools have been used to study possibilities of applying folded plate principles to timber structures. The research has resulted in the design and fabrication of a number of prototypes and full scale projects. In their research, practical obstacles such as joinery and assembly have been dissected and solved proving possible further exploitation of these principles in architecture. (Weinand (Ed.) 2017).

(2) CNC milling to produce a digitally designed wooden ornament.

(3) CLT-panels, Svenskt Trä (n.d.)

A CASE FOR WOOD

The role of timber has varied throughout the history of construction. While being commonly used in framework for smaller buildings, the emergence of steel and concrete as building materials saw timber construction retract in the early 20th century. During the second half of the 20th century however, new innovations in the timber industry led to an increase in timber based projects. (Jeleč et al., 2017)

In present day, threats of irreversable climate change has made wood a more frequently used building material. Wood has the capacity to store carbon and an increase in wood consumption can have a positive effect on forest growth. Relative to materials such as concrete and steel, the carbon emissions related to production and transportation of wooden products is low. Furthermore, wood can be reused and recycled for several purposes and finally, wood can be used as fuel minimizing the amount of waste generated throughout its lifetime. (Beyer, n.d.).

By continuous questioning of what is possible to design and fabricate using available wooden products, the application of wood in construction might be expanded. By combining elaborate knowledge of design and fabrication methods with a deepened understanding of wood as a product material, new solutions of constructions can be developed. (Weinand 2017).

CROSS LAMINATED TIMBER

In the 1990´s the product known as cross-laminated-timber (CLT) was first developed and put to use. CLT is a timber sheet material based created by glueing several layers of wood together. Each layer is usually rotated 90 degrees relative to the preceding layer to create a strong sheet capable of resisting high loads in each direction. In recent years, the use of CLT in construction has increased greatly, it is easy to prefabricate building elements which can be assembled on site allowing for quick construction. CLT can be seen in both residential and office buildings and its applications is ever expanding. (Jeleč et al., 2017).

Today, there are companies producing CLT elements of up to 20m in length and 3,5m in width. (APA, n.d.). CLT performs relatively well in regards to thermal insulation, acoustics and fire resistance and due to its structural properties it is great for long span construction. (StoraEnso, n.d.).

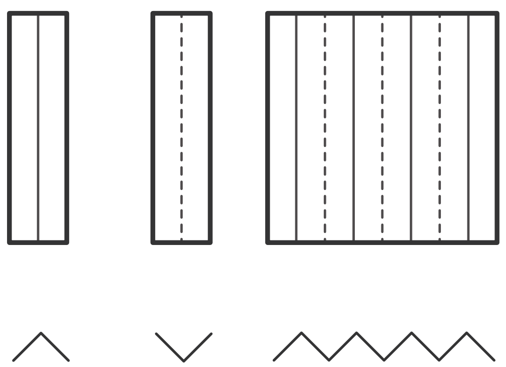
And so, for the purpose of designing and constructing folded plate structures, CLT can be a highly relevant option due to both its structural and environmental performance.

ORIGAMI AS DESIGN MEDIUM

By folding paper, one can quickly develop a basic understanding for how the geometrical arrangement of a sheet material affects its structural characteristics. Described below are a number of known origami principles which can be used to better understand the concept of folded plates and hence inspire the design process of a folded plate structure.

MOUNTAINS AND VALLEYS

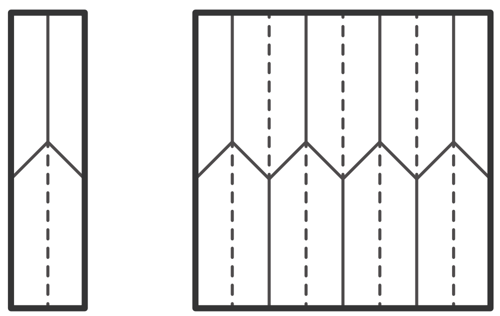
One can argue that there are two main folds in origami. Namely mountain and valley folds respectively. The mountain fold creates a ridge and the valley fold a trench. The possible resulting geometries obtainable by folding are seemingly endless. These geometries however, are all made up of different combinations of mountain and valley folds. (abrashiorigami, n.d.) In illustrations shown here, mountain folds are represented by a continuous line and valley folds by a dashed line.



(4) Mountain an valley folds.

THE INVERSE FOLD

A common fold in origami is the inverse fold. (5) The inverse fold is a way to create a transition from a valley fold to a mountain fold or vice versa. It is possible to do this by adding angled folds from the intended point of inflection to the sides of the parallel folds. The change in direction is dictated by the angle of these folds. The curvature of the folded surface is mandated by the angles of these folds. The inverse fold can be repeated across a sheet. (Buri & Weinand, 2008)



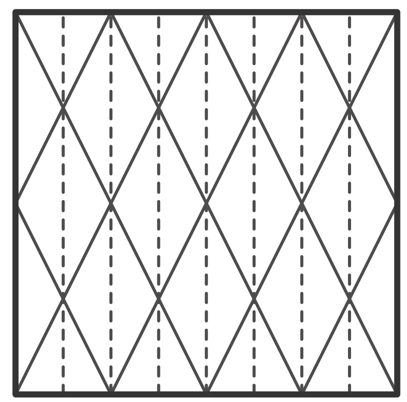
(5) The inverse fold.

PATTERNS FOR ARCHITECTURE

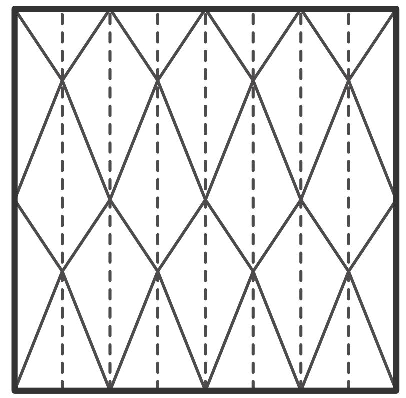
In their research paper "ORIGAMI – Folded Plate Structures, Architecture", Buri and Weinand (2008) discusses folding patterns which can be particularly interesting for architectural and structural applications. These include the Yoshimura pattern and the Miura Ori pattern.

YOSHIMURA PATTERN

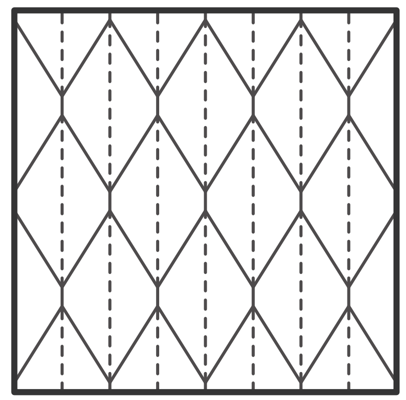
The Yoshimura pattern (also known as the diamond pattern) is a seemingly common folding pattern used in origami as well as folded plate structures. The pattern is created by mirroring inverse folds creating a series of diamond shapes. The diagonals in the diamond shapes are parallel valley folds while the sides of each diamond are mountain folds. (6) The alternating nature of this folding patterns creates a geometry where there is always a certain depth to the cross section, suggesting its structural advantages if applied in a folded plate structure. The diamond shapes can be distorted to take on a "kite-like" shape, (7) creating opportunities for varying curvature over the folded surface. Also, if stretched, the diamonds can be turned into hexagons consisting of two mirrored trapezoids, (8) thus minimizing the number of connecting panels in each vertex. (Buri & Weinand, 2008).



(6) Regular Yoshimura pattern.



(7) "Kite-like" variation.



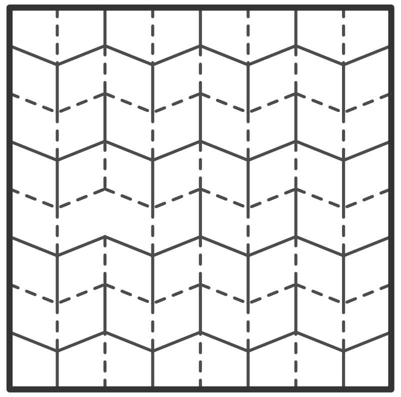
(8) Hexagon variation.

MIURA ORI PATTERN

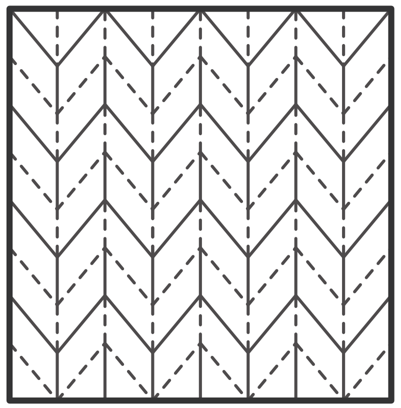
In contrast to the Yoshimura pattern, the Miura Ori pattern (herringbone pattern) consists of a series of symmetrical trapezoids or rhombi. (9) While in the Yoshimura pattern, the inverse folds are mirrored, in the Miura Ori pattern, the inverse folds are repeated. This makes for continuous "zig-zag" ridges and trenches along the length of the pattern. The Miura Ori pattern expands in both directions, making it interesting for deployable structures and has

CONTEXT | ORIGAMI AS DESIGN MEDIUM

hence been used in for example space engineering in the development of solar sails. If the legs of the trapezoids have varying inclination, the folded surface will have a curvature. (Buri & Weinand, 2008).



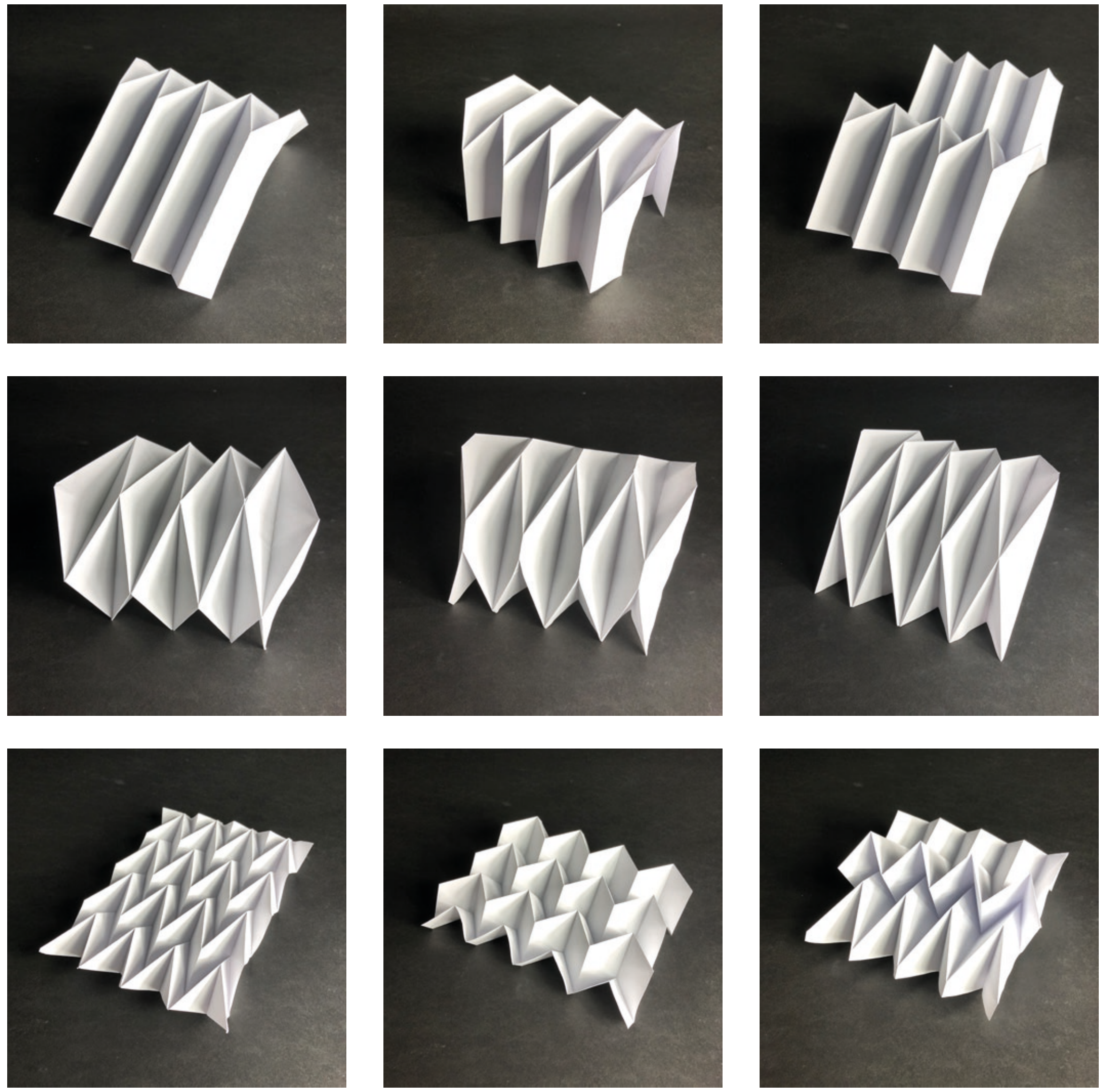
(9) Variation of the Miura Ori pattern.



(10) Variation of the Miura Ori pattern.

VARIATION WITHIN THE TOPOLOGY

Naturally these folding patterns can be varied greatly by changing lengths and angles of the folds. Also, the number of repetitions and spacing of folds play an important role in the final outcome. The folding patterns presented here were further explored in a number of paper models As mentioned, different curvatures of the folded surface can be obtained through changing the angles of the folds. both regular and irregular shapes can hence be created.



(11-19) First row: series of inverse folds. Second row: variations of the Yoshimura pattern. Third row: variations of the Miura Ori pattern.

DESIGN STRATEGY

A COMBINATION OF METHODS

The design process of the folded structure in this thesis can be divided into a number of parts. However, these parts overlap each other greatly and have not been used in a linear fashion. Rather, they have been informing each other, forming a dynamic design process where an expanded creativity has derived from an expanded knowledge of the topic as well as improved modeling skills.

PART 1: PAPER MODELING

By folding paper and learning about the relationship between mountain and valley folds and how they can be arranged, an initial understanding of the mechanics of folding was gained. Later, revisiting the paper models and doing new iterations of folding helped in shaping and understanding the design.

PART 2: CARDBOARD MODELING

By making the cardboard models based on Heino Engels collection, further understanding of how a folded structure can be put together was developed. Along with the paper folding, these models became key in finding a suitable folding system for the arising architectural ambition.

PART 3: REFERENCING

Looking at built references was important in order to understand how the folded plate principles could cater to a specific architectural need. These references provided different qualities which were evaluated and later combined to inform the design of this proposal.

PART 4: PARAMETRIC MODELING

Setting up a parametric workflow was crucial in iterating through various options and refining the design. Grasshopper was used to define and parameterize a specific folding topology which was then tweaked and adjusted to fit the program of the building as well as the urban context.

PART 5: CONCEPTUAL DESIGN AND DETAILS

Development of the structural concept as well as conceptual design of selected details was done in order for the architectural vision to gain credibility in terms of realization. As the delimitations of this thesis states, it was not possible to fully develop construction-ready details but nevertheless, implementing their design on a conceptual level was important for the end result.

PHYSICAL EXPLORATIONS

To create a solid starting point, a collection of physical models where made using both paper and cardboard.

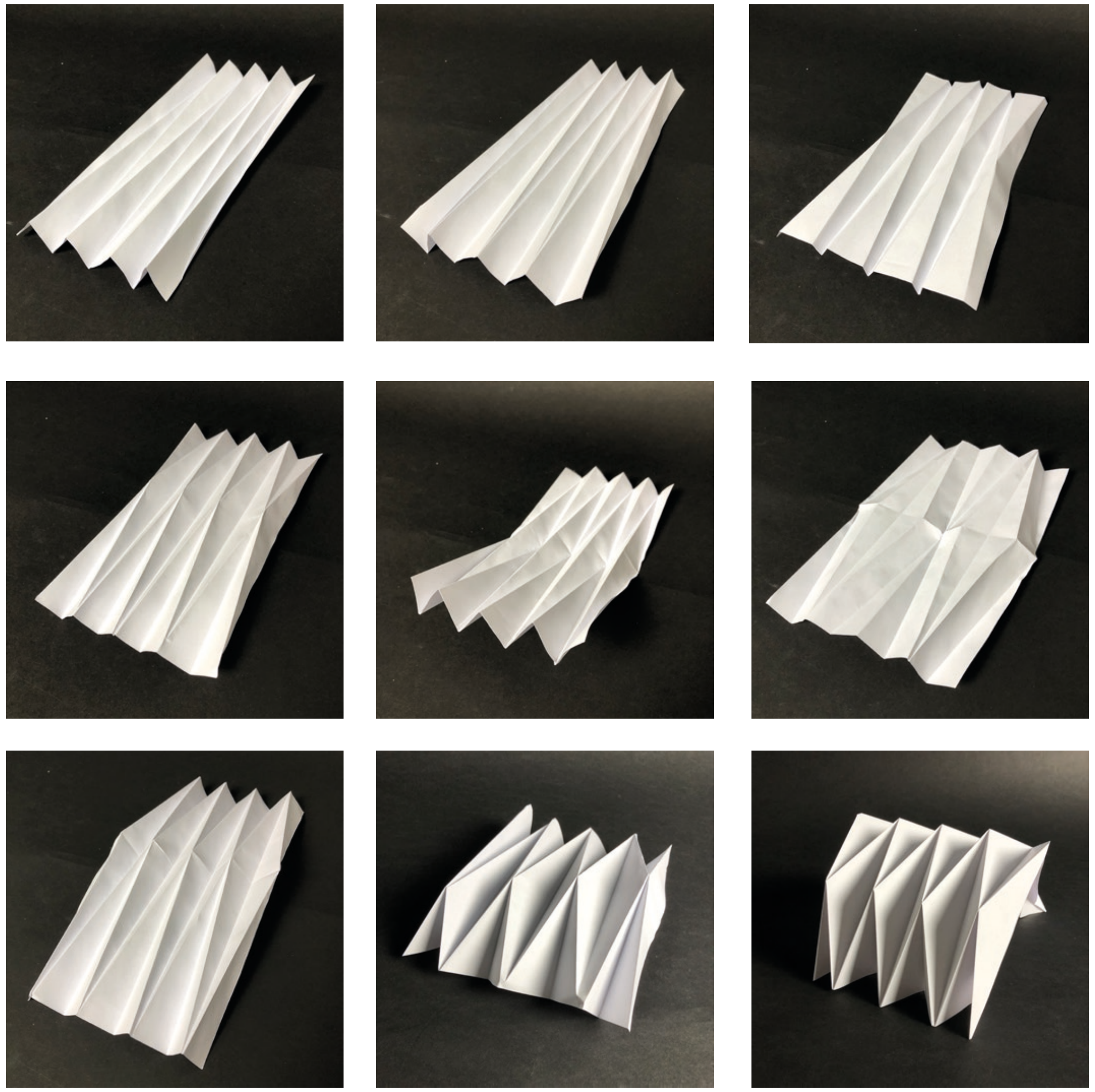
PAPER MODELS

By folding the paper models, some initial intuition on what is obtainable from flat sheets was developed. However, it also proved to be somewhat difficult to tell whether or not a double-curved surface was created due to the flexibility of the paper. The early paper models are a mix of the folding patterns explained in "Origami as design medium" in this thesis, examples found in Heino Engels "Structure Systems" and a few being completely explorative.

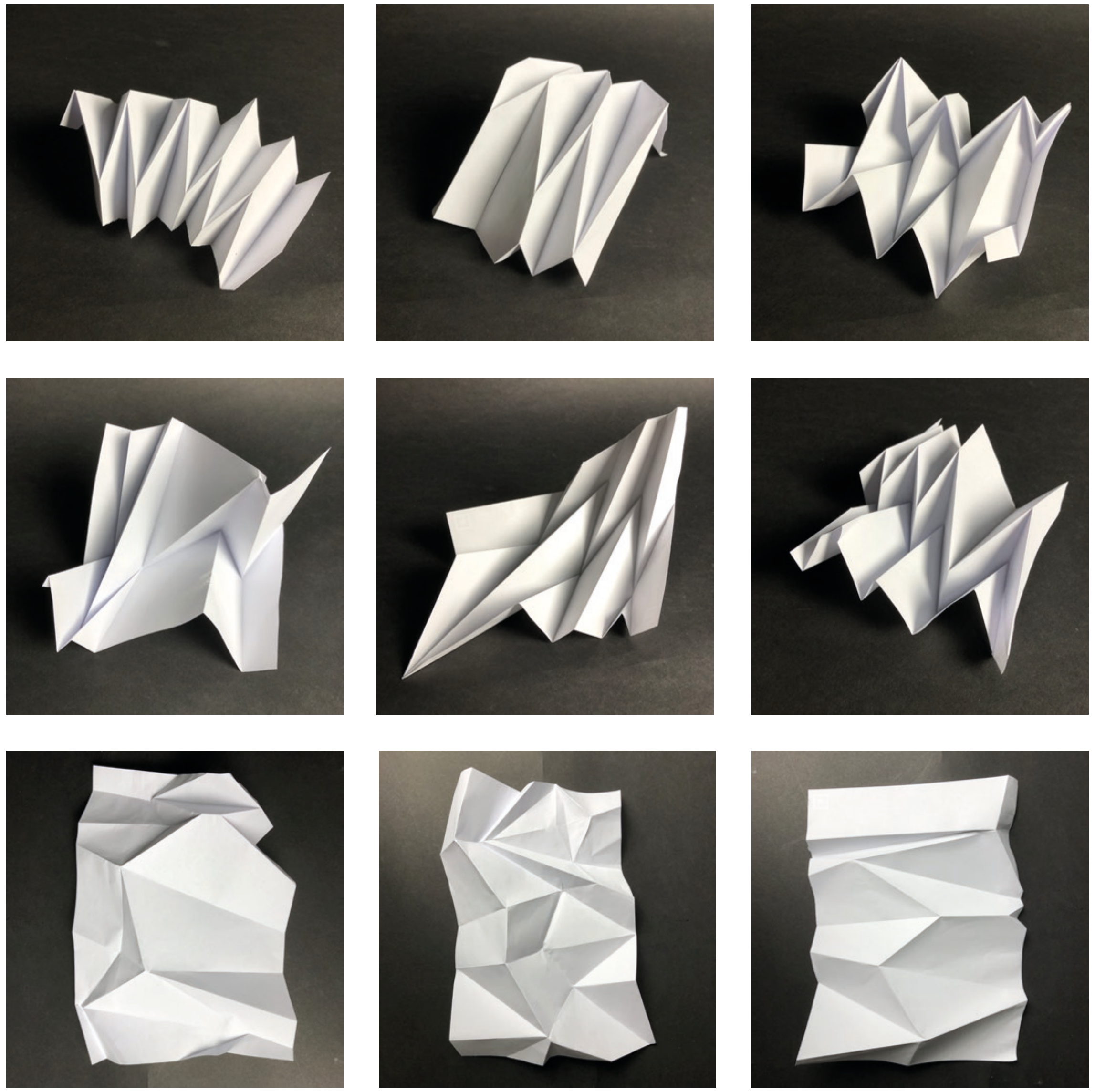
CARDBOARD MODELS

The paper models were succeeded by a number of card board models entirely based on the models from Heino Engels Tragsysteme. Some of them completely deployable while others could not be flattened into a flat surface. The cardboard models were modeled using the images from "Structure Systems" as reference for 3d-modelling in Rhino. The geometry was cut from a 1.25mm thick cardboard using the Aristomat in the Architecture Workshop. They were assembled using regular masking tape. One should mention that the taping process adds a layer of uncertainty to the models. Some of the more complex models became somewhat asymmetrical making their structural behavior more difficult to evaluate. However, these models were mainly made to create a basic understanding of the differences, similarities and overall aspects of the different examples shown in "Structure Systems".

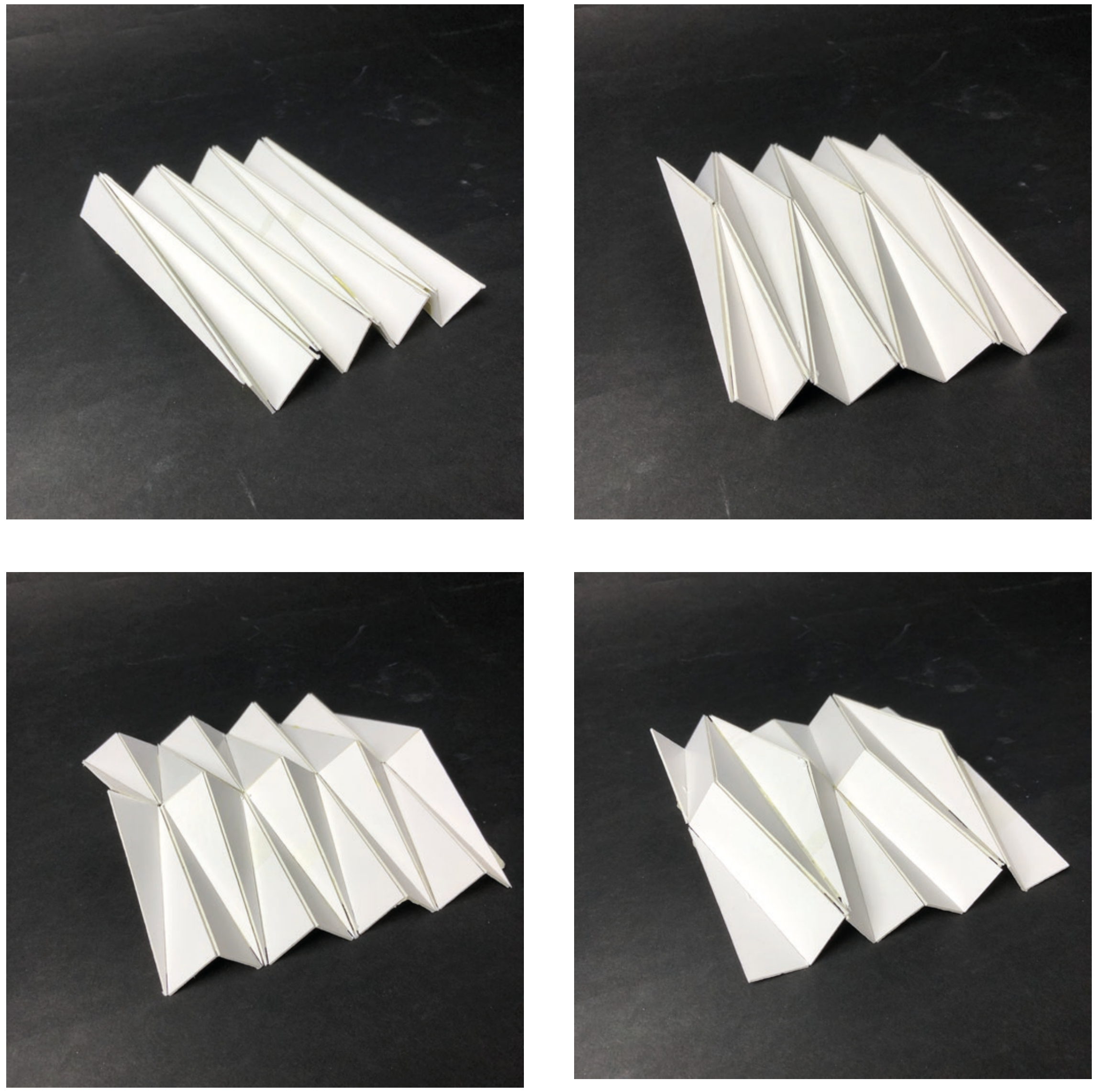
The folded roof structure in the design proposal of this thesis is inspired by one of the concepts shown in Tragsysteme. The intention to create a central path with a high ceiling spanning the length of the building matched well with this specific folding topology. By taking into consideration some local references for geometrical expressions, additional arguments for the specific topology arose. The original folded structure was then developed further to create room for the different functions of the building, a number of different types of apertures and to better relate to the site.



(20-28) Early paper models with combinations of triangular and quadrilateral surfaces.



(29-37) Explorations of irregular or asymmetrical folding geometries.



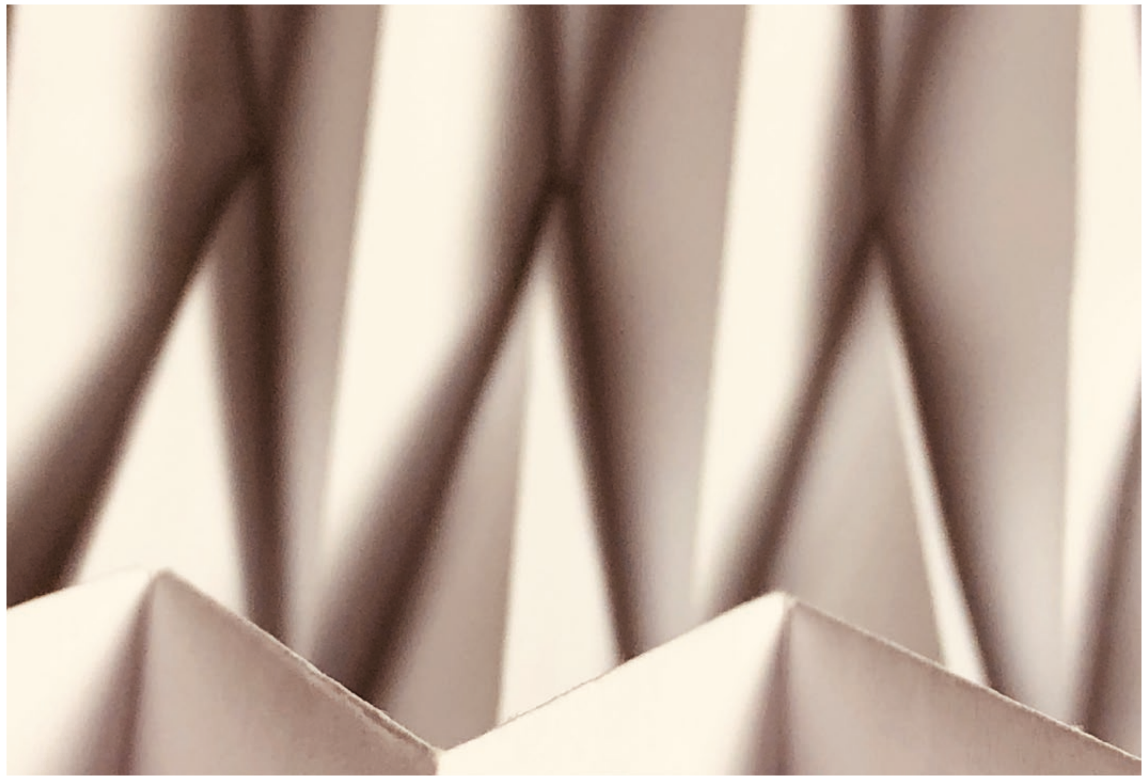
(38-41) First row: Completely deployable cardboard models following origami principles. Second row: Non-deployable folded geometries of triangular and quadrilateral panels.

(42-45) Options for space enclosure. The use of many panels across the span induces opportunities for curvature on the folded surfaces.

46) Yoshimura pattern up-close.

(47) Miura Ori pattern up-close.

(48) Zig-zag trenches and ridges of the Miura Ori pattern.



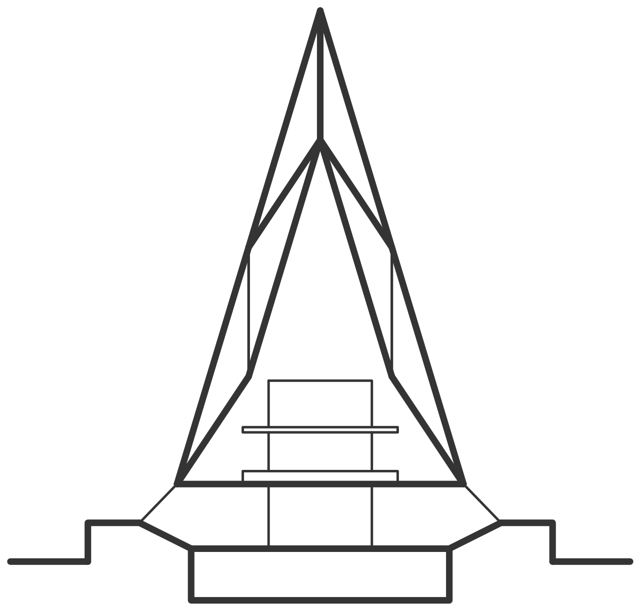
(49) Miura Ori folds in front of a wall of Yoshimura folds.

(50) Miura Ori folds with a more acute angle.

BUILT REFERENCES

THE CADET CHAPEL BY SOM

The Cadet Chapel is located at the U.S. Air Force Academy campus in Colorado Springs, Colorado. The Chapel stands 150 feet tall and consists of 100 tetrahedrons arranged as a series of 17 triangular shapes pointing to the sky. (SOM, n.d.) While the idea behind this design was for the chapel to point towards the heavens, it has also been acknowledged that it resembles fighter jets taking off. (PPLDTV, 2019) Aluminum and glass is used in combination to allow light to enter not only from the two ends but also through the folded geometry itself. (SOM, n.d.). The tetrahedrons constituting the chapel are placed in an alternating fashion. Since the tetrahedrons are closed volumes, placed next to each other, it would not be possible to simply fold this geometry from one sheet of paper. By flipping the "direction" of every other row of tetrahedrons, the resulting geometry is neither convex nor concave. This gives the chapel its sharp expression. Showing in the illustration is a simplified section, perpendicular to the length of the building.

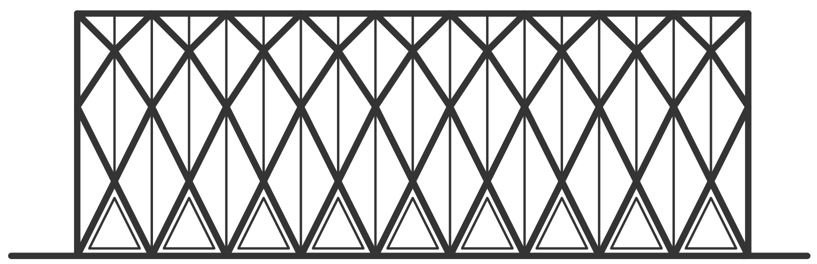


(51) Section of the Cadet Chapel by SOM

SULPHUR EXTRACTION PLANT BY RENZO PIANO

One of Italian architect Renzo Piano's early works was the Sulphur Extraction Plant in Pomezia. Upon realizing that transportation costs accounted for a large percentage of the overall costs when mining, Piano decided that a movable structure could diminish this problem. This inspired a modular design using light-weight elements. The ability of the structure to move is made possible by keeping the geometry regular. So that the individual elements share the same shape and dimensions. (Piano, 2017).

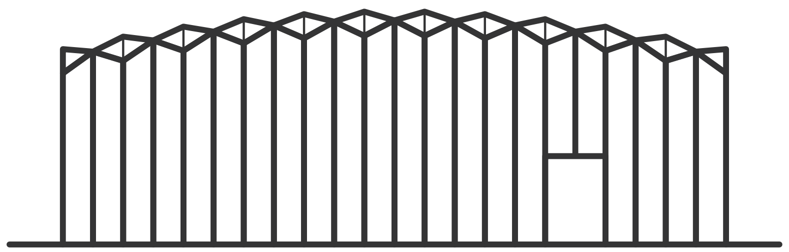
The structure has openings not only in the two far ends of the cylindrical shape, but also along the two parallel edges that connects to the ground. A frame-like element is used as a substitute to the triangular plate elements suggesting an approach to including apertures in a folded plate structure.



(52) Repetitive folding in the Sulphur Extraction Plant by Renzo Piano.

THEATRE VIDY IN LAUSANNE

A recent example of how folded plate principles can be used creatively in architecture is the Theatre Vidy in Lausanne, Switzerland. The arch and the walls exploits the structural benefits of the folded plate concept, leaving the internal space free from disruptive pillars and thus making it suitable for a variety of performing arts. The folded structure is made of wooden panels and consists of a double shell solution, where the two layers are placed 300mm apart from each other. This allows the plate thickness of the individual panels to be no more than 45 mm. In addition to a reduction in material, the double shell also makes possible the insertion of loose insulation. The panels are connected through wood-wood joinery. The geometry of the joinery has the added benefit of guiding proper alignment when connecting the panels. This eliminates the need for complex support systems during assembly. (Robeller et al., 2017).

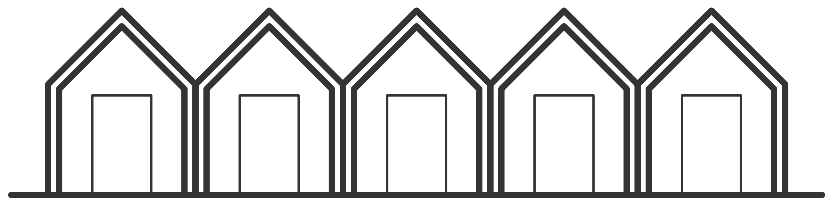


(53) Folded walls and roof of the Theatre Vidy.

LOCAL REFERENCES

Inspiration for the visual expression of the proposal in this thesis was drawn from a few local references. Gothenburg has a strong relation to the sea and the proposal nods to geometries linked to that.

The iconic rows of fishing sheds often found on the west coast of Sweden are mimicked by the two sides of the building. These lift up the folded roof structure to help create a generous space underneath. The series of narrow "peaks" rising up behind these sheds is a loose translation of the silhouette of sailing boats lined up in the marina.



(54) A row of fishing sheds as seen on the west coast of Sweden.

PARAMETRIC MODELING

A parametrically defined 3d-model was made using Grasshopper. The purpose of this model was to be able to with ease explore possible variations of the folded structure. And so, once the precursor was found among Heino Engels models, a grasshopper definition was written to explore variations of that specific model.

FOOTPRINT AND DIAGONAL

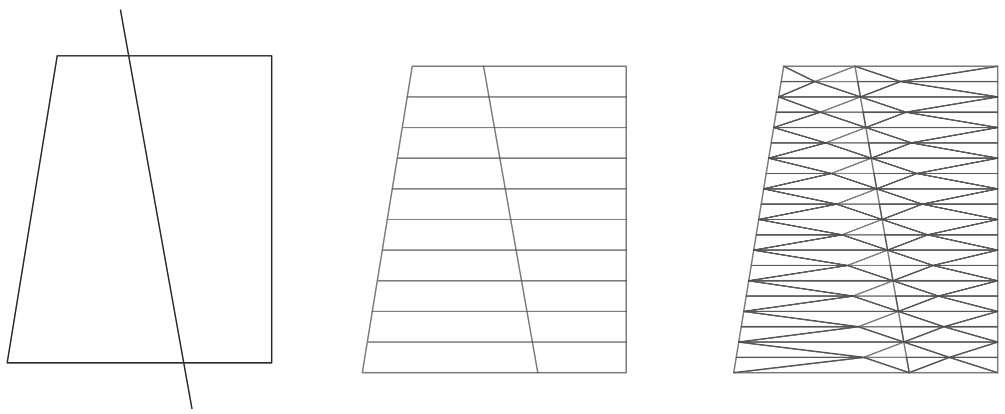
The footprint of the building is drawn as a closed quadrilateral polyline in Rhino and referenced to Grasshopper through a Geometry Pipeline. By changing the shape of the polyline, the shape of the entire structure changes accordingly. Furthermore, a diagonal defining the direction of the walk through the building is also drawn in Rhino. The division of the surface is based on the footprint, the diagonal and the chosen number of divisions in the longitudinal direction. The centre line of the folds lie directly above this diagonal. By changing the diagonal the folds change accordingly.

PARAMETERS

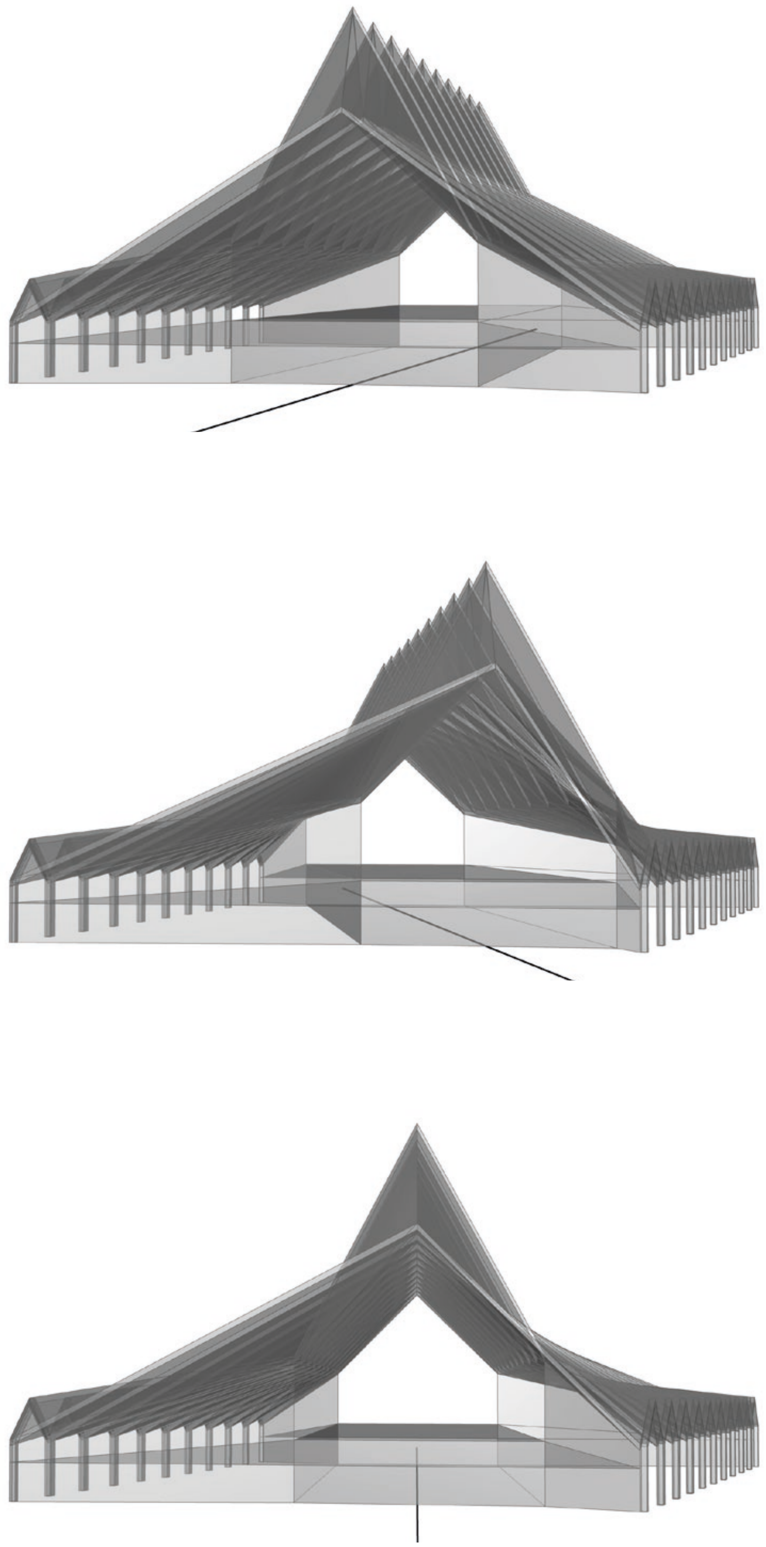
The parameters which are possible to control with the script include: the number of folds in the longitudinal direction, the height of the nodes of the triangular panels, the elevation of the folded structure above the ground level and the distance between the nodes in the transversal direction.

ITERATIONS

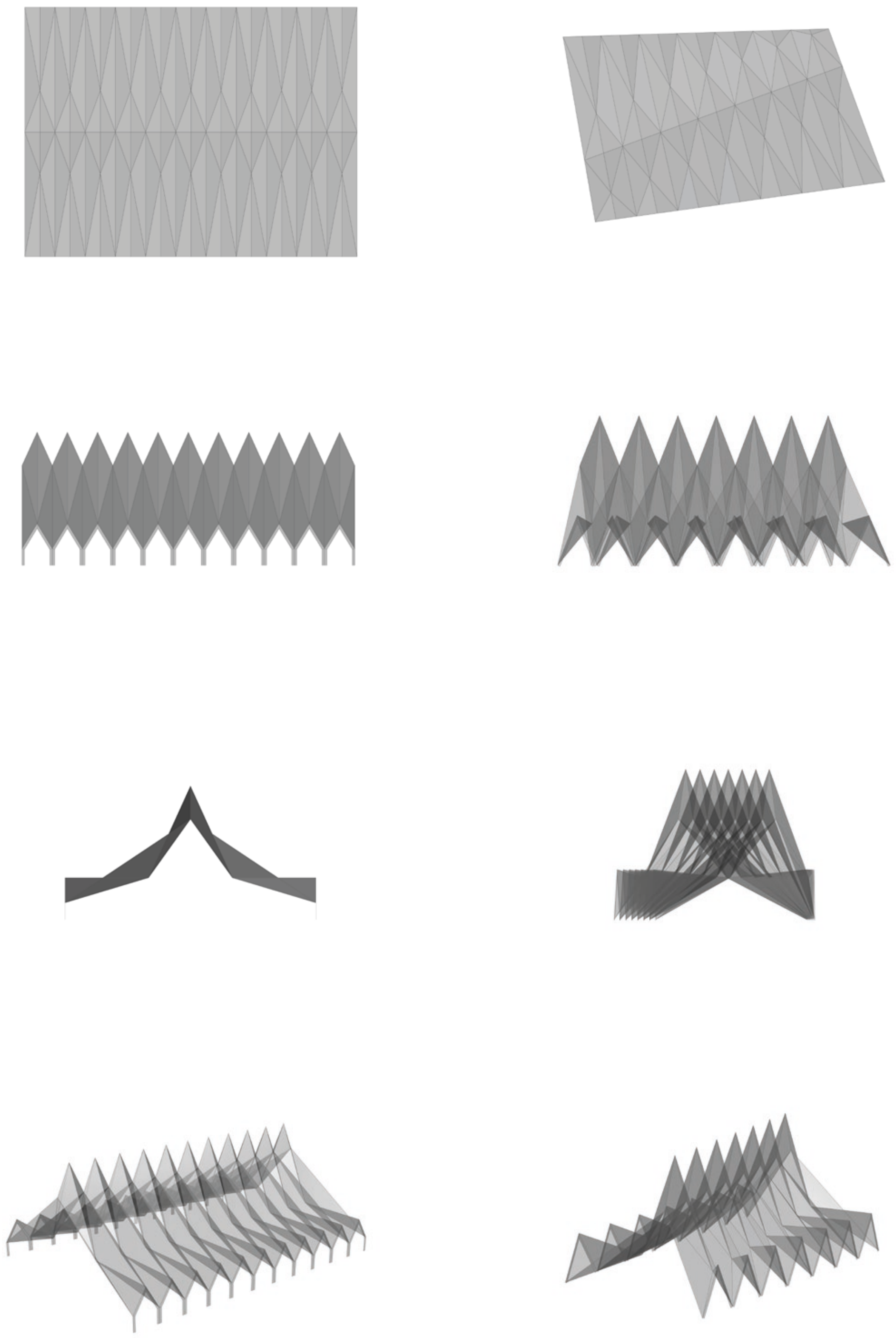
A number of iterations was made precursing the final model. Showing on the next pages are a number of these iterations, each looking at different settings in height, number of folds as well as changes in footprint and diagonal direction.



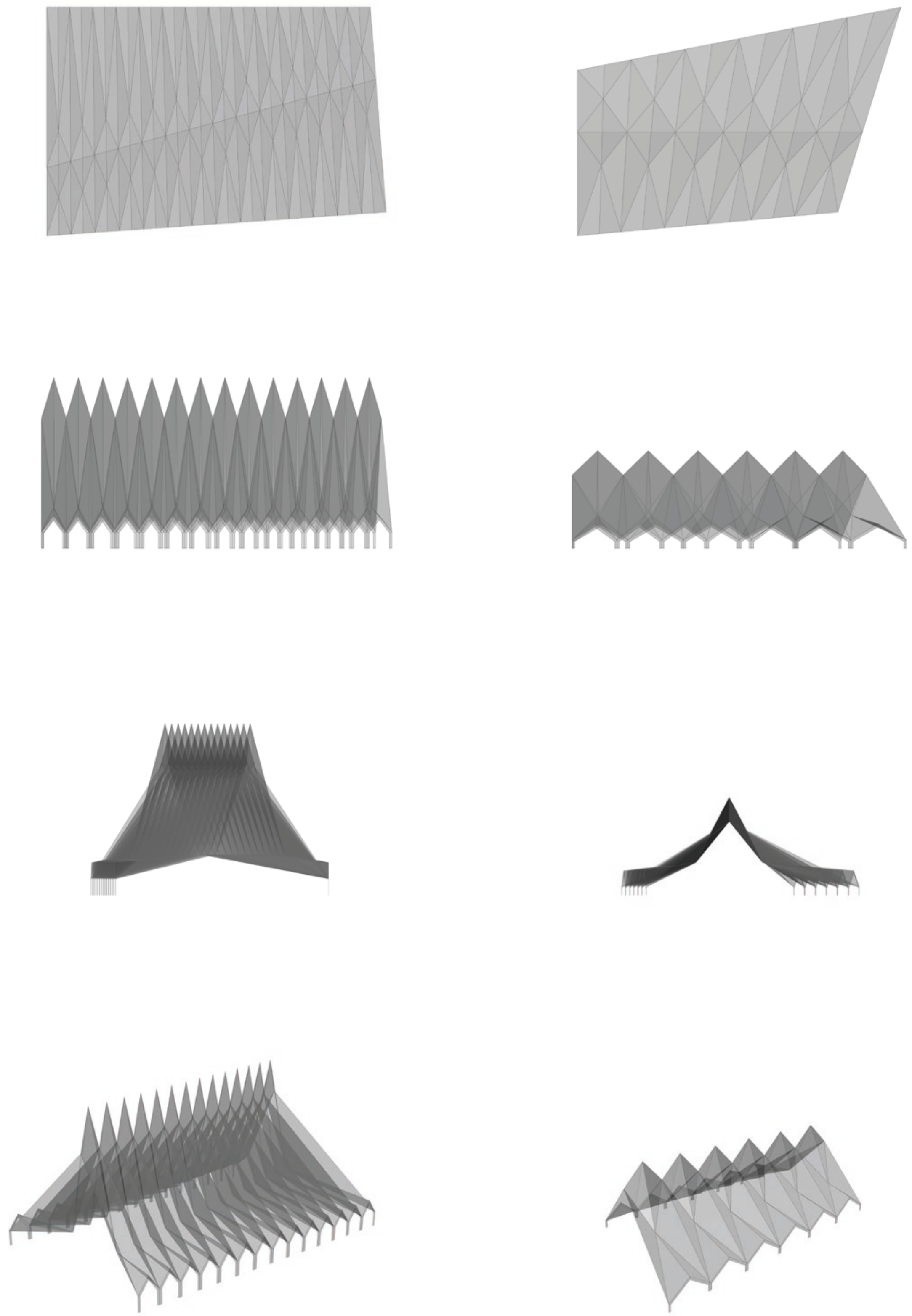
(55) Division of footprint into folding pattern.



(56-58) Outcomes from different placements and rotations of the diagonal axis.



(59-66) Different variations of the folded roof structure. Each with different footprints, diagonals and node heights.

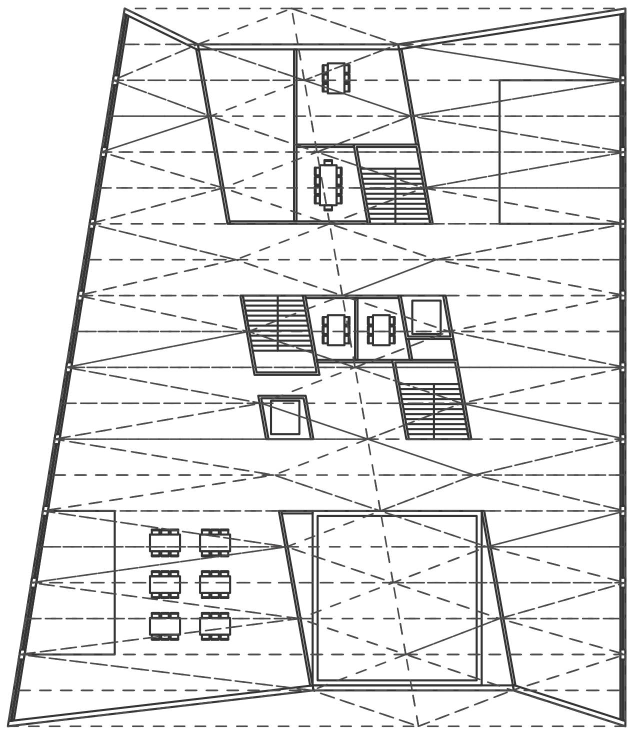


(67-75) Different variations of the folded roof structure. Each with different footprints, diagonals and node heights.

SPACE DIVISION

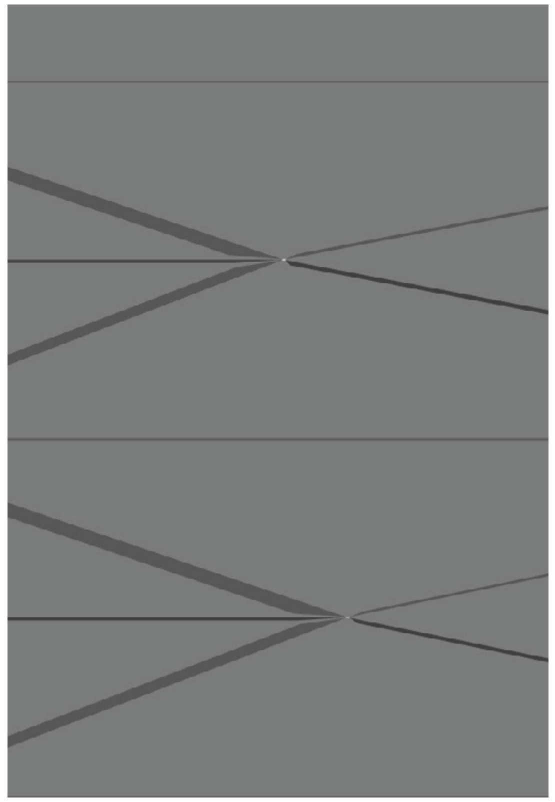
Once the overall logic of the folded structure was set, a projection of the folded pattern was used to guide the division of the interior into the different functions. Further adjustments of the folded roof structure were then made so that suitable shapes and sizes of the different interior spaces were created. Through this looping process, a final result was obtained.

Stairs and elevators are arranged so that the different functions of the ground floor are easy to reach. The skewed shape of the walkway is countered by orthogonal walls inside the podium to increase the functionality of the rooms inside. The width of the walkway was determined by the need for sufficient space within the podium to fit certain functions including the black box.

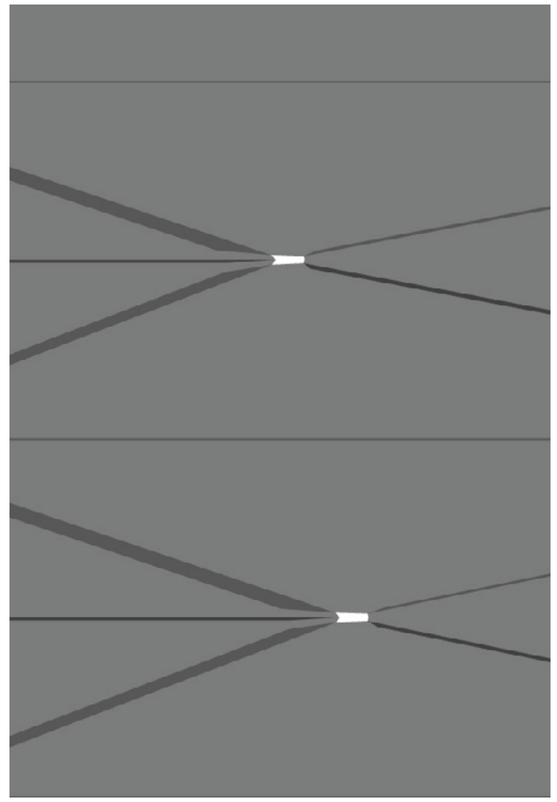


(76) Space division based on the projected folding pattern.

DESIGN STRATEGY | PARAMETRIC MODELING



(77) Panel intersection without chamfered edges.



(78) Panel intersection with chamfered edges.

PLATE THICKNESS

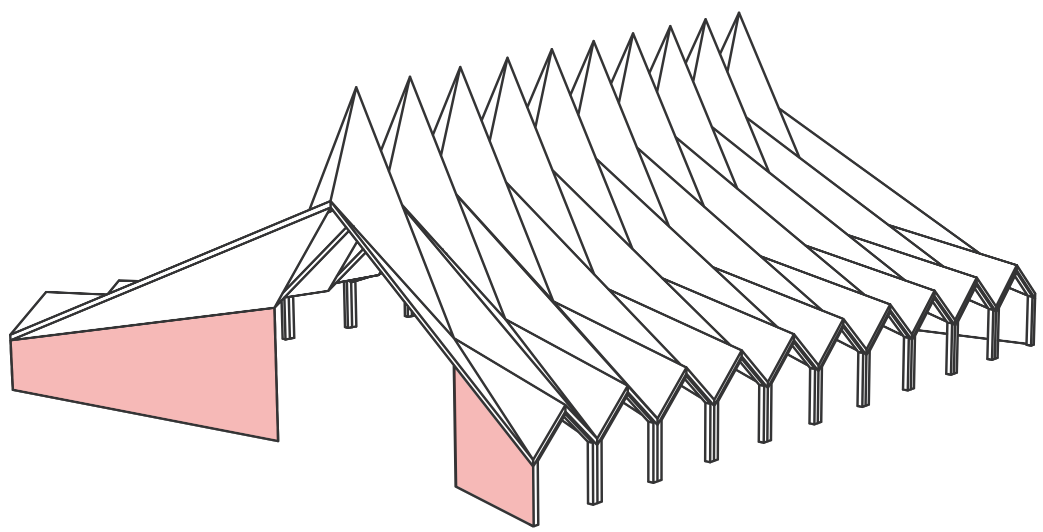
While the script written for these design explorations enable a large number of options to be evaluated, it does not encounter for the challenge of plate thickness. The TPS set of Grasshopper components developed by Christopher Robeller (TPS7 GHA Rhino7 Windows, 2021-11-24), was used to get some initial understanding of this.

One issue is that it is not always possible to create a perfect offset of the folded surface. CLT panels have constant thickness so the interface between different panels can become tricky to solve, especially in the nodes where several panels meet. By chamfering the edges of the panels at these locations, this can be solved. However, this also means that there will be holes in the folded surface. If cladding is used externally and internally, these holes can be covered. CLT structures needs some sort of cladding externally to not deteriorate. However, on the interior, it can be desirable to keep the wooden surface visible. And so, careful consideration of the chamfered edges is important to preserve the intended expression of the folded structure.

CONCEPTUAL DESIGN AND DETAILS

STRUCTURAL CONCEPT

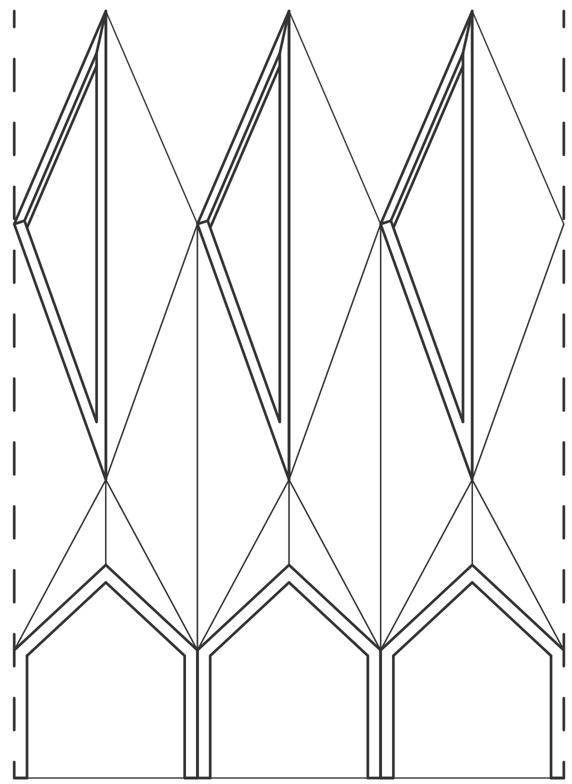
The roof structure consists of a two-hinged folded system. The folds are mirrored around a diagonal axis in the longitudinal direction of the building. This creates an asymmetrical shape which helps creating differently sized spaces internally and the twisting expression externally. The horizontal forces in the transversal direction of the building are controlled by the vertical plates at each end of the building as well as rigid connections at the top hinge. The horizontal forces in the longitudinal direction are controlled by the rigid connections between the plates. Some bending capacity from the vertical posts can also help in preventing longitudinal deployment of the structure.



(79) Large vertical wall elements at the two short ends are used to control the horizontal forces and to frame the two main entrances.

APERTURES

There are three main ways that light can enter the building. Firstly, through the large openings at the two short ends. Secondly through the smaller gates along the sides of the building at the ground level. And lastly, through the skylights placed in the top panels of the south-west side of the diagonal axis. These skylights are made possible by substituting the wooden plates for rigid steel frames in these particular places. Showing in the image below is a segment with the smaller gates and the skylights on the south-west facade.



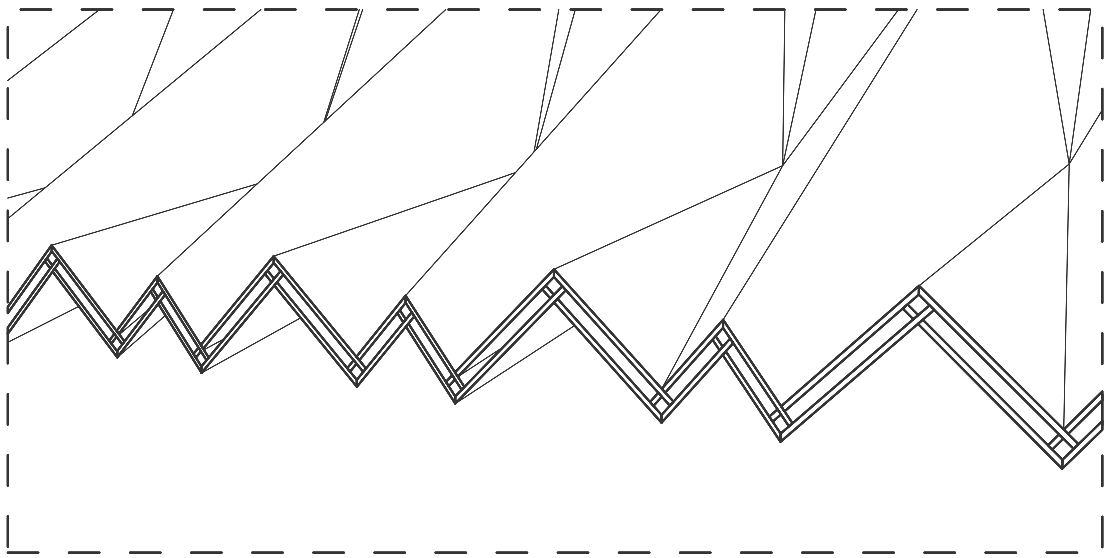
(80) Apertures at ground level and at the top made possible by use of rigid frame elements.

DESIGN STRATEGY | CONCEPTUAL DESIGN AND DETAILS

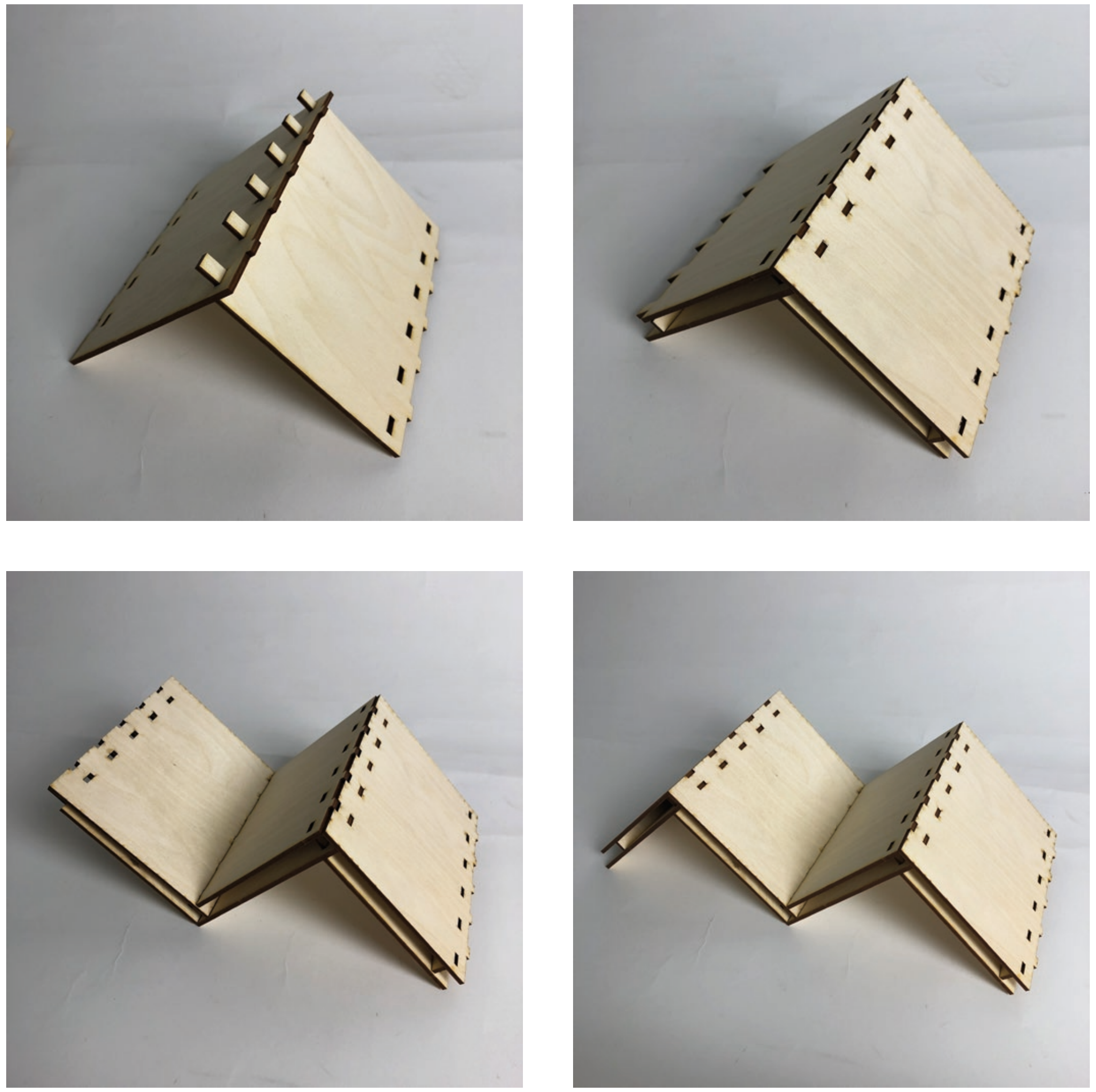
SHELL CONSTRUCTION

To minimize material use and simplify the incorporation of insulation a double shell is used to make up the folded structure. The double shell consists of 70mm thick wooden panels which are interconnected using mortice and tenon joinery. The two shells are offset by a distance of 210mm making the total shell thickness 350mm. In between the two shells, loose insulation is inserted which is an easier and cheaper solution than what using CNC-cut solid insulation would be. However, in terms of design of the joinery, the double shell is more complex than what a single shell solution would be. In effect, this means that in order to accommodate for a material efficient and hence cheaper construction, an increased complexity of the design phase is due.

The exterior is clad with copper panels cut out to fit the folded structure. Due to the size of the individual plates, the copper cladding needs to be divided into smaller segments. The cladding is needed to waterproof the structure and runoff water and the folded shape creates funnels for the water to follow.



(81) A double shell would enable insulation to be put in the space in between. Holes from the mortice and tenon system would be covered by cladding which also solves potential problems from chamfering the edges of the panels.



(82-85) A simplified model of how the two shells are connected to each other. To be able to create the necessary geometry for the joinery, robotic milling is needed.

DISCUSSION

CONCLUSION

By compiling and evaluating existing research done on the topic of folded plates, the following conclusions were drawn:

Folded plate structures have existed as a concept for structural and architectural design for close to a century. However, practical challenges make these structures difficult to construct and hence uncommon in the built environment. Research on the topic supports new methods and materials to be used for further application of folded plates in architecture. Potential benefits of using timber products in combination with digital modeling and fabrication tools have been investigated on prototype and full scale level. Arguments for combining folded plate principles, digital fabrication and timber products can be found by looking towards possible reductions of environmental impact, time consumption and cost in design and construction.

The purpose of this thesis however, was not only to map existing knowledge but also to approach the challenge of design using folded plate principles in a timber structure. And so, by looking towards fundamental theory in both structural design and origami as well as available built and written references, an initial understanding of the concept of folded plates was developed. This understanding was expanded further through physical explorations looking at a variety of different folding patterns and topologies. Based on this, a design strategy for implementation of folded plates in architectural and structural design was shaped. The design strategy included both physical and digital modeling and sketching. Through use of parametrically controlled workflows for geometry generation, the design could be refined through iteration. Site specific aspects, local references and the programmatic ambitions of the building were all accounted for throughout this iterative process. The structural concept of the folded structure could thereafter be shaped and adjusted accordingly. The specific challenges pointed out by the initial research questions were investigated through both references and design explorations and the following conclusions are drawn:

If a folded topology is allowed to be non symmetrical, options for differently sized spaces increase. Depending on the folding topology, the ceiling height might change drastically throughout the building. This can be used as a means of spatial division. In combing this with added internal structures such as the podium used in the design proposal of this thesis, it is possible to fit several different functions and rooms under the same roof structure.

Apertures can be included in a folded plate structure in a number of different ways. Large openings due can be innate to the structure depending on the direction and topology of the folds. By elevating the folded structure from the ground, additional spaces for fenestration or entrances can be created. It is however then crucial to account for horizontal loads which can no longer be countered by reactional forces in the ground. By adding additional structural elements, this issue can be mitigated. To retain the open space made possible by the folded structure, it is important to think about the placement and attachment of these added structural elements. Lastly, it can be possible to substitute solid panels of the folded structure for transparent members. These members can either have an inherent capacity to redistribute loads or be placed in spots where no forces are acting. The latter requires an exstensive understanding and design of the load paths within the structure.

In regards to additional practical challenges in building folded plate structures in timber a number of conclusions are drawn from the reference literature as well as the design work done throughout this thesis:

For insulation of a folded structure, several methods exist. By using a double shell, less expensive means of insulation can be used. The dimensioning of such a shell affects the visual appearance of the structure. In the design proposal of this thesis, this is important to note due to the shell thickness being revealed at the two longer sides of the building. Shell thickness therefore can have a large effect on the visual expression of the building. By knowledge gained from design processes such as this one, these aspects can be brought into early stage design with more intention.

Proper cladding and weather-proofing of the external shell is important in order to protect the timber panels. A metal cladding can work well to do this while also help mitigating internal heat gains. For a structure like the one shown in this thesis, careful design of the cladding would be needed as large parts of the roof is visible from ground level. Additionally, when placed in an urban context where surrounding buildings are relatively high, solar glares from the metal cladding might become problematic and potentially disturb nearby operations.

In summary, the final design proposal combines architectural and structural design and seeks to investigate a number of challenges and opportunities related to this intersection which are found and discussed in the initial readings. Thanks to these predecessors within the discussion of folded plate structures, specific aspects such as asymmetry, space division, apertures and joinery/assembly could be discussed and solutions to the corresponding challenges could be implemented in the design proposal on a conceptual level.

REFLECTION

In learning about a new structural concept, new realms of creativity can be entered. However, it can also be difficult to step outside of the convention that a specific structural concept entails. The work done in this thesis is perhaps in some ways a testimony to both sides. It was difficult to fully engage in free-form explorations using the folded plates due to a limited ability to make proper structural analysis for those types of geometries. By aiming towards a feasible design proposal, the deviation from perfect symmetry hence became relatively small.

However, by selecting a specific folding topology for further investigation, its potential architectural applications could be explored and creatively discussed through use of an iterative design method. This methodology would likely translate well onto other folding topologies for an expanded investigation of how folded plate structures can be designed to be both structurally and architecturally relevant.

By working with both physical and digital modeling, a greater understanding for the possible spaces created by the folded plates was gained. One benefit of working with the physical models was that it gave a greater understanding for how the material responds to being folded in different ways and how the thickness of the material affects the interfaces between different panels. The largest benefit with working with the digital model was the ability to use the parametric definition to sketch and iterate. It is however important to note that the digital modeling in this design work was done mainly after a folding topology had been selected. Of course, there are also opportunities to implement digital modeling at an earlier stage, to compare different topologies and to evaluate their different strengths and weaknesses.

Lastly, it became clear that in order to develop a design like the one in this thesis further, it is important to move onto more accurate prototyping. By making larger models with higher level of detail, it would be possible to distinguish possible ideas from impossible ideas with greater confidence and to further investigate the true potential of these structures. Nevertheless, this study has been of great value begin that investigation.

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