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Hereby I declare, that I have written this thesis independently. No academic degree has been applied for based on this material. All works, major viewpoints and data of the other authors used in this thesis have been referenced.

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FLORENCE PAVILION - UTILISATION OF A TIMBER GRIDSHELL NEAR THE WATERFRONT

FIRENZE PAVILJON - PUIDUST VÕRKKOORIKU RAKENDAMINE RANNAJOONEL

Master’s Thesis

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Academy of Architecture and Urban Studies

Tallinn 2023

EESSÕNA

Käesolev magistritöö on koostatud Tallinna Tehnikaülikooli inseneriteaduskonna arhitektuuri eriala integreeritud õppe raames.

Soovin tänada kõiki, kes käesoleva magistritöö vamimisels kaasa aitasid ja suunasid. Tänan oma juhendajat Üllar Ambost, kes insipireerivate mõttevahetuste, nõuannete ja julgustamisega aitas lõpule via käesoleva magistritöö.

Tänan lisaks ka oma elukaaslast, perekonda, töökaaslasi ning sõpru, kelle toetus on olnud oluliseks osaks magistritöö koostamise protsessi vältel.

ABSTRACT

In the field of architecture, gridshell structures provide an alternative approach to the simple geometrical forms used in modern building designs. In addition to their aesthetical value, gridshells depict the close interlinking relationship between architects, engineers, manufacturers [2], and the successful realisation of one is in quite a large amount reliant on the knowledge base gathered during previous generations' designs and experimentations.

The following master's thesis, upon reviewing the design and construction processes of previous timber gridshells and experimentations in the field, puts forward two designed structural models to represent the true nature and an accurate digital representation of a physical double-layered timber gridshell. The parametrically based methodology in the creation of the large scale digital geometries and imprinted structures describes the efficiency of the approach in terms of material use and time and how the implementation of material programming could increase the efficiency and safety of the construction process.

The double-layered grid shell structure is utilised in the old city of Florence, by the waterfront of river Arno. Particular attention is also given to the prevailing natural circumstances in the area, as occasional floodings of the site are not uncommon occurrences. The need to strengthen the existing sites' connections to the surrounding city has also been taken into account.

Keywords: architecture, timber gridshell, Florence, flooding, Master's Thesis

ANNOTATSIOON

Võrkkoorikud arhitektuuris pakuvad alternatiivseid lähenemisviise lihtsatele geomeetrilisetele vormidele, mida kasutatakse üldiselt kaasaegses hoonete disainis. Lisaks oma esteetilisele väärtusele illustreerivad võrkkoorikud arhitektide, inseneride ja tootjate tihedat omavahelist koostööd [2], mille edukas realiseerimine sõltub suurel määral ka eelnevate põlvkondade poolt projekteerimise ja katsetamise käigus kogutud teadmistest.

Järgnevas magistritöös, milles tehakse kokkuvõtlik ülevaade varasemate puitvõrkkoorikute projekteerimis- ja ehitusprotsessidest ning erialastest katsetustest, esitatakse kaks konstruktsioonimudelit, mille eesmärgiks on illustreerida füüsilise kahekihilise puitvõrkkooriku tegelikku olemust ja esitada selle ligilähedaselt täpset digitaalset kujutist. Parameetrilise disaini metoodika kasutamisega proovitakse esile tuua selle lähenemisviisi eeliseid materjali- ja ajakulu seisukohast suuremõõtmeliste projektide puhul ning lisaks kirjeldada, kuidas programmeeritava puitmaterjali rakendamine konstruktsioonis võiks suurendada ehitusprotsessi tõhusust ja ohutust.

Kahekihilise võrkkooriku rakendamise asukohaks valiti ala Arno jõe kaldal Firenze vanalinnas. Suurt rõhku pööratakse ka piirkonnas valitsevatele looduslikele oludele, kuna projekteerimise ala võivad ohustada perioodilised üleujutused. Samuti arvestatakse vajadusega tugevdada olemasoleva ala sidemeid ümbritseva linnaga.

Märksõnad: arhitektuur, puidust võrkkoorik, Firenze, üleujutused, magistritöö

CONTENTS

I. THEORY AND RESEARCH

1. INTRODUCTION

> *"Everyone who has seen a timber gridshell will have experienced their delightful uniqueness and spellbinding magic. Their beauty lies in the way the 'bones' of the structure are exposed to express their form. The assemblage of filigree components creates a strong sense of materiality and tectonic understanding.*
>
> *The curved nature of the gridded surface also allows the titillating play of light and shadow to accentuate the changing perspectives of the structural system, bringing about a visually stimulating surface rich with variations in daylight. Come nightfall, with imaginative lighting schemes, the structural net comes alive with spectacular visual drama. Gridshells depict structural logic, reveal construction technique and showcase the hand craftsmanship of the carpenters or digitally-controlled precision of the machines that have brought them into existence."* [2]

Within the growing world of free-form architecture and our increasing awareness of the limitations set forth by the natural environment, timber gridshells have the characteristic to impose a viable alternative language of construction in the field of long-span, lightweight, affordable and sustainable architecture. Yet when researching architectural magazines and the vast database presented by the internet, it's use remains limited in numbers, manifesting itself mostly in smaller scale experimental pavilions and in very few large-scale permanent buildings.

The traditional gridshells fundamental structural characteristic lies in the perforation of a continuous shell membrane, a spatial structure which resists loads through its inherent shape and concentrating the material into strips. In the case of a traditional timber gridshell, the inherent natural properties of wood are being utilised for deriving of the latter by post-forming of a flat grid structure of long thin structural elements and it is the nature of the material that allows for the doubly curved shape, for the strength as well as for the construction method.

Being first used in the 1960's, the traditional timber structural typology is one which can also be easily applicable to the modern paradigm of sustainability. The efficient use of material, by implementing leftover material as shear blocks in-between layers, potential overall negative carbon balance in construction can be achieved, due in addition to the materials property of acting as a CO2 storage.

However, in a larger prospect, co-operation between design, analysis and construction plays a vital role in the realisation of a successful timber gridshell structure. Analysis of the timber gridshells structure and its behaviour under loads allows for the derivation of an accurate model, and with the implementation of the required safety parameters to materials, geometries and loads in the design phase, the possibility of ensuring safety to an acceptable degree during and after construction can be ensured already in early stages. Therefore, to increase the use of the aforementioned technology in architectural language, a better and increased base of knowledge and understanding of the spatial structure is required for the purpose of increasing the confidence of specialists to use it in their future projects and for it to become a more everyday structural solution.

Emerged to broader attention around the middle of the 20th century, timber gridshells have since evolved in form, shape, structure and construction methodology, creating a discussion in its definition and what is to be considered a true gridshell structure or a freeform grid structure. In the context of the following master's thesis, a detailed view is made of the spatial lattice structure while supporting on the initial definition laid out in IL 10 : Gitterschalen. This is followed by an overview of possible alternatives in structure, materials, fabrication, and smaller-scale experimentations of timber gridshells, which are the outcomes of the advancement of technology and experimentations in the field and have emerged in the architectural and structural field of expression.

1.1 CONTEXT AND ACTUALITY

In the field of architecture, gridshell structures provide an alternative approach to the simple geometrical forms used in modern building designs. In addition to their aesthetical value, gridshells depict the close interlinking relationship between architect, engineers and manufacturer [2], as the latter can be achieved mostly through the combined efforts and collaboration of separate research fields.

A recent systematic mapping study on gridshell research [8], indicates that the field is growing in interest and in the years from 2011 to 2020 the number of research articles published yearly on gridshells has increased from 10 to 58. With the majority coming from the fields of structural engineering, architectural contribution has remained scares, mostly related to the education of students and small-scale case studies. Yet as an exception to the rule, high quality architectural gridshell structures, where the architectural concept has been leading to innovation, can be found in different publications [8].

In the field of construction, wood and timber products have had a long history. The availability, machinability and having a strength and stiffness to weight ratio which can be considered equivalent to the properties of steel [13], wood presents a well-suited material for the creation and construction of lightweight, long-span, affordable and sustainable structures [14]. Additionally, the low torsional stiffness of timber makes it possible in the creation and development of a doubly curved lattice gridshells from a flat grid structure, [5], which are raised or lowered into shape and were pioneered in 1960s by architect Frei Otto. Wood as a recyclable and reusable material provides further opportunity to influence the impact of construction on the environment by acting as a CO2 storage and affecting the existing carbon balance.

The rapid advancement of technology in the last decades, has eased the digital processing of complex geometry, structural modelling and digital manufacturing, revolutionising the design and manufacturing of freeform gridshell structures. As a consequence, designers are no longer dependant on the deformation of a regular square or rectangular mesh to generate double curved gridshell surfaces as for example they were in the second half of the 20th century [2].

Even though with the evolution of technology, accessibility to computational processing power and remarkable number of research papers into the structural behaviour analysis, the analysis of physical construction of timber gridshell structures, together with the ecological and economic impact, remains little in number.

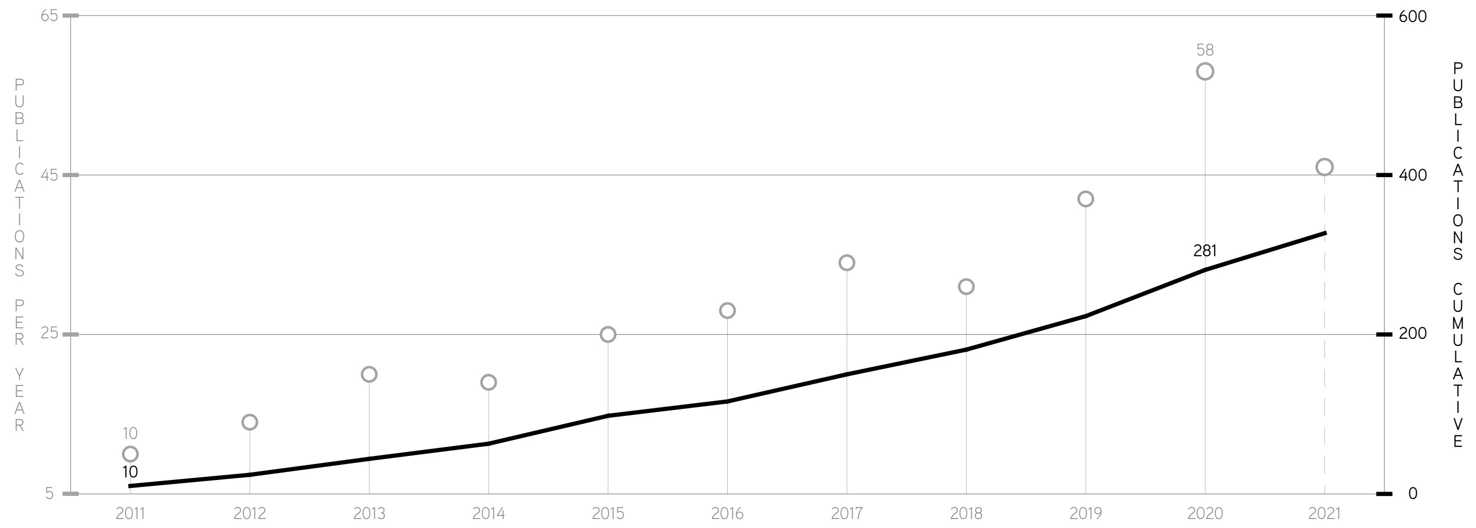

Figure 1. Publications per year of mapped articles. Research conducted in September 2021. Source: Dyvik, S.H., Manum, B. and Rønnquist, A. (2021)

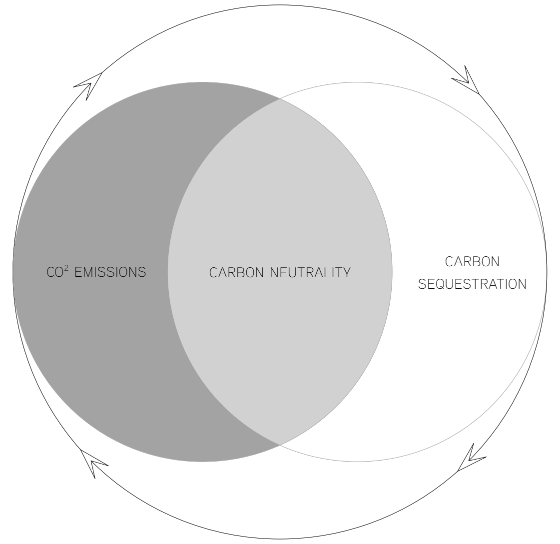

Figure 2. Concept for achieving carbon neutrality.

Figure 3. Hooke's analogy between an arch and a hanging chain. Illustration based on Poleni's drawing. Source: Block, P., DeJong, M.J. and Ochsendorf, J. (2006)

1.2 PROBLEM STATEMENT

In the designing and construction of large-scale timber gridshells, a variety of knowledge in structural engineering and construction is needed. The successful realisation of the aforementioned structures usually involves counterparts, who have had previous experience in the construction of lightweight timber structures [4], indicating that a certain degree of confidence, specialisation in skills and knowledge, and resources in workforce and time is required.

Several attempts in modern complex gridshell designs and interpretations of the typology try to simplify the process of construction and manufacturing by utilising the methodology of digital fabrication and by milling the different or irregular elements out of material blocks. This in turn creates an impact on the ecological and economical part of the overall process, expressing in the form of an un-optimisational use of material and resources [2].

1.3 OBJECTIVES

The aim of the master's thesis is to explore the underlying theory, principles and methodologies in the creation of a timber gridshell structure. An overview is presented on how the construction process could be influenced by implementing the modern knowledge achieved in the research of wood as a material, its sustainability aspect, and how the structure typology has evolved. Based on the derived knowledge and conclusions achieved in the theoretical part, a vision of a timber gridshell structure is designed.

1.4 APPROACH AND METHODOLOGY

The methodology of the master's thesis concludes of a detailed literature analysis and study into the principles of timber gridshells, their evolution and the material it is constructed of.

In the first part of the theoretical development a bottom-up approach is implemented, where the defining principles of a gridshell are established. This is followed by a study into lattice gridshells, their development, compositional elements in terms of acting forces, structural build-up and early construction methodology. Middle part of the theory analyses the evolution of timber gridshell structures, beginning with the construction of Mannheim Multihalle and concluding with modern interpretations in the field of timber gridshell structures. Third part analyses the materiality of wood, its use in gridshell constructions, modern research achievements in its programmability and the limitations and critique of the structure typology in architectural use.

1.5 STRUCTURE OF THE MASTER'S THESIS

The master's thesis is divided into two parts – a theoretical research and an architectural project.

The theoretical part presents an overview into the structural principles of timber gridshells, using the methodologies described in chapter 1.4. In the project design part, a conceptual solution is presented for a competition site in the city of Florence. The project is composed of the initial task and requirements set forth in competition brief and on the theoretical conclusions on timber gridshell structures made in the master's thesis theoretical part.

2. TIMBER GRIDSHELLS

2.1 DEFINING A GRIDSHELL

One of the most extensive research publications into grid shell typologies, IL 10 : Gitterschalen – Grid Shells [1], has been published in 1974 by the University of Stuttgart.

"The grid shell is a spatially curved framework of rods and rigid joints. The rod elements form a planar grid with rectangular meshes and constant spacing between the knots [nodes]. The form of a grid shell is determined by inverting the form of a flexible hanging net. To invert the catenary so that it becomes the thrust line of an arch free of moments is an idealisation. Analogously, inverting the form of a hanging net yields the support surface of a grid shell free of moments." [1]

The fore mentioned description presents the gridshells definition, what might be considered, in its purist form and is in the research field considered as the base definition. [2]

A more general and simplified definition to grid shells has been presented by Steve Johnson of Edward Cullinan Architects in the article "Gridshells & the construction Process", defining it as "essentially a shell with holes, but with its structure concentrated into strips" [3]. In contemporary architecture, the latter definition has led to a new interpretation of the term grid shell [2]. Together with the advancements in technology, digital production and manufacturing, variety of complex forms and structures have started to appear, blurring the lines between what might be considered a true grid shell structure according to definition.

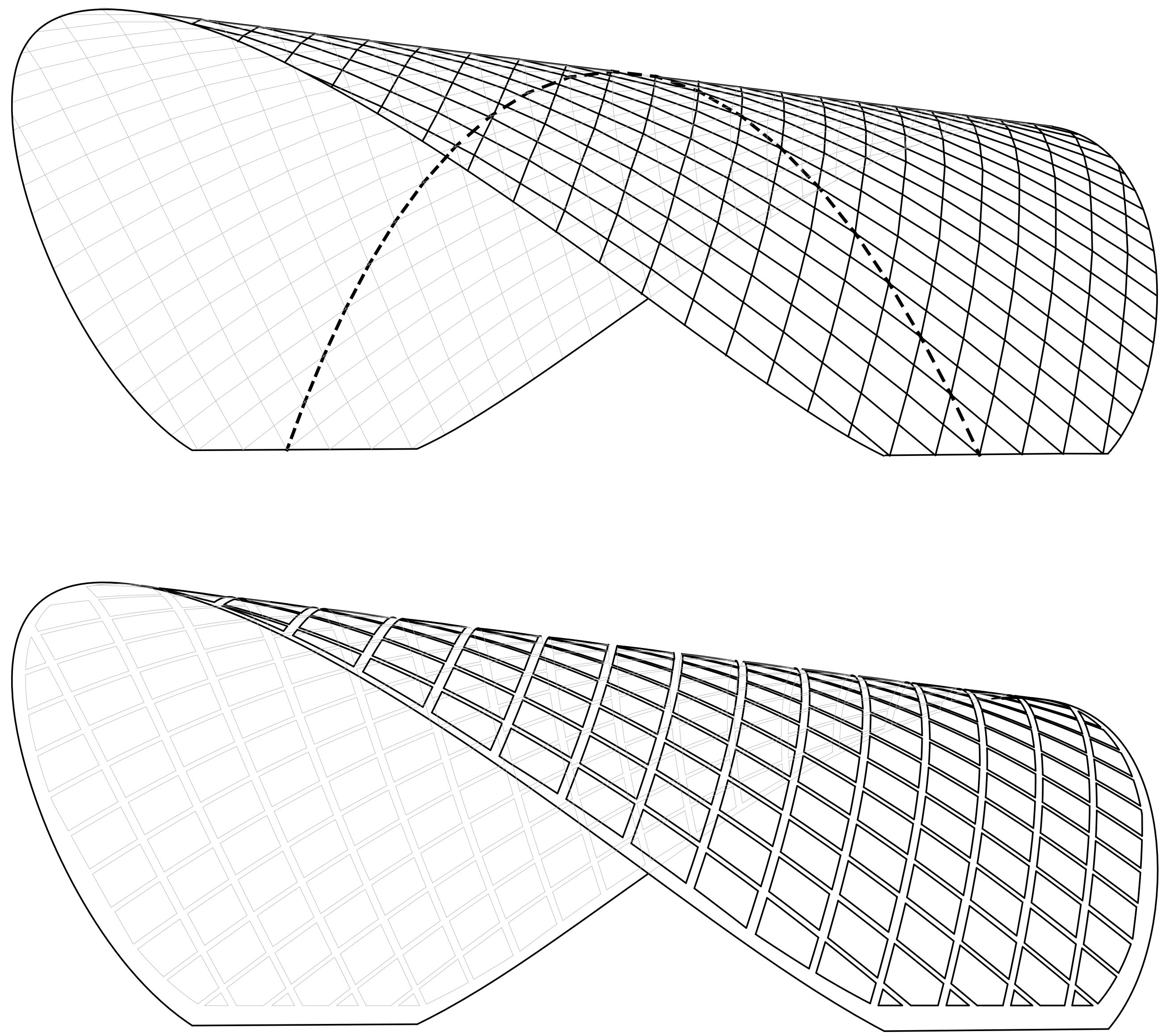

Figure 4. Two definitons of a gridshell structure. Upper drawing - IL 10. lower drawing - Steve Johnson of Edward Cullinan Architects.

2.1.1 LATTICE TIMBER GRIDSHELLS

Timber grid shells, together with membrane structures, continuous shells and cable-net structures among others, form a class of structure typology which is referred to as the "light weight structure" [9], with its additional property of enabling the creation of long span open spaces [10].

In the late 1950s, German architect and engineer Frei Otto started to investigate light-weight structures with the principles set forth by Robert Hooke and with the use of an inverted hanging chain net [11]. According to Hook's principle, a hanging chain creates a catenary in pure tension and in inversion an arch in pure compression, when subjected to its own weight [12].

This led to the development of a timber grid shell prototype by Frei Otto in Essen in 1962, and with his realisation that the three-dimensional form of a quadrangular network of hanging chains can be reconstructed by semi-rigid lattice of wood or steel rods, provided that the rotational properties of laths are preserved at the inter-section points [7].

In the erection of a timber gridshells, the most used construction methodologies are by pushing upwards or downwards into shape a flat interconnected grid-map of identical lattice components. The creation of a double curvature in a grid shell shape is also made possible by the woods material property of having a low torsional stiffness. [10]

Yet practical and physical limitations exist to timber grids shell structures. Dependant on the cross-section dimensions, there is a limit to the curvature tightness to which particular laths are able to be bent. A lattice with a depth, required for guaranteeing the structural stability, might prove to be too deep for bending into shape a thigh radii curvature. As a solution, double layered lattice gridshells where created and utilised.[5]

Wood as an anisotropic material does not allow the creation of a true shell structure, exhibiting different mechanical properties in different directions [13]. A continuous shell out of a isotropic material is able to "direct forces and out-of-plane bending on orthogonal directions", while a lattice timber grid shell "can only resist forces in the direction of the laths" while also remaining permeable to diagonal forces.[7]

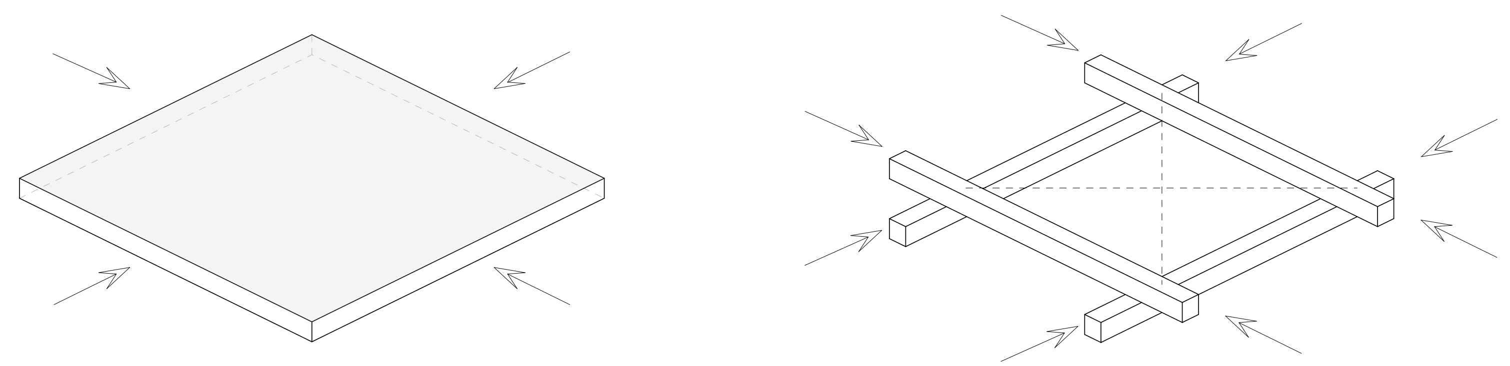

Figure 5. The continuety of a shell provides the neccessary structural in-plane diagonal resistance while lattices work only in the direction of individual elements.

2.1.2 STRUCTURAL BEHAVIOUR

The nature of a continuous shell allows it to withstand applied loads through its innate shape, transferring them into the shell's membrane structure, and expressing themselves as in-plane tension, compression and shear force [5]. Grid shells on the other hand are defined as double curved structures, which have the load carrying behaviours and strength of a continuous shell but are concentrated into strips [6].

The behaviour of gridshell is affected mainly by two types of distinct loads: funicular and disturbing. The first one leads to the emergence of direct forces in the laths, which is caused by the "equilibrium between external loads and the axially loaded members". [4] As these forces might be considered preferable, increasing funicular loads also affect its resistance capabilities to disturbing loads, decreases the structures stiffness and, after reaching a critical point, might lead to the collapse of the whole structure [7]. Disturbing loads, for example side winds, impose bending moments and deflections to the structure, leading to the creation of adjustments in the initial shape [4].

In construction of classical gridshells, the woods property to sustain partial deformations after exposure to long term loads has proven to be of beneficial use [2]. Initial bending stresses which are induced into laths by deforming a flat grid into a double curved surface subside partially over time due to the creep effect in wood, leaving behind residuals for the later assessment in construction stability [7].

2.1.3 LATHS AND LAYERS

The nature of the traditional curved timber gridshell lies in the structural system of overlapping a series of bent continuous timber laths in a two directional structure.

During the formation of a curved surface, laths and battens can be subjected to conditions, where tight radii bents are required out of them. This can be achieved more easily with laths, that have a wide, thin section and little imperfections in material. Contrary to form shaping, when subjected to applied external loads in form of wind, snow or point load, narrower and deeper sections are preferred as these resists more efficiently the local bending of the surface, creating a contradicting situation in the overall design process [2].

The initial design methodology of Frei Otto for a timber gridshell utilised the implementation of a single layered grid structure, overlapping crosswise only two sets of long members [7]. Due to the forementioned limitations in structural behaviour in the single layered formation, an alternative method in form of a double layered gridshell structure had to be implemented in his later designs. This was derived partly due to the circumstances that "larger spans require higher out of plane bending stiffness and higher second moments of area in individual timber members" [4]. In short, the first layer in principle is used for the forming of the shape and giving it an initial structural strength, while the second layer with in between shear blocks is used to increase the structural strength [5].

However, the initial pinned configuration of the structure cannot transfer forces between laths, leaving it vulnerable to diagonal forces. The latter can be achieved in various ways, for example by adding rigidity into the joints at the nodes, by adding diagonal cross ties, by introducing cross bracing of equal area to the laths, or by introducing a cladding membrane with necessary strength properties.[7]

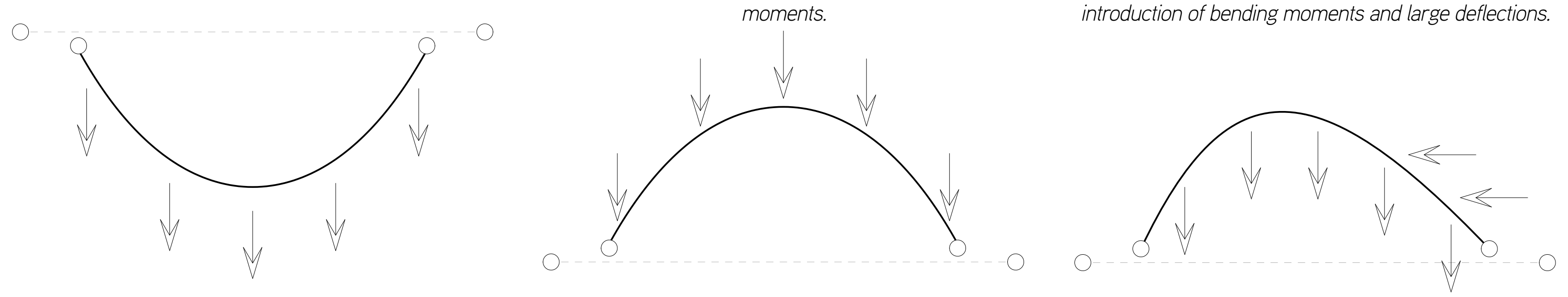

Figure 6 Funicular and disturbing loads

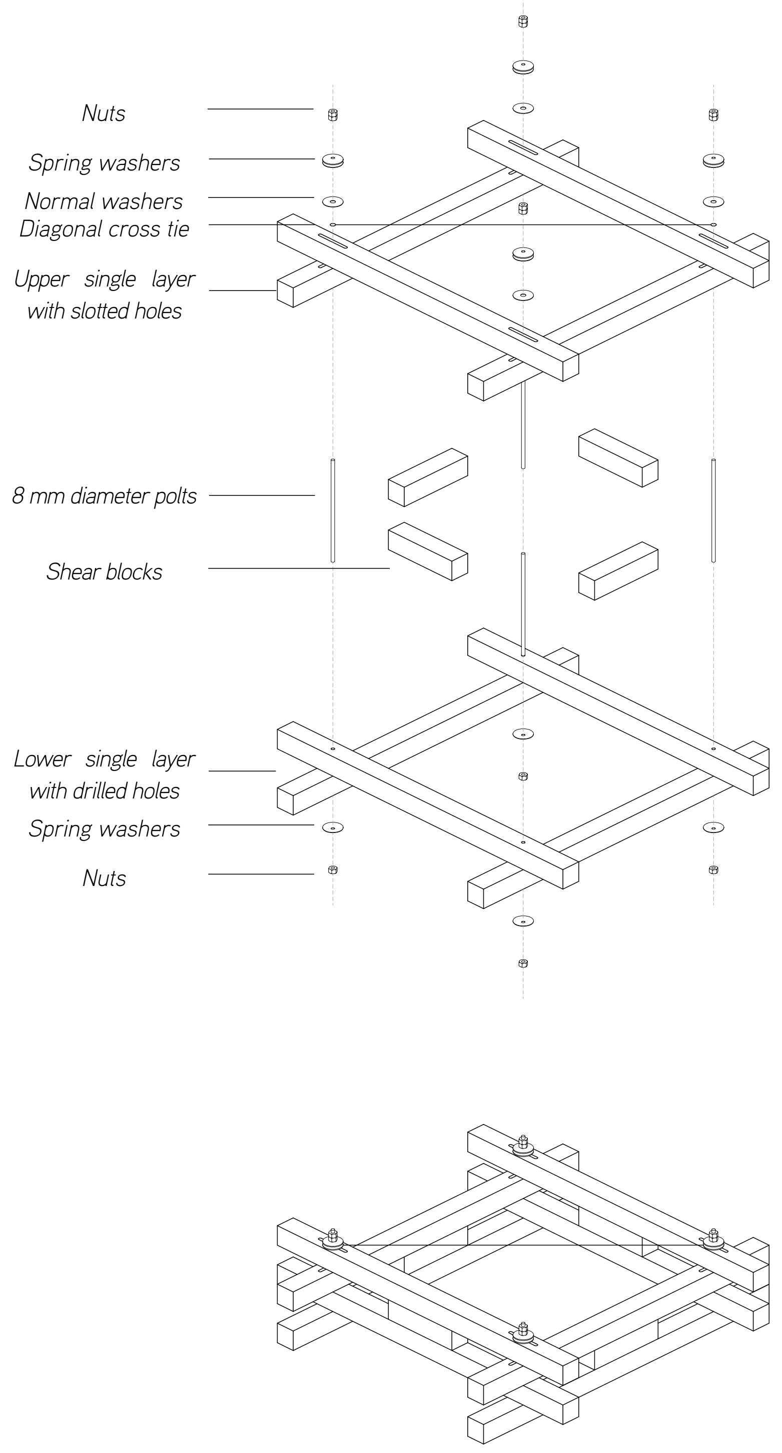

Figure 7. Double-layered timber gridshell element

2.1.4 NODES

In the deployment of curved grid surfaces from an initially flat state, the capability to accommodate for movements in the nodal intersections, including possibilities for rotation, torsion, and in some cases the sliding of different grid layers, is of essential importance [2].

In the case of a double layered gridshells, there exists an additional need for the transference of shear forces between the parallel grid layer elements [7], which is attained via the nodal connections themselves and through the implementation of shear blocks in-between the layered laths, leading in all to a greatly strengthened composite section and increased stiffness in the surface [5].

In the nodes of the double layered Mannheim Multihalle gridshell, threaded steel bars were passed through the four intersecting timber elements, with rounded holes in the inner two layers and slotted holes in the outer two, enabling the necessary movements in the connections during formation [10].

Afterwards, clamping forces were applied in the nodes via washers and tightening of the steel bars [7]. This methodology of drilling holes in the structure however potentially weakens the timber grid [2].

An alternative approach was developed for the Downland timber gridshell, where the connectors enclose the intersection point. The patented connector works on the principle of placing steel plates in-between the separate layers and connecting them without penetrating the grid elements via bolts [5]. This allows the two middle orthogonal layers to maintain the form, while external layer elements retain the ability to move throughout deployment and the option to attach additional stiffeners if needed [15].

2.1.5 INSTALLATION

In the deployment of lattice timber gridshells, a variety of methods have been used over time, where the main ones are represented as follows [2];

- crane lifting of a pre-assembled flat grid
- crane lifting of a partly or fully assembled pre-formed grid
- pushing up of a pre-assembled flat grid or pulling it down from higher level
- direct installation of a grid with prefabricated elements

As with every construction methodology, there are aspects in the processes which present advantages or disadvantages for the individual deployment of the forementioned methods. By careful evaluation, a decision can be made which suits best the circumstances. As in the case of crane lifting a pre-assembled grid provides the opportunity of ease of access and control of dimensioning, as in most cases the assembly takes place on the ground level and is later lifted into place. Another advantage presents in the form of gravity and in the deformation of the grid under self-weight. With the careful evaluation of the lifting nodes positioning, forming of the curved shape can be made easier.[2] In the methods of pushing up or pulling down a gridshell, a considerable assessment has to be made in matters of safety, as workers must be able to navigate under a heavy moving structure. Additional concerns arise when the flat grid has to retain its ability to slide on the ground, in order for it to being pushed up, or when it turns out that deformation by gravity alone is not sufficient enough and additional loads have to be applied to the structure.[2]

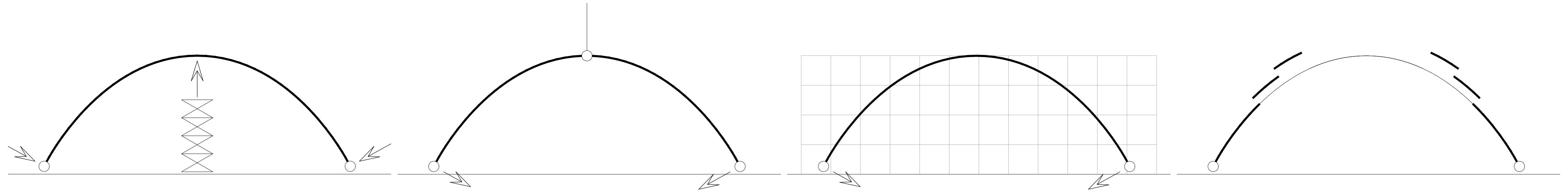

Figure 8. Deployment methodologies of lattice timber gridshells

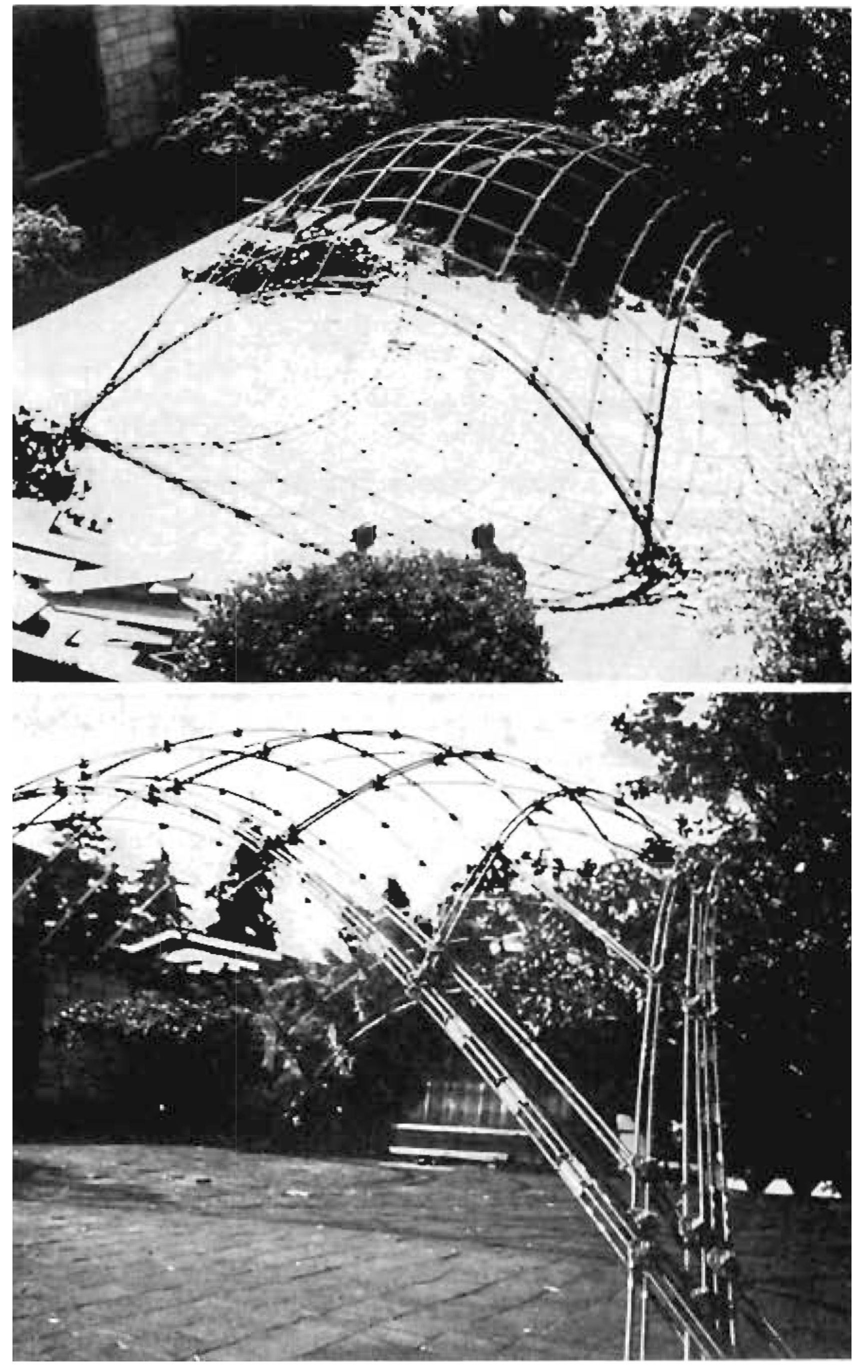

Figure 9. Steel bar gridshell in Berkeley. Source: Happold, E., Liddell, W. I. (1975)

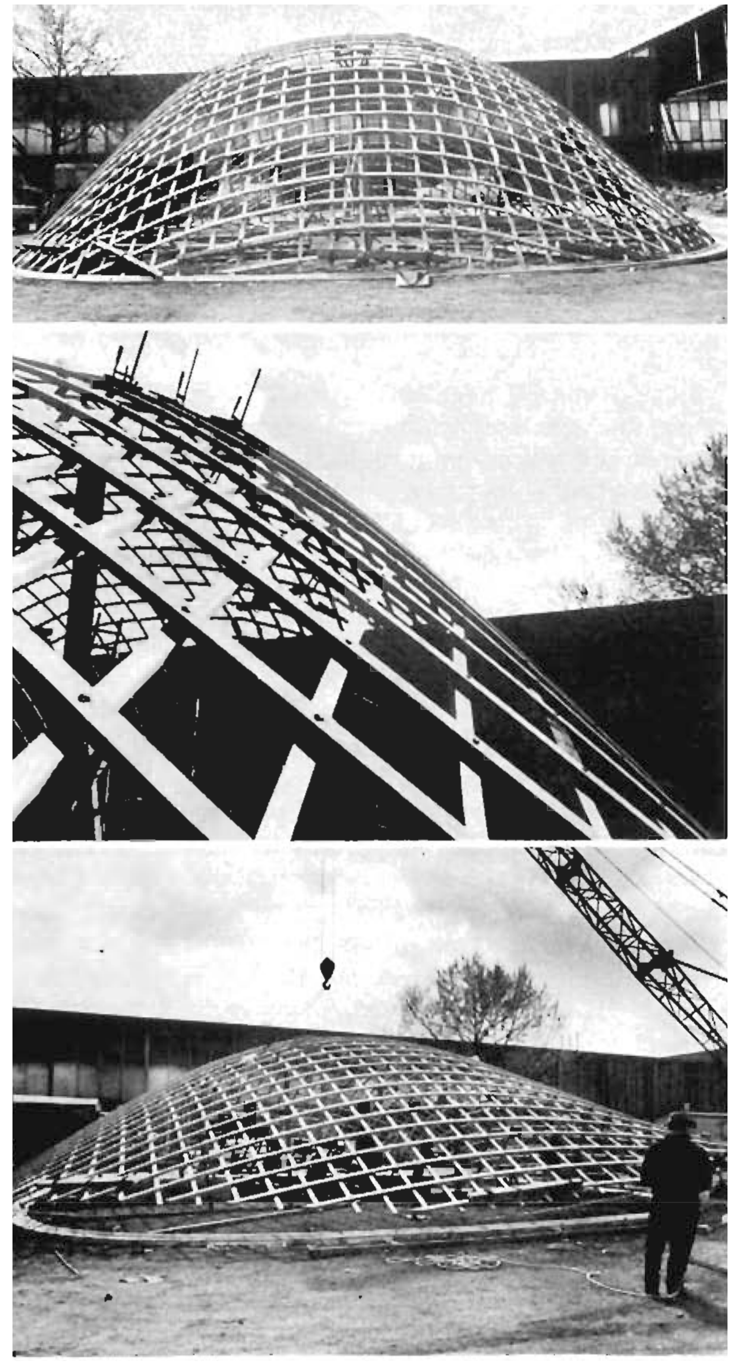

Figure 10. Trial timber gridshell in Essen. Source: Happold, E., Liddell, W. I. (1975)

2.2 EVOLUTION OF TIMBER GRIDSHELLS

2.2.1 FIRST GENERATION

DEUBAU

Location:	Essen, Germany
Architect:	Frei Otto and Bernd Freidrich Romberg
Year of construction:	1962
Size:	198 m2

Before the construction of his first timber gridshell, Frei Otto led a student project during his visit at University of California, Berkley in 1962, where a trial version of a dome structure using steel reinforced bars was created. However, later that same year, a trial 15m x 15m timber gridshell pavilion was constructed for the German Building Exhibition at Essen.[11]
Developed by Frei Otto and Brend Freidrich Romberg, the pavilion had a super-elliptical plan and was designed by using hanging physical models and had a central height of 4.85 m, maximum span of 16.82 m between corners, and a mesh grid of 482 mm in size. Wood used for the laths in the construction was hemlock pine, which were finger jointed together from smaller members [7]
After the initial assembly of a flat square grid on the ground and bolting of the nodes, the grid structure was later crane lifted and moulded into form and ground anchored [2]. The reinforced access opening for the pavilion was cut later into the mesh grid [1].

MONTREAL WORLD EXPOSITION

Location:	Montreal, Canada
Architect:	Frei Otto and Rolf Gutbrod
Year of construction:	1967
Size:	365 m2

In 1965, Frei Otto and Rolf Gutbrod won the competition for the design of the German Federal Pavilion for World Expo 67 at Montreal. Even though the larger part of the pavilions design consisted of mast supported cable nets and from tensile membranes, the interior vestibule roof for the main auditorium was designed out of a timber gridshell.[7]
The plan shape no longer depicting a regular form, was composed out of two irregular parts and joined via a common valley beam. For determining the shells profiles, an initial precise suspended model was constructed and measured, which later was scaled up to the size of 1:10 by using 2x3 mm timber strips. The final irregular forms, with a maximum span of 17,5 m, a maximum height of 4m, where constructed using a 500x500 mm timber lath grid configuration.[2]
After an initial trial assembly in Germany, the lattice layout where then later collapsed diagonally into bundles and transported to Montreal as complete sections, after which they could be opened up and assembled on site [11]. This was done through winching of the separate elements into position by suspended cable hoists from the main roof net [2].

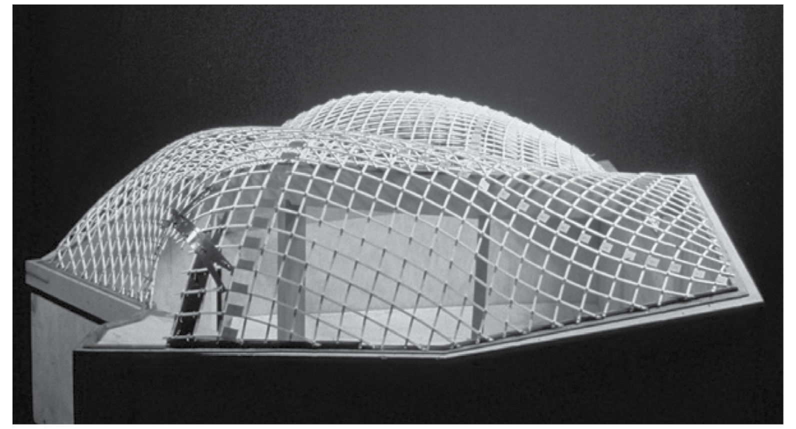

Figure 11. Montreal Expo physical model. Source: Chilton, J.C., Tang, G. (2016)

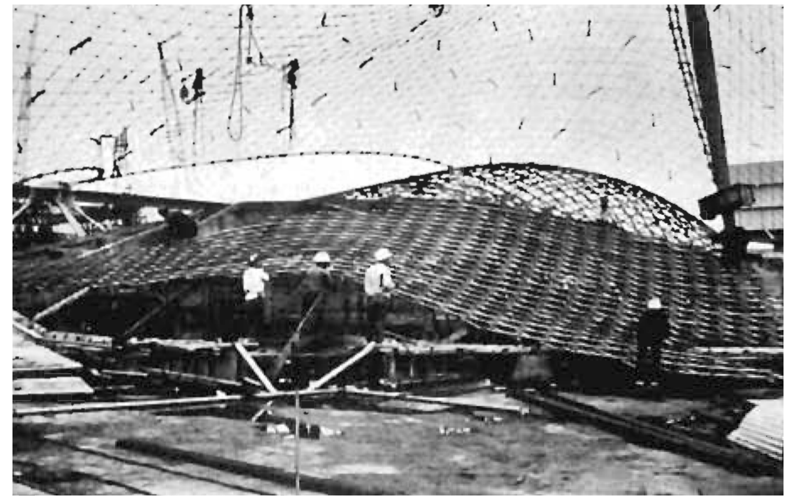

Figure 12. Lattice domes at Montreal. Source: Happold, E., Liddell, W. I. (1975)

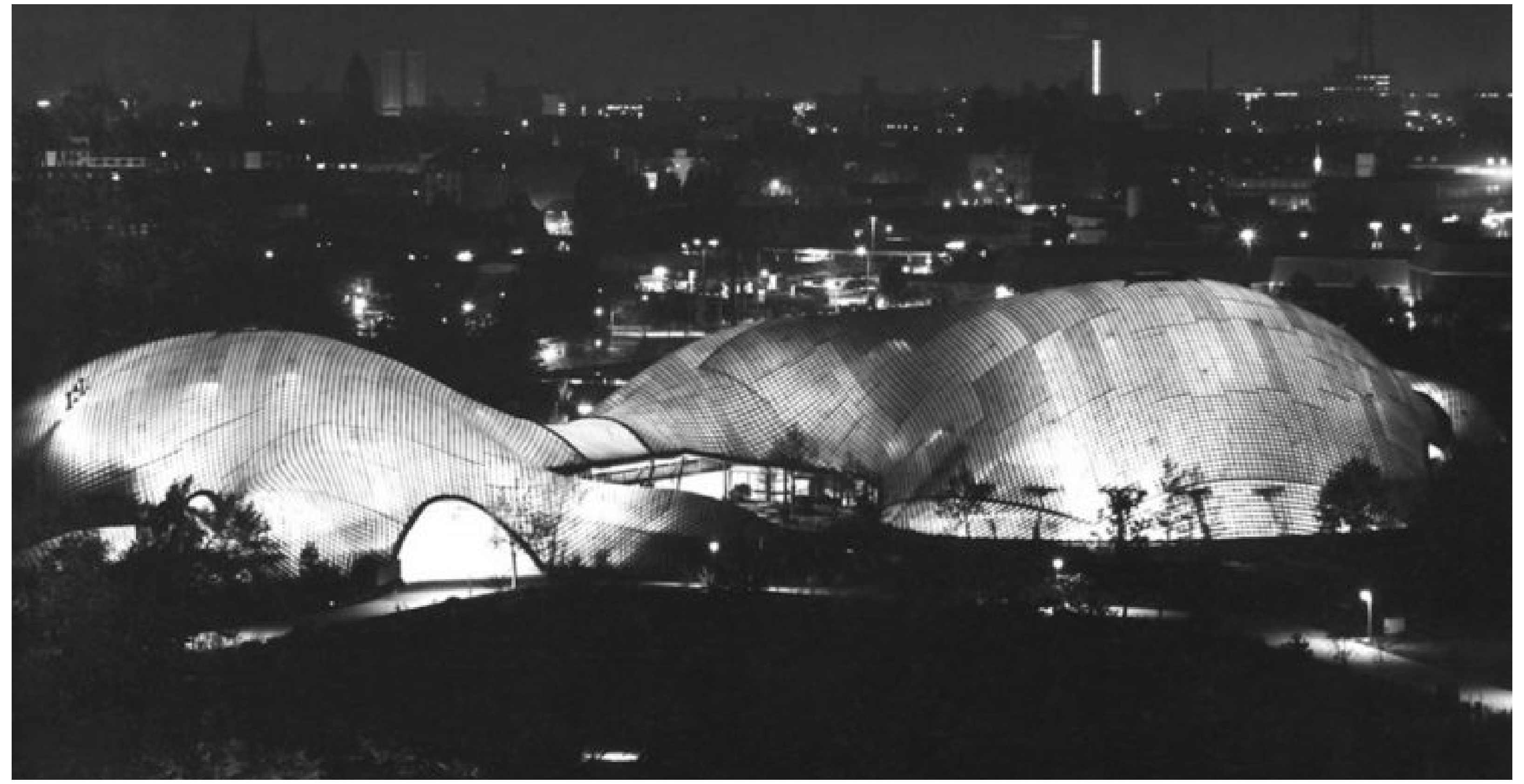

Figure 13. Mannheim Multihalle. Source: mannheim-multihalle.de (2022)

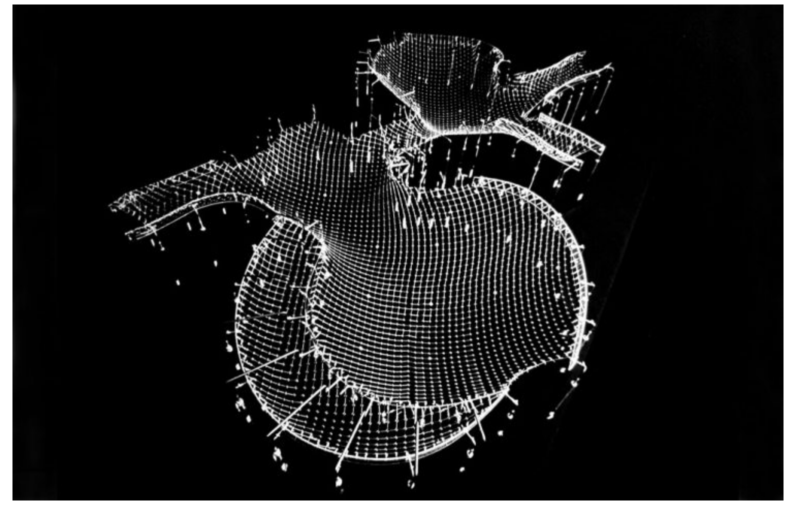

Figure 14. Hanging chain model. Source: mannheim-multihalle.de (2022)

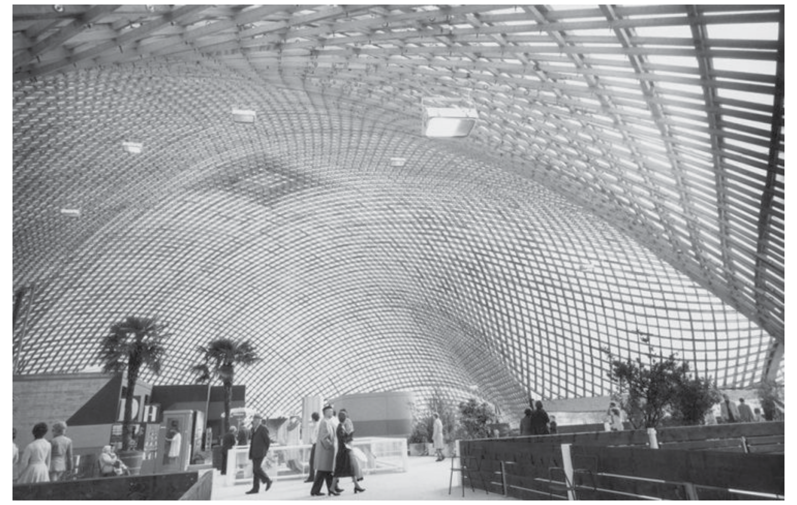

Figure 15. Lattice timber gridshell. Source: mannheim-multihalle.de (2022)

MULTIHALLE AND RESTAURANT

Location:	Mannheim, Germany
Architect:	Frei Otto, Carlfried Mutschler and Joachim Langner
Year of completion:	1975
Size:	ca 7400 m2

Developed by Frei Otto and architects Mutschler & Partners, the Mannheim Multihalle roof was the follow-up to the previously extensive pioneering work carried out on timber gridshells [4]. It was intended as a temporary structure for the Federal German Gardening Exhibition, Bundesgartenschau, which took place in 1975 in Mannheim and can be considered as an overall successful realisation of a timber grid structure due to its remaining presence nowadays in Herzogenried Park.

In retrospect to previous achievements in constructing timber gridshells, the multi-purpose hall and restaurant complex presented a bigger challenge, as the desired structure was more complex, much more larger in plan size and had to provide a proof of concept in matters of structural integrity and extended lasting.

The proposed architectural solution consisted of two shells, covering respectively the multi-purpose hall and restaurant, an curving annex to the Multihalle and from interconnected tunnels and passageways [7], where the largest dome span reaches up to 60m with a height of 20m.

In the beginning of the design phase, a 1:500 scale wire mesh model was made at Frei Otto's studio for determining the gridshells spatial form. This was followed by a 1:100 hanging chain model, where hooked 1.5 cm long links connected via small circular rings helped to define the geometry of the building and respectively at the same time represented every third lath line of the real structure. Afterwards, by measuring the model with stereo photography and analysing the photos, coordinates of the individual nodes were determined for on-site location. [11]

For the construction of the double layered structure of the main shells and single layered passageways, Canadian hemlock was chosen due to its relatively high mean Modulus of Elasticity (E) and maximum dry bending strength. Six meter long and 50 mm x 50 mm in profile hemlock laths where finger jointed up to 40 m in length and laid out on site in four layers, generating a 500x500 mm timber lath grid configuration, and fixed together at nodes with 8 mm in diameter galvanised threaded bolts. As wood expands or contracts with change in internal moisture content, and for the purpose of maintaining frictional contact between laths, Schnorr spring washers were added to the nodes. [17]

As discussed by Happold and Liddle [7], a crucial aspect in the Mannheim project construction proved to be the provision of diagonal stiffeners. Initial tests on the bolted nodes indicated a low rotational stiffness, which in case of an applied load on the irregular shaped structure would lead certain modes of gross deformations. For a possible solution to the problem, the Trevira-Reinforced PVC skin for external cladding was considered but deemed inefficient due to its low elasticity properties and its physical behaviour in exposure to ultra-violet light. As a final available option, 6 mm cables every 6th node were used to provide the in-plane stiffness [16].

An initial proposal for crane lifting the grid structure into place was dismissed by the engineer's team of Ove Arup, indicating that large cranes would be required for an extended period of time before structural stability could be reached in the construction, leading to an excessive increase in the existing budget [2]. For a viable alternative method, fork-lift trucks and scaffolding towers spacing 9 m in horizontal plane and supporting 2,5 x 3,5 m spreaders was implemented [7]. With the use of eighty carefully distributed scaffolding towers and a lifting process, approximate final form was able to be achieved through the sequential lengthening of tower sections one at a time [17].

For the supporting and anchoring of the structure along the perimeter, four typologies where used [4]:

- Lattices attached to a concrete base via steel brackets
- To multiple specific surface profiles cut and ground anchored laminated timber arches
- Steel column supported laminated timber beams
- And a partially supporting steel cables boundary on the restaurant shell.

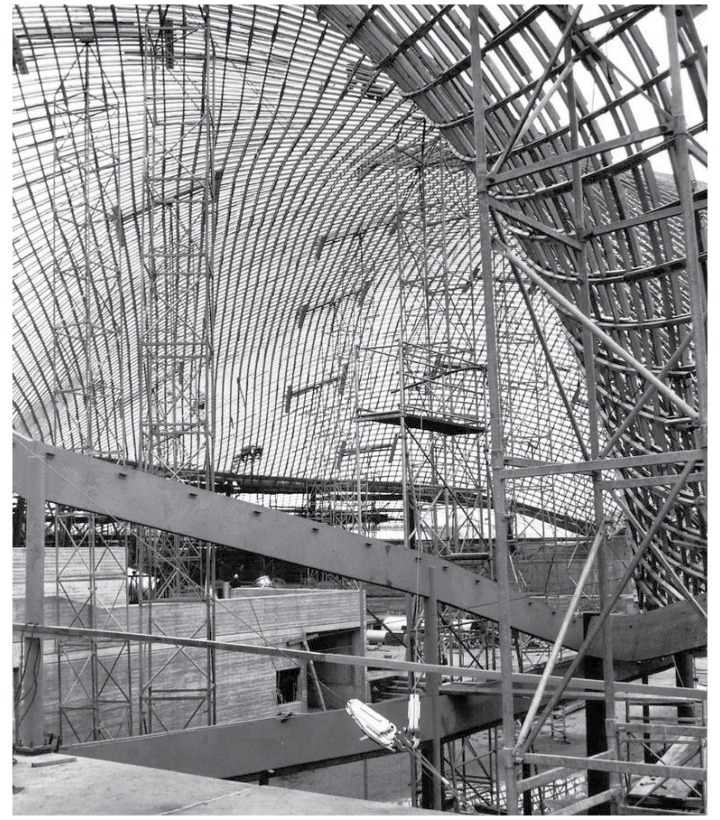

Figure 16 Placement of scaffolding towers during the construction of the Mannheim Multihalle. Source: Deutsche Bauzeitung (2015)

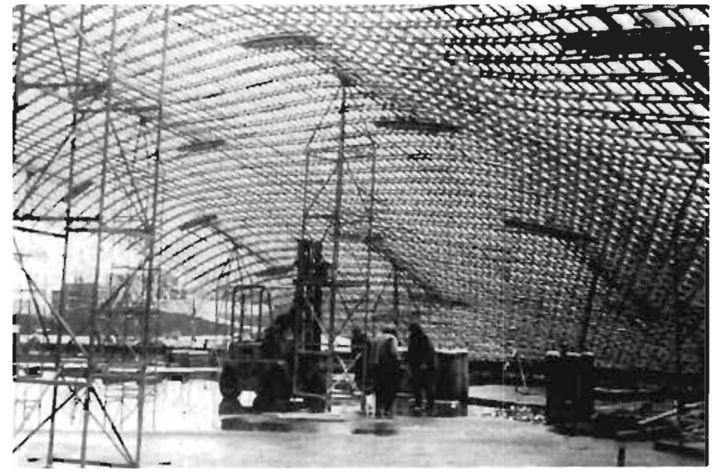

Figure 17. Fork lift truck being used to rise a tower. Source: Happold, E., Liddell, W. I. (1975)

Figure 18 Exterior view of The Weald and Downland Workshop Source: BURO HAPPOLD

Figure 19. Interior view of the barrel vaulted workshop. Source: BURO HAPPOLD

Figure 20. Earth Centre timber gridshells. Source: Chilton, J.C., Tang, G. (2016)

2.2.2 SECOND GENERATION

EARTH CENTRE

Location: Doncaster, UK
Architect: Grant Associates, Buro Happold
Year of construction: 1998
Size: ...-... m2

Designed for the Earth Centre Forest Garden, the small-scale experimental timber gridshells where an attempt to demonstrate "an efficient, elegant and structurally inventive way of creating habitable structures from timber" [2]. Considered as forerunners to the following timber gridshells built in the UK [18], these small-scale structures additionally provided viable information about material properties and structural behaviour for the construction of the Weald and Downland gridshell in Singleton [5].

Engineered by Buro Happold, the flat timber lath grid configurations were created from two orthogonal layers of split oak. After fixating the nodes with threaded steel rods, they were crane lifted into position, shaped into form with struts and ties, and stabilised with thin stainless-steel cables. [18]

To prevent chemical reactions by the tannins in the wood material, lath joints and grid nodes had to be connected via stainless steel rods. [2]

THE WEALD AND DOWNLAND WORKSHOP

Location: Singleton, UK
Architect: Edward Cullinan Architects
Year of completion: 2002
Size: 1200 m2

Designed and built by Edward Cullinan Architects in co-operation with Bure Happold, the workshop was commissioned by the Weald and Downland Museum in 1997 for the purpose of conservation historic timber buildings in the UK. As per client's request, the workshops floor needed to be sufficiently large enough, with a stable temperature, sufficient ventilation and with a constant humidity level, for the purpose on working on large sections of laid out building parts. [5].

The participation of Buro Happold's in the project was of instrumental value, as the knowledge and experience gained from their similar previous constructions lead to an extensive advancement in the understanding of timber gridshells in forms of digital form-finding and analysis. [2]

The triple bulb hourglass shaped timber gridshell has a maximum length of 50 m, varies in width between 12,5 m at valleys to 16 m at dome centres and a maximum and minimum heights of 7.35 m to 9.5 m [19].

The non-funicular form finding process of the workshop roof incorporated both computational and physical modelling, requiring

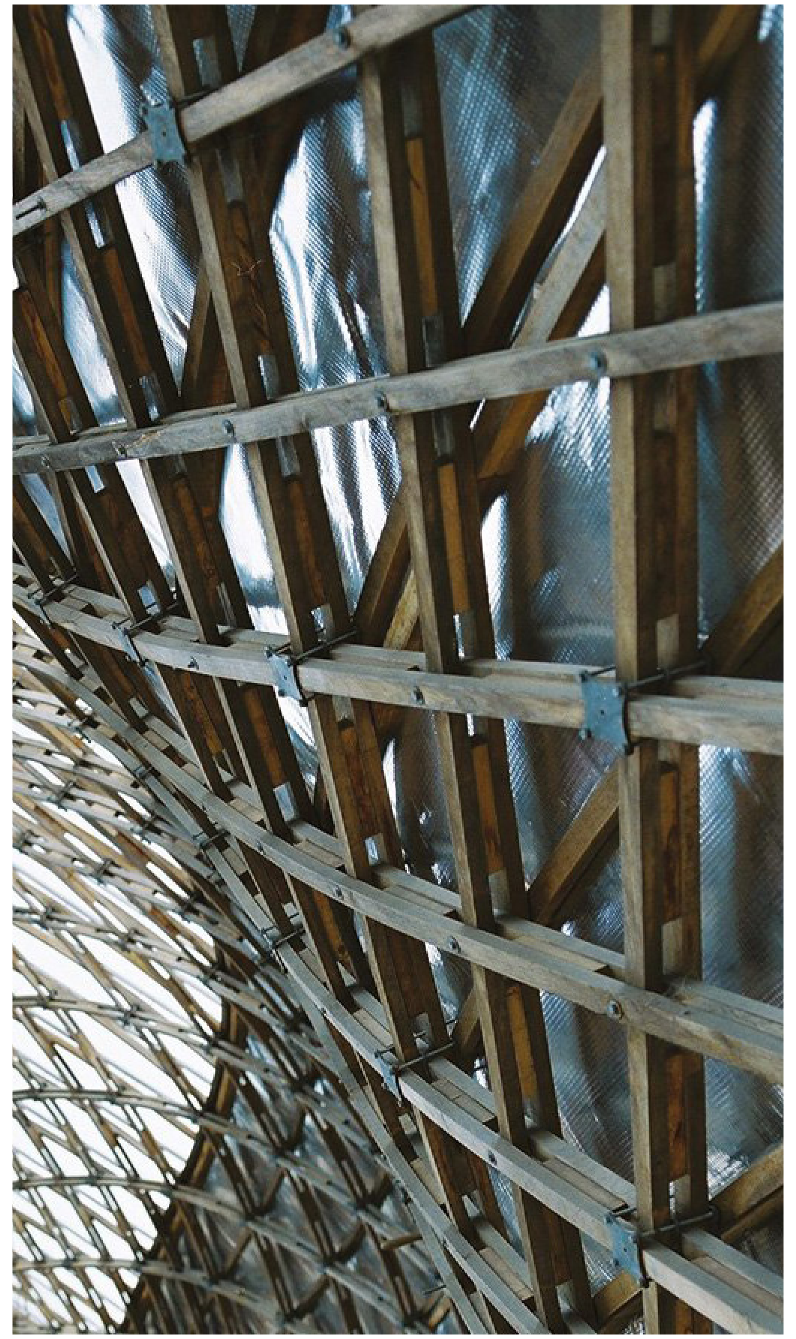

Figure 21. Workshops timber gridshell stukture. Source: Source: Cullinan Studio

a tight cooperation between the teams of architects and engineers. Drawings provided by the architects helped to give shape to the form and physical models, which subsequentially lead to the creation of a dynamic relaxation-based software computer model. [5] The initial concept for the erection of the shape was to tighten the waists of a barrel-vault, which in turn would lead to the forming of an hourglass. While the method worked in the creation of scale models, it was found that in the realisation of the real structure, significant out of plane forces would be required for forming of the shape which in turn would lead to a significant number of breakages in laths. Therefore, a progressive method of simultaneous formation in shape was introduced. [19]

In comparison to the Mannheim gridshell, numerous departures were made in the construction methodology of Downland gridshell, among others in the non-funicular shape and form finding process, nodal connection design and erection methodology.

A flat deployable double layered oak lath gridshell, consisting of 50 mm x 35 mm section profiles, was initially deployed on top of a PERI scaffolding system 7m above the floor. The approximately six-meter-long finger-jointed laths where site assembled to lengths of 50 m, using scarf joining, and assembled to general grid configuration of 1 m x 1 m in spacing, while increasing in density to 0,5 m in critical areas. [18]

By utilising the gravitational force, a partial formation of the gridshell form could be achieved, which compared to Mannheims push-up methodology proved more cost effective and safer. At the 25% completion state, ratcheting straps had to be induced to the project, caused by the failure of valley formations and due to the flattening out of laths, preventing the activation of shell action.[2]

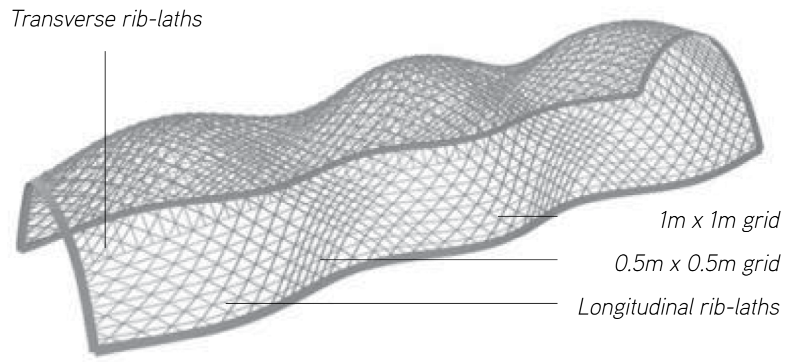

Figure 22. The Weald and Downland gridshells AutoCAD model - structural layout. Source: Kelly, O., Harris, R., Dickson, M., Rowe, J. (2001)

Figure 23. Construction of the Weald and Downland gridshell using PERI scaffolding. Source: Cullinan Studio

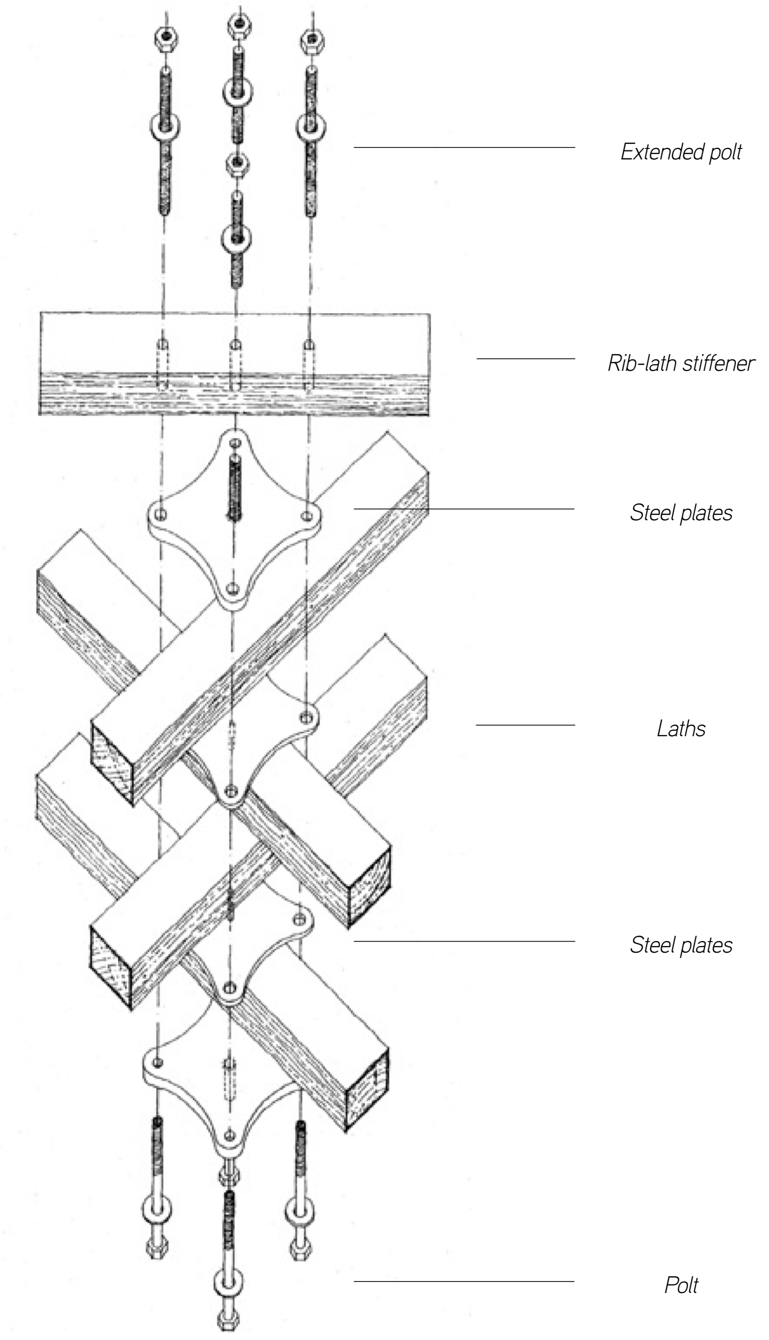

Figure 24. Patented nodal connection with rib-lath stiffener. Source: Cullinan Studio.

Figure 25 Savill Garden Centre. Source: BURO HAPPOLD

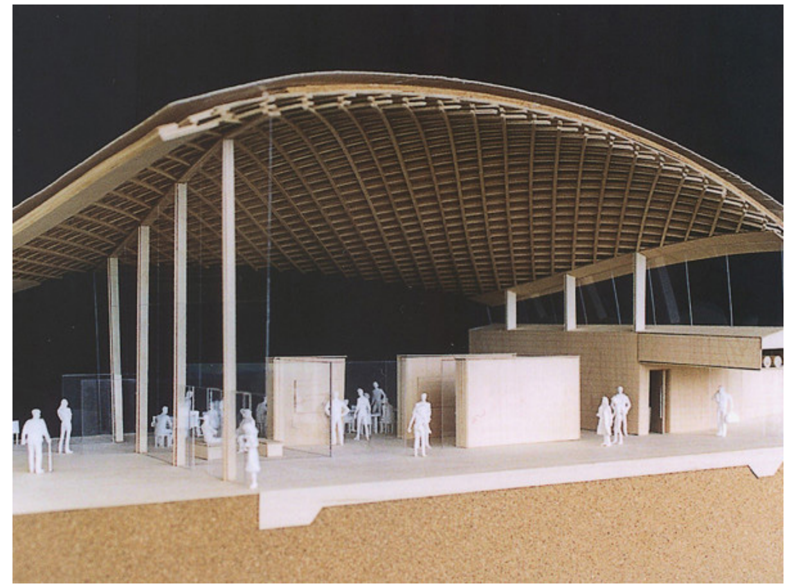

Figure 26. Physical model section. Source: Glenn Howells Architects

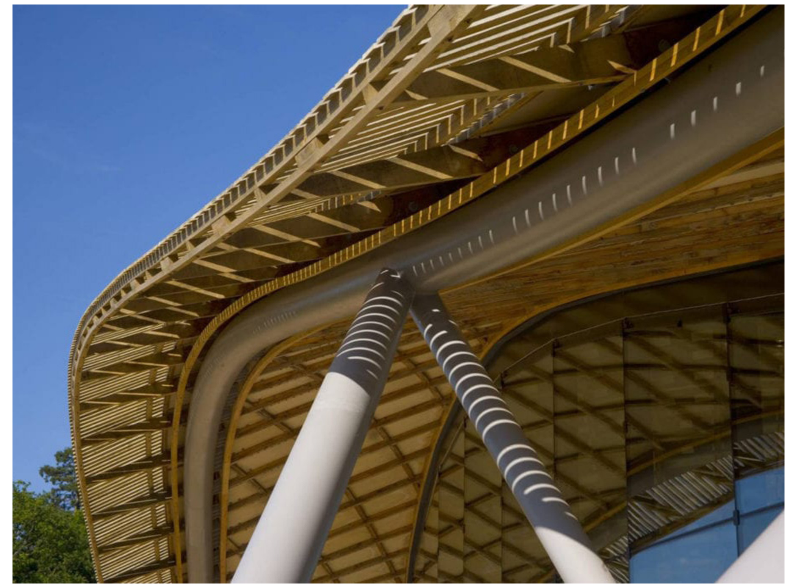

Figure 27. Elevated gridshell on steel columns. Source: Glenn Howells Architects

THE SAVILL GARDEN CENTRE

Location:	Berkshire, UK
Architect:	Glenn Howells Architects
Year of completion:	2006
Size:	ca 2000 m2

In reference to the Weald and Downland structure, the much shallower and floating gridshell of Savill Garden functions only as a roof, generating an open view to the surrounding garden and landscape. The illusion of lightness of the roof structure is accomplished through the detachment from the ground, by placing a steel beam on the perimeter of the roof and rising it with inclined steel columns for the transferring of loads into the ground.[2]

The theory behind the shape formation lied in the principle of using parabolic curves of varying shape to run along a sinusoidal centre line varying in amplitudes. Therefore, with a clear geometrical basis to the shape, architects and engineers were enabled to make adjustments in form while at the same time consider the aesthetical aspects and construction practicalities. Even though a scale model was used in the initial sketch design phase, majority of the form finding process was carried out in digital form with sophisticated software's. [20]

Similarly, to the Weald and Downland workshop, the triple bulbed hourglass shaped timber gridshell roof has a maximum length of 90 m and a varying transverse span of 25 m in maximum. The perimeter, forming a gradually changing elevation line onto the garden, varies in height between 4.5 m up to 8.5 m. [10]

The double curved gridshell, consisting of 80 mm x 50 mm laths, was milled from local larch trees. 6 m long lath elements were finger jointed together from smaller pieces, which subsequentially were scarf jointed together, with a gradient of 1:7, up to 50 m long elements.[20]

The four alternating layers of laths were laid out in a 1 m x 1 m grid configuration and placed into position by one grid layer at a time. This allowed to exploit the force of gravity for deriving the initial shape and was followed by the addition of the second grid layer for a full gridshell depth and structural strength. Shear block where later-on added to the structures in-between space for a greater out of plane strength and stiffness. [2]

To provide the diagonal stiffness to the structure and add additional strength to load behaviour, a continuous deck was formed over the gridshell from two layers of 12 mm butt-jointed plywood [18].

The construction and erection methodology of the Savill Garden roof structure, similarly to the Weald and Downland gridshell, consisted of the assembly of the grid on top of a platform, and by utilising additionally gravitational force was lowered and formed into shape.[20]

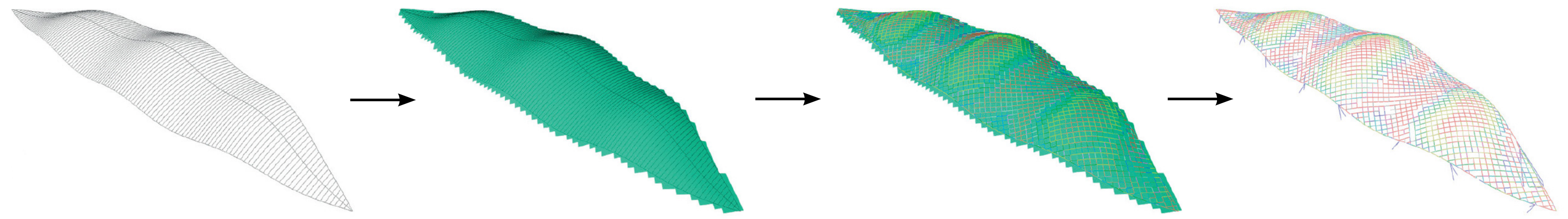

Figure 28. Form finding and analysis model and setting out plane. Source: Parker, D., Dickson, M. (2014)

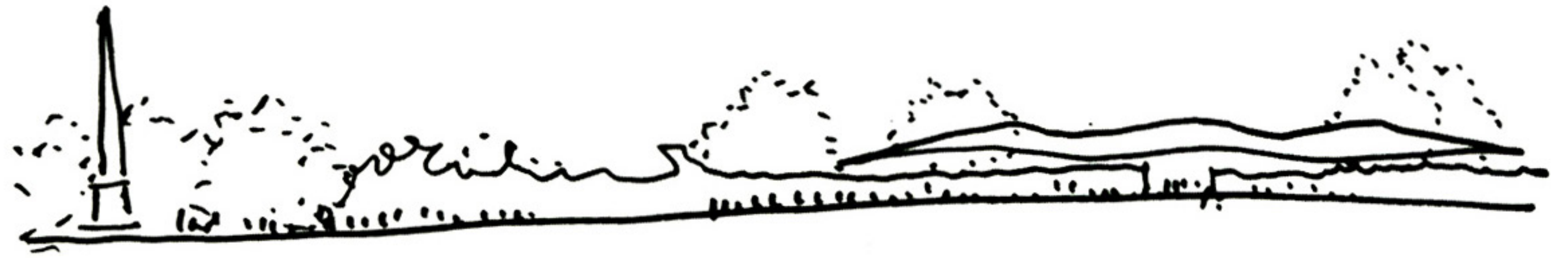

Figure 29 Initial sketch by Glenn Howell. Source: Glenn Howells Architects

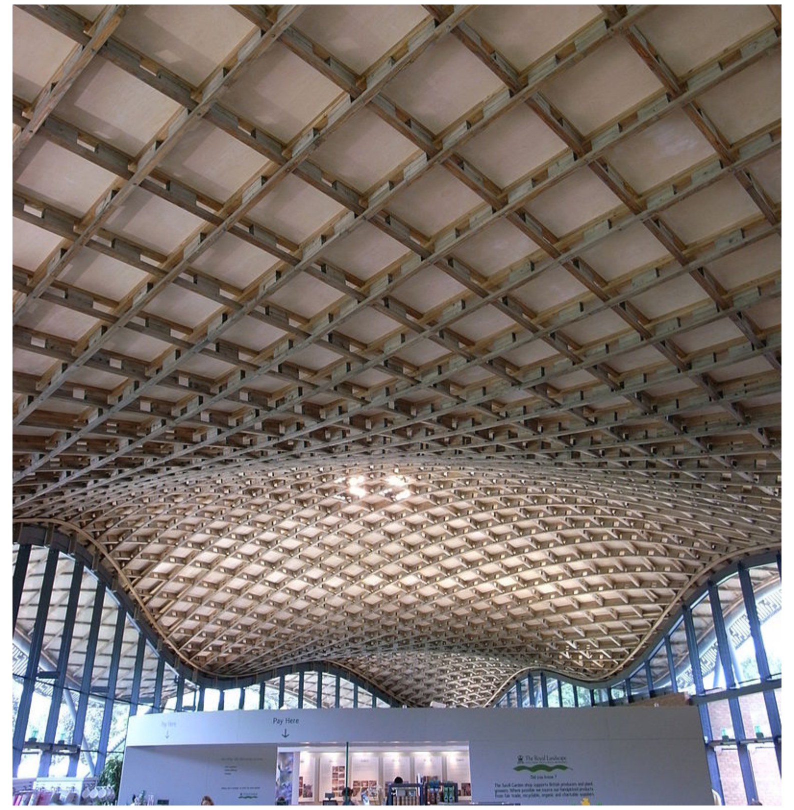

Figure 30. Timber gridshell structure. Source: Wikipedia

Figure 31. Construction in progress. Source: Glenn Howells Architects

2.2.3 DEVELOPMENT OF GRID STRUCTURES AND MATERIALS

By observing and analysing the development of design, structure and construction principles, underlying in the creation of an traditional lattice timber gridshell structure, we are able to create an sort of basis of knowledge for the branch of lightweight construction typologie, which in turn aids us into the understanding of it's contemporary approaches and translations. The following chapters, but not limited to the full extend, presents an overview of few examples of grid structure alterations, design approaches, material experimentations, fabrication and contemporary timber gridshell structures with their interpretations of the definition presented in chapter 2.1, and smaller scale experminetations in the spacial shape structure.

2.2.3.1 GRID STRUCTURES

Ribed gridshell, developed by Julius Natterer, includes several differentiations in comparison to Frei Otto's deployable lattice gridshell in manners of structure and deployment. It allows the designer to explore a greater diversity of non-funicular surfaces, including free-forms, domes, rotational and saddle shapes [21]. As with the double-curved Polydôme, designed by Julius Natterer in co-operation with Badic et Associés in 1991, the ribs run in a diagonal geodesic pattern, where the density of laths has been focused into the dome's diagonals, leading to an uneven grid pattern. The *hexagonal grid* roof of the Centre Pompidou – Metz has its nodal connections originate from the forerunning Mannheim Multihalle gridshell structure, designed by Frei Otto. The doubly curved freeform three-way timber gridshell structure works as a hybrid system, incorporating partial shell and catenary action and significant bending. Grid spacing was driven largely by architectural aesthetic considerations, where the goal, among others, was to create the impression of an existing interwoven structure.[17]

In-plane shear resistance to generate full shell action is most effectively achieved via a *triangular grid* arrangement. This especially against the asymmetric load effects of wind and snow, which are carried in the plane of the surface by direct compression and tension forces. The first project to implement this grid structure was a cupola structure in Tacoma, Washington in 1982, engineered by Wendell Rossman in co-operation with Hine, Wessel Associates. [17]

Figure 33. Hexagonal grid roof of the Centre Pompidou – Metz. Source: Shigeru Ban Architects

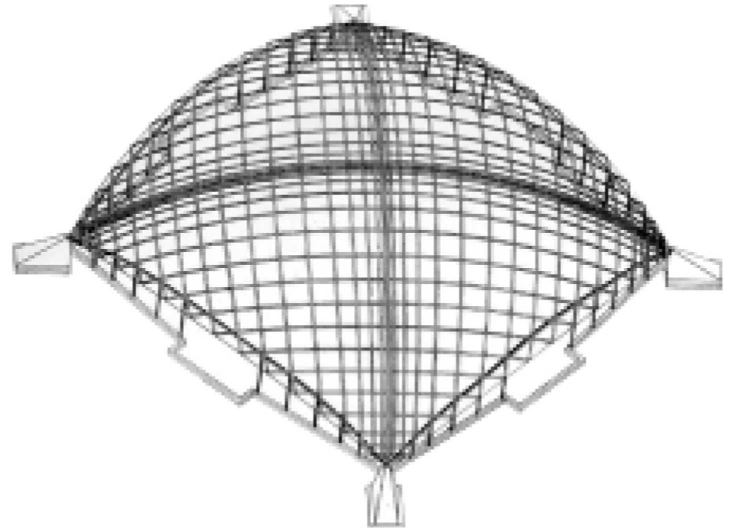

Figure 32. Ribbed gridshell design of the Polydôme. Source: BCN Natterer

Figure 34. Triangular grid of the Tacoma cupola. Source: SPS+ Architects

2.2.3.2 MODULAR GRIDSHELLS

A large part of timber gridshell structures are built on their unique structural principles which are specific for the project and requiring software solutions tailored for their structural needs. With a standardized modular element and a system, economical effectiveness could be achieved via simplification of design process, structural stability calculations and cost effectiveness in production.[28]

The wood-based gridshell in Trodenheim, developed by students at the University of Science and Technology in Norway, implements the structural design method of the Segmential Lath. The grid is constructed with a two-layer module of four 900 mm laths. Each lath has five milled holes, one in the centre for the node, and two on each side for weaving. Since the module only consists of a node and up to four connectors, the Segment Lath can adapt to any grid size.[29] This structural solution is currently applicable only in small-scale projects [28].

A second approach in the construction of a modular gridshell is the use of prefabricated elements with a repeating pattern in the structural elements. This however results in the creation of a form which is not variable and is strict in its geometrical shape. Even though useful in the prefabrication stage, due to limited numbers of differentiating elements, it misses the element of customization and adaptability. [28]

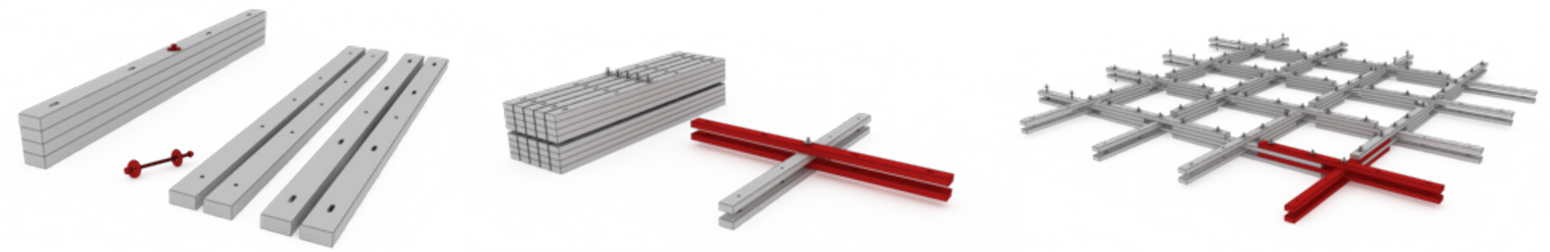

Figure 35. Segment laths. From module to assembly. Source: Dyvik, S.H., Mork, J.H., Nilsen, M. & Luczkowski, M. (2016)

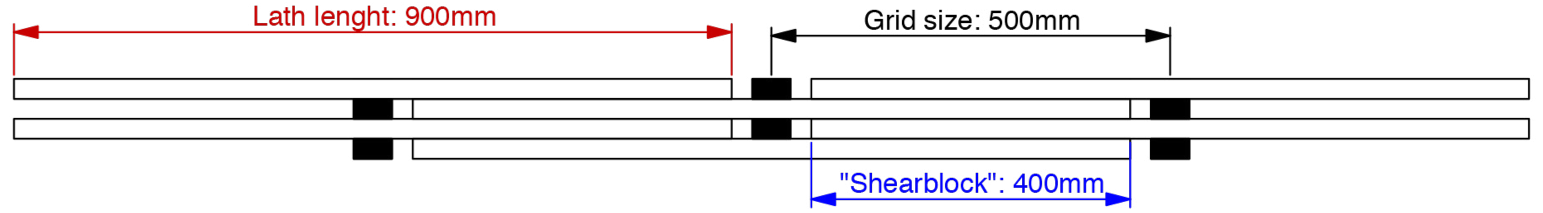

Figure 36. Overlaping of segment laths functions as shear blocks. Source: Dyvik, S.H., Mork, J.H., Nilsen, M. & Luczkowski, M. (2016)

Figure 37. Filmwell Woodland Enterprice Centres modular timber gridshell. Source: Atelier Ten

2.2.3.3 DIGITAL FABRICATION

With the arrival of the 21st century rapid advances in digital processing of complex forms, structural modelling and digital manufacturing have led to a metamorphosis in the design process of freeform timber gridshell structures. This was further extended through the appearance and availability of engineered timber, which possesses enhanced material properties in comparison to sawn timber and includes the better understanding of material's behavioural features. [2]

As an example, glulam or glue-laminated timber as a building material presents couple of advantages in construction compared to solid wood. With a greater load-bearing capacity and due to the removal of defects like knots in advance, homogeneous cross-sectioned extended length beams can be manufactured, leading to the possibility of creating column free spaces with large roof spans. [33]

For generating a gridshell structure, these are processed on multi-axis milling machines to fabricate high-precision, double-curved components [2].

As a consequence, designers have lost the dependency on the deformation of a regular square or rectangular mesh to create double-curved gridshells, which can be specified and built now directly [2]. Even though surface active structures benefit from curvature in both structural geometry and building components the curvature itself however is expensive to produce in terms of costs, material, and environmental impact.[32]

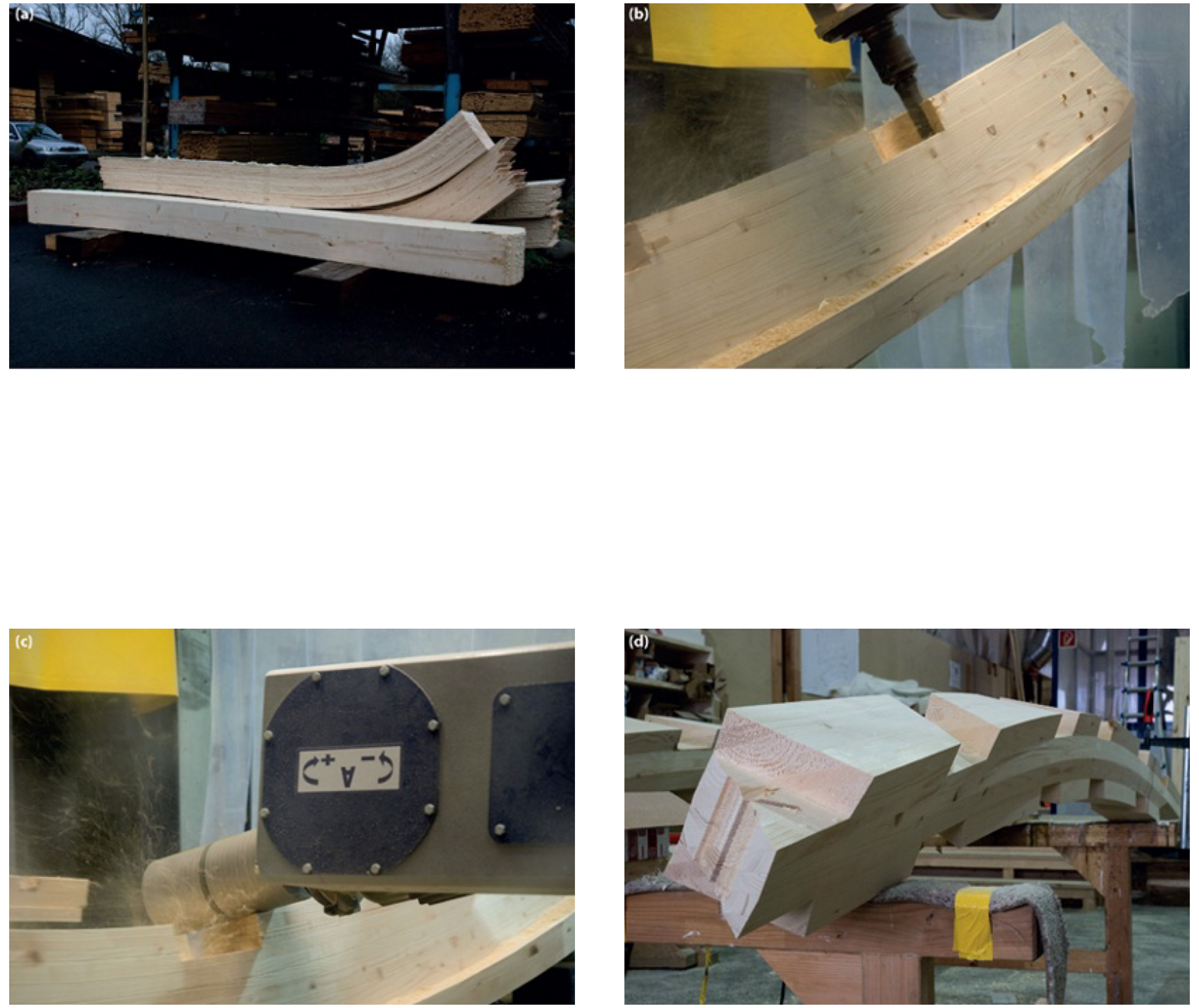

Figure 38. (a) Glue-laminated timber blanks being (b) cut and (c) milled to form (d) complex CNC-machined components. Source: designtoproduction GmbH

2.2.3.4 PROGRAMMABLE MATERIALS

Complex forms are usually achieved by the combination of pre-shaped framework, application of brute mechanical force, robotic manipulation, and subtractive machining from large elements, where the materials innate behaviour is considered counter effective or cast aside [32].

A variety of bio-based materials have the inherent ability to change shape according to the conditions they are subjected to, for example heat or humidity. In addition to being sustainable, easily machinable and a high-performance construction material, wood has the natural ability for moisture-induced and direction-dependant swelling and shrinking. In combination with a double layered configuration, wood poses a natural capability to create shape changes in curvature through bending. [30]

A recently carried out research project concluded that self-shaping wood enables positive changes in the curvature of narrow single and bilayer strips, creating a potential value for its use in gridshell constructions.

The presented self-shaping would replace many constraining factors which are present in the construction of post-formed timber lattice gridsehells in manners of complex lifting and forming, replacing it with a distributed autonomous actuation. [31]

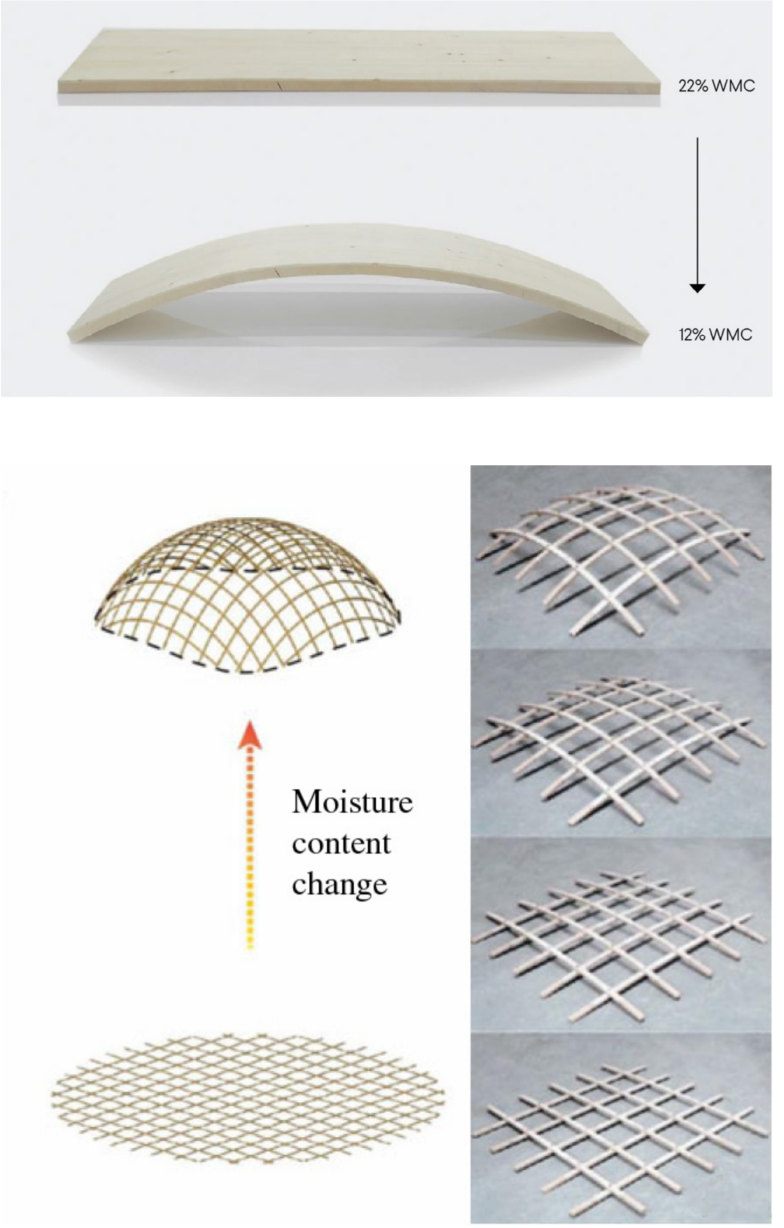

Figure 39. The evoking of curvature based on internal moisture change and the following gridshell shaping procedure. Source: Grönquist, P., Panchadcharam, P., Wood, D., Menges, A., Rüggeberg, M. & Wittel, F.K. (2020)

Figure 40. Crossrail Palace. Source: Foster + Partners

2.2.4 CONTEMPORARY PRACTICE

CROSSRAIL PALACE

Location:	London, UK
Architect:	Foster + Partners
Year of completion:	2015
Size:	53 500 m2

Commissioned in 2008 and designed by Foster + Partners, the overground structure of the Canary Wharf rail station encompasses a mixed-use space, including the access and bridging connections for the station, retail spaces and a partially open green roof with cafes and restaurants. [22]

Full scale prototyping and flexible parametric models played a vital role in the realisation of the timber roof structure. By using the language of visual scripting, refinements in the design logic could be implemented even while dimensioning according to structural analysis was still ongoing, and with a shared database, in form of flexible relational digital model, between collaborating designers, engineers and fabricators, adaptions where possible right up to the point of fabrication. Full scale prototypes provided crucial feedback with performance tests and illustrated the robustness and resilience of the design system to the client. With nodes, beams, and ETFE cushion cladding designed, prototyped and fabricated as one unit, an innovative systems approach needed to be implemented for not only ensuring the structural analysis, fabrication and design of the roofing, but also for a rapid accurate assembly. [2]

The 310 m long glulam timber roof, cantilevering 30 m outward at each end, arches 12 m above a landscaped roof park while supporting inflated triangular ethylene tetrafluoroethylene (ETFE) cushions. Though simple looking in its geometry, a degree of complexity belies in the overall form. The axis of each successive diagonal beam twists as it coils around the roof. As timbers extend in length towards the cantilevered ends, the incoming angles at nodes become successively more acute and asymmetric. Consisting of 1418 straight glulam beams, except four, a variation exists in the structural grade, depth, length and visual quality of the individual elements of the grid structure.[22]

For the compensation of axial twist of each successive diagonal beam, a large complexity in steel node connections had to be created. This led to the creation of 564 individual nodes, generated as a single family with geometric rules adaptable to each condition, from which half had their own unique, but essential, geometric configuration.[2]

Fabricated almost 100 per cent by automated processes, five axis machines were used for milling, cutting and drilling in preparation for hand welding of node connections. ID numbers denoting specific orientation and position of each element in which order they had to be welded were milled into each element. [22]

Constructed without the use of scaffolding, elements of the roof were accommodated at the different node joints by method of element numbering. In the areas where the ETFE foil cladding was omitted, weather protection in manners of aluminium cladding was introduced to the timber.[2]

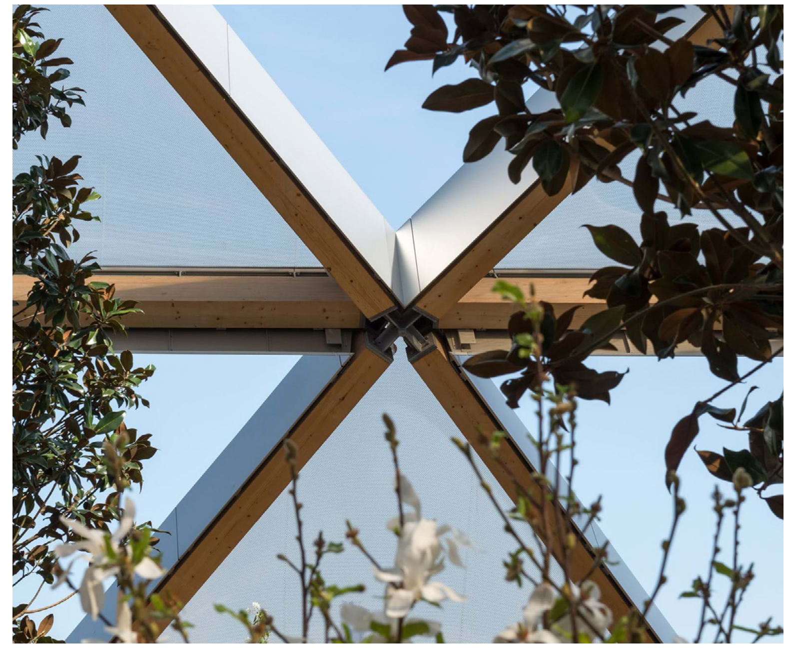

Figure 41. Nodal connection. Source: Foster + Partners

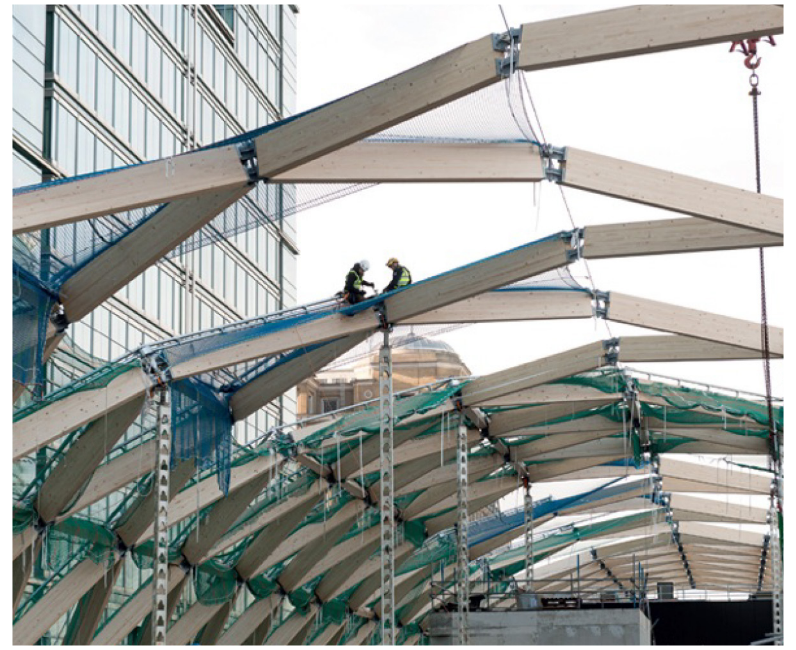

Figure 42. Construction in progress. Source: Foster + Partners

Figure 43. The France Pavilion at Expo' 2015 Source: X-TU Architects

THE FRANCE PAVILION AT EXPO' 2015

Location:	Milan, Italy
Architect:	X-TU Architects
Year of completion:	2015
Size:	3286 m2

The France Pavilion at Expo 2015 in Milan, based on a regular square grid, incorporated the use of small cross-section timber elements to create the double curvature for a partial shell action. [2]

Converted from smaller sections of timber, the larger glulam beams were transformed by bending or machining into single or double curved elements, which were assembled later on into a spaced square grid plan, interconnected by mechanical joints. In addition to supporting a roof, the grid structure had to withstand the bending and compression loads from an intermediate floor and accessible roof terrace, which was accomplished through advanced timber production, joint systems, digital design, manufacturing, planning and fabrication. Constructed from spruce and larch timber, the structure was designed for an easy disassembly and possibility for a re-erection in different locations. [23]

The 35m x 56.7m three story building, with a vaulted spruce glue-laminated timber gridshell, rises 12 m of full height in one corner while at the same time supporting two upper floors and arching the internal market space. With a grid configuration of 1.5 m in spacing, the undulating orthogonal grid of curved timber beams are oriented 45° to the building façade. Single-curved beams, with a thickness of 200 mm, vary between 380 to 960 mm in depth while primary grid elements, spacing at 4.5 m in centres, vary up to 2.4 m. [2]

In the design stage, 3D parametric models played a vital role as without them it would have been impossible to execute the vaulted timber gridshell. By implementing the use of various software applications, estimations in timber quality, production time, fabrication quality and structural analysis where able to be made.[23]

For the 730 beams three varying types of timber elements were used: straight, arched and curved with very low, constant or high curvature respectively. Details of all required cuts, drillings, machined pockets and slots for connectors were generated with the parametric model.[2]

Due to the limited time frame and the possibility of digital fabrication 1450 timber elements were fabricated in about 1750 hours, where detailing of each progressive element was running in tandem with the fabrication and on-site construction, resulting in the erection time of five months.[23]

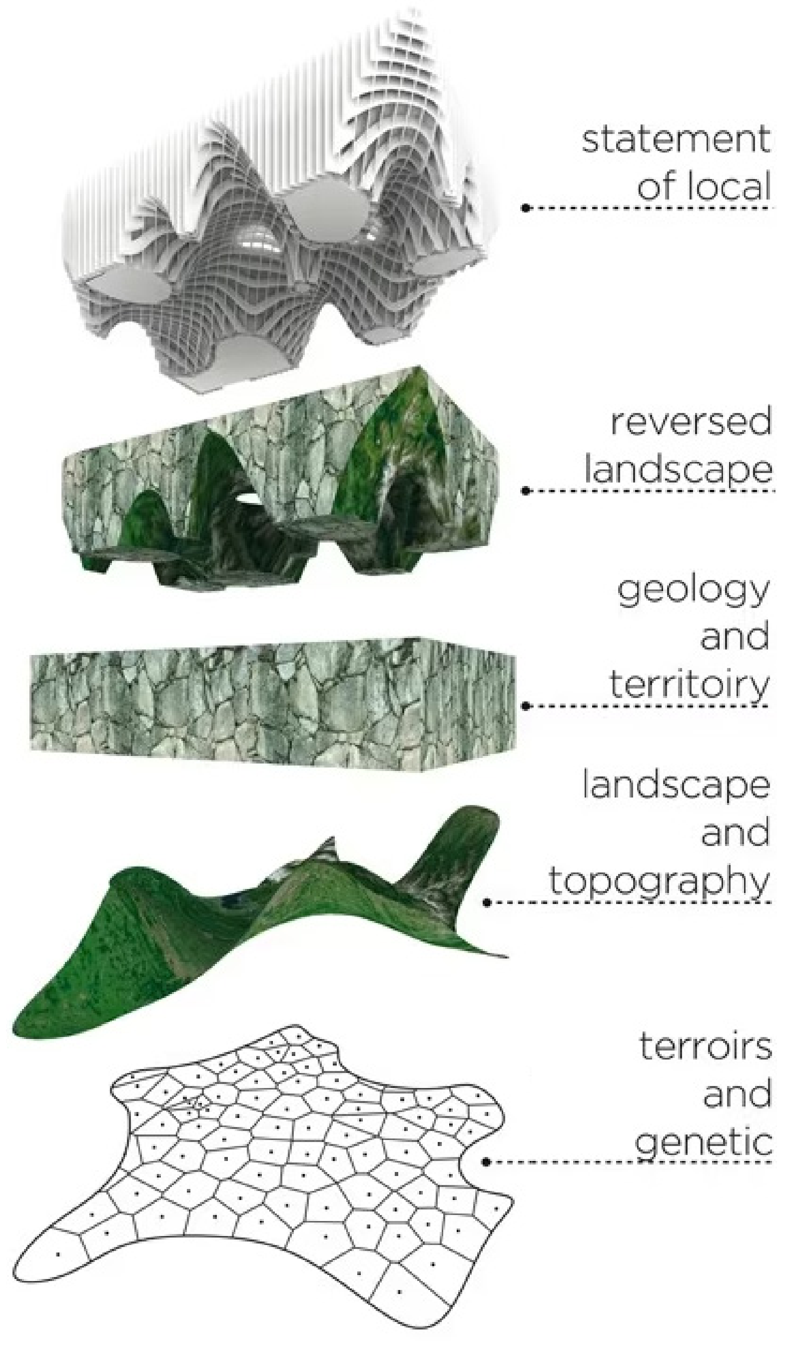

Figure 44. A landscaped building. Source: X-TU Architects

Figure 45. Shigeru Ban Architects competition vision of Swatch / Omega Headquarters Source: Dezeen

SWATCH / OMEGA HEADQUARTERS

Location:	Biel, Switzerland
Architect:	Shigeru Ban Architects
Year of completion:	2019
Size:	25 000 m2

Designed by the Japanese architect Shigeru Ban, the winning proposal of the 2011 competition consists of an all timber set of buildings located amid the Omega campus of Swatch Group. While two out of the three buildings remain rectilinear in form, the new Swatch headquarters comprises of three levels of open offices within a flowing timber gridshell. With a surface of over 9300 m2 the form sweeps along the site, encompassing the plaza and the entrance area while at the same time gradually transforming into the roof of the adjacent conference hall.[25]

The 240 m long and with a maximum height of 27 m curved wooden roof structure consists out of 4600 individual wooden beams, from which no two are the same. Three different types of glulam beams where used: straight, single curved and double curved. By using the method of interconnection, where individual beams reach lengths of 30 m, continuous gridlines of up to 120 m were able to be achieved. [24]

The timber grid structure itself has been divided into two directions, primary and secondary, where the biggest bearing loads are carried by the first one and consisting mainly of double curved beams. Repeating nodes at every 2-3 m are interconnected via milled wooden components, locking accordingly each other into place, with tolerances being kept to a precision of 0.1 mm. [24]

The construction of roof structure was divided up into 13 sections, beginning from the middle. This methodology enabled a more efficient approach, as continuous assembly could be made in two directions at the same time. As fabrication and storing of elements was not able to be done in advance, each unique element had to be milled and delivered onto site at the right time and in the exact order as they were going to be used. [24]

The biggest challenge in the construction of the gridshell however lied in the integration of timber components with the building infrastructure and with the 2800 uniquely shaped cladding elements. Consisting of metal panels, glass and cushions of ETFE, designers had to understand the different behavioural properties of each element and how to fit them into the building infrastructure without compromising structural integrity. [25]

Figure 46. Swatch headquarters Source: Archdaily

Figure 47. Construction in progress Source: Archdaily

2.2.3 DISCUSSION ON TYPOLOGY OF TIMBER GRIDSHELLS

2.3.1 ADVANTAGES vs. DISADVANTAGES

The gridshell typology presents various opportunities in the creation of complex surfaces and spaces by using a set of straight elements that are moulded into form [16].

Including to the advantages listed above in previous chapters, the presented typology has also several, but not limited to, shortcomings as a structural enclosure. Domes in general are limiting in the volume they enclose by their incidence angle at the support level, leading to the creation of spaces inside the enclosure which might be considered unsuitable for use due to the elevation limits [4]. This situation can be present also in timber gridshell structures. The Saville Garden building eliminated this variable by lifting the roof structure and its supports from the ground level, leaving the sides open.

As a construction material, wood is easily available, shaped, and highly sustainable storing large amount of greenhouse gasses. However, its vulnerability to cracking, especially in solid sawn timber elements, is one of the main challenges for the use of wood in construction of timber gridshells. Furthermore, with strong anisotropic properties, additional difficulties are created for the use of parametric and analytical modelling tools. Detailed analyses require a digital database of strength properties of various wood species, which in turn are an essential element in the development of digital tools for structural engineers.[36] At the moment, the existing programs with incorporated databases are deemed too insufficient for creation of detailed wood analyses. [37]

On the other hand, timber gridshells are associated with relatively low-cost values [16]. A research paper published at the World Conference on Timber engineering in Quebec City, Canada, 2014 presented a comparison between similar gridshell structures utilising different construction materials. In addition to cost, a self-weight against covered area analysis was made. In the conclusion it was found, that compared to steel construction of similar structure, the use of timber elements in gridshells results in a more relatively lower overall cost and lighter structure, illustrating its financial viability against other materials like steel [16].

2.3.2 SUSTAINABILITY OF DESIGN

The use of timber in construction sector, weather structurally or through other means, imposes a positive contribution to global carbon emissions by absorbing and storing CO2 from the atmosphere and fixing it via photosynthesis in wood [26].

Additional advantages include: [17]

- Timber from forests is a renewable resource.
- Possibility for reuse, recycling and energy production at the end of its use.
- Biodegradable.
- Long lasting and durable if detailed and maintained adequately.
- With comparatively small investments, large volumes of optimised engineered products can be manufactured.
- Easy to machine and joint.
- Provides great strength to weight ratio.

According to some previously carried out research, every kg of carbon in wood fixes 1.44 kg of CO2 equivalent [26].

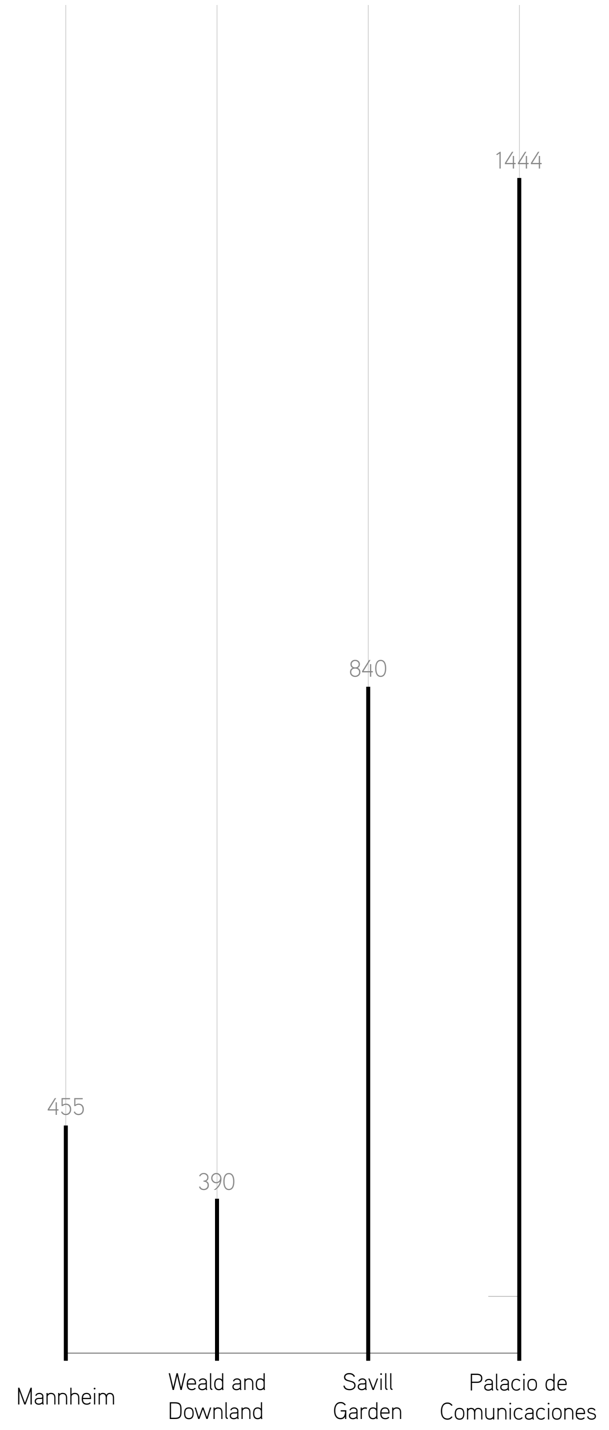

Figure 48. Timber gridshell cost comparisson. Units GBP/m^2. Values adjusted to 2010.
Source: Naicu, D., Harris, R. and Williams, J.K.C. (2014)

However, incorporating timber into a building structure does not immediately lead a sustainable result. When used in the wrong way, the result might end in a building's design and construction which is a less sustainable in its goal than for example a steel or concrete structure would have provided. It also provides significant positive attributes outside the considerations of embodied carbon, for example reduced construction time and minimised labour costs. "As with any technology, material or process, the wider context needs to be considered". [34]

Including to the forementioned, there is an additional key aspect to timber gridshells which categorises them as sustainable architectural structures. Gaining strength through form, shells use efficiently a minimum amount of material to carry imposed loads via the existing membrane action [27].

This was further expanded in the case of the experimental timber structures at Hooke Park in Dorset in 1994-1997, where different aspects of timber technology were explored for better and more sustainable utilisation. Local forests thinning's, which are usually discarded and are a by-product of timber production, where used for the construction of the Westminster Lodges student houses gridshell roof structure, with the key principle lying in the use of greenwood and in its roundwood form. [35]

Under strong digital influence and through advancements in manufacturing, these previously deemed low value materials have also found a use in contemporary timber design via engineered timber products. Although glue as not considered to be the most sustainable fabrication component, with new material like laminated veneer lumber, challenges of joining smaller sections of timber together have been solved as laths can now be dimensioned and fabricated with predetermined curvatures and twists. [2]

2.4 SYNTHESIS BASED ON ANALYSIS

The preceding study showcases the many different aspects that come along with timber gridshell structures and with its construction, including the benefits of low self-weight, high load carrying capacity, cost effectiveness, sustainability of material, and the challenges of the structures.

For the construction of the waterfront pavilion project, the double-layered lattice timber gridshell with a rectangular mesh was chosen due to the following factors. While simpler in structural grid configuration, nodal connection, and oldest typology in the forementioned timeline, publications available in analysing the structure and its implication in construction, creating the base know-how, where predominantly found on the forementioned spatial structure during the writing of the master's thesis. Furthermore, in retrospect to material use, it was taken into account that the traditional timber gridshell typology utilises material in a more optimised manner. By reducing elements into simpler forms and placing shear blocks from left over material in-between layers for strength, reduces construction and manufacturing waste and time, leaving a smaller impact on the environment in comparison to other previously researched methodologies. In conjunction with the current research into programmable materials, future large cuts into economic impact could be added by pre-bending individual elements forehand, leading to a reduced time and construction safety factor.

Architecturally lattice timber gridshells allow to create structures with high aesthetical values and is a typology that is being researched in contemporary times. However, a deep understanding is needed in the elemental principles, their limitations and possibilities, for with the aim and to lead to an innovation in the spatial structural field and in an sucsesful physical realisation of it.

II. FLORENCE PAVILION

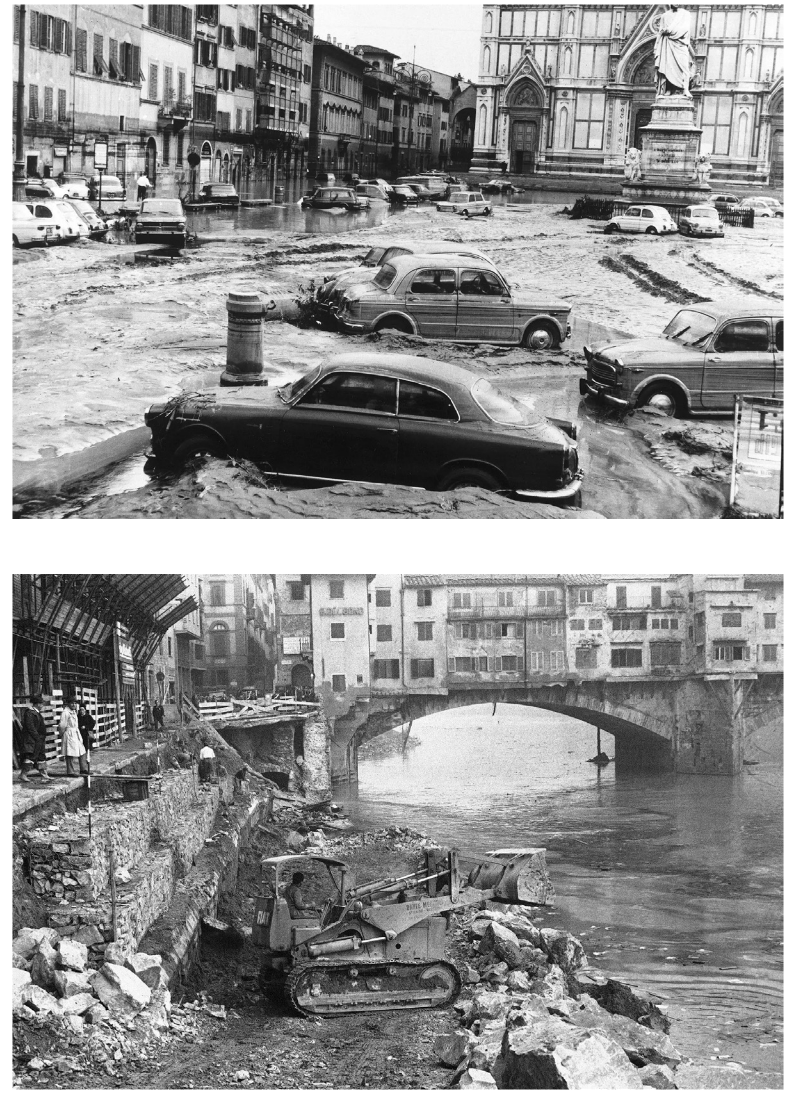

Figure 49. Flooding of Florence in November 1966 and the following reconstruction. Source: The New York Times (2016)

Figure 50. Terzo Giardino landscaping project in 2017. Source: futurearchitectureplatform.org

Figure 51. Upper - Kayaking near Ponte Vecchio. Source: viator.com
Lower - Summer activities on the sands of Terzo Giardino. Source: www.flickr.com

3. PROJECT

3.1 BRIEFING, OBJECTIVE

The Arno River has played an important role in the growth of Florence as a city, providing historically a source for work while at the same time acting as a recreational tool for everyday life. Today the city and the river attract millions of tourists every day and has been declared as a world heritage site by UNESCO in 1982 [38].

Before the arrival of modernity and the last great flood in 1966, where major damage was implicated on the city's urban structures, cultural heritage, and businesses, leading to the loss of confidence of Florence citizens on their river, everyday scenes like sand-digging, clothe washing, bathing and fishing could be witnessed taking place along the river embankments. Additionally, in the past, Arno has also acted as an important transit route between the mouth to the sea and the Apennines, enabling the transportation of the needed timber for the city's architectural works [38]. However, this was not a case for the following half a century. [39]

Within the recent years, with substantial investments into water purification and with the construction of a hydro-electric dam upstream of the city, first signs of a return to the river shores have been noticed, in terms of summer events. [39]

The aim of the project is to present a sustainable redesign solution for a waterfront site in the old city of Florence, that considers by its nature the prevailing conditions created by the river and location, and functions as an open public space along the bank of Arno. The new site proposal together with the pedestrian bridge offer in their solution an adaptable public platform design which allows diversity in use and time and to additionally increase the connectivity of the site to the existing city of Florence.

The projects outline of proposal is based on the international architectural competition task of Crested – Waterfront pavilion design challenge near river Arno [38]. It calls for a flood-resistant waterfront public space at the site of Terzo Giardino, which is oriented to serve the needs of the public. The built form must be able to connect with the people, through its form, layout or spaces and be unique in design solutions, while preserving and conserving the river waterfront. The design solution must impose a reduced negative impact on the environment, ensure the comfort of occupants and balance a mix of open, semi-open and closed spaces in functionality. The overall function for the site can be retained or be determined by the individual participants themselves.

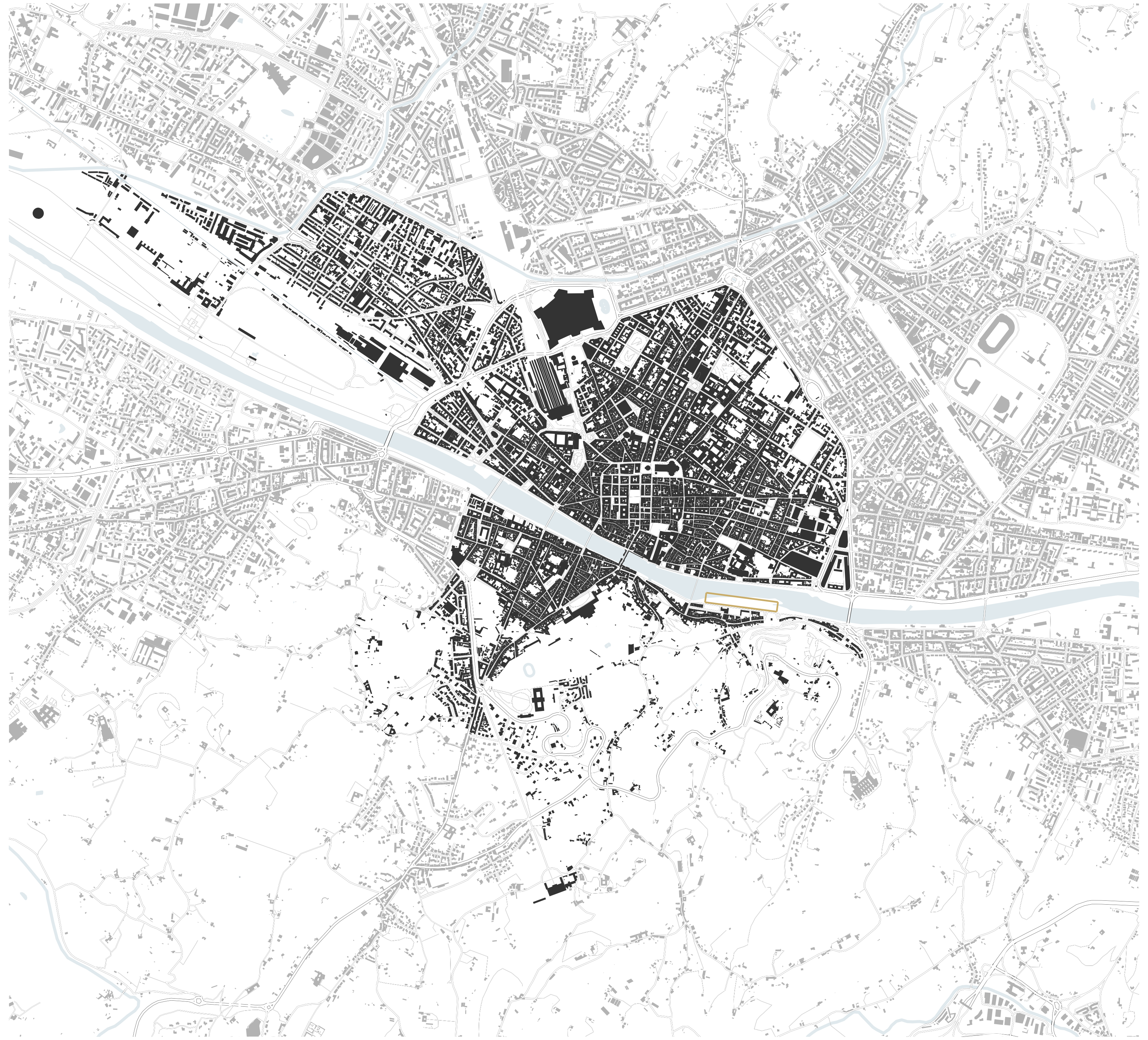

Figure 52. Site scheme Source: Author

3.2 EXISTING CONDITIONS AND SITE ANALYSIS

Situated in the northern part of Italy, between forested hills to the north, east, and south, Florence is a city that has been divided into two by the river Arno and is interconnected by a number of bridges across the high banked passing river.

Due to its location in a small basin, encircled by hills, the climate of Florence tends to be extremely hot and humid during summers, with an average daytime high of about 35 C°, and cool and wet during winters, with the average monthly temperature of about 5 C°[43].

The old part of the city consists of a network of narrow streets with high building fronts, creating an intimate and covered space in-between. After the flood of 1966, the embankments of the river where reinforced with high stone wall structures [38], creating a more predominant separation from the waterfront and are nowadays in use as logistical connectors e.g., vehicle roads and pedestrian pathways.

The competition site of Terzo Giardino is located on the southern riverbank of Arno, inside the old city boundaries, and on the foothill of Piazzale Michelangelo.

For around fifty years the area had lain neglected and unused due to the emotionally charged events that took place in 1966. Only minor interventions by the municipal employees were taken in manners of security and trimming of the growing vegetation.[44] In 2017 a temporary landscaping project was carried out on site to try to reconnect it with the city and its citizens, but a more permanent design solution is expected to be achieved with the architectural proposal.

3.3 ARCHITECTURAL CONCEPT

The following design solution was inspired by the goal of creating an open waterfront area, which exists in limited quantity inside the old city of Florence and would provide a public platform space for the citizens and tourists to reconnect with river Arno.

The proposal projects a linear public space in site planning design, following the rivers direction from east to west, and is integrated to the existing public contact zone and northern river front through a new pedestrian bridge. At the same time, it remains representative, complimenting the surrounding site, and imposes a landmark like effect, creating its own space and identity around it. The directionality, openings and structure of the main pavilion and pedestrian bridge have been designed in consideration with the prevailing natural conditions of possible flooding, trying to create least water load surface areas for structures in case of a rise in water level. By aligning the main entrances of the pavilion to the river flow direction, and integrating it with a gridshell, reduced loads are introduced into the structure during water level rise compared to a continuous surface, making it a sustainable solution for the unique area.

Figure 53. Intervention area

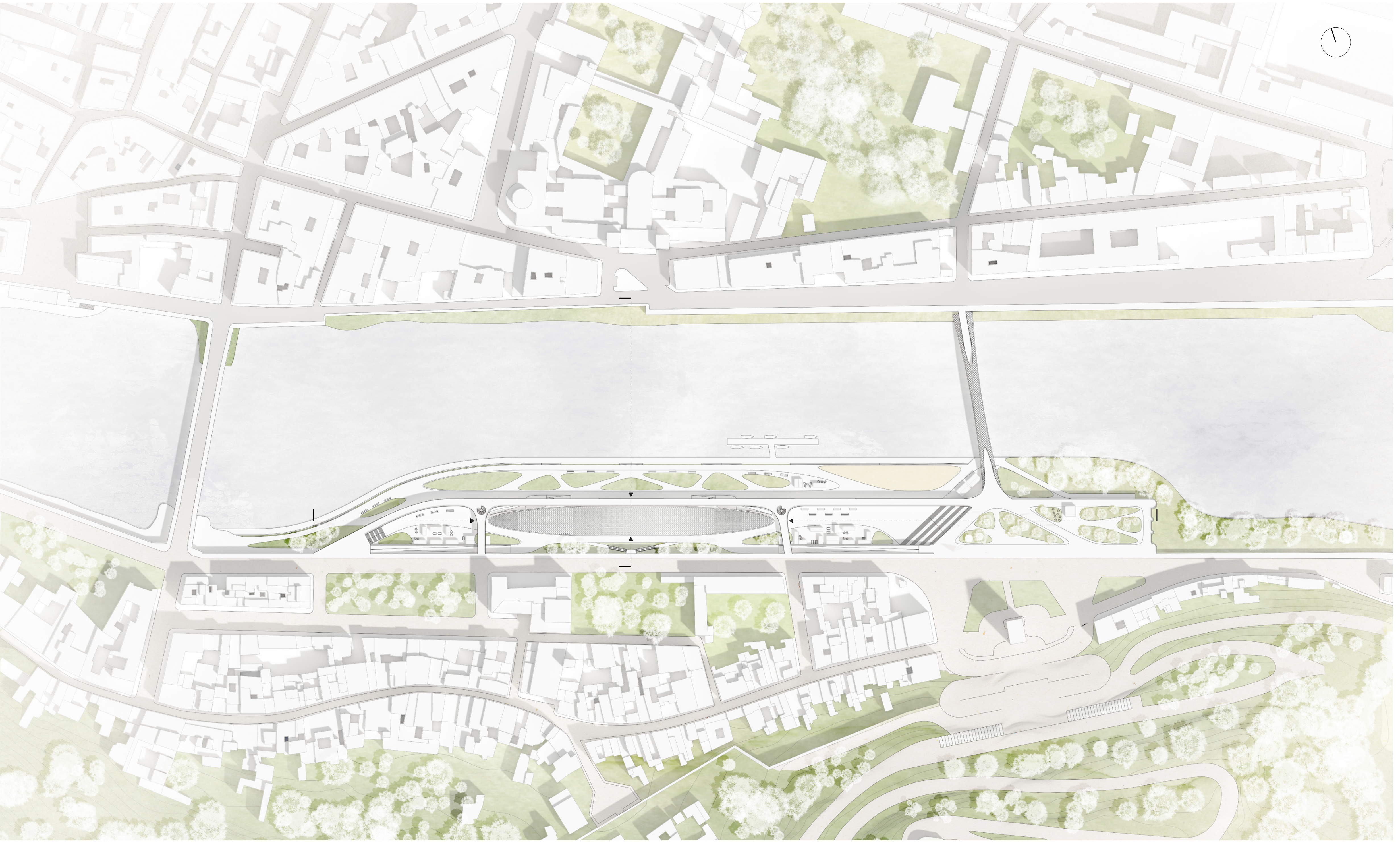

Figure 54. Siteplan M 1:1000

3.4 SITEPLAN

In functionality, the site has been divided into three conceptualised zoning areas:

- The river front area with the lowest elevation rise to normalised water level remains an open public space, with a beach area, promenade, and shallow vegetation, allowing direct access to water activities, leisure time and views from the street level.
- The pavilion level has been elevated by 1.8 m compared to river front, enabling a continuous functionality on site in cases of minor water level rises. The eastern and western extremities of the level have been provided with wide stairs for ease of access, and areas for modular units creating diversity in function and time.
- The elevated promenade follows the linear concept of the site, extending the existing street level closer to the river front and allowing for a visual line between the functionally active front to leisure area. The new pedestrian bridge and improved connection to Terrazza Riccardo Marasco allows for an strenghtened connection of the area to the surrounding city, supporting its integration into the structure and creating a more holistic solution for the site.

Due to its immediate connection to the old city and public transportation hubs, no additional parking spaces are meant to be added and existing needs are met with the spots located on the street level. Logistical access, for example fire safety, ambulance, waste disposal, etc. is maintained via two ramps at the eastern and western extremities.

In nature, the proposed solution is innovative, adaptive and considerate of the local conditions and site, while working in twofold as a new focal point in the city and as a unique design solution in the old city of Florence.

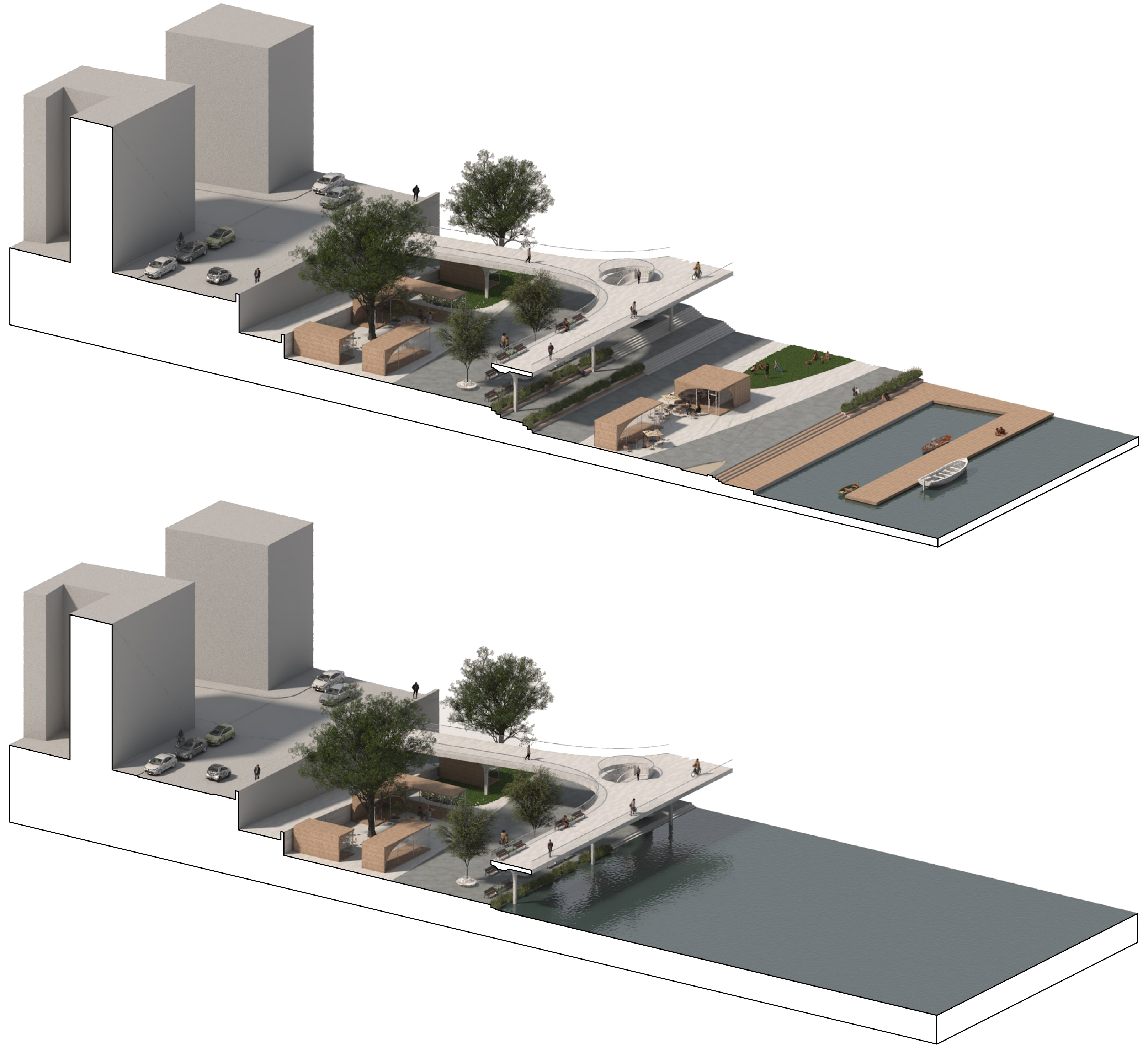

Figure 55. Axonometric sections. Rise of normalised water level by 2.5 m.

3.5 FORMFINDING

The pavilion roof structure and the pedestrian bridge are based on the funicular curve principle. This enables, as indicated in chapter 2.1, for the structures individual elements to work in compression and free of moments. Additional considerations were given to the condition of future possible elevated water levels, leading do adjustments in form and profile.

The primary surfaces for imprinting of the grid were achieved via the modelling software Rhinoceros3D and its visual scripting plug-in Grasshopper. After the moulding of the primary surfaces using the simulation program Kangaroo2, a 1x1 m rectangular grid line was imprinted. This followed with the generation of the double layered 50x80 mm lattice grid system with shear blocks. By using visual scripting, modifications to shape, structures, and elements were possible in short intervals, avoiding time consuming manual digital- or physical labour. This is especially relevant in larger scale projects, where in future stages changes in shape and form are very probable to happen, reducing respectively cost and time in production. However, this should not exclude the use of physical models in the design processes, as programs may not be able to represent the full nature of materials, like wood, and their properties. By implementing both methodologies, a more holistic understanding and approach of the designed structure can be achieved, leading to a higher probability of successful realisation of the structure.

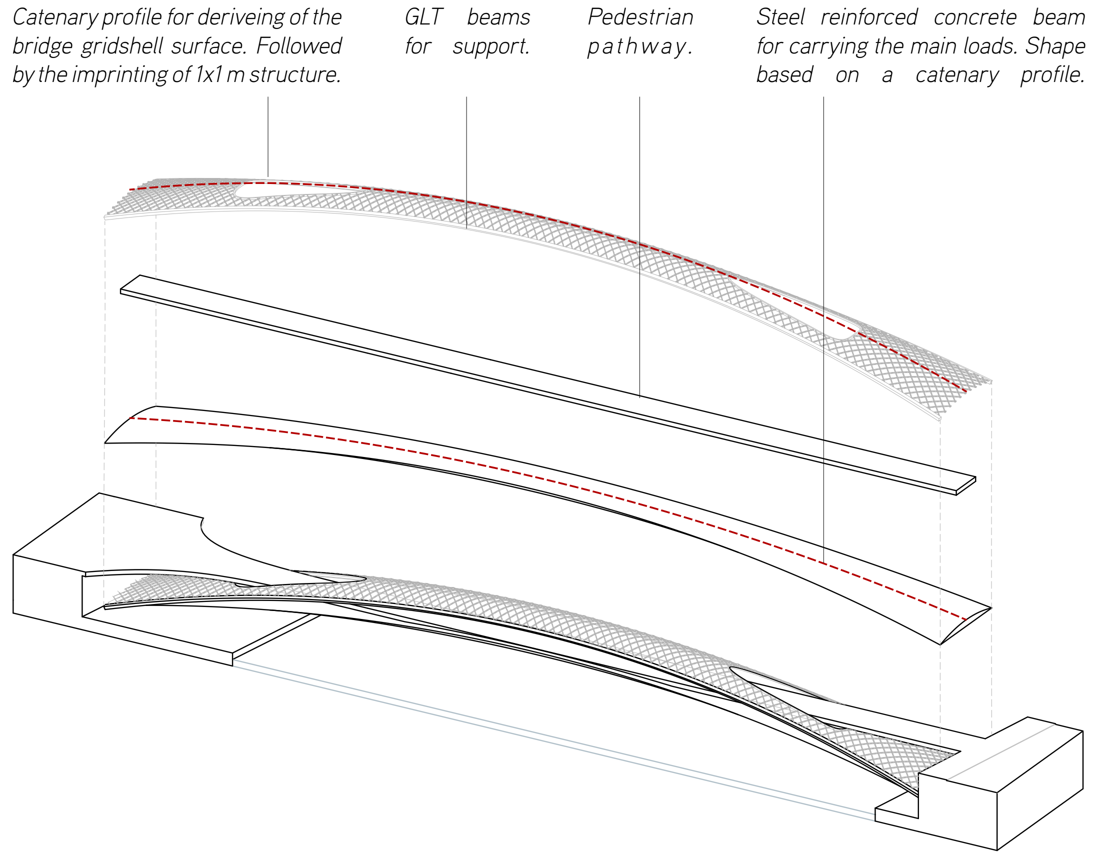

Figure 56. Pedestrian bridge axonometric diagram

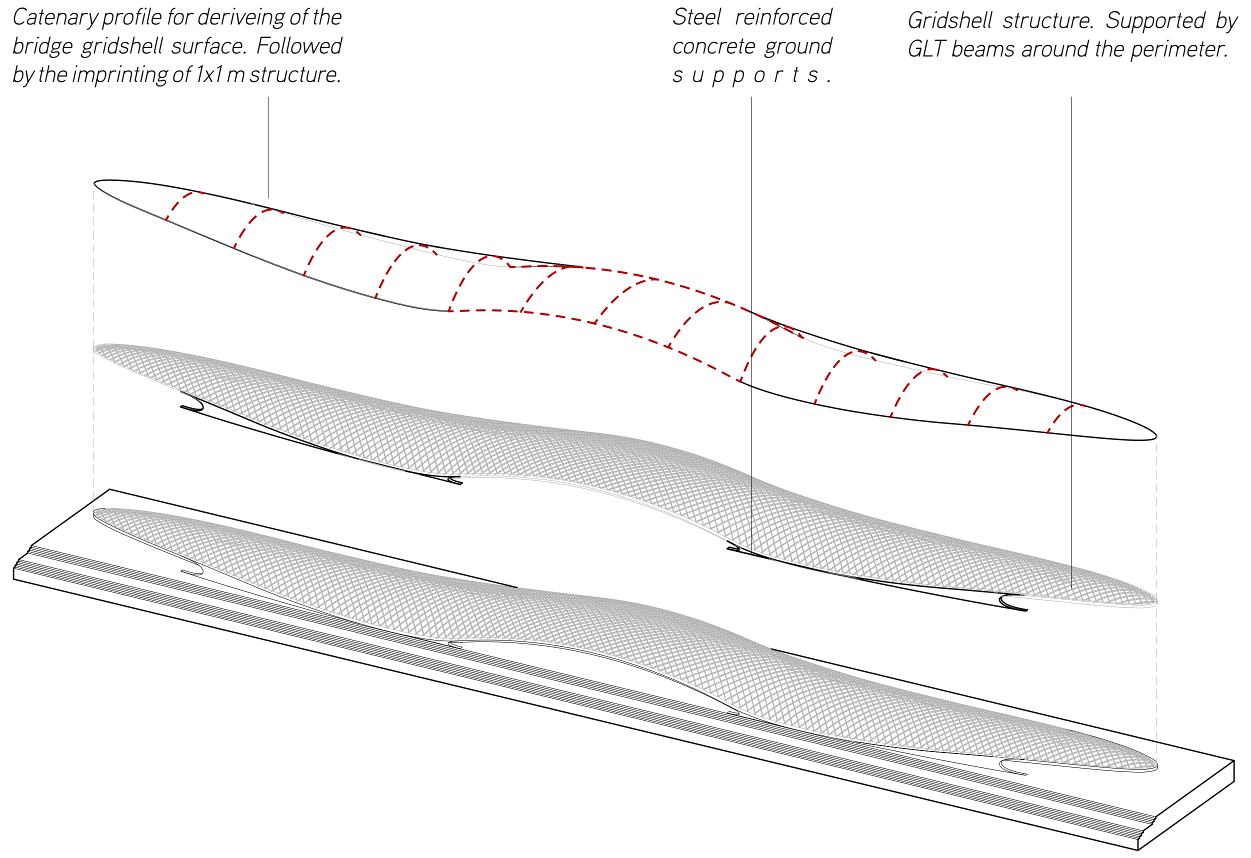

Figure 57. Pavilion axonometric diagram

3.6 FUNCTIONAL SCHEME

The spaces of the site have been designed for ease of access, the possibility to evolve over time, and by detaching the pavilion from the surrounding structures construction can proceed in multiple phases. In determining the logistical aspects and overall site functionality, emphasis was placed for it to function very well in each stage untill completion.

In the first phase, the new pedestrian bridge connecting the northern shore to Terrazza Riccardo Marasco and its redesign lays the base for the future developments and adds a new focal point to the surrounding site.

The second phase, or the construction of the pavilion level with the elevated promenade, introduces first functionalities to the riverfront area with mobile modular units and with the designated area for the future pavilion, which in meantime can be used for open-air public events. First groundworks are also to be laid on the new waterfront promenade area. The modular elements may be programmed to function individually or be grouped into clusters, allowing for the change in form and shape and creates a variety of diverse sub-zones for multitude of functions.

In the third phase, the new timber gridshell pavilion will be added to the site. With the construction of the elevated promenade forehand, workers are provided with platforms to gain a more eased access to the structures upper levels and the opportunity for locals to view the erection process of the gridshell structure. The proposed approach allows for the site to evolve over time, with functionalities changing in designated areas. New timber gridshell structures could be added or replaced while the overall concept remains, creating an adaptable, intriguing space, and a new focal center in the old city of Florence.

① - Seating area ② - Designated area for modular elements ③ - Designated area for public restroom modules ④ - Food court ⑤ - Retail ⑥ - Open market ⑦ - Beach ⑧ - Beach support units ⑨ - Open areas ⑩ - Promenade

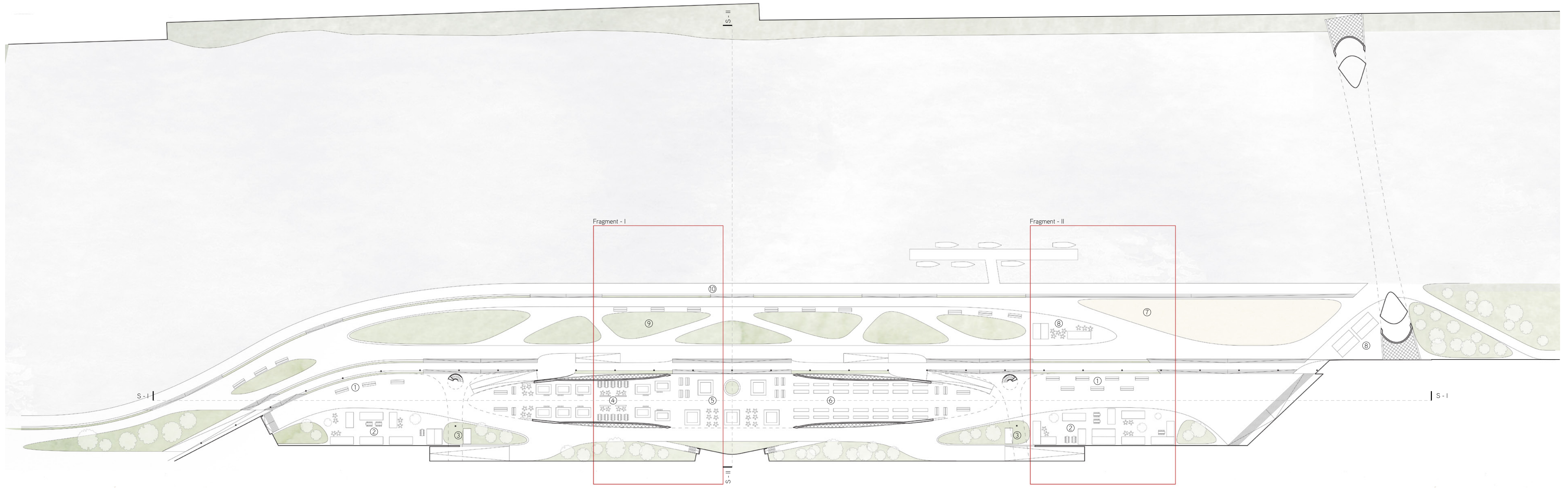

Figure 58. Riverside plan M 1:500

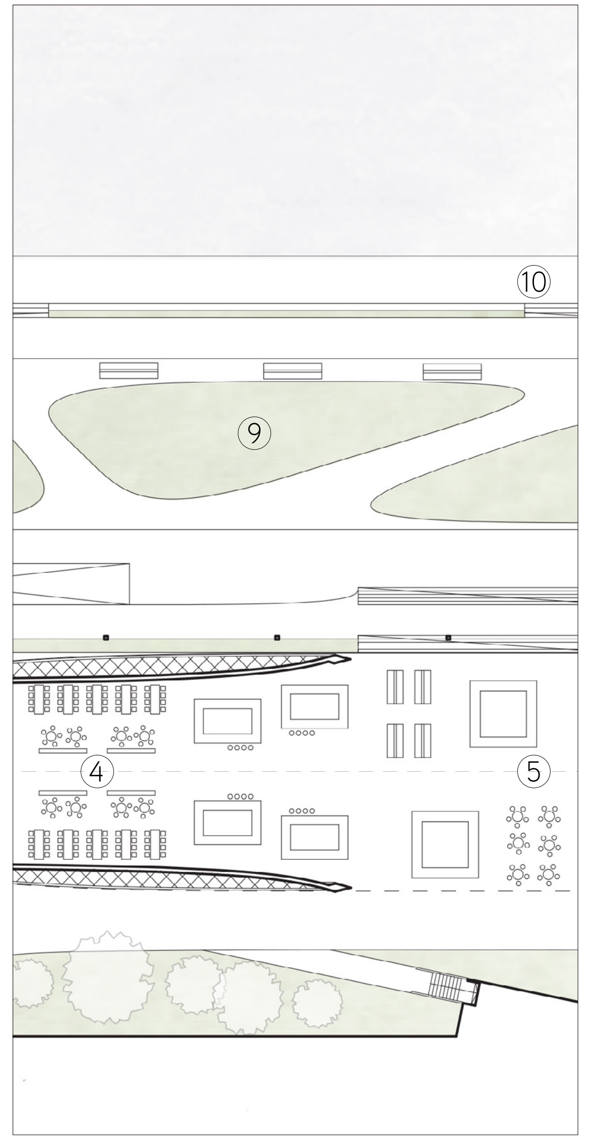

Figure 59. Fragment - I M 1:200

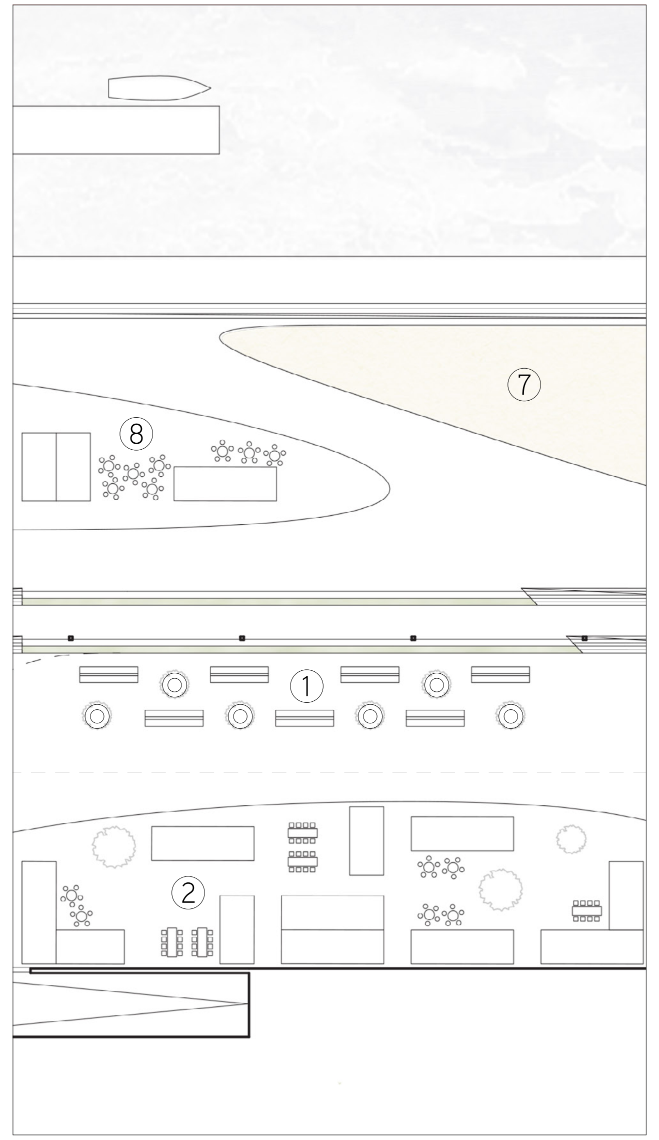

Figure 60. Fragment - II M 1:200

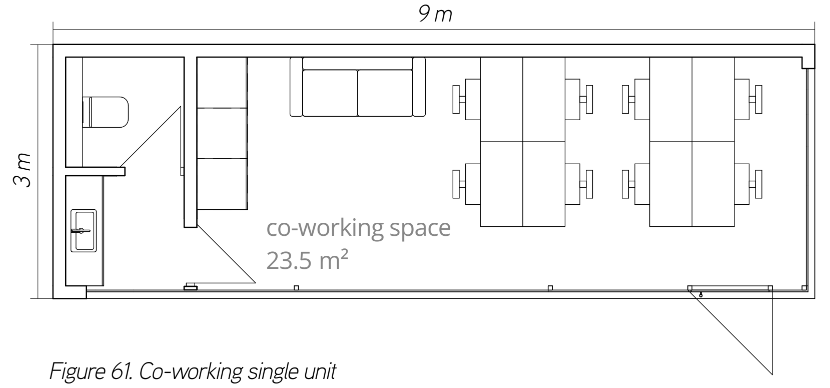

Figure 61. Co-working single unit

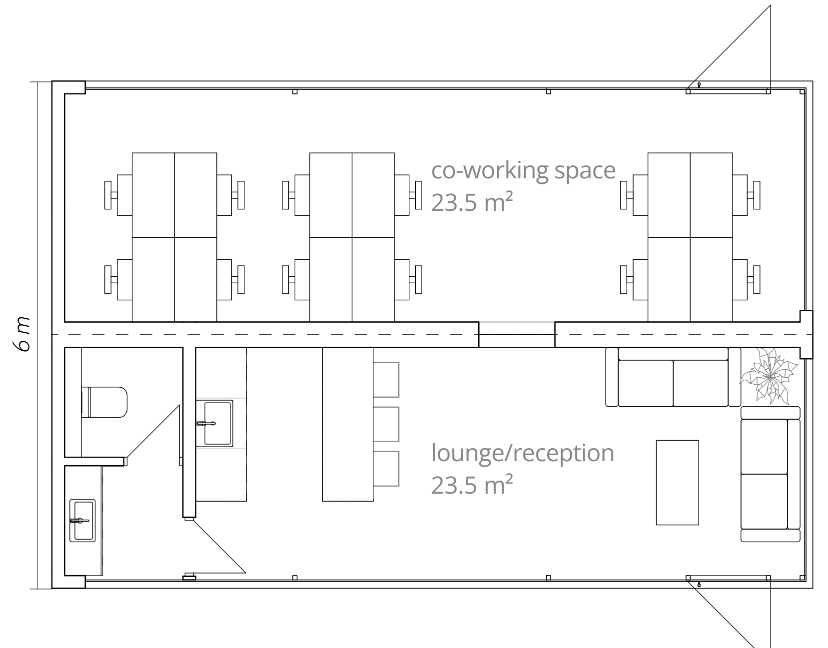

Figure 62. Co-working double unit

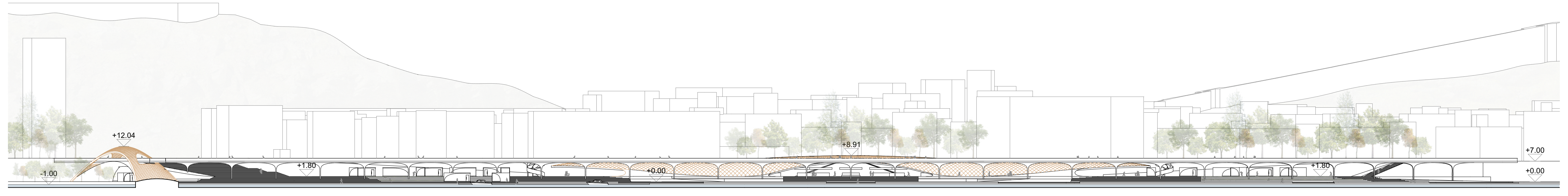

Figure 63. North elevation M 1:600

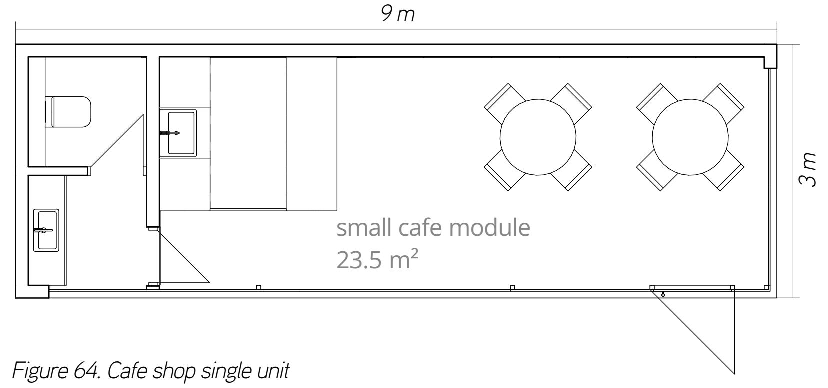

Figure 64. Cafe shop single unit

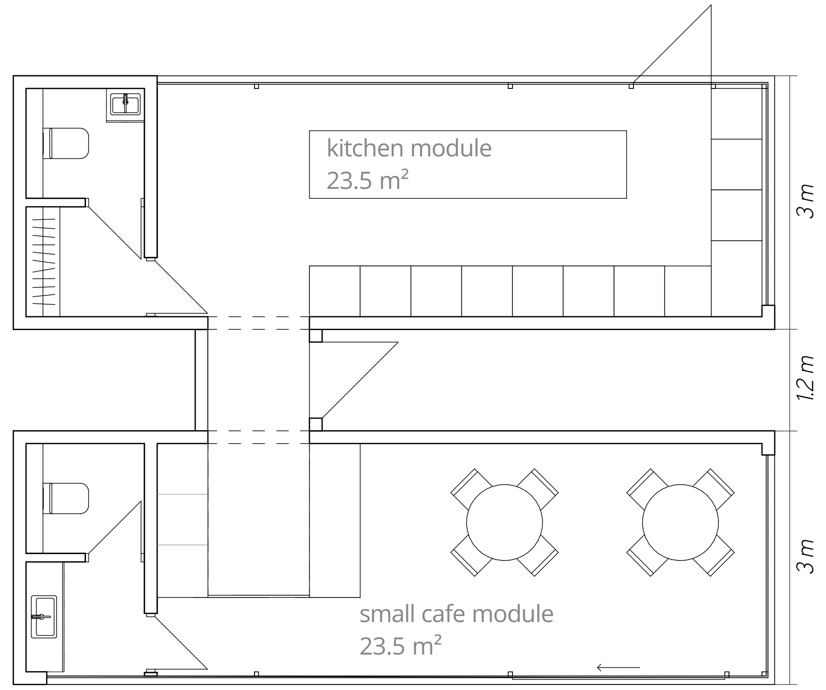

Figure 65. Cafe shop double unit. Servicing mainly arranged on outdoor terrace

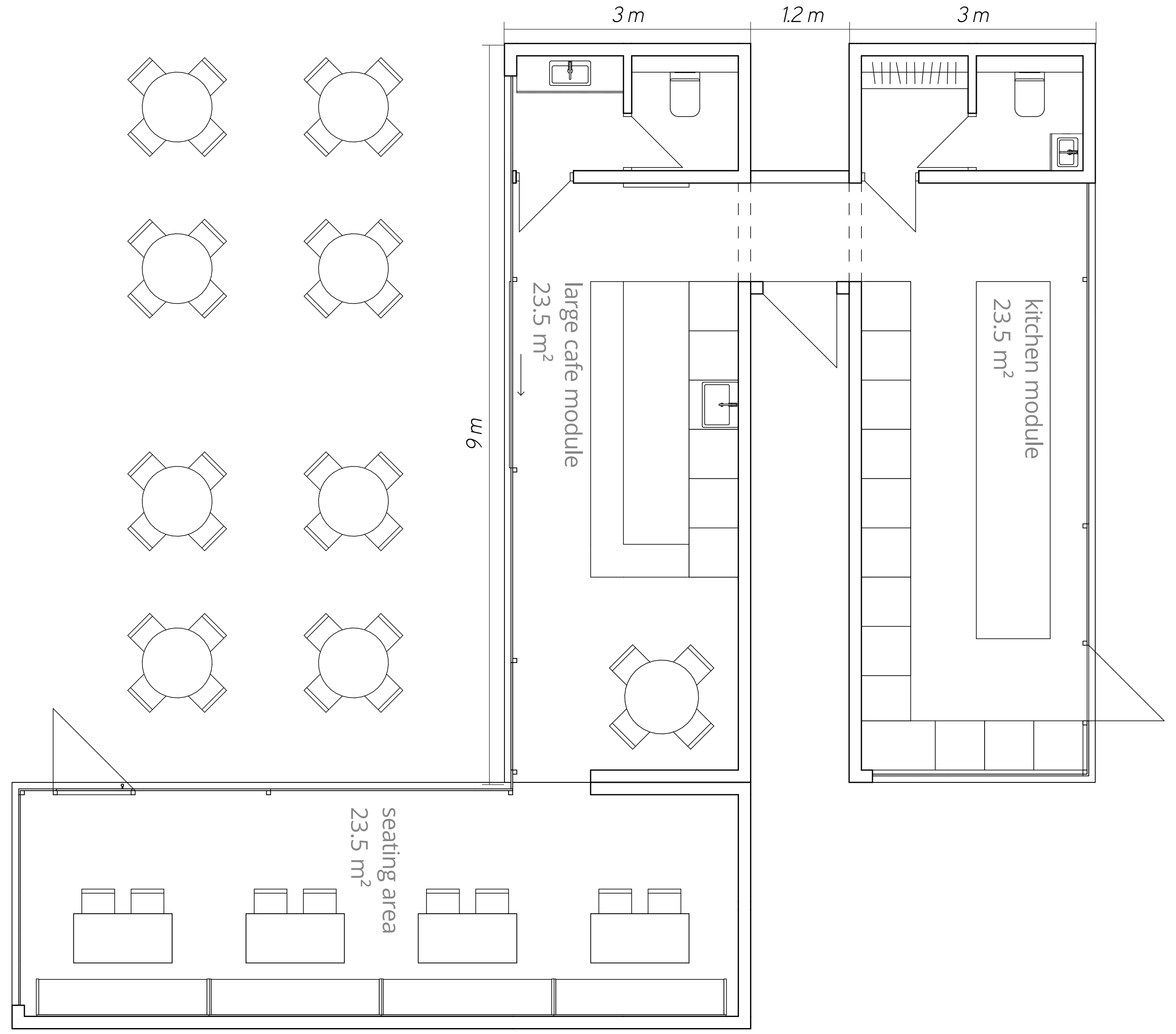

Figure 66. Restaurant triple unit

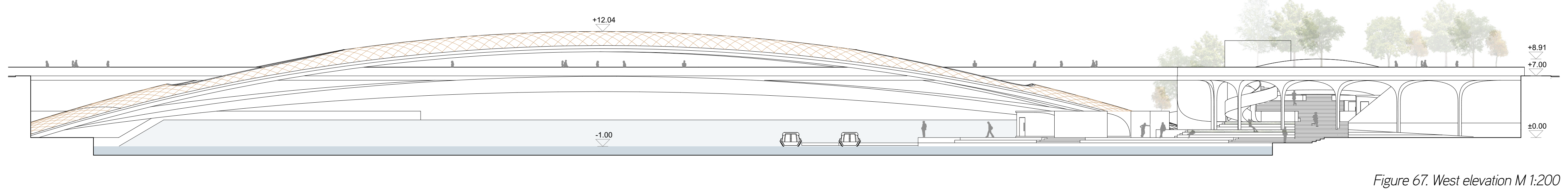

Figure 67. West elevation M 1:200

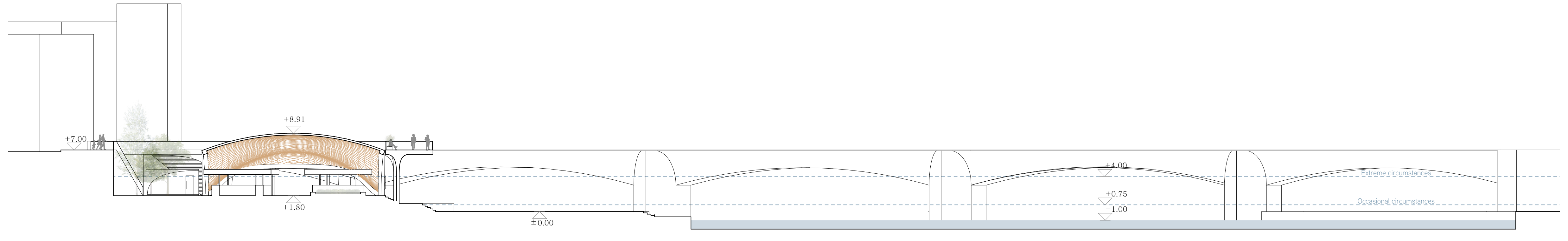

Figure 68. Section II-II M 1:200

3.7 CONSTRUCTION

For the construction of the 1x1 m rectangular configuration pavilion roof and bridge structure, 80x50 mm profiled timber lattices from local holm oak timber are intended to be used, as its one of the five most common tree types in the area [42]. The selected wood typology has proven to be suitable in terms of material properties by previous generations of timber gridshells and imposes a more sustainable and cost-effective approach for the project. However, analysis on its behavioural properties should be carried out, as different climate regions and locations impose variating effects on wood materials.

Around the perimeter of the pavilion, clue laminated timber elements with steel reinforced concrete supports derive the initial layout shape of the structure and the transference of loads into the ground. Flexible base isolators in form of pads are ment to be added between the clue laminated beams and concrete supports, as the city is also not uncommon to recieving occasional earthquakes. Diagonal stiffness is provided by steel wires between the perimetrical nodes and finished with a sustainable environmentally friendly semi-translucent composite fabric material, like ECOHEMP, providing overall breathability, interior lighting and waterproofing to the structure.

A steel reinforced concrete element provides the main load carrying support of the pedestrian bridge with flexible padded base isolators. With a non-uniformal profile, central thickness of about 2 m and decreasing to the extremities and resembling close to an airplane wing, direct possible impact load area from water mass were minimised, giving it an increased structural stability and strenght in case of risen water levelling. Similarly, to the pavilion, clue laminated beams provide the initial shape support of the bridges gridshells superstructure. With the selected approach, a unique design is created which additionally to visual value also acts a shading element for pedestrians.

As stated in the master's thesis chapter 1.2, in the construction and successful realisation of large-scale timber gridshells, a variety of knowledge in structural engineering and construction is needed. Therefore, consultation with engineers and construction teams should be kept in deriving of the most suitable and safest erection methodologies for the gridshell structures at the location. The initial proposal is to use the pull-down method for the pavilion structure, due to the limited amount of space on the site for a ground assembly and as it's deemed a safer method to push-up methodology. The first layer of the grid shell will be used for deriving the shape of the structure with the later addition of shear blocks and the second layer for structural stability and integrity.

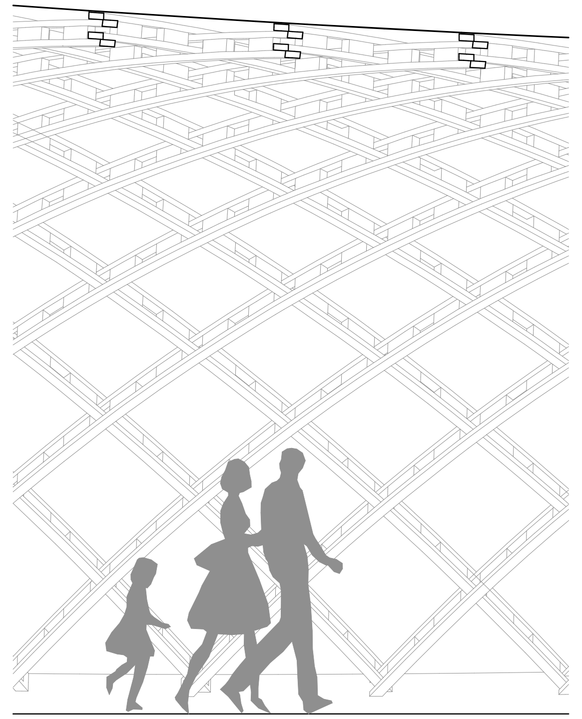

Figure 69 Fragment detail M 1:25

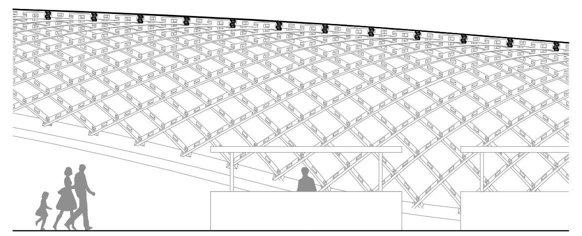

Figure 70. Section I-I fragment M 1:100

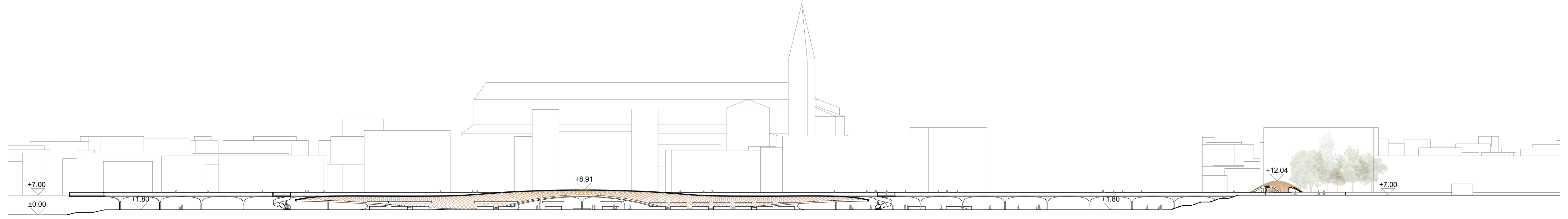

Figure 71. Section I-I M 1:600

SUMMARY

The master's thesis presentes an in-depth review of timber gridshell construction technology, within a wide architectural and engineering framework concerned with the design and construction of the projects that have been built so far. The specificities of sawn timber as a construction material for gridshells have been outlined and compared to digitally fabricated clue laminated timber elements, green wood and programmable materials, while placeing it in the current context of environmental awareness. Addidtional emphasis was placed in the field of modularity and alternate structures to acchieve a more holistic understandig and to analyse alternative methods to the construction technology.

Through the study of precedents, it has become evident that timber gridshells are a very effective means to cover large areas and span long distances. Structurally, they act in a similar manner as continuous shells, but there are significant differences as well. By concentrating the material of a shell into long strips, the paths of direct forces are now directionally limited and there is therefore a need to introduce some form of diagonal resistance. In contrast to modern interpretations of the structure with digitally manufactured complex elements, continuous member timber gridshells feature sets of laths which are stacked onto each other creating a layering system that eliminates the need for complicated geometry connections at the nodes, thus allowing for standardisation.

In addition, timber gridshells have proven to be an extremely cost effective way to cover large areas,while the use of timber as primary construction material, adequately sourced, is beneficial for the environment.

Most importantly, through the limited number of projects realised so far has been clear that the potential for innovation, both in structural design and in architectural expression, is vast and that the last decade has seen the timber gridshell technology closer to entering the mainstream.

The project part of the thesis proposes an architectural concept and construction methodologies for two gridshell structures in an area subjected to occasional flooding. A formerly abandoned site due to the dramatic events in 1966, a new, more permanent, sustainable solution has been proposed, strengthening the areas' connection to the city structure and increasing the citizens' trust in it.

Furthermore, in addition to outlining the advantages of the structure to the prevailing conditions, the use of parametric design in form finding, use of modular units for adaptability and variety in functionality, construction in phases and use of local materials in the aspect of sustainability were described, to create a resilient, cost-effective, and unique design that would support the surrounding site, compliment it, and create an attractive public space for the citizens and tourists visiting the city of Florence.

KOKKUVÕTE

Käesolevas magistritöös esitatakse põhjalik ülevaade puidust võrkkoorikute ehitustehnoloogiast laias arhitektuurilises ja tehnilises raamistikus, käsitledes sealjuures seni ehitatud projekte, nende projekteerimist, ja ehitamist. Lahti on kirjeldatud saematerjali kasutuse eripärad võrkkoorikute ehitusmaterjalina ja võrreldud seda digitaalselt valmistatud liimpuitelementide, rohelise puidu ja programmeeritavate materjalidega, asetades selle samal ajal kaasaja keskkonnateadlikkuse konteksti. Täiendavat rõhku pööratakse modulaarsuse aspektile ja alternatiivsetele võrkkooriku struktuuridele, et saavutada täiuslikum arusaam ja analüüsida alternatiivseid meetodeid ehitustehnoloogiale.

Läbi eelnevate juhtumite uuringu on selgunud, et puitvõrkkoorikud on väga tõhus viis suurte pindalade- ja pikkade vahemaade katmiseks. Konstruktsiooniliselt toimivad need sarnaselt pidevkoorikuga, kuid neil on ka olulisi erinevusi. Koondades ühtse kesta materjali pikkadeks ribadeks, on koorikus tekkivate jõudude liikumisteed piiratud ja seetõttu on vaja kehtestada ühel või teisel viisil diagonaalne vastupanu struktuuris. Erinevalt tänapäevastest võrkkooriku tõlgendustest, mille puhul kasutatakse digitaalselt ettevalmistatud keerulisi elemente, on jätkuvate elementidega puitvõrkkoorikute puhul tegemist üksteise peale laotud lattidest kihtide komplektidega. See eemaldab vajaduse keeruliste geomeetriliste ühenduste järele sõlmedes, võimaldades seega standardiseerimist.

Lisaks sellele on puitvõrkkoorikud osutunud äärmiselt kuluefektiivseks viisiks suurte pindade katmiseks, samal ajal kui puidu kasutamine esmase ehitusmaterjalina, hangituna vastavalt olukorrale, on keskkonnale kasulik.

Seni teostatud piiratud arvu projektide kaudu on selgunud kõige olulisema aspektina, et innovatsioonipotentsiaal nii konstruktsioonis kui ka arhitektuurilises väljenduses on puidust võrkkoorikutes suur ja viimase kümnendi jooksul on selle tehnoloogia kasutamine jõudnud lähemale peavoolule.

Magistritöö projektiosas pakutakse välja arhitektuurne kontseptsioon ja ehitusmeetodika kahe võrkkooriku jaoks piirkonnas, kus esineb aeg-ajalt üleujutusi. 1966. aasta dramaatiliste sündmuste tõttu mahajäetud alale on pakutud uus, püsivam ja jätkusuutlikum lahendus, mis tugevdab piirkonna sidet linnastruktuuriga ja suurendab kodanike usaldust taas projekteerimisalasse.

Lisaks välja toodud struktuuri eelistele valitsevas looduslike tingimustega keskkonnas, kirjeldatakse lahti parameetrilise disaini kasutamist vormi leidmisel, moodulite kasutamist kohandatavuse ja funktsionaalsuse mitmekesisuse tagamiseks, etapiviisilist ehitamist ja kohalike materjalide kasutamist jätkusuutlikkuse aspektist, et luua vastupidav, kulutasuv ja ainulaadne disain, mis toetaks ümbritsevat keskkonda, täiendaks seda ja looks atraktiivse avaliku ruumi Firenze linna kodanikele ja külastatavatele turistidele.

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