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Modulated corrugations

by *differential growth:*

integrated FRP tectonics towards a new approach to sustainability, fusing architectural and energy design for a new students' space

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Abstract

Questo progetto nasce da un interesse sull'attuale situazione della Sede di Via Terracini della Scuola di Ingegneria e Architettura di Bologna. Nonostante sia in programma un ampliamento del plesso nel vicino futuro, al momento si tratta di un luogo isolato e poco invitante. In particolare, fatta eccezione per un bar al piano terra della facoltà, l'edificio manca di luoghi di svago, relax e socializzazione. L'idea è quella di creare un nuovo spazio per studenti universitari dove possano rilassarsi, studiare, fare pranzo. Si sceglie di localizzare il nuovo padiglione sopra all'edificio esistente, evitando consumo di suolo e riusando uno spazio terrazzato esistente, facilmente accessibile da due vani scala interni.

La presente ricerca si promette di esplorare il concetto di "tettonica integrata", sviluppata a partire dall'utilizzo di materiali compositi fibro - rinforzati in architettura (FRP), con integrazione degli impianti al loro interno. La morfologia dei gusci FRP nasce da considerazioni sulla natura del materiale e si ispira al concetto di crescita differenziale dei tessuti. Ne derivano dei pattern di corrugazioni che sono valutati qualitativamente in termini di estetica, funzionalità, comportamento strutturale ed energetico. In particolare, si effettuano delle simulazioni energetiche dinamiche per stabilire qual è il comportamento complessivo del padiglione. Infine, si progetta e fabbrica un prototipo per mostrare le proprietà del materiale e le possibilità che può avere in architettura.

In conclusione, si discute il concetto di sostenibilità e si dà una visione di insieme sul protocollo LEED. L'obiettivo è quello di evidenziarne pregi e difetti e provare a proporre un nuovo approccio al tema, basato sul concetto di ecologia in senso lato.

This project was born from an interest in the situation of the Engineering Campus in Via Terracini, out of the Bologna city centre. Even if a major University expansion will take place there in the near future, currently it is an isolated and uninviting place. In particular, except for a small cafeteria, there is an evident lack of services, break rooms and dining areas. The idea is to create a new space for University students, where they can relax, study, have their meals and socialize. The chosen location is on top of the existing building: in this way, the new construction does not occupy new land; on the contrary, it gives new function to an unused terrace, easily accessible from two internal stairs.

Research connected to the pavilion design investigates how a new concept of "integrated tectonics" can be developed from the use of fiber-reinforced polymers (FRP) and integrated systems in architecture. The morphologies of the FRP shells are created considering the material properties and taking inspiration from research on tissues differential growth. The resulting corrugations and patterns are qualitatively evaluated in terms of aesthetics, functionality, structural and energy performance. In particular, dynamic energy simulations are carried out to assess the overall behaviour of the pavilion. Moreover, a prototype has been fabricated in order to show material properties and possibilities of FRP in architecture.

In conclusion, the author argues about the concept of "sustainability" and gives an overview on the LEED rating system. The aim is to discuss values and defects of current systems and try to propose a new approach to this subject, based on the concept of ecology.

Contents

Conceptual Background

1.1 | Differentiated environments

1.1.1 | Environmental management

In the Architecture of the Well-Tempered Environment", Reyner Banham analyses how mankind in history always managed to adapt to different environments, starting from the basic need of creating heat in winter and chill in summer, protecting from rain and organizing one's belongings and activities in space. He describes his theory by means of a parable about some savages who find a site full of timber and decide to settle there. Banham claims there are only two ways they can possibly exploit that kind of available resource: either use all the timber to construct a shelter or use it to make a fire. The former is called the *structural solution* and would entail a large, single investment at the beginning; the latter is named the *power-operated solution* and would probably involve a steady drain on resources through time. The tribe would choose one of the two solutions according to its cultural habits and predispositions, which in turn would depend on the community previous experiences [1].

Structural vs power operated solution

Banham claims that all the main civilizations, those who have shaped the physical world we live in, have chosen the first option, constructing substantial, massive structures to satisfy their environmental needs. This kind of response lays the foundations for Western predominant vision of architecture as the art of creating massive, perdurable structures enclosing bounded and well delimited spaces.

On the other hand, nomad people, who have chosen the "power-operated" or "non-substantial" solution in order to cope with environmental problems, have a completely different way of living and experiencing space. These societies usually organize their activities around a central focus, like a campfire, a tree or a river, and the space they occupy is heterogeneous, it has vague boundaries, adaptable depending on momentary needs and influenced by other external environmental conditions. These dynamically differentiated spaces allow people to choose the position they prefer among the gradient threshold conditions, instead of imposing rigid partitions between inside and outside [1].

The massive "substantial" trend in history have rarely encountered the "non-substantial" principles, except for some minimal provisions in buildings for consumption of power, like smoke outlets and conduits for water. However, these services have always been considered as something marginal and completely different from architecture, which remained the art of shaping massive structures and spaces enclosed by walls [1].

The adjective "massive" has always been associated with something permanent, durable, resistant to natural calamities and reliable, especially in the Mediterranean tradition, from which most Western architecture has been developed. Because of their massive structure, these constructions had a series of environmental advantages naturally embedded in them, like better sound and thermal insulation and heat storage capacity. However, after centuries of practice, architects started to assume these characteristics as a sort of intrinsic feature of all buildings and they eventually ended up separating the idea of architecture from its performance. This led to major problems since the arrival of Modern Age, when the shift from massive to light-weight structures made some completely new issues arise [1].

1.1.2 | Homogeneity vs heterogeneity

Modernist discourse

The modernist concept of architecture was primarily concerned with the idea of universal and democratic space. So, traditional highly partitioned space was replaced by an ideally infinite and homogenous open plan, which was meant to create the same conditions of living for everybody. Old segregation of spaces for the sake of privacy and security was substituted by a universal, endless grid. At the same time, ribbon windows were intended to eliminate advantaged points of view of the outside [2]. An emblematic example was the Bürolandshaft, an open-plan office which was seen as the perfect working environment as it minimized any visual, aural or tactile distraction [3].

The same uniformity was expected from indoor climate conditions by means of strict environmental control. As a consequence, thin and glazed walls which were meant to fuse internal and external insight and reduce threshold perception, eventually had to become neat, inefficient climatic boundaries between the inside and the outside [2].

Single-objective optimization

During the “Machine Age” big changes in design and technology carried with them standardization and modularization of spaces and systems as well as rational and rigid division of tasks among all the building constituent parts. Each component or system was designed and optimized to address one main function, such as primary and secondary structure, covering, sun shielding. It was the rise of single-objective optimization, a new principle born in the “Machine Age” and intended to influence all future architecture until now. Lightweight structures, for example, were the result of material optimization, seen as the minimum amount of material used in order to reach maximum performance [2].

It is clear that the dominant standardization and this idea of efficiency strongly affected the rise of variability in architecture.

Heterogeneous environment

A shift towards heterogeneity in architecture has taken place in the last decades, when standardization has started to coexist with mass customization. Contemporary architecture has embraced variability as a well-established principle for creating different opportunities of use and perception of space, while the idea of uniformity in plan and shape started revealing its drawbacks. Even in working environments, it is demonstrated that uniformity – which was seen as “absence of distraction” in the Bürolandshaft model - is useless or even counterproductive.

Nevertheless, while variability is highly desired and recognizable in building envelope, plan and finishes, it still never substantially affects material and building systems [3]. In fact, the latter are still mono-functional and their scope is to keep the zones uniformly conditioned, in perfect conformity to modernist principles described above. This uniformity requirement often leads to unnecessary heating, cooling and electricity consumes in buildings designed with little or no regard to environmental variability. Moreover, a rigid homogeneous indoor environment is clearly not able to satisfy varied and subjective needs in terms of comfort, lighting and so on.

But this is not just matter of energy engineering nor it is about coordination between different disciplines: this in first place involves architectural design. Environmental and climate conditions can be designed exactly in the same way as the rest of architectural features. Again, Banham's dichotomy between substantial and non-substantial tradition helps clarifying the difference between mere envelope design and careful study of generated gradients of environmental conditions, like those that take place around a campfire [1]. These gradients differentiate the space without the use of physical boundaries. Instead of thinking about separation between outside and inside or cold and warm, dynamic thresholds can generate a differentiated environment where each person can choose its own favorite condition according to its sensibility and experiences [3].

Heterogeneous environments may definitely push the concepts of environmental and social sustainability one step forward. In order to do that, a new paradigm needs to be developed in order to connect physical thresholds and environmental dynamics. Space must no longer be seen as a static container of something else. Instead, it should become the content itself, made of social relations, dynamic activities, local, temporary and accidental occasions, each one of them fostered by a specific environmental condition [3].

Composites

2.1 | Material properties

2.1.1 | Polymers

Polymers in the construction industry

Since the 50's plastics have been permeating our everyday life as symbol technical advancement. Nevertheless, at the end of the 20th century synthetic materials started been regarded in a bad light, mainly because of increasing environmental consciousness. The tendency of the public's opinion to demonize plastics in architecture has limited its employment in this sector until nowadays. Yet, according to PlasticsEurope, Germany in 2007 handled approx. 1,5 million tons of polymers, while 25% of the total consume was related to the construction sector. The reason why the building industry is still the second main consumer of plastics - after the packaging sector with 32.4% - lies in the incredible diffusion of common synthetic elements used for technical and constructional "non-visible" applications such as pipes, adhesives, tints, seals, insulation or sheeting. Anyway, application for self-supporting envelopes and structures is growing in importance.

Polymers are synthetic macro-molecules resulting from combination of single molecules called monomers. This process entails a variety of different possible assemblies, creating more than 200 different kinds of polymers, not to mention additives. That is why, unlike traditional materials, polymers offer a variety of possibilities in terms of customization of physical, mechanical and visual properties. Here lies one of the main advantages of plastics: they can be designed from the production stage in order to achieve the desired strength, form, feel or any other required feature. In this sense, possibilities of applications in architecture are almost unlimited and still unexplored.

Polymers classification

Polymers are divided in three main categories according to the type of molecular bonding:

- Thermoplastics (or thermosoftening plastics)
- Elastomers
- Thermosets (or thermosetting plastics)

In general, thermoplastics are characterized by low degree of molecule cross-linking. This property allows them to be easily recycled because of their predisposition to be melted and molded many times. On the other hand, they tend to have lower strength and heat resistance.

Elastomers' molecules are cross-linked, so they cannot be melted. They are not appropriate for construction applications because of their low mechanical properties. Usually called "rubber", this material is mainly used for products such as seals and tyres.

Thermosets have highly cross-linked molecules, resulting in higher strength, heat resistance and durability. Like elastomers, they cannot be melted again.

Two of these categories can be fused in order to create a new polymer with different properties. For instance, thermoplastic elastomers (TPE) have the elasticity of elastomers but can be melted, as thermoplastics.

Environmental Impact and LCA

Although the trend towards efficiency in buildings is ever-growing nowadays, the construction sector is still one of the most resistant to change, compared to other industries which have already moved many steps further. We often talk about operational costs, materials production and disposal and subsequent environmental impact, but the building sector is still lacking a real rationalization in the use of materials and their recycling.

In this scenario, plastics industry is in a fundamental position. Talking about plastics means both considering the primary energy and emissions embedded in their production and, at the same time, evaluating new possibilities in terms of material efficiency and consequent savings.

Life cycle assessments (LCA) play a leading role here, in order to appraise and weight all the complex environmental impacts. All the stages of the product life are considered in there, from raw materials used and production to transportation, use, reuse and disposal: this approach is called "cradle-to-grave", in contrast with "cradle-to-gate", which evaluates only the production stages. LCA method is specified by DIN EN ISO 14040, which distinguishes four parts: "Definition of goal and scope", "Inventory analysis", "Impact assessment" and "Interpretation". The first one defines the appropriate functional units, boundaries and cut-off criteria of the system to be considered and the second one quantifies the relevant material and energy processes. In the impact assessment part, the different elements are categorized in different kinds and degrees of environmental impacts which are quantified by means of a *material equivalent*. As the various categories to be considered are not established by any universal regulation, they must be chosen each time depending on the specific case. Examples of impact categories are climate change potential (CCP, measured in kg CO_2 equivalent), acidification potential (AP, measured in kg SO_2 equivalent), ozone depletion potential (ODP, measured in kg R11 equivalent), primary energy intensity (PEI, measured in MJ, renewable or not) and so forth. The latter is the only category that does not consider the resulting emissions of the material production and use, but focuses on the related consumption of energy sources. The interpretation phase analyzes results of the previous steps and draws conclusions and specifies instructions in a final report, better if validated by another independent team of professionals.

LCAs are usually finalized by manufacturers and ecological characteristics are reported by means of specific declarations. In particular, standards ISO 14020 differentiates three kinds of *environmental labelling*. The first category (Type 1) is the eco-labels' one. An eco-label is achieved by a product if it reaches specific required values that make it be recognized as more environmentally friendly with respect to the average of other products belonging to the same category. Eco-label has to be verified by an independent institute. Type 2, instead, refers to declarations made directly by the producers, in compliance with the relevant standards. Type 3 is represented by the environmental product declarations (EPD) where there are comprehensive descriptions and detailed information about the product environmental impact, in compliance with product category rules (PCR). This information can be used by third parties for the making of a LCA, but no actual assessment is given in this labelling type.

When it comes to assessing the environmental impact of polymers, it is particularly significant to choose the right functional unit for comparison with other materials. In fact, if correlation between two materials is done in terms of primary energy intensity per mass or volume, polymers are among the worst ones . Nonetheless, this comparison does not consider the actual material quantity employed by a building component in order to perform a certain function. So, it is much more interesting to compare environmental impacts of different materials referring to the same final performance required by design. For example, in the case of a beam IPE 360 with a given prescribed bending moment capacity, steel and pultruded GFRP (glass fiber reinforced polymer) materials are compared in terms of environmental impact. The results show that, because of its lower density, the GFRP beam allows for less material utilization and therefore has lower primary energy intensity and ozone depletion potential.

In conclusion, the main advantage of polymers is that they can perform in the same way as other materials, but with a lower weight, resulting in a better LCA. This property is due not only to the lightness of the materials, but also to the possibility of integration and customization of polymers, which allows for better performances with use of less components. In the building industry, considerable savings in material quantities has particular importance, considered the large volumes usually employed.

Reuse and disposal

Polymers durability depends on various factors, including type, use and environmental conditions. Of course, in case of short service lives it is paramount to attempt to recover the material embodied energy. In order to do that, different strategies are available such as reuse, recycling or incineration.

Reuse is the most environmental-friendly way of handling a polymer that has reached the end of its life, but greatly depends on the designer skill to account for that from the beginning of material production.

If the material cannot be reused, recycling should be considered. Only thermoplastic elements can be melted and recycled to create new components because the polymer chains are reversibly cross-linked. This is impossible for thermosets and elastomers, which can just be used as bulk fill. Anyway, except for PET, the quality of the recycled material is always worse than the initial product because of the presence of no recyclable additives embedded in the polymer and deterioration of plastic properties. That is why usually recycled polymers are mixed with new ones in percentages which depend on the required performance of the final product. Actually, this process should be called downcycling. In general, the more different polymers are used at the same time, the less easy it is to separate and recycle them. In case of inseparable elements, compatible polymers should be combined, such as PC and ABS.

When material recycling is not possible, it can be decomposed in its macro molecules which can be reused in new processes. For example, thermal depolymerisation works for PMMA and PUR, in which case the new products show properties which are different from the original ones. Polymer waste can also be cleaned, crushed and used in petrochemical processes, if there are not traces of heavy metals inside.

In case all the other options are not feasible, polymer can be incinerated in order to generate electricity, reducing the use of other non-renewable resources. In fact, since polymers are petroleum-based materials, they have almost the same calorific value of natural gas or petroleum.

2.1.2 | FRP composites

FRP polymers are composed of two main constituents: fibers and polymer matrix. Fibers determine the finished product structural capacity and stiffness, while the polymer defines the element shape, contains and shields the fibers from environmental media such as chemicals, moisture or UV radiation. Just like every synthetic material, the FRP properties can be modified by means of additives, for instance fire retardants. The final product features are highly customizable and will be determined by type, orientation and number of fiber layers as well as adequacy of the resin matrix.

Resins

FRP polymer matrix is almost always a thermoset as this kind of resin is most resistant to external agents and has low viscosity which allows the fibers to be better soaked. The most frequently used resins for FRP components are:

- *Unsaturated polyester resins* (UP), suitable for glass fiber-reinforced polymers in particular;
- *Epoxy resins* (EP) for carbon fiber-reinforced polymers;
- *Vinyl Ester resins* (VE) for high protection to chemicals;

- *Phenolic resins* (PF) for better fire resistance.

Fibers

Different methods of production depend on the required properties of the final product. Fibers can be:

- *Long fibers* are bundled fibers with no additional treatments, for linear reinforcement. They are mainly used by mechanized processes like wrapping, braiding or pultruding. When rovings are all parallel (UD – unidirectional reinforment) they are suitable for elements loaded in one principal direction.
- *Short fibers* are randomly distributed in the matrix. For convenience, they are often handled as chopped strand mats or fleeces. Then, when wetted by the resin, they adapt their arrangement according to the element shape;
- *Textiles* are easier to manage in manual processes and are laid in layers. These fabrics are traditionally composed of fibers which are woven together in different directions, but non-crimp textiles are also available. The latter exhibit better mechanical properties than the former, because their fibers are purely laid on top of each other and therefore stay straight, with no ripples.

The most common fibers used in the construction sector are *glass fibers*, especially for their good mechanical properties and rather low cost, and *carbon fibers*, which are more expensive but show higher strength. Both CFRP and GFRP products can reach the same strength as structural steel, but only those based on carbon fibers have similar elastic modulus.

Other types include less diffused fibers such as a*ramid fibers,* which are more difficult to handle because of their toughness and *natural fibers*, that are still inadequate for outdoor applications as a result of their scarce resistance to moisture.

Fibers – resin interaction

Interaction between polymer and fibers is a key factor in the production final component. As mentioned before, fibers play a decisive role in determining the final strength, but polymer matrix ought to be considered as well. In fact, resins used in FRP composites should have fairly high maximum permissible strain in order to avoid ruptures in the polymer matrix and consequent cracks in the final product. Moreover, it is paramount that fibers must perfectly adhere to the matrix, otherwise the component will exhibit noticeably lower strength. Another phenomenon which has to be prevented is delamination: this happens when the single plies separate from the others because of excess shear, like in the case of adhesively bonded joints.

Fiber arrangement

Fiber arrangement is highly customizable. In each ply, fibers can be arranged in different directions, depending on the required final properties. For example, fibers in a middle, thick, load-bearing layer can be unidirectional, while other plies of multidirectional textiles can be added externally in order to enhance shear resistance and strengthen potential bolted connections.

Finishing

Surface finishes are essential for determining the appearance of the final product and, at the same time, they serve as protection against external media. In fact, loadbearing fibers should never be left directly in contact with the exterior, as they tend can be attacked by chemicals, damaged by UVs or corroded by absorbed moisture. Consequently, a layer of resin is necessary to complete the outermost layer. In compression molding or pultrusion techniques this is represented by a protecting fleece. In the case of hand lay-up, instead, this is called *gelcoat* and can be ether spread on the mould at the beginning or sprayed on the final element at the end of the process. If water is allowed to penetrate the outer layer, the surface can show blisters; this problem can be solved by eliminating the old coating and applying new gelcoat.

Fire resistance

Reaction to fire and high temperature depends on the type of resin used. Its heat resistance can be improved with addition of fillers, additives. Common FRP generally are flammable, that is class B2, according to DIN 4102-1. Phenolic resins (PF) or unsaturated polyester resins (UP) with a retardant additive can lead to a better performance and achieve class B1 (not easily flammable). Class A2 (non-combustible materials) can be reached with a ceramic matrix. Hydration fillers contain ATH (alumina trihydrate) which at high temperatures emits water, reducing flame diffusion and smoke. Same function has calcium sulfate for fiberglass. Stabilizers, instead, help inhibit degradation in case of continued exposure to heat or UV radiation.

Recycling

Full reuse of materials means being able to separate the components properly. That is why in general composite materials are not recyclable. Moreover, CFRP and GFRP are usually made of thermosets, which can not be liquefied. The only possibility is downcycling or incineration for energy generation.

Production methods

Many different methods can be used for the production of FRP products. Hand-operated laminating is applicable in case of small amounts of fairly large elements, even better if they are unique components. Resin infusion and vacuum techniques are meant to ease the process of reproducing the product in multiple copies and enhance its quality. On the other hand, mechanized systems of production are cheaper and good for large batches but small products. Some of the main FRP production techniques are described below.

In the *hand lay-up* technique fabric reinforcement is manually placed in a mould with subsequent application of resin. This method is suitable for low volume production of components with unusual or unique morphologies, or those which are too large for automated fabrication, like boat hulls, swimming pools, large tanks, automotive components and so on. Moulds can be shaped out of wood, metal sheets, polyurethane foam, other FRPs and so on, depending on the required durability and number of uses. Then, moulds are coated with a release agent to help demoulding and avoid resin absorbtion by the mould. Lamination starts with a thin (less than 1 mm thick) layer of gelcoat made of non-fibrous hard resin with good resistance to impacts, which has to protect the laminate surface [5]. Then, reinforcement fibers in the form of textiles are put in place according to designed direction and organization. Fabric reinformenet can be either dry or pre-impregnated with resin (prepreg). In case of dry textiles, resin is catalyzed and added to the fibers. Each ply is debulked in order to consolidate the layup and remove air pockets trapped in the resin which would create voids in the final laminate [6]. Debulk can be done by hand or using vacuum-bagging. In the first case, the technician impregnates fibers with a uniform distribution and right amount of resin and then uses rollers to debulk the various layers. In this stage, the laminator's skills are essential for the good quality of the final product. In the second case, the layup is put inside a plastic bag or sheets sealed at the edges and ports for air hoses are created. Then, by means of a vacuum pump the air is evacuated from plastic sheets and laminate, consolidating the layup and removing air pockets. Consequently, many different methods can be used for the curing. The simpler one is to leave the cure to take place at room temperature until the component is hardened and can be removed from the mold; this method requires a catalyst or hardener additive to be pre-mixed with the resin. Cure can be accelerated with high temperatures and pressure by means of an oven, a vacuum bag - similar to the one employed in debulking – or an autoclave. After curing, the fully hardened part is removed from the mold; when high-performance components are required, the element and can undertake a second cycle of postcure at higher temperatures [6].

*Fibre spray*ing is an easy and cheap way of hand-laminating complex shapes which don't require high mechanical properties. A roving is chopped in small pieces and spayed with resin by means of a spray gun. Just like hand lay-up method, the laminate is then rolled to remove air pockets. Of course, fiber direction can't be determined and the component thickness is not precise [5].

Vacuum infusion process (VIP) is a closed mould process. The mould cavity can be a flexible bag, a single mould with bagging film or a two-sided mould. Once the stack of reinforcements and porous materials are put in place, air is evacuated and replaced by resin which is pushed inside the cavity through special inlets. This is the only closed mould method that uses athmospheric pressure to push the resin inside. The flow of resin depends on permeability of the infused materials, resin viscosity and differential pressure. Given these parameters, the process is accurate and consistent. Closed mould methods have the advantage of limiting styrene emissions because cure takes place in a closed environment. Also, this technique allows for production of high glass-to-resin ratio components, which have less air gaps inside and therefore exhibit better mechanical properties.

Pultrusion is an automated method which is really diffused in the building industry because it allows to easily create sections and sheets with high fiber ratio - up to 70% by vol. - and determined mechanical properties. Impregnated rovings are pulled and quickly cured at high temperature by means of a heated mould. Otherwise, fibers can also be pulled dry and resin can subsequently be injected. Since the fibers are unidirectional, the pultruded components have good flexural strength but mechanical properties under transversal loading are lower. That is why sometimes rovings can be joined by complex mats, which are composed of long fibers - responsible for transversal and longitudinal loadbearing capacity –

and short fibers for consistent covering. Resin matrix can be UP or rarely VE, PF and EP for carbon fiber composites. Because pultrusion is and industrial process, manufacturing tolerances are satisfactory, although there might be faults in fiber arrangement or uncertainties due to thermoset matrix shrinkage. Dimension of the sections depend on the plant, anyway common maximum measures are 650-1250 mm. Even if some complex shapes are occasionally beginning to emerge, pultruded standard sections are usually straight and similar to common structural stealwork. Industrial plant has high costs that make production profitable only in case of great batches.

*Wrappin*g is a highly mechanized and precise method used for radial symmetrical hollow elements like tanks or pipework. A spinning mandrel is used in order to wind rovings which can be already impreganted or dry. If dry, they are then wetted using infusion. Mandrels usually have a conical shape to ease demoulding and can be one-offs or reusable.

Braiding is principally used in aerospace sector, where components with excellent mechanical properties and impact strength are required. This process is akin to wrapping; a lot of rovings are continuously wrapped and overlapped around a mandrel by means of a braider. Various kinds of fibers can be employed and combined in special positioning, so that complex shapes can be produced. Fibers are wound dry and then they are wetted using injection or infusion technique.

2.2 | Integrated tectonics

2.2.1 | From assemblages to fusion

"If *plastics* was the word of the future in the 1967 film *The Graduate,* then today's graduates should understand the future of caulks and glue. Instead of hammering, bolting and screwing disparate elements together mechanically, this is an era of chemistry and cooking."

Greg Lynn

Every construction system brings its own materials, possibilities and constraints, specific techniques, technologies and, ultimately, tectonics. No matter if traditional or innovative applications, the choice of a particular construction material influences architectural and structural design in a unique way. But looking at the various examples which characterized the history of architecture until now, they all have something in common that is all about the way of conceiving tectonics. In fact, it is common to intend tectonics as an assemblage of discrete parts, a superposition of different components and systems, each with its own specific function and related industry. Even contemporary architecture, with its free forms and fluid aesthetic, still uses framed structures concealed under the surface for load-bearing function, a jungle of different pipes and channels hidden inside unused and resulting spaces and so on with other attachments. Integration is always sought, but never completely reached because functions, physical components and materials are just put near each other or bolted together. Even though they can work well together, they remain independent and essentially separated.

Composite materials, instead, allow for a radical shift in the way tectonics can be seen in architecture. The word "composite" itself embeds the concept of something mixed, a sort of compound, where different elements blend and fuse their specific features in order to create something radically new - the analogy with cooking used by Greg Lynn is particularly explicative here. Composite thinking is all about layers, fabrics and fibers, glue, additives and resin, all possible materials embedded and consolidated in a unique object. This is the final frontier of efficiency and integration. Designers and architects now should start looking at other industries that already use these technologies and have anticipated in a certain sense this innovation. Take the aerospace sector, for example, where efficiency in the use of materials and resources is paramount. The first aircrafts were organized like buildings, with framed structure, cladding, finishing with wooden or metal panels; now both their surface and structure are made out of high performance composites, locally customized or thickened in order to resist external forces, glued with reinforcements, embedded with cores and pipes [7].

Curves and waves

Moreover, this new paradigm brakes the traditional juxtaposition of horizontal planes, seen as spaces where organization and motion happens, and vertical elevations, representative of structural and static dimension. Composite shells need double curvature by their own structural nature. The same curves and waves that characterize the shape of boats, aircrafts and cars can be introduced in architectural design, introducing fluid transitions between horizontal and vertical elements, new perceptions and original ways of living the space [7].

2.2.2 | Systems integration

When talking about composites, surface and structure are fused together, so that the envelope can have at the same time load-bearing, insulating and aesthetic properties. But integration can go even one step further and include building systems. As mentioned in Chapter 1, in history systems have always been considered as a separate and secondary aspect in respect to the real essence of architecture, mainly concerned with shapes and structures. Moreover, they have always been seen as independent from the architectural and spatial discourse, with their own specific and standardized design and organization. They have been either stuffed inside walls and ceilings or shown and elevated to an expressive feature, as happened in High Tech. Anyway, in both cases they remained independent and scarcely integrated in the architecture [8].

With new composite technologies, instead, true integration of systems in the building envelope discloses new unexplored possibilities. Composite surfaces are highly customizable both in shape and material properties, so that surfaces can fold and wrap creating cavities while resistance to corrosion is no more a problem. Channels can be created inside the composite shell itself and they can conduct fluids and energy systems. At this point the question is: how this extreme integration of systems will influence architectural morphologies and vice versa? [9].

Tom Wiscombe talks about Ediacaran biota, primitive multi-cellular organisms as an example of multifunctional skin. Their epidermis could articulate in different ways, creating inflections to generate local stiffness, embedding air in special vesicles, developing gradients of features and so on [8]. Wiscombe claims:

"Rather than thinking of architecture in terms of abstract solid mass, it becomes all about the ability of two-dimensional surfaces to shift toward one or three dimensionality [8]."

He thinks that an extreme interdisciplinary approach and recognition of the relationship between the different parts in terms of ecology are fundamental. Technology can be embedded so deeply inside the architectural surfaces that *"high-tech snaps into a higher level of order and begins to appear low-tech again"* [8]. This means that biological world is no more so far away. Like living organisms, integration between different features will be so rich that elements will start losing their their individuality and functions will blend together. At the end, it will be impossible to distinguish if a certain task is performed by a single element, because it might be carried out by a multitude of different components together. At the same time, considering the single element, it will be hard to define his function, because it might have multiple ones.

Differential Growth

In parallel with investigations about composite surface tectonics, my research about membrane systems has been extended to biological processes of cellular morphogenesis and tissue growth mechanisms. Morphogenesis literally means creation ("genesis") of the shape ("morphê") and refers to all biological processes which underlie the generation of natural forms. It represents one of three aspects of developmental biology, together with cellular growth and differentiation. This study is not meant to reproduce or emulate a particular biological process or morphology. Instead, it aims to explore elementary principles at the basis of tissues growth and differentiation in general and how they can generate interesting patterns and shapes. The final scope is to find out what potentialities and opportunities these forms can offer to architectural applications.

Reference projects

A key reference has been Andy Lomas' paper "Cellular Forms: an Artistic Exploration of Morphogenesis" [10] in which the author describes experiments in generating various and intricate organic shapes starting from a very simple ruleset. Results show an incredible similarity to biological organisms, organs and plants. The model is inspired by cellular division and deliberately conceived as simple as possible in order to be more flexible and allow a wide range of possible developments. Each cell is represented by a particle and connected to a determined quantity of uniformly distributed cells around its surface (Fig.1 a)[10]. Cells can divide, consequently creating new links and changing overall topology. The division process is influenced by the nutrients that cells receive from the environment. When the amount of nutriments reach a certain threshold, the cell splits in two. At the same time, internal forces compete to determine cells relative equilibrium positions. In particular, links between cells tend to maintain their original length, like a sort of elastic bond, while other forces stimulate cells to assume planar arrangements or, otherwise, boost their tendency to bulk. Depending on various combinations of these forces intensities, different cellular spatial arrangements arise (Fig.1 b)[10]. It is interesting to outline that all the different structures generated by this algorithm arise without cell differentiation; that is, cells are all the same type and behave the same way. In case nutrients are evenly distributed in space, a uniform growth takes place. That produces emergent arrangements which mainly look like internal organs. Otherwise, if nutrients production is simulated by incident sun rays and their diffusion rate among cells is low, plant-like structures tend to arise [10].

Another interesting project related to differential

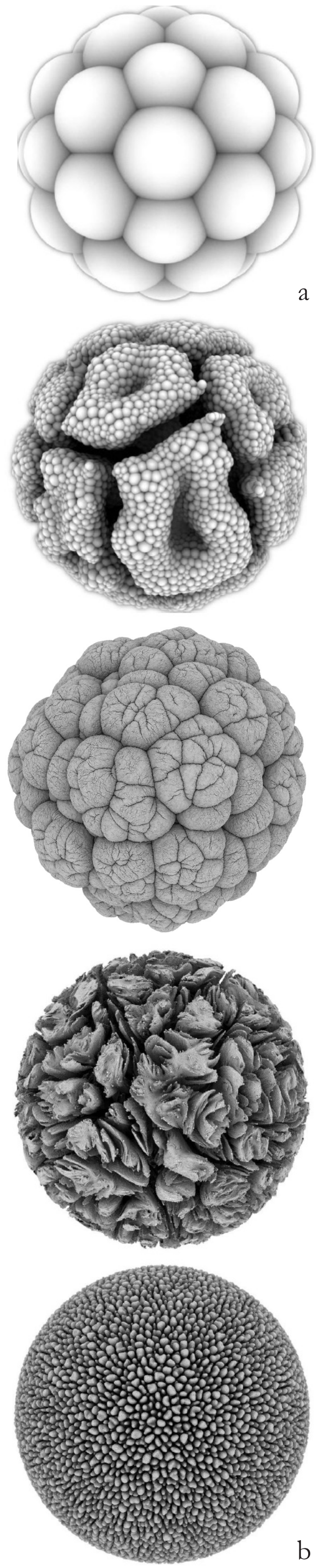


Figure 1. *a: initial basic ball of cells; b: examples of different results of Cellular Forms by Andy Lomas [10]*

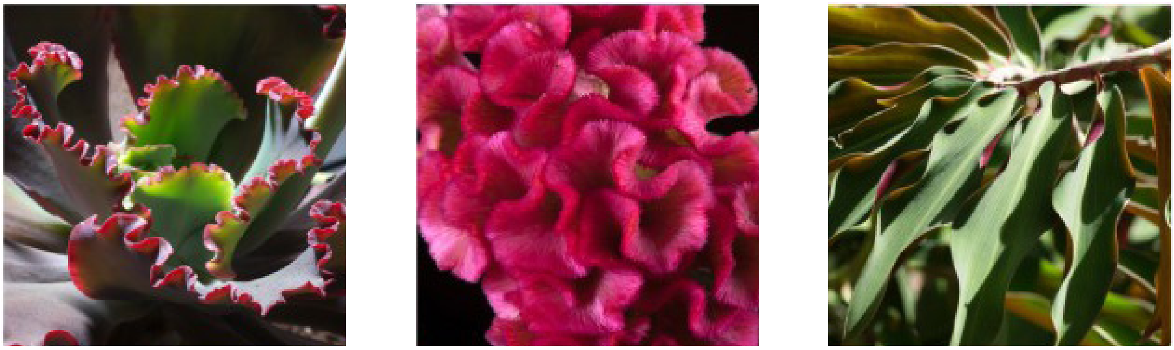


Figure 2. *Some examples of ruffled plants analyzed [11].*

growth is “Floraform” by Nervous System [11]. This work is inspired by growing mechanisms of plants and, in particular, it follows L. Mahadevan’s papers “The shape of the long leaf” and “Growth, geometry and mechanics of the blooming lily”. Mahadaven suggests that the creased shape of many leaves and flowers can be the result of an increased growth rate at the edges of the developing plant surface. It is all about some parts of the surface that locally grow more than others, generating macro-shape differentiation and specific structures. Another example is tropism: a plant can respond to light directional stimuli growing more on one side of the stem than the other: as a macro scale consequence, it bends towards the sun [11].

Nervous System selected and analyzed a series of organisms and plants that show this kind of ruffled shape (Fig.2) and developed an algorithm to simulate differential growth with digital tools. The computational simulation is based on a mesh, some physics defining elasticity and repulsion and a rule for subdivision. At each time step the forces are applied at each vertex and new positions are updated. When one of the longest edges of each triangular face of the mesh reaches the maximum length allowed, it is split, consequently changing the mesh topology. Edges are flipped as needed. (Fig.3 d)

Many experiments have been done changing the starting conditions of growth: it can begin from a single point which splits in two (Fig.3 a), a point from which the surface expands (Fig.3 b) or the edge (Fig.3 c). With all these folds continuously arising and growing, it is paramount to avoid the problem of self-intersection. This issue is addressed introducing collision detection: each vertex has an ellipsoid around it which detects proximity of other spheres and introduces a repulsion forces to prevent overlapping (Fig.3 e) [11].

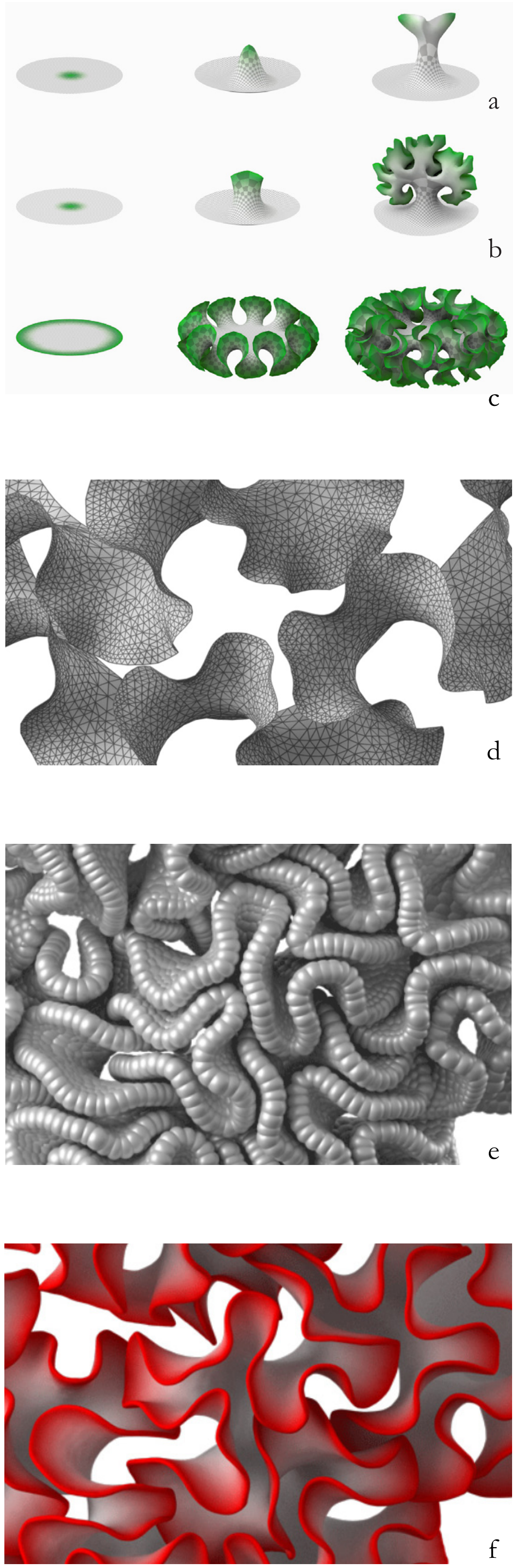


Figure 3. *Floraform by Nervous System, differential growth. a: growth from point; b: point expansion; c: edge expansion; d: adaptive subdivision; e: collision; f: geodesic distance [11]*

Figure 4. *Florescence Ornata 2, Floraform sculptures by Nervous System. Nylon 3d printed by Selective Laser Sintering [11]*

The Pavilion

4.1 | Context

This project was born from the interest in the situation of the existing School of Engineering and Architecture Campus in Via Terracini, Bologna. It is the second Campus of this School and is located out of the city center, in a quite isolated suburb of Bologna, intercluded between the railway lines and rural area (Fig.5).

It is especially difficult to reach for students, who are mainly used to live in the city center. A student without a car has to reach it either by bus (only a couple of bus lines available) or by bike (bicycle paths are not continuous and even dangerous in some points). But the worst part is that this place is uninviting by itself as it has no adequate services and facilities to sustain the local activities, except for some little insufficient activities.

A major expansion of this University Campus might take place there in the near future, but, still, the current situation is unsustainable: hundreds of students, researchers and teachers have spent years working and studying there.

Figure 5. *Top: School of Engineering and Architecture main entrance; bottom: site view: School of Engineering and Architecture in the middle.*

Moreover, the existing building mainly comprises offices, laboratories, libraries and classrooms but it is noticeable the fact that in a such isolated district, the University building has just one, small cafeteria. It serves as café and canteen at the same time only during lunch hours. In there, people can have their meals and drinks, but the space is usually crowded and not comfortable. There is a small green area outside with a gazebo, but it is not sufficient, especially when outside it is really cold or too warm (Fig. 6).

The idea

There is no one unique way to solve all the mentioned issues. Of course this looks as the result of a temporary situation, waiting for the planned big Campus extension; in reality, this building has been in operation for almost ten years and, still, students do not have basic comforts such as a place where to relax and calmly have their meals.

What can architecture do in this cases? If we assume that we cannot create a completely new masterplan or make big urban changes, only the small-scale intervention seems to do the trick.

The existing building is composed of an assemblage of mono-functional rooms were students can perform only the prescribed tasks, with no possibility of deviation. In the classrooms they can only attend lessons, in libraries they can only study, in the café-canteen they can only eat and so on. The rest of the space is connection between these functional units, that is: corridors and low quality, resulting space. This is the opposite of what a productive environment should look like. According to L.Malcic:

"Workplace designers need to keep in mind that psychologists believe the three basic human requirements are security, identity and stimulation. […] With this in mind, it will be important to create micro-environments that help people to control their own spaces. […] More simply, they can be allowed to choose their own chair." [N5]

The perfect work environment should differentiate, create variability and stimulation. We have already discussed the importance and possibilities of heterogeneous environments in Chapter 1.

In conclusion, the idea is to design a new space for University students where they can relax, study, have their meals and socialize. It will become an informal shelter from long lesson hours and crowded corridors and, at the same time, a sort of hub of new social interactions where people will be able to meet and have the chance to exchange ideas, experiences and, ultimately, develop creativity and innovation.

Figure 6. *Right: mono-functional spaces in the existing building; from the top: gazebo, classroom, café, corridors. Left: Existing building perspective from East.*

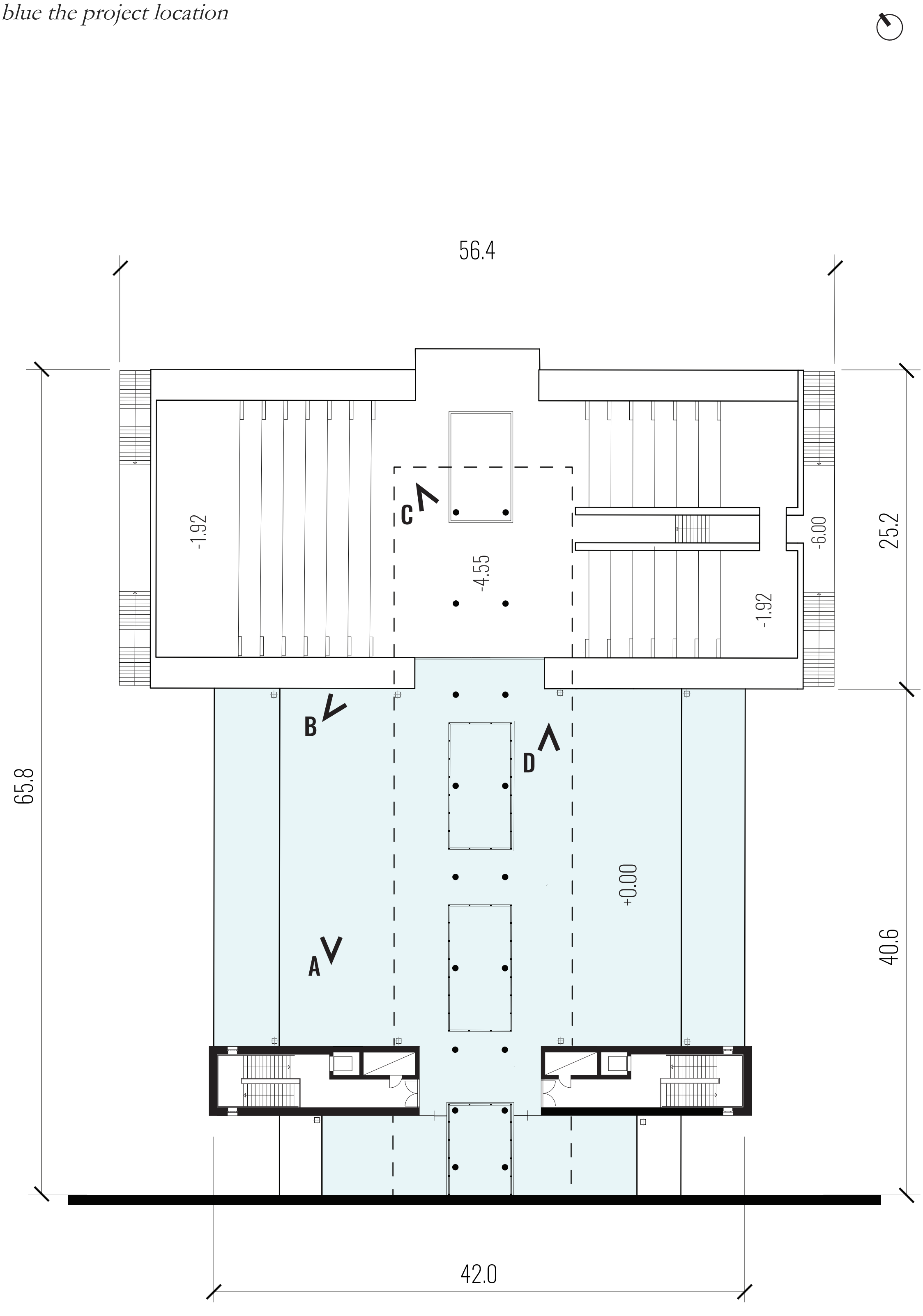
4.2 | Spatial organization

The chosen location for this new Pavilion is on top of the existing building: in this way, the new construction does not occupy new land; on the contrary, it gives new function to an unused terrace, easily accessible form two internal stairs and elevators (Fig. 8). This is a privileged location for the views it offers of the surroundings.

The terrace is situated exactly on top of the main classrooms. The space is interrupted by three full height internal glazed bodies which let light come inside the building. In the middle, along the longitudinal symmetry axis, a long, white framed structure and roof dominates the terrace and the whole building. In North/East direction, but in a lower position, there is another outdoor space commonly used by students during breaks (Fig. 8 C). Our idea is to connect this space with the pavilion by means of a new external stair. In this way, both internal and external accesses are guaranteed and the terrace can be visited independently from the main building opening hours.

Figure 7. *Right: mono-functional spaces in the existing building; from the top: gazebo, classroom, café, corridors. Left: Existing building perspective from East.*

Figure 8. *Views of the terrace, outlined in light blue the project location*



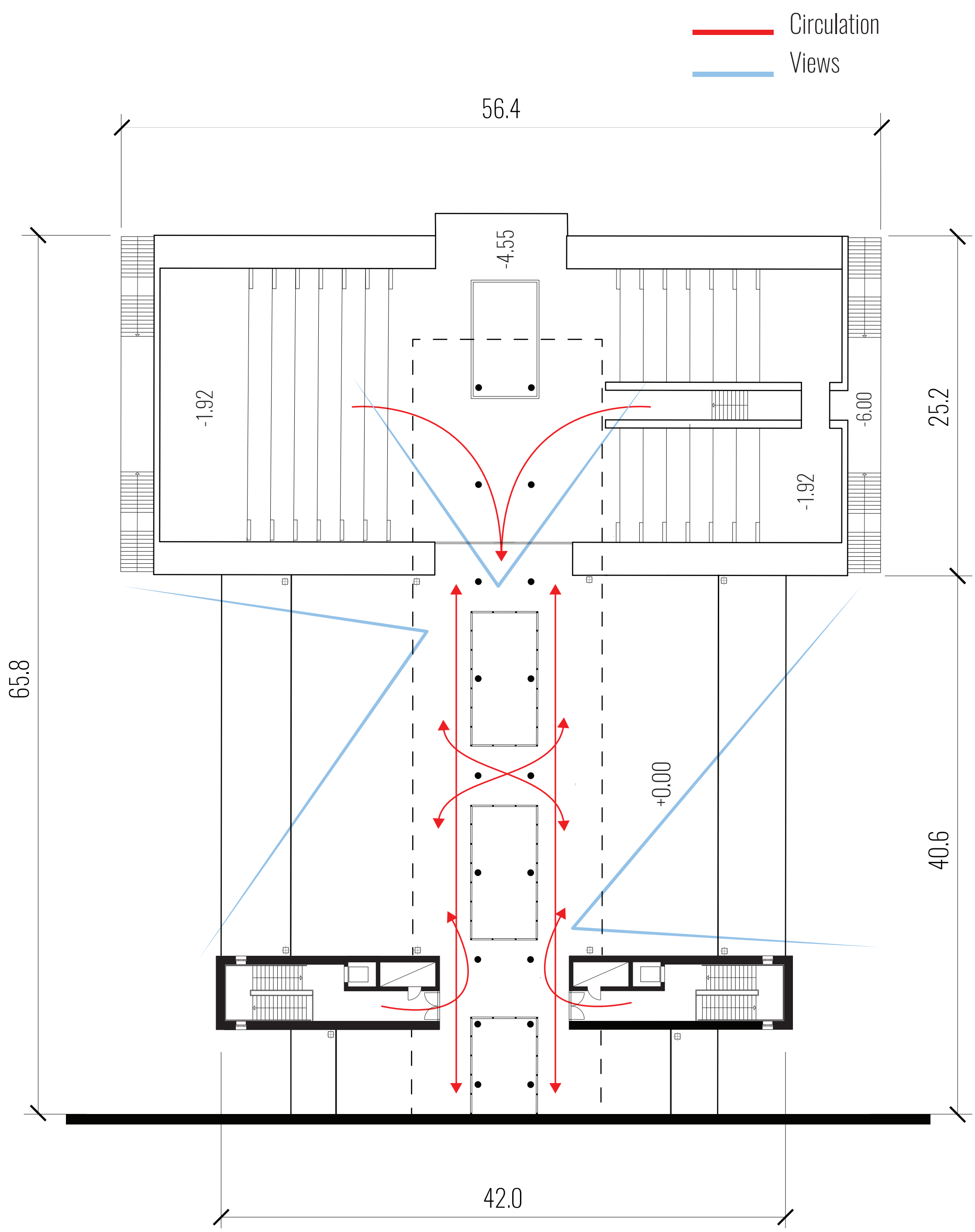
A

B

C

D

Figure 9. *In red basic circulation and existent access system plus a new one designed to connect the terrace with the rest of outdoor space ; in light blue the views;*



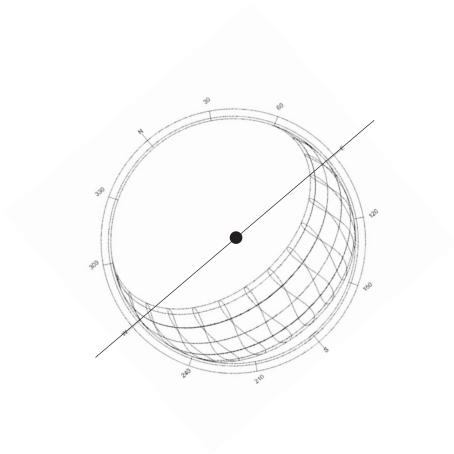
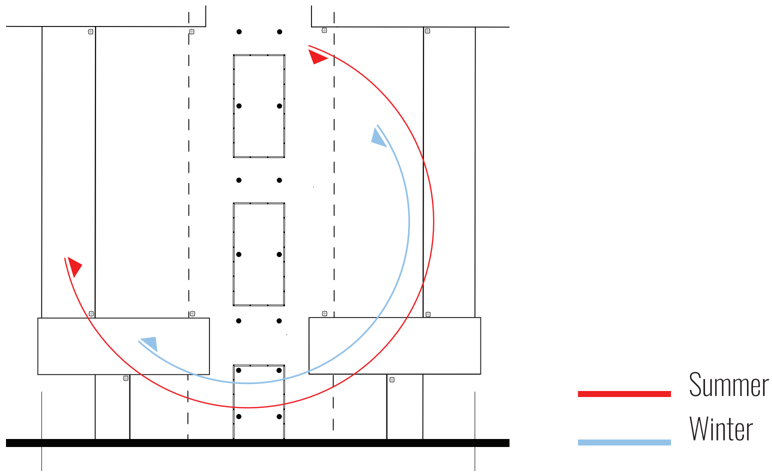
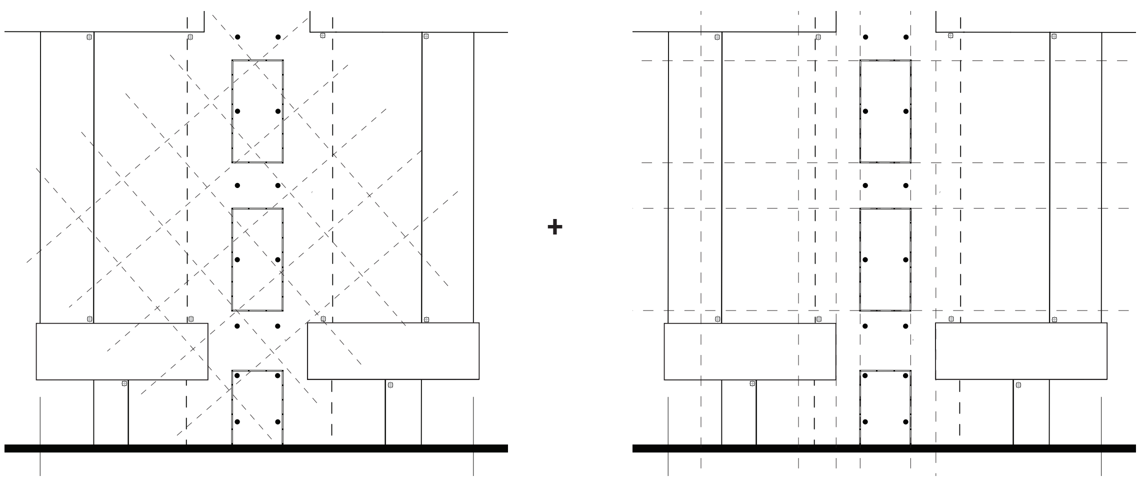


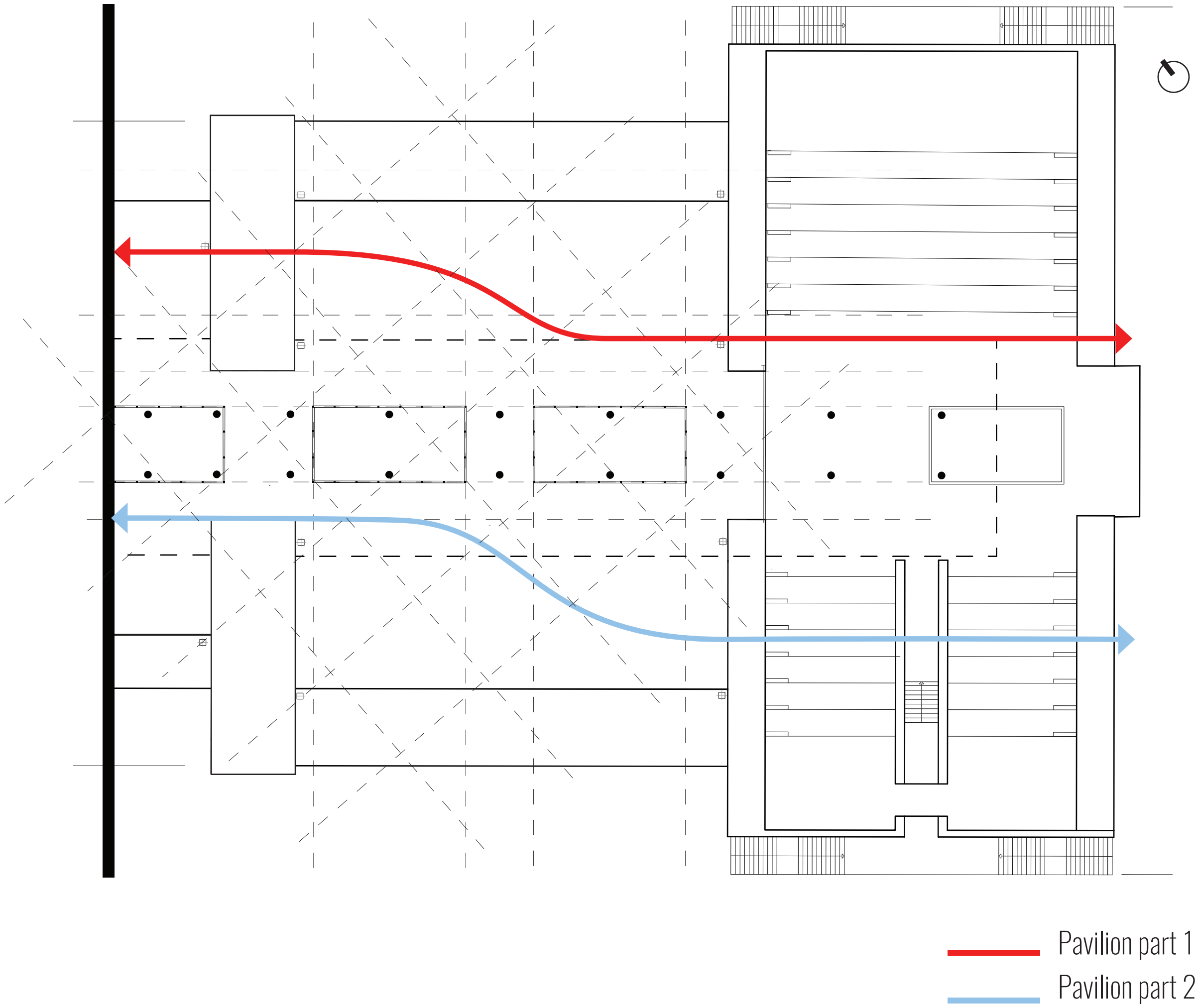
Figure 10. Solar study; orientation and existing grids





Orientation Grid

Existent Grid


Pavilion part 1
Pavilion part 2

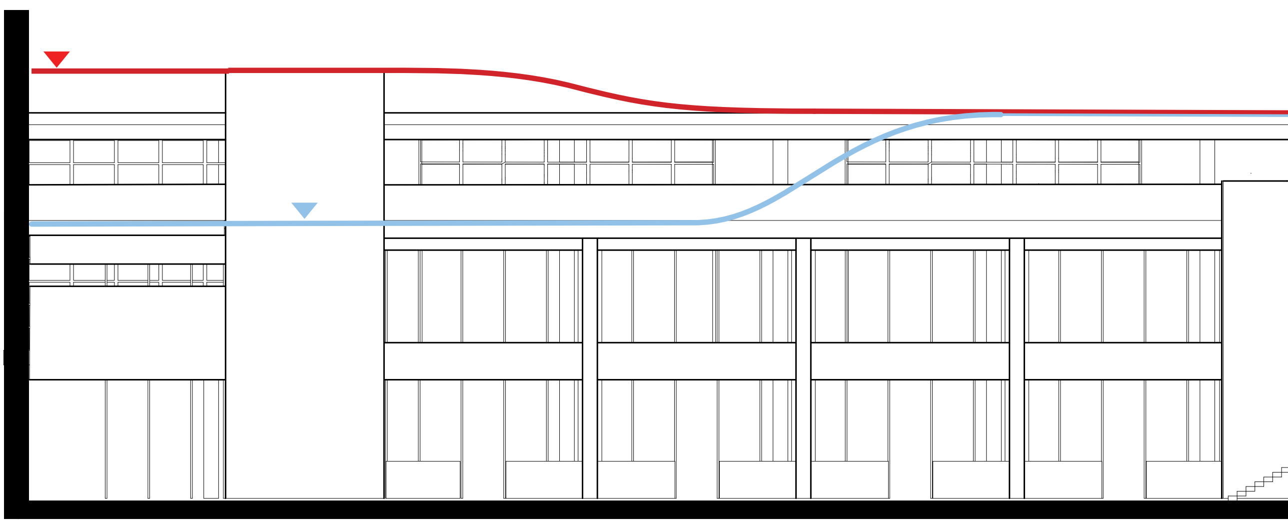
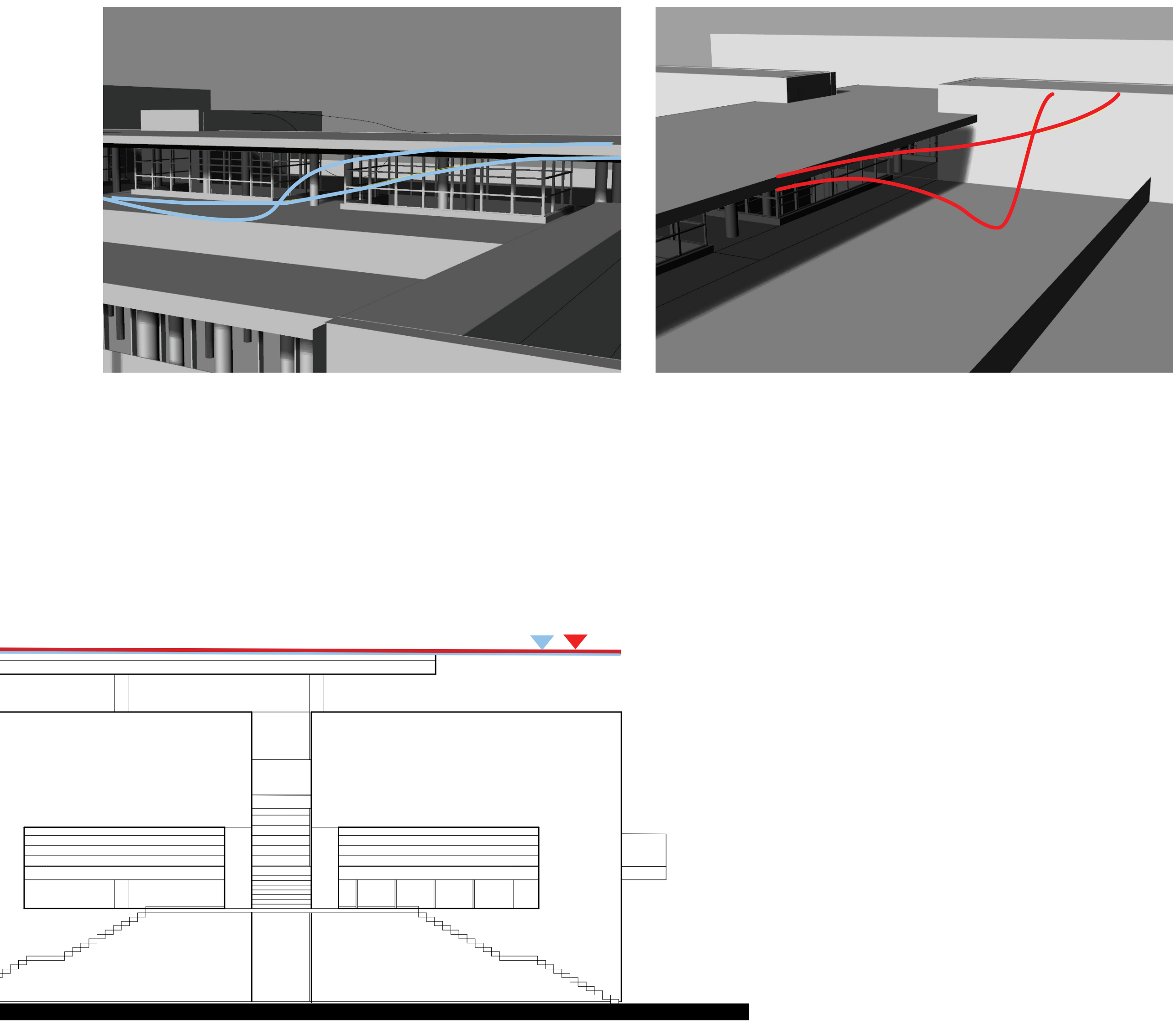
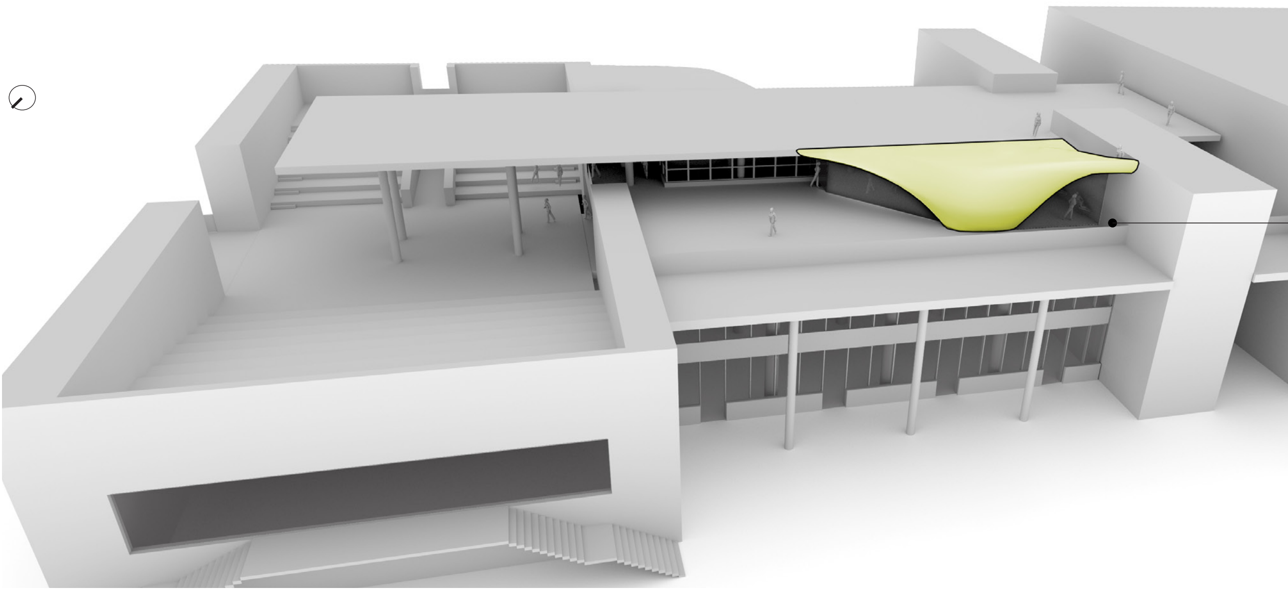
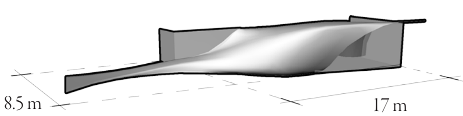


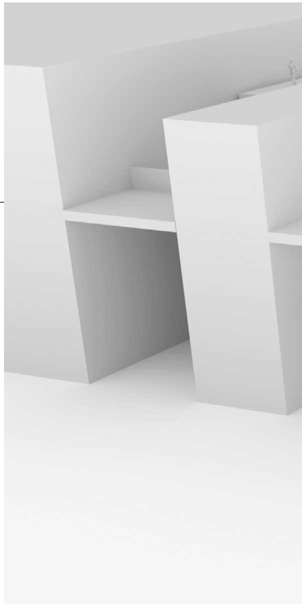
Figure 11. *Lines in plan, elevation and 3d follow exitent geometry and orientation considerations.*





Pavilion 2

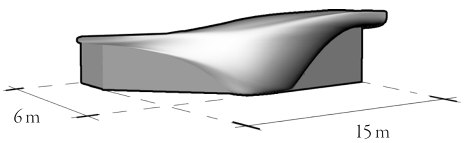




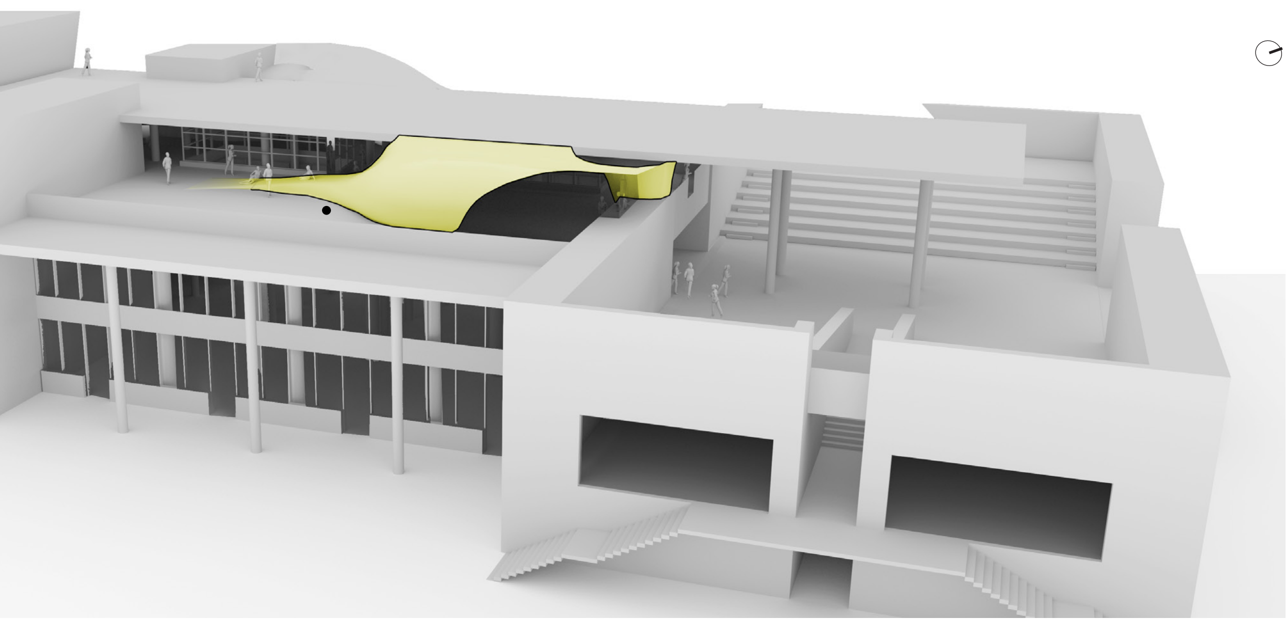
Volume:	442 m3
Floor area:	140 m2
Tot surface:	454 m2
Prevailing Orientation:	S / SE

Figure 12. *3d models of the two shells.*

Pavilion 1



Volume:	442 m^3
Floor area:	123 m^2
Tot surface:	438 m^2
Prevailing Orientation:	N / NW



4.3 | Corrugations

Corrugations arise from an algorithm inspired by differential growth mechanisms of biological tissues in general and how the generated excess surface can create new interesting arrangements in space.

The starting point is a thin surface of variable shape and curvature represented by a triangular mesh in the digital model. Each mesh vertex is the equivalent of a cell in the tissue and can be considered as a sort of moving particle constrained to stay on the mesh itself.

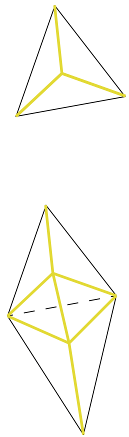
Internal forces

Internal forces make the mesh behave as an elastic membrane and help keeping it consistent and avoiding self-intersection.

Elastic force is represented by springs along the mesh edges: they connect the points and tend to keep them at a certain relative distance from each other. Parameters influencing this kind of force are the springs rest length and the springs strength.

Repulsion force prevents the mesh from self-intersecting or overlapping.

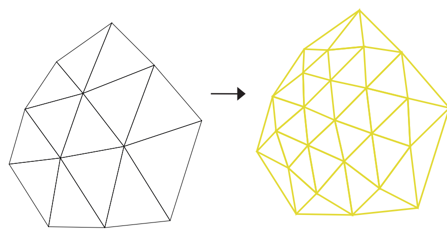
Subdivision rule



Then, a rule is developed in order to subdivide mesh faces and consequently multiplicate mesh vertices. Changing the mesh topology in this way allows to simulate new cells generation. (Fig. 13)

The process is structured in cycles: after each subdivision, the mesh is allowed to relax according to internal elastic/repulsion forces taking place along the edges. (Fig. 14)

Feedback



Then, a feedback mechanism selects the faces to be subdivided next, depending on environmental features and the loop starts again. The feedback influences the ridges according to aesthetic, functional, energetic, lighting and /or structural criteria, depending on the considered position.

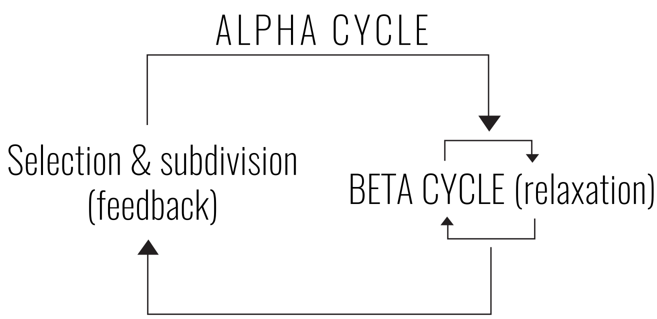
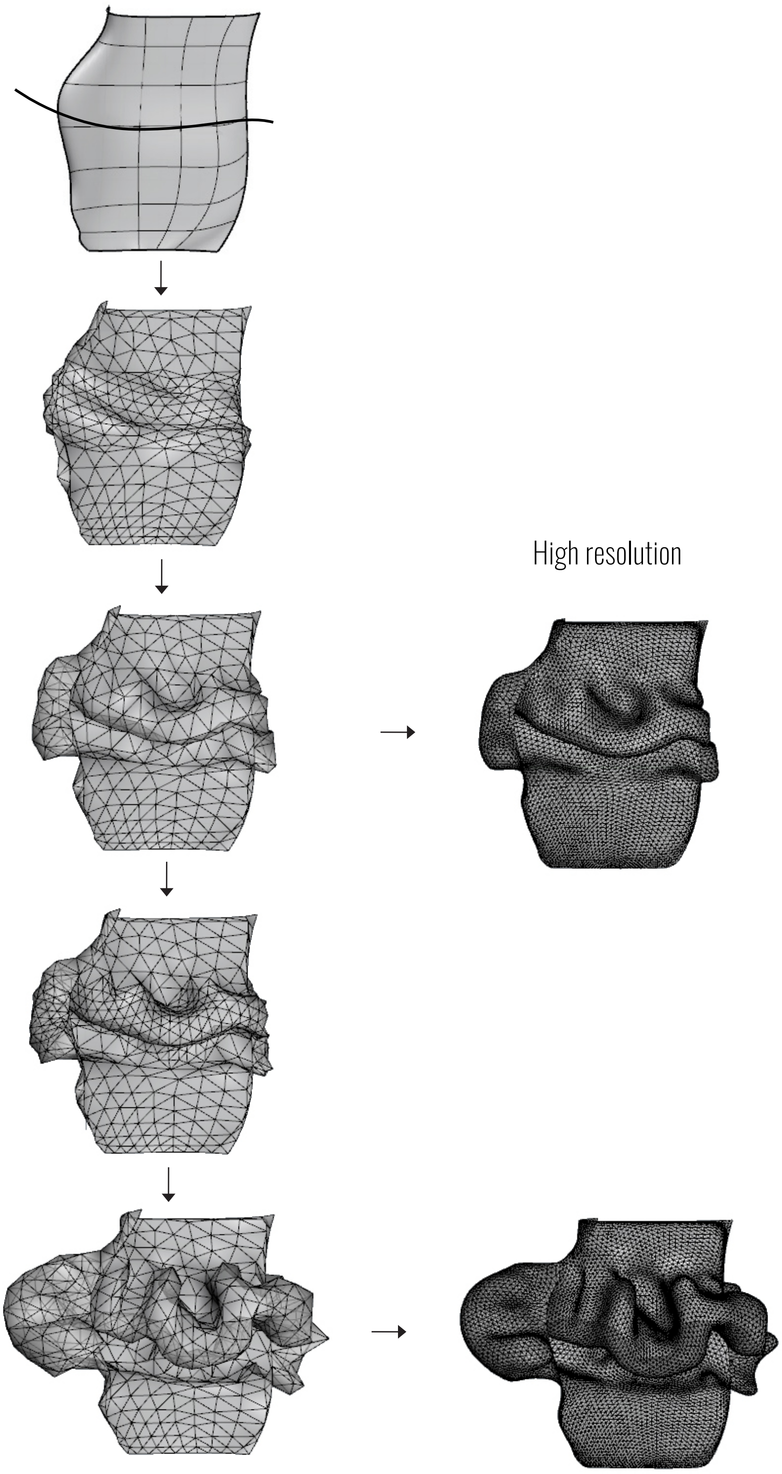
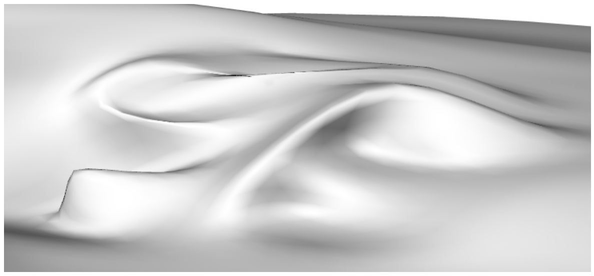


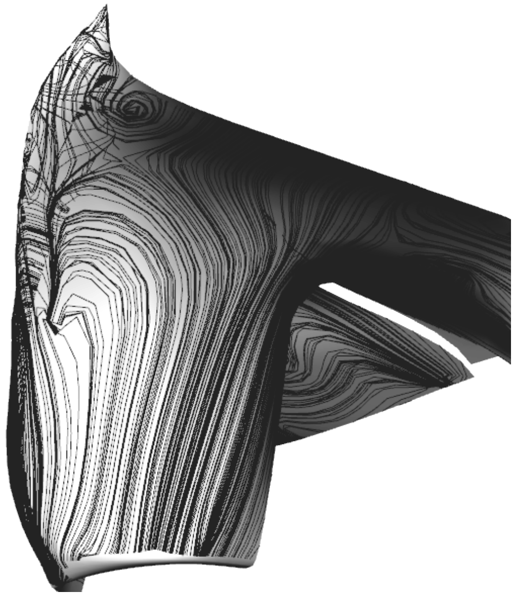
Figure 13. *Top: subdivision rule; bottom: scheme of algorithm cycles*

Figure 14. *Process example*





On the structural point of view, composite technology allows almost every possible form and shape. Addind layers to the FRP or changing its fiber direction can make it resist to all possible loads without affecting the shape. Although, on big shells like these, instability is possible, that is why double curvature geometries are useful. While double curvature stabilizes the geometry of the shell, ridges can concentrate in areas of higher deformation in order to locally stiffen the surface. An initial evluation of expected principal stress distribution and force field has been used to inform the ridges directions.



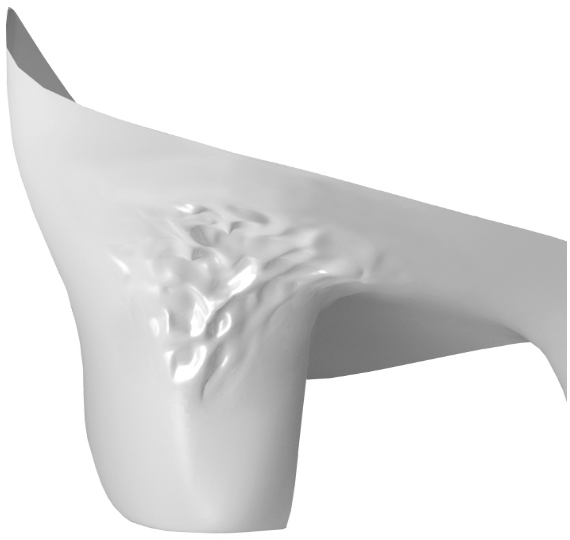


Figure 15. *Process results. Bottom: force flow analysis with Karamba on the surface and corrugations*

4.4 | Energy

A series of dynamic energy simulations are carried out to assess the energy performance of the Pavilion.

The used software is Energy Plus, with a series of plugins that allow its connection with Rhinoceros. These are Grasshopper plugins called Ladybug and Honeybee. With these tools, it is possible to use the Grasshopper interface to set up all the required data in order to carry out the energy simulation.

Thermal zones

The pavilion is considered autonomous, that is, its systems are not connected or dependent by the existing ones. It is divided in four different zones: the parts under the two shells of the pavilion and other two resultant spaces. Only the first two zones are conditioned.

The overall internal space, anyway, is all open, with no walls or partitions. That is why some "air walls" have been used to separate the zones. Under the floor, the existing building is an already conditioned space, so dispersions are considered only through the external surfaces which are not adjacent to the existing building.

A series of context surfaces, included the existing photovoltaics, are added to calculate exact sun shading on the zones (Fig.16 b).

Surface types and construction

Each zone has been decomposed in its boundary surfaces. For each of them a type has been defined: common types are “wall”, “window”, “roof”, “floor” and so on.

Moreover, each surface has its own construction and boundary conditions.

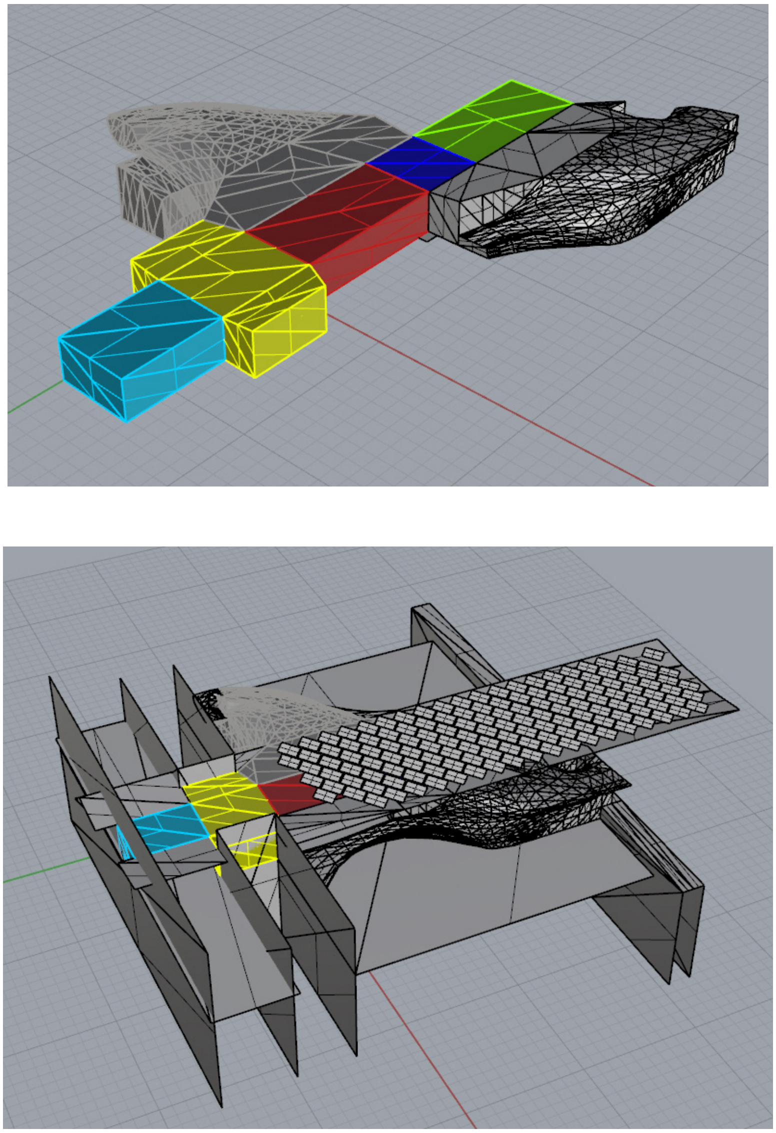
Schedules

Schedules have been created to reflect students habits during the day. The pavilion is closed on Sunday, so in that day occupation is zero. Important schedules are occupancy, occupancy activity, lighting, equipment, infiltration and ventilation.

System

A VRF system with heat pump is completely autonomus and serves the pavilion when needed, thanks to a system of sensors. Moreover, occupants can control set points and adapt their environment locally.

The most critical situation is during the summer season, so a venitilation system has been developed in order to naturally refrigerate during the night.



a

b

Figure 16. *a: Zones in the energy model; b: zones with context shading.*

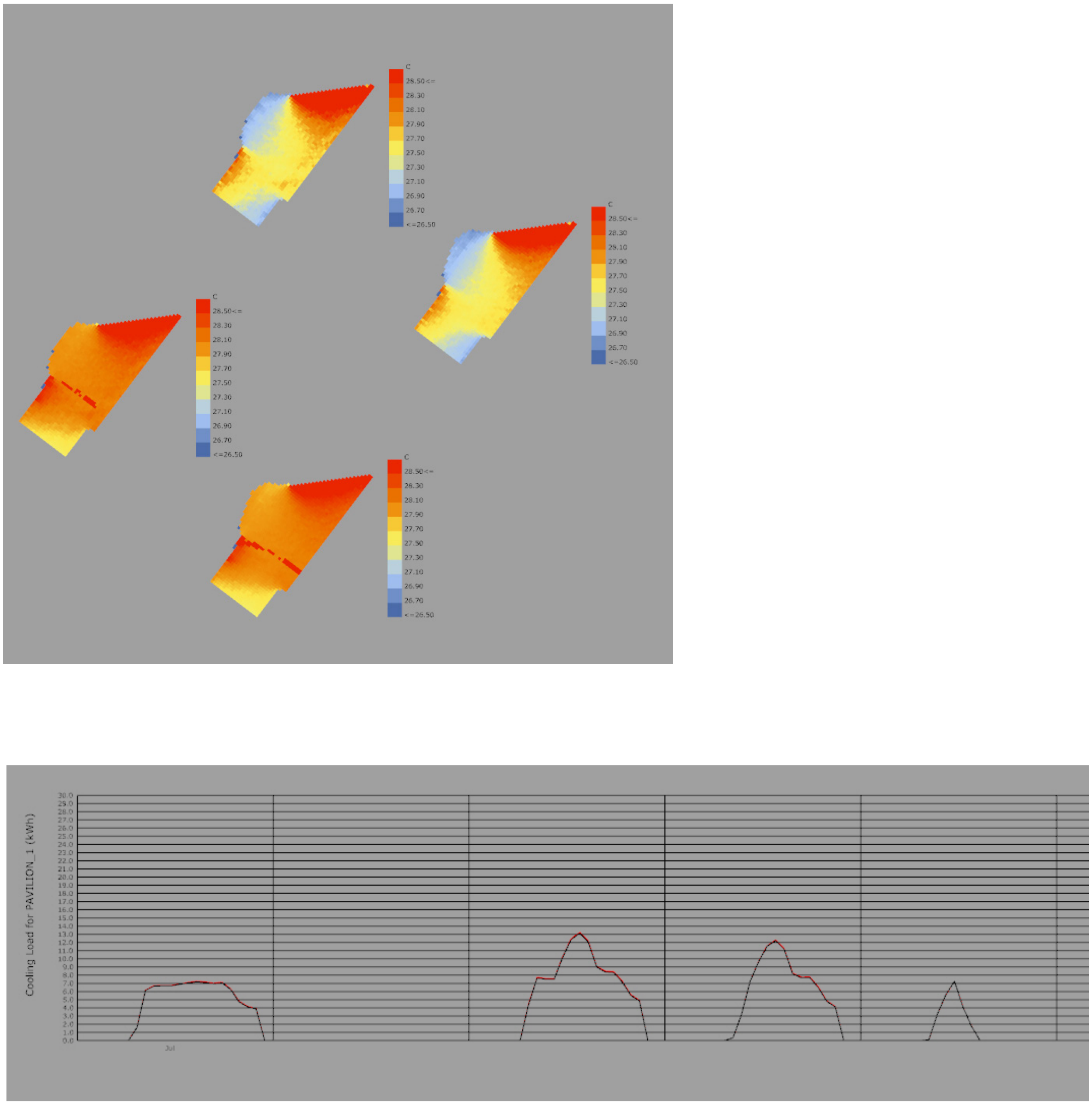
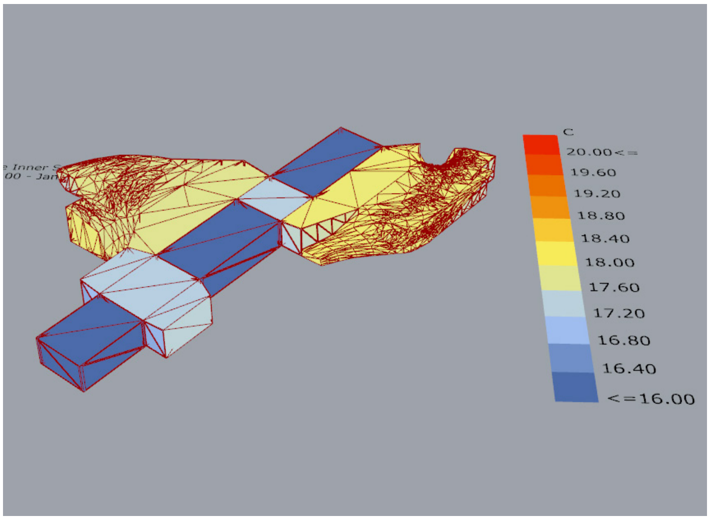
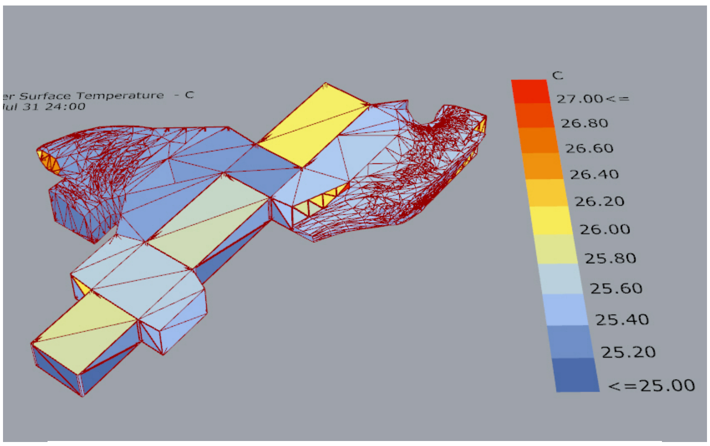


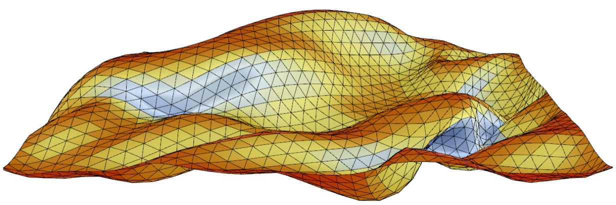
Figure 17. *a: Examples of comfort maps (at 11:00 and 18:00 , 15th July) showing operative temperature of pavilion 1. b: cooling loads for the first pavilion the 15th of July.*



a

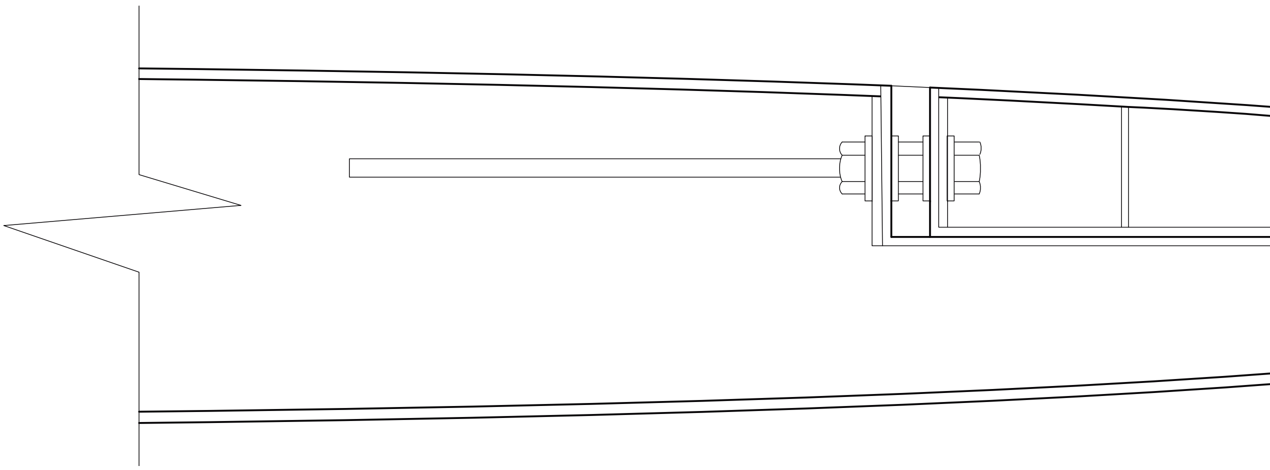


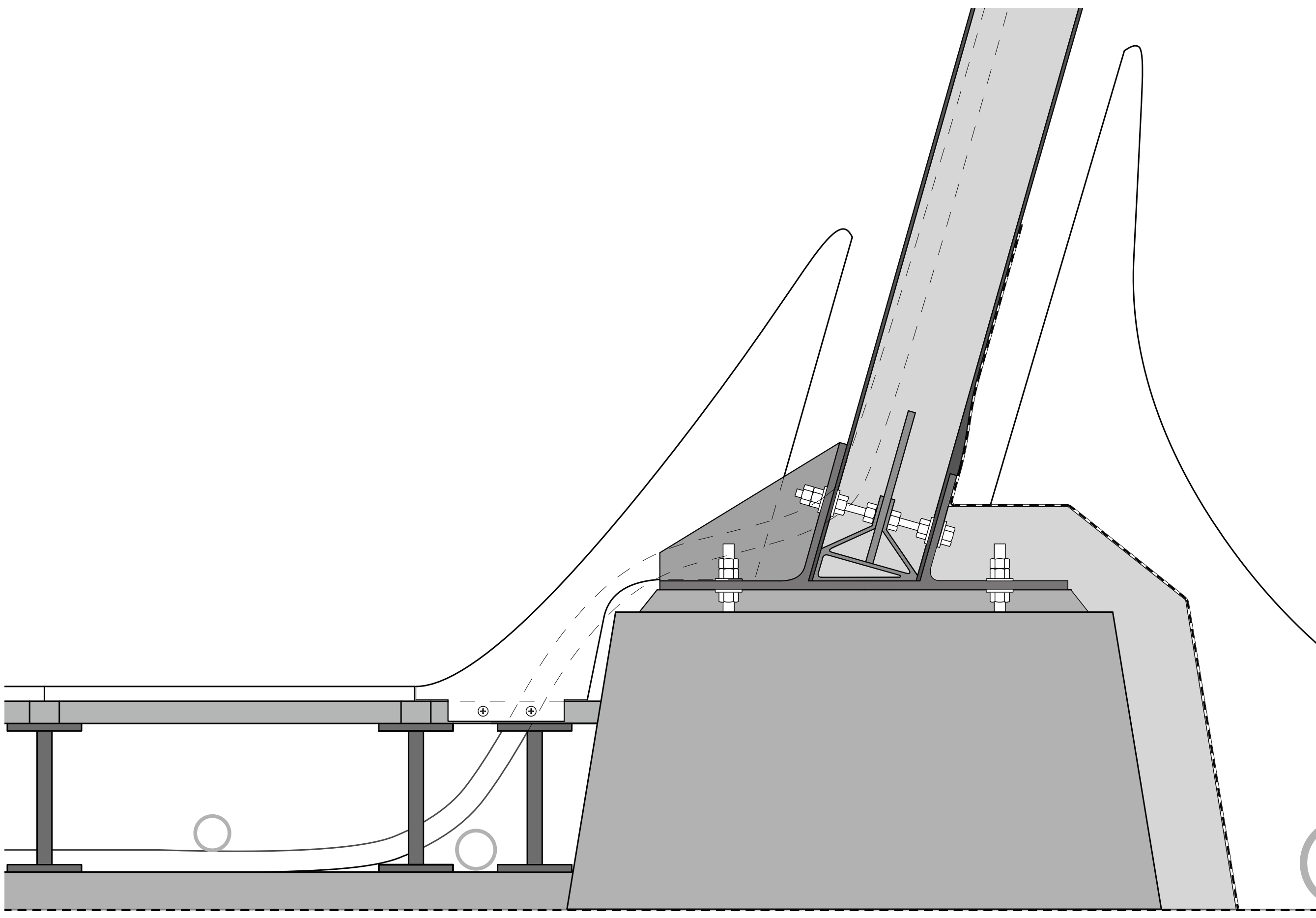
b



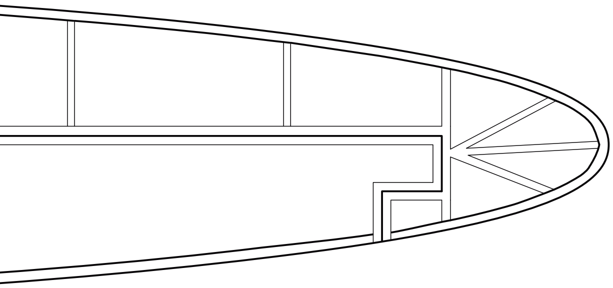
c

Figure 18. *a: Averaged inner surface temperature in January ; b: averaged inner surface temperature in July; c: potentiality of corrugation to reduce surface temperature by means of self-shadng*

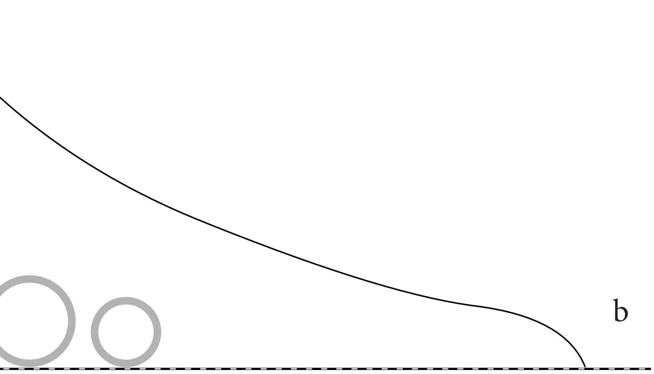




4.5 | Final views

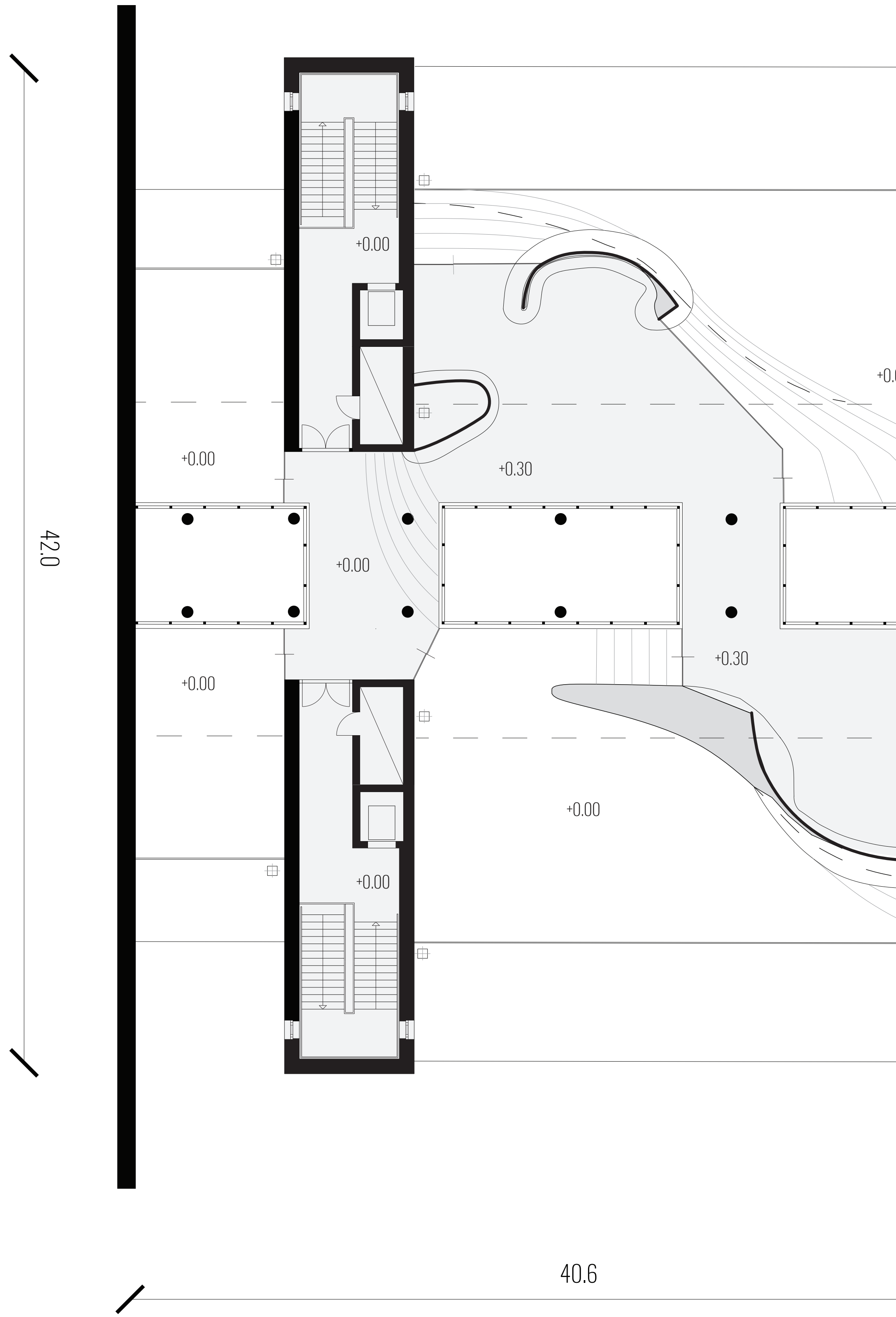


a



b

Figure 19. *a: detail of closure at the corner of the sandwich FRP shell, scale 1:2; b: detail of the base of the sandwich shell, scale 1:10*



+0.00
+0.00
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+0.00
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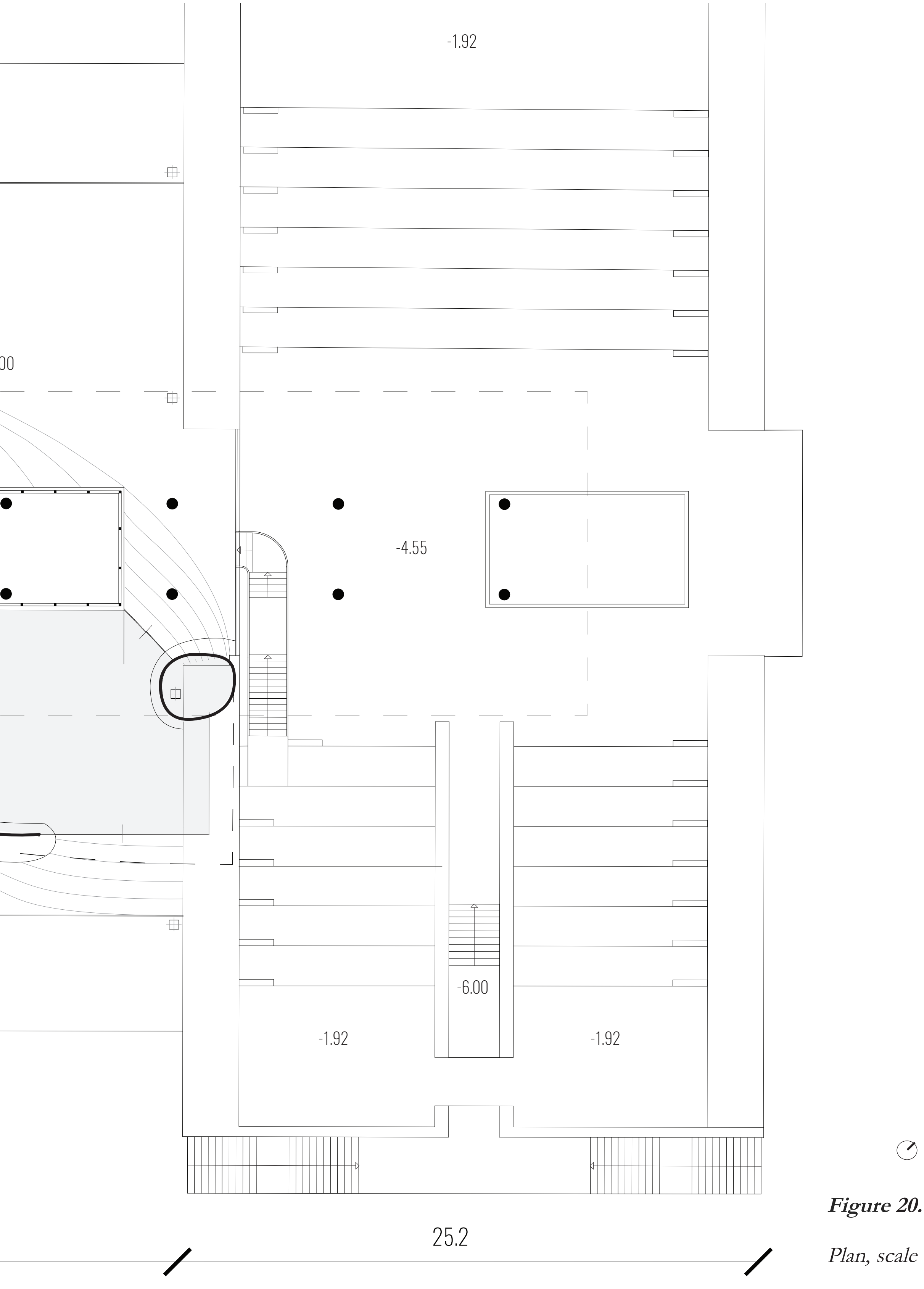
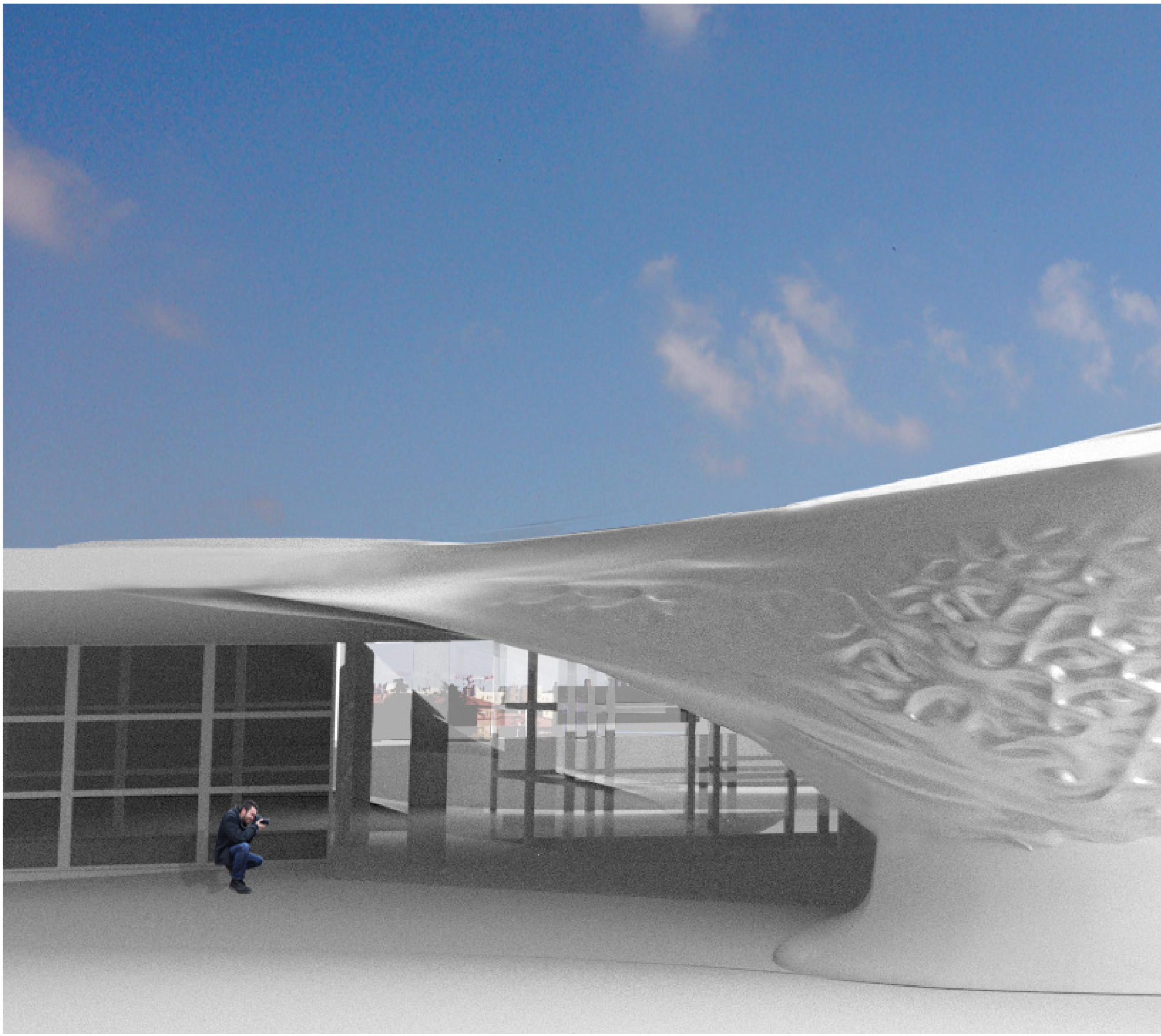
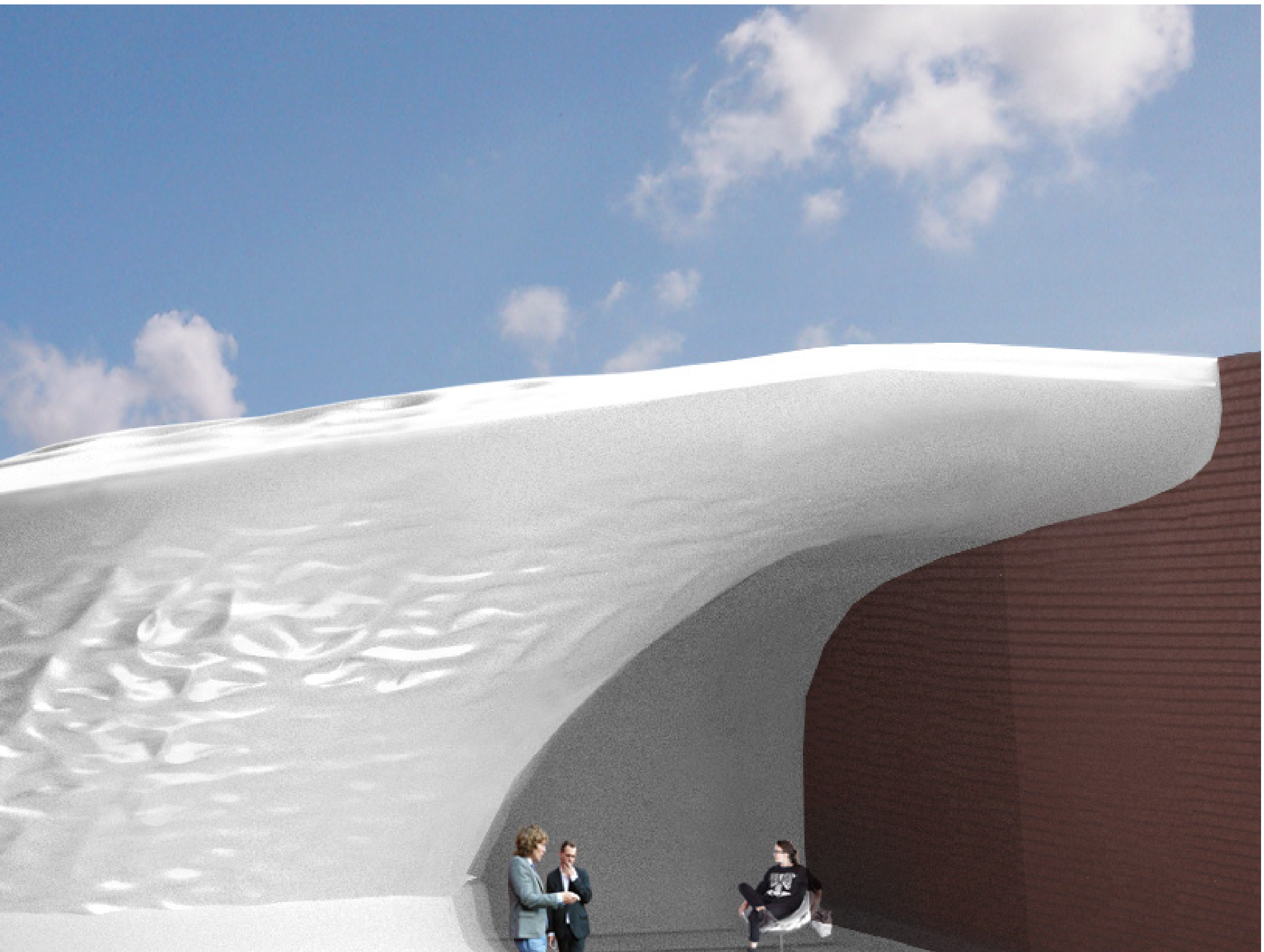


Figure 20.

Plan, scale 1:250

Figure 21. *render fron N/W*





Prototype

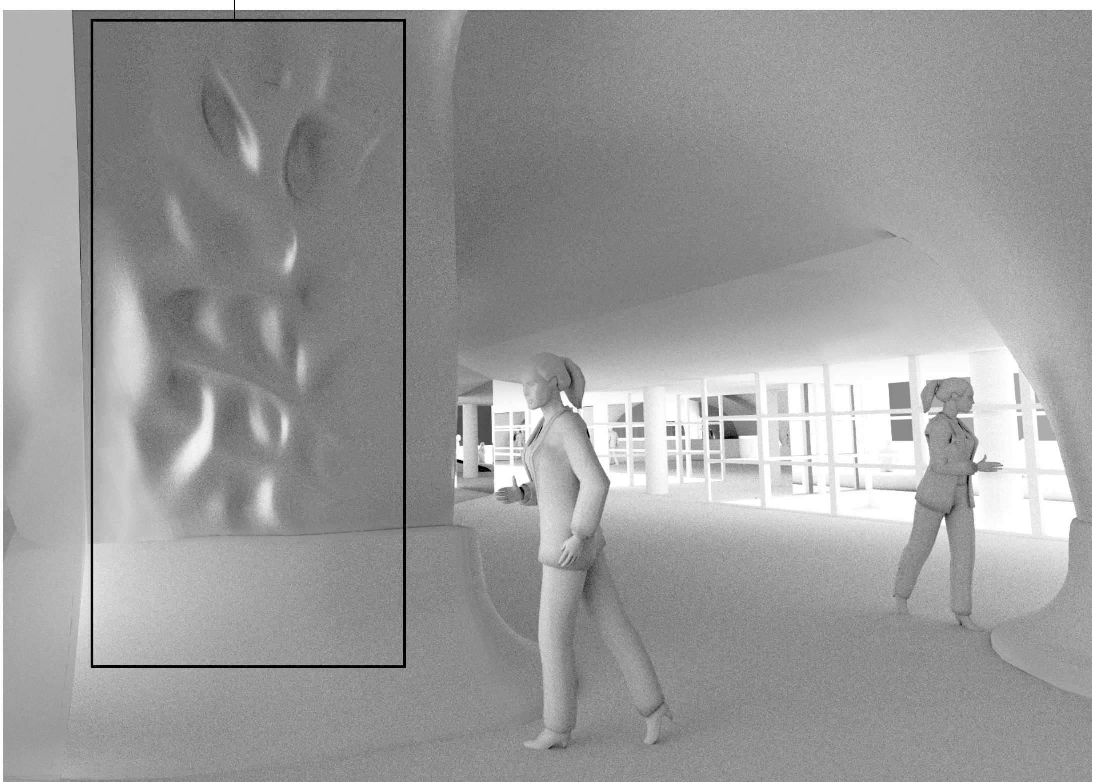
5.1 | Design

5.1.1 | 3D Model

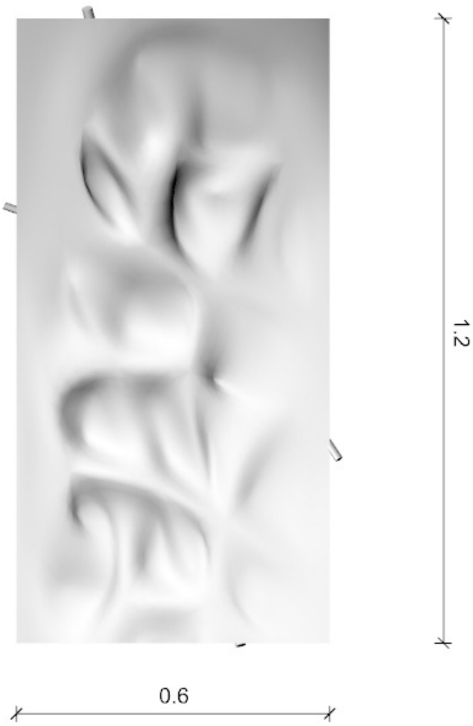
Prototyping is an important step to start testing the possibilities of composite materials in architecture. In this research, a small part of the pavilion shell has been selected and adapted for fabrication. The idea is to test in a smaller scale and with a lower budget approximately the same workflow, techniques and know how that can be used for the entire pavilion fabrication off-site. According to functional and aesthetic considerations, a part particularly suitable for fabrication is the one shown in Figure N. A scale of 1:2 has been chosen for this prototype. Therefore, a part of the shell 1.2m wide and 2.4m large corresponds to a 0.6m x 1.2m fabricated panel.

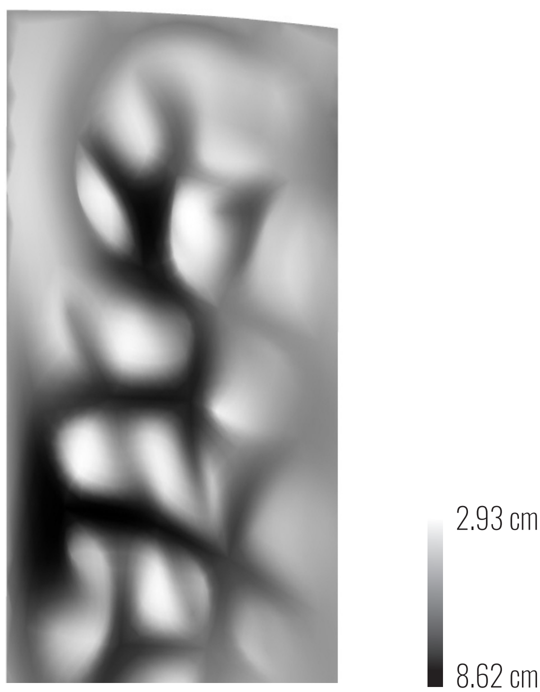
The prototype, as well as the pavilion, is fabricated as a sandwich shell with fiber reinforced polymers at both sides. The external side is corrugated and made of carbon FRP and then coated with white gelcoat. The internal laminate, instead, is made of glass FRP and coated with a very thin layer of white gelcoat. Inside the polyurethane filling there are some systems and a LED lighting system. The latter is placed adjacent to the GFRP laminate, so that light can pass through it, exploiting the typical translucency of glass fiber reinforced polymers. This is the reason why internal coating has to be really thin, in order to let the light come out and create a glare effect in the evening hours.

Figure 21. *Bottom: portion of shell to prototype. Right: extracted 3d model for fabrication in scale 1:2 and relative thickness map.*



Scale 1:2





Carbon fiber reinforced laminate

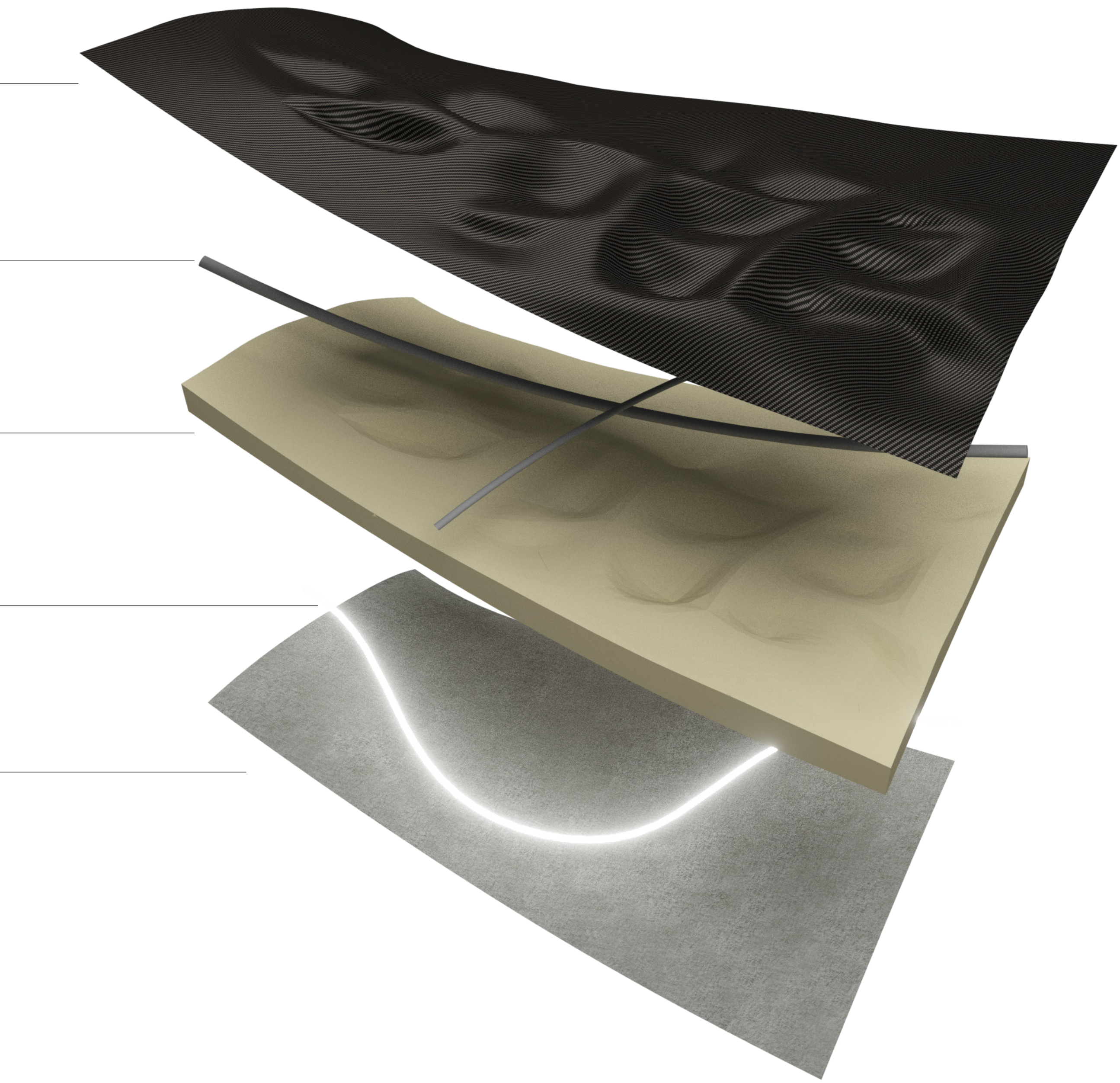
Integrated systems

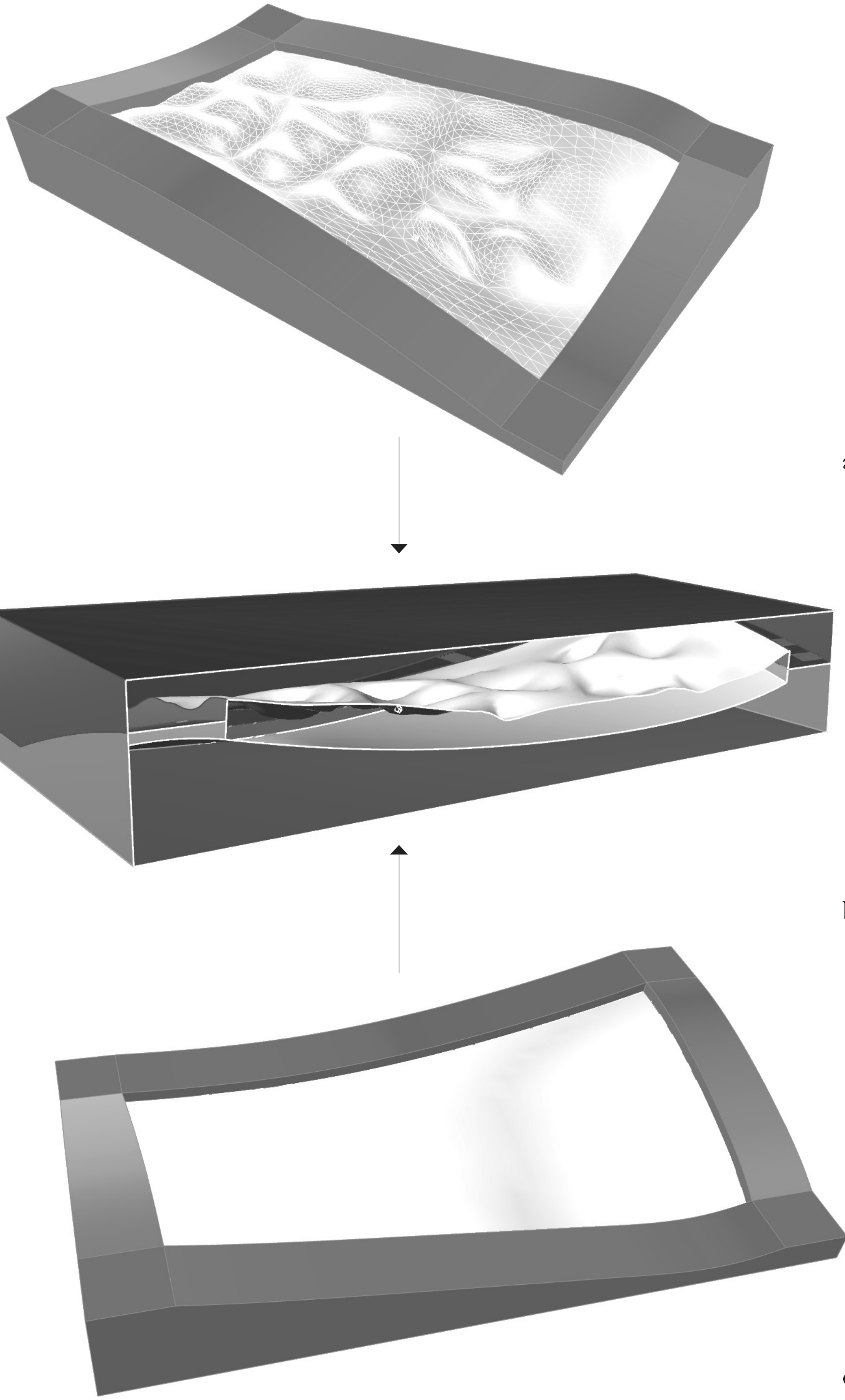
PUR foam

LED lighting system

Glass fiber reinforced laminate

Figure 22. *Exploded view of the sandwich panel. Additional white coating will be applied on both sides.*





a

b

c

5.1.2 | Mould model

After some reasoning on the best production method to choose, hand lay-up has been chosen as the most feasible in terms of fabrication possibilities and time/cost constraints.

Prepreg carbon fiber textiles would have been a good choice in terms of ease of lamination, mechanical properties, efficiency and aesthetics of the final component, but that would have required the use of an autoclave and, in conclusion, would have been too expensive. Another method would have been resin infusion, but the two laminates have different shapes and that would have required a custom filling panel with variable thickness.

Therefore, two moulds have been designed for hand lay-up of each FRP composite face (Fig.N a, c). Moreover, they have a shape that is studied specifically for allowing their overlapping, creating a closed block (Fig.N b). This box will have some holes to pour polyurethane inside the internal cavity once closed. PUR will expand and eventually escape from the same holes when it will have filled all the internal space.

Figure 23. *a: Mould for the CFRP part; b: Two molds coupled, ready for PUR injection; c: Mould for the GFRP part.*

5.2 | Fabrication

The prototype has been fabricated with the help of two companies based in Emilia-Romagna, Italy: Idesco for the moulds design and fabrication and Stilplast for composites production. Therefore, the fabrication process has involved two main stages which are illustrated below.

Mould production

Mould production is done by Idesco, a company based in Forlì, Italy.

The geometries of the two moulds are digitally generated starting from the initial 3d model as described above. The company chooses Medium Density Fiberboard (MDF) as mould material.

Then, the rough molds are assembled and milled by means of a CNC machine. Consequently, after a sanding with P220 sandpaper, a polyester primer is applied.

After the necessary treatments, the moulds are coupled, stacked together and prepared for transportation to the second company which will take care of the FRP composites production by means of hand lay-up.

Figure 24. *Top: MDF Mould before milling; bottom: CNC machine milling the two moulds.*

Figure 25. *Top: Sanding with P220 sandpaper; bottom: final moulds.*

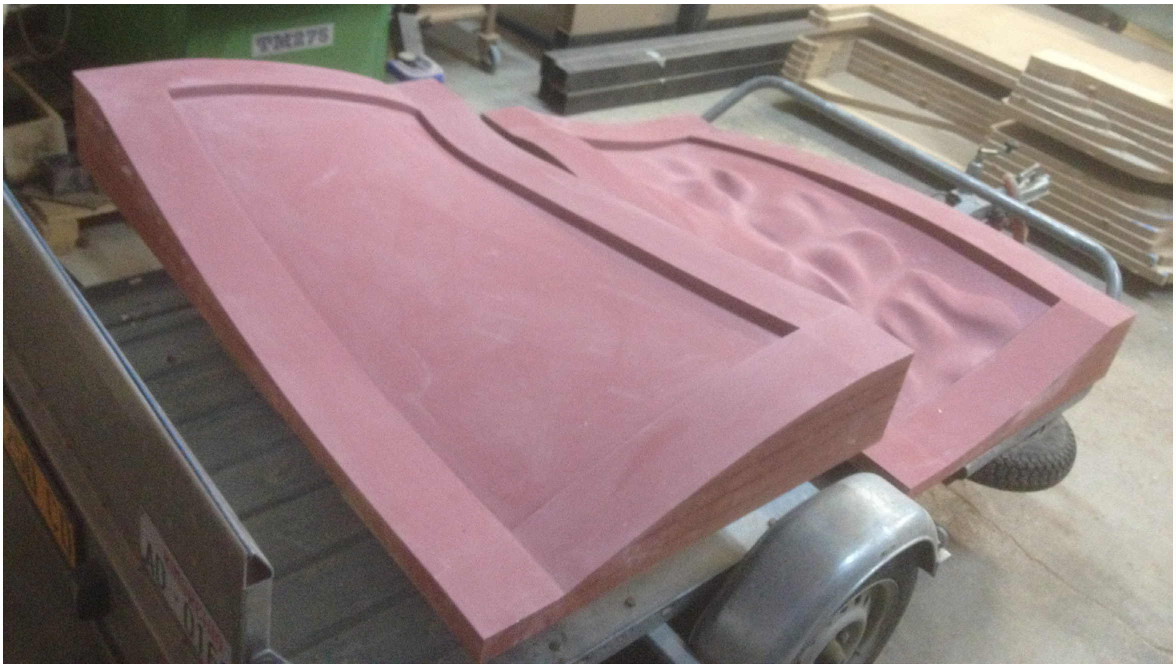


Figure 26. *Top: moulds with polyester primer; bottom: packing of the heavy moulds to be transported to the next phase*

Composite production

The second stage of production has been carried out in collaboration with Stilplast, a company based in Ravenna, Italy.

The first step is to treat the moulds surface with a release agent to help demoulding and avoid resin absorbtion by the mould; after that, we apply white gelcoat only to part of the first mould (the one for the carbon FRP composite). The day after, when gelcoat is dry, we start hand lay-up. CRFP is laminated in the first, corrugated mould, while GFRP is produced in the second mould. After a thin layer of non-fibrous gelcoat applied only to the sharper edges, dry reinforcement textiles are manually placed in the moulds with subsequent application of catalyzed resin. The technician impregnates fibers with a uniform distribution and right amount of resin and then uses rollers to debulk the various layers. In this stage, the laminator's skills are essential for the good quality of the final product. After the resin has cured at room temperature, system pipes are placed over the carbon mould, while a LED light strip is secured to the inner surface of the glass FRP. Consequently, the two moulds are coupled, secured together and placed in vertical position. Polyurethane in liquid solution is poured from the top inside the internal cavity between the moulds through three holes. In a few minutes it expands and escapes from the same holes at the top. Then, the prototype is demoulded. The glass FRP side is spray-coated with a thin layer of white gelcoat, so that when the LED is on, light can pass through the glass FRP skin and gelcoat. The carbon FRP, instead, is partially coated with transparent gelcoat. The borders are cleaned up and final refinements are made.

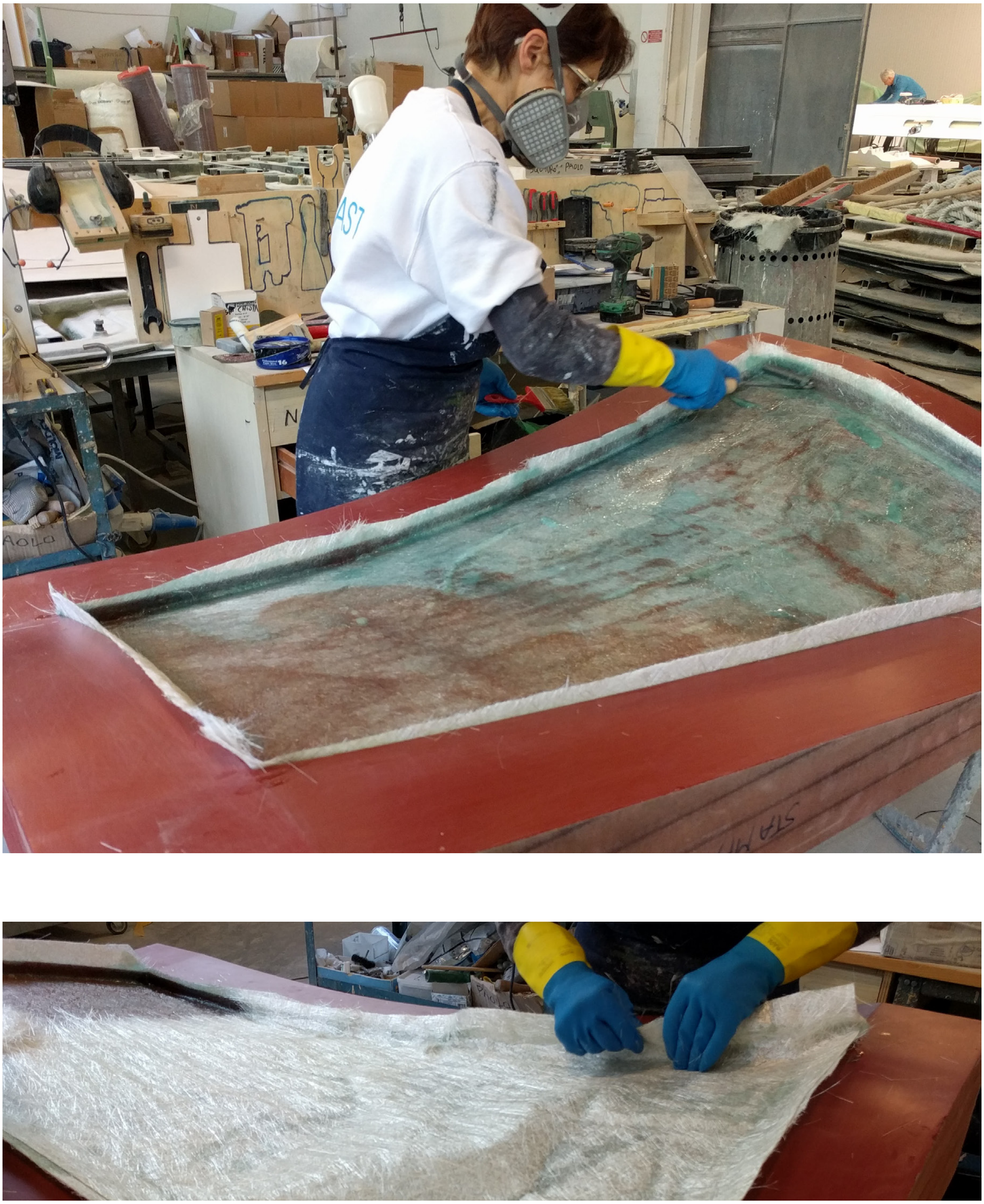


Figure 27. *Hand lay-up of glass fiber reinforced polymer*

Figure 28. *Top: after white gelcoat has been applied directly to the mould and is already dry, a special non-fibous gelcoat is applied only to the sharper edges, which are difficult to be reached by the roller; bottom: part of carbon fibre reinforced polymer applied over gelcoat.*

Figure 29. *Right: LED is attached to the inner face of the GFRP laminate; bottom: the two moulds are coupled.*

Figure 30. *Left: The two moulds are fastened and put in vertical position; bottom: polyurethane is poured inside the internal cavity from the top holes.*

Figure 31. *Right: Glass FRP and transparency test with thin layer of white coating; bottom: GFRP after opaque gel-coating, LED off.*

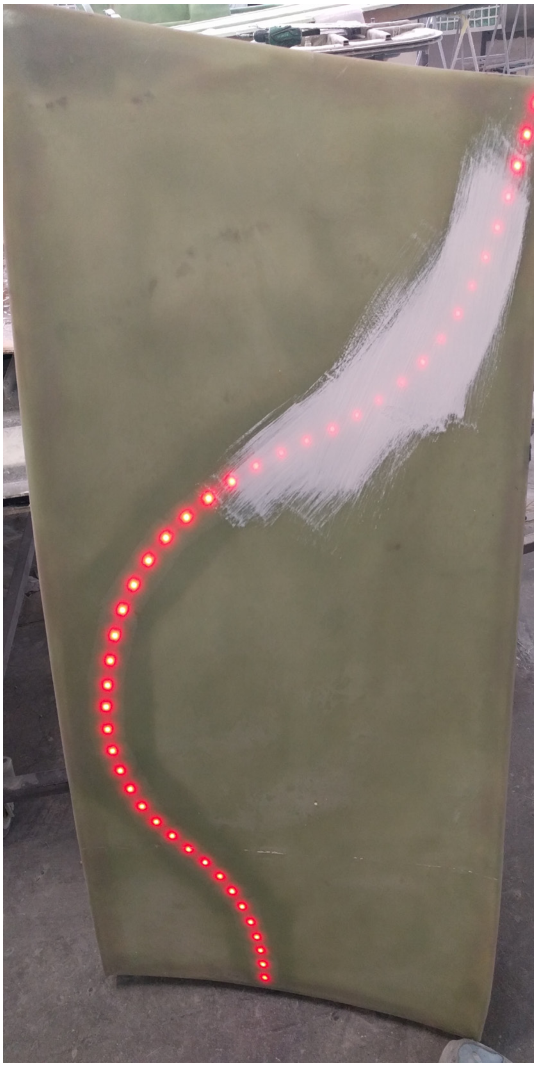


Figure 32. *Left: Carbon FRP, partially coated; bottom: CFRP after transparent lucid gel-coating.*

Sustainability

6.1 | Current practices

6.1.1 | What does "sustainable" means?

"Sustainability" is a very popular word in almost all disciplines nowadays. People have been using it so much in the last decade that it has acquired many different meanings and, at the same time, it has lost any possible sense. The main problem is mostly connected to its definition, which is vague and qualitative and essentially tends to express an idea, a sort of feeling which, by its own nature, tends to suit better to humanistic disciplines than scientific ones. Nonetheless, it is precisely to these same technical fields that this word applies.

The definition of sustainable development given in 1987 by the United Nations' World Commission on Environment and Development is: "development that meets the needs of the present without compromising the ability of future generations to meet their own needs". This definition is left intentionally vague, ready to be specified in many different situations and times; it introduces a sort of awareness about the topic, an appeal to moral duty, not a real rule or standard.

To overcome this problem, many have tried to define and propose a standard paradigm to quantify sustainability and express it with a number, a category or a rank. But, although climate change is undoubtedly one of the biggest threats we have to face in these years, sustainability is not just about environmental consciousness, energy savings and reduced carbon emissions. Sustainability primarily means holistic approach. This means that it has to encompass all different aspects of design: from economical to environmental, social and aesthetic considerations. But how to take into account all these aspects? How to reduce complexity and end up with a quantitative evaluation? When it comes to this kind of problems, for the sake of simplification many aspects are inevitably either neglected or taken for granted. Unfortunately, all the benchmarking systems we have today essentially reduce all this complexity to nothing more than a checklist.

Establishing a ranking system has another drawback: it creates a sort of market. In fact, nowadays sustainability "seems to have less to do with saving the world than it does with making money. Sustainability as it exists today has become a consumer commodity [12]". Being "eco-friendly" or "green" is a marketing strategy in first place for many companies and practices. This is not necessarily a negative thing because it adds a strong incentive towards the diffusion of awareness about these important topics. Problems arise when it comes to the so called phenomenon of "Greenwashing": companies that superficially claim to be "green" or "sustainable" without any tangible evidence of environmental concern. Here, we come back to the necessity of a standard, a reliable system to guarantee and define eco-conscious practices.

The contradiction between this need and the impossibility to reduce complexity to a single number has to find a new balance; that is why researches about new sustainability paradigms are still in progress today.

6.1.2 | LEED Rating System

One of the most popular forementioned benchmarking systems is LEED: Leadership in Energy & Environmental Design. According to the official website [13], around 1.85 million square feet are certified with this system daily. This is a growing trend as in the U.S. the rate of green buildings in the construction industry is rapidly increasing: in 2005 only 2% of nonresidential buildings were "green", 12% in 2008 and 28-35% in 2010 [14].

LEED is a framework developed by the U.S. Green Building Council (USGBC) for "identifying, implementing and measuring green building and neighborhood design, construction, operations and maintenance [15]". According to USGBC, the main goals that LEED aims to encourage in the construction industry are:

- Fight climate change;
- Protect water resources;
- Enhance human health and well-being;
- Enhance biodiversity;
- Promote sustainable material resources cycles;
- Build a greener economy;

- Social equity, environmental justice, community health and quality of life.

LEED Certification Process

When a project team decides to undergo the LEED Certification process, it needs to carry out an initial research in order to gather sufficient information on the project and discuss the desired goals.

Then, the team has to choose the right Rating System that suits their project type. The possible project categories are:

- Building Design and Construction;
- Interior Design and Construction;
- Building Operations and Maintenance;
- Neighborhood Development;
- Homes.

Choosing between different Rating Systems can be a difficult task when more than one category seems to apply. In this case, LEED proposes the 40/60 rule (Fig. 33): a Rating System can be assigned to each square meter of the building gross floor area; the Rating System which is valid for more than 60% of gross floor area is the one that must be considered for the whole building. In case the percentage is be-

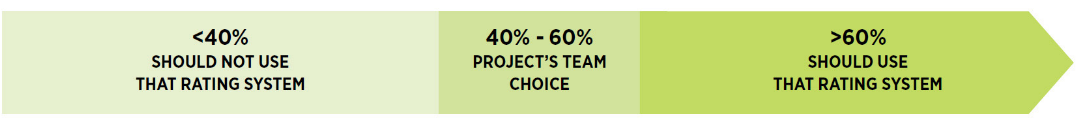


Figure 33. *LEED 40/60 rule: Percentage of floor area appropriate for a particular Rating System [15].*

tween 40% and 60%, it is up to the project team to decide [15]

Once the Rating System has been chosen and the project has been registered, the project team decides which credits are going to be pursued, along with all the related requirements and prerequisites. Each credit gives a certain amount of points which are added up at the end, representing the final score. Goal-setting workshops are advisable for the team members and the owner. Anyway, all projects must comply with the minimum program requirements (MPRs) of the chosen rating system in order to be considered appropriate to pursue LEED Certification.

Then, project documentation is submitted for certification and preliminary and final reviews are carried out. The preliminary review gives some technical support in order to improve the desired credits, while the final one releases the score and certification level. LEED has four levels of certification:

- Certified (40 to 49 points);
- Silver (50 to 59 points);
- Gold (60 to 79 points);
- Platinum (80 or more points).

Figure 34. *LEED levels of certification.*

6.2 | Preliminary evaluation

In order to be able to argue about the concept of sustainability applied to the present project, the author tries to analyze the logics of LEED Protocol and carry out a preliminary evaluation in order to verify the present project eligibility for starting this process. Anyway, it is important to note that this is just the first step and that a complete LEED Certification is out of the scope of this Thesis.

LEED Building Design and Construction (BD + C) is the Rating System that best suits the project type. This in turn is divided in eight different types:

- New Construction and Major Renovation;
- Core and Shell;
- Schools;
- Retail;
- Data Centers;
- Warehouses and Distribution Centers;
- Hospitality;
- Healthcare.

New Construction and Major Renovation is chosen for this project as it is considered as an independent building. The aim is to assess the pavilion project by itself, not in conjunction with the existing building. Although the latter is a building with educational purpose and so the category could be “Schools”, the new space is not a learning space as traditionally intended.

Given these assumptions, relevant prerequisites and credits are examined with their relative weight. They are organized as following:

- Integrative Process;
- Location and Transportation;
- Sustainable Site;
- Water Efficiency;
- Energy and Atmosphere;
- Materials and Resources;
- Indoor Environmental Quality;
- Innovation;
- Regional Priority.

Integrative Process is a single credit which comes before all the other categories and is applied to all the BD+C types.

Minimum Program Requirements

The Minimum Program Requirements (MPs) are the basic requisites a project has to fulfill in order to be eligible for LEED Certification process.

First of all, the project has to “be in a permanent location on existing land” [N4]. This means that it is important that the building is a permanent structure and will never move in any different location. The pavilion is permanent, but highly pre-fabricated. In this case, LEED lays down that it may be certified only once it will be permanently installed [N4]. Moreover, it has to be constructed on existing land, so that it does not create any artificial land mass that could be harmful for ecosystems.

Second, it "must use reasonable LEED boundaries" [N4]. Establishing the project boundaries is essential in order to define what components of the surrounding space might influence the new construction and vice-versa and decide whether they should be included or not. For example, land modified by the construction and features used mainly by the project occupants, such as parking lots, shower facilities, other buildings and so forth. The latter, in particular, can be included only following the USGBC's multiple building guidance. In total, the project gross floor must be no less than 2% of the project boundary gross area. In the specific case of the pavilion: "An addition to an existing building may certify independently, excluding the existing building in its entirety. Alternatively, the addition and the entire existing building may certify as one project [N4]".

Third, it "must comply with project size requirement [N4]". In practice, for BD+C the project gross area must be more than 1000 square feet (93 square meters). The pavilion gross area is bigger than 93 square meters.

Therefore, the pavilion is appropriate for starting a LEED Certification process.

Credits and Prerequisites

All the possible prerequisites and credits for BD+C - New Construction have been organized in Fig.34

NDL: LEED for Neighborhood Development Location
SLP: Sensitive Land Protection
HPS: High Priority Site
SD: Surrounding Density and Diverse Uses
AQT: Access to Quality Transit
BF: Bicycle Facilities
RP: Reduced Parking Footprint
GV: Green Vehicles

OW: Outdoor Water Use Reduction
IW: Indoor Water Use Reduction
BWM: Building-Level Water Metering
OWR: Outdoor Water Use Reduction
IWR: Indoor Water Use Reduction
CT: Cooling Tower Water Use
WM: Water Metering

MAQ: Minimum Indoor Air Quality Performance
ETS: Environmental Tobacco Smoke Control
EAQ: Enhanced Indoor Air Quality Strategies
LEM: Low-Emitting Materials
CAQ: Construction Indoor Air Quality Management Plan
AQA: Indoor Air Quality Assessment
TC: Thermal Comfort
IL: Interior lighting
DL: Daylight
QV: Quality Views
AP: Acoustic Performance

SCR: Storage and Collection of Recyclables
CWP: Construction and Demolition Waste Management Planning
BIR: Building Life-Cycle Impact Reduction
EPD: Building Product Disclosure and Optimization -- Environmental Product Declarations
SRM: Building Product Disclosure and Optimization -- Sourcing of Raw Materials
MI: Building Product Disclosure and Optimization -- Material Ingredients
CWM: Construction and Demolition Waste Management

FC: Fundamental Commissioning and Verification
MEP: Minimum Energy Performance
FRM: Fundamental Refrigerant Management
EC: Enhanced Commissioning
OEP: Optimize Energy Performance
AEM: Advanced Energy Metering

CAP: Construction Activity Pollution Prevention
SA: Site Assessment
PRH: Site Development - Protect or Restore Habitat
OS: Open Space
RM: Rainwater Management
HIR: Heat Island Reduction
LPR: Light Pollution Reduction

IN: Innovation
LAP: LEED Accredited Professional

RP: Regional Priority

IP: Integrative Process

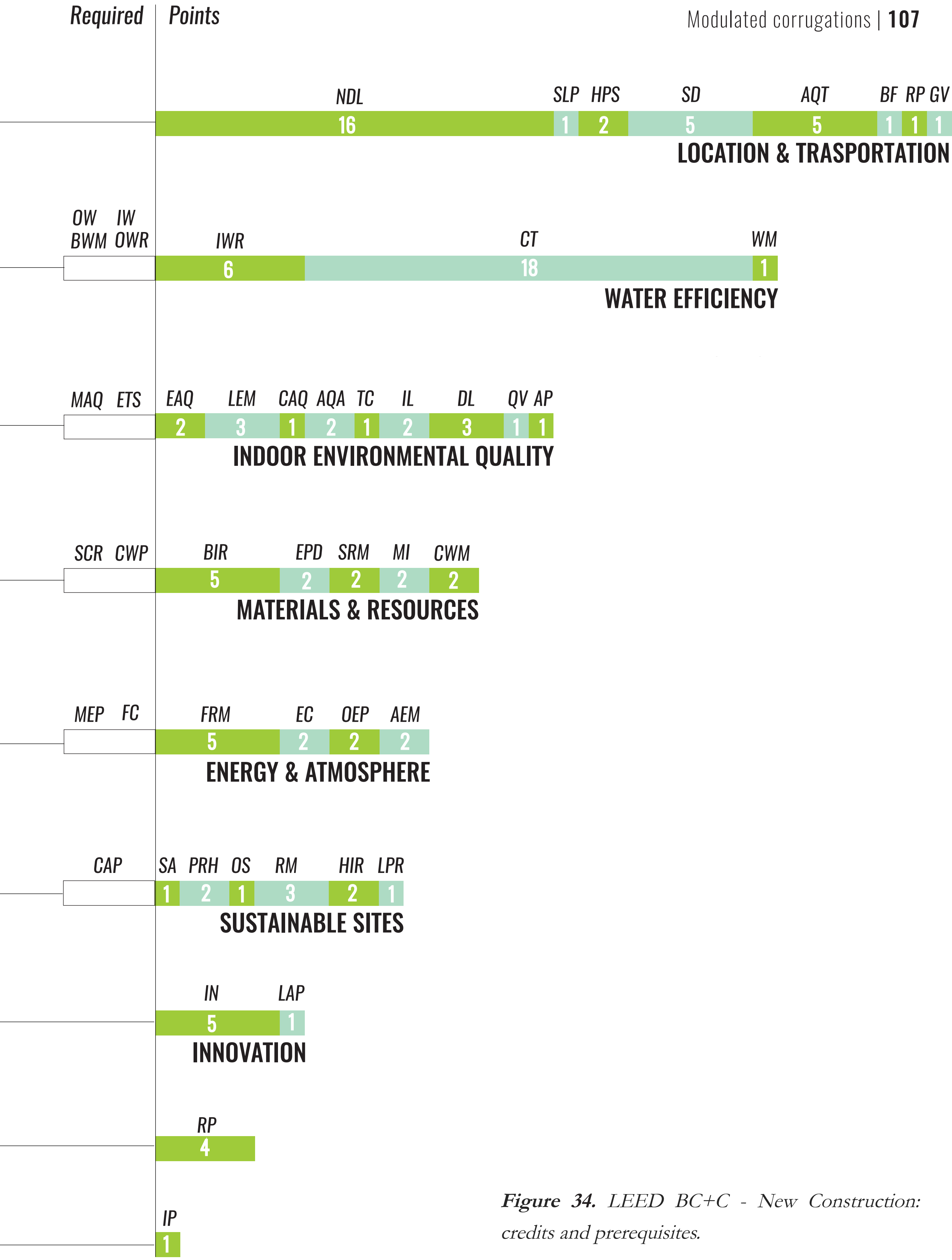


Figure 34. *LEED BC+C - New Construction: credits and prerequisites.*

in a way that it is easy to understand the relative importance of each category and, at the same time, the weight of each single credit or prerequisite. This can serve as an overview, a starting point to be used at the beginning for initial planning of which credits will be pursued and how.

6.3 | New paradigms

The concept of ecology, intended in its wide sense of system of inter-relations among organisms and parts, is particularly useful in order to bring the holistic approach to sustainability one step further.

We normally see optimization as a good thing, and we would like to optimize all the different aspects of buildings. We want the less use of material possible, the best solar gain in winter, the perfect photovoltaics orientation and so on and so forth. The problem relies in the concept of integration itself and in understanding that all the different aspects and parts belong to the same ecology. So, efficiency has no meaning if we talk about all the single aspects separately and evaluate them one by one. In a really integrated logic, optimizing the single parts makes little sense with respect to what can arise from a good interaction and collaboration between the different parts.

LEED, as well as other protocols, claim to be holistic and to consider all the aspects of a project. In the reality, it neglects many important aspects, such as economic factors or aesthetics and sense of well-being, which are essential in everyday life and go beyond air quality or comfort. But the most important fact is that it reduces an entire ecology of interrelations among systems to a mere checklist.

The whole is not the sum of the different parts, each one with its score. Instead, the total evaluation should consider primarly the inter-connections between all the different requisites and should give a value to "good" interactions and penalize conflicts. The overall result may be a compromise, but still much more valuable than the sum of "optimized" single parts. Less-efficient components which perform more than one function or functions performed by more than one component, all these possibilities are reduced to zero in a check list.

This is a really complex topic and much effort has to be done in order to develop a new paradigm, which could give the opportunity to operate a radical, positive shift from current trends of climate change. LEED, with its diffusion worldwide, has undoubtedly increased social awareness on these topics. But it is still not enough.

Conclusions

This research has investigated how a new concept of "integrated tectonics" can be developed from the use of fiber-reinforced polymers (FRP) and integrated systems in architecture. The morphologies of the FRP shells are created considering the material properties and taking inspiration from research on tissues differential growth. The resulting corrugations and patterns are qualitatively evaluated in terms of aesthetics, functionality, structural and energy performance.

In particular, dynamic energy simulations are carried out to assess the overall behaviour of the pavilion. Moreover, a prototype has been fabricated in order to show material properties and possibilities of FRP in architecture.

In conclusion, the author argues about the concept of "sustainability" and gives an overview on the LEED rating system. The aim is to discuss values and defects of current systems and try to propose a new approach to this subject, based on the concept of ecology.

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