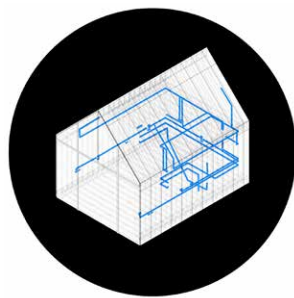


FABFIELD



*a new approach to
building services design*

Peggiovà...

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INTRODUCTION

The building industry was one of the very first industries to sprout and has evolved dramatically throughout the centuries, from the first muddy or wooden shelters, depending on the location, to nowadays' mega structures which seem to grow taller and more complex every year. The technologies, tools, machines and professional subjects involved in the construction of a building are multiple and make the building process very intricate and hard to manage and predict with accuracy; it is currently very likely for any construction to have consistent delays and consequent increased construction costs, mostly due to problems related with delivery of materials, unfavorable weather conditions, accidents in the construction site, problems in the original design that need to be solved during construction and so on. Meanwhile, other industries such as automotive, aircraft, shipping and IT have sprouted in the last century and have evolved to become incredibly efficient in the design and production of their final goods, thanks to the different approach they adopt compared to the traditional building industry.

Nonetheless, efficiency in the construction is not the only issue as another problem has been raised and became more and more important over the last decades: sustainability. It is nowadays of vital importance for the building industry to evolve and become more environmentally friendly and aware in order for it to survive as more and more laws and regulations are determining new high standards on this matter; The EU directive on energy performance of buildings requires for all new constructed buildings to create all the energy they consume from renewable sources directly on site, by 2020 (Lenz B. et al, 2011).

New regulations set up new restrictions that the industry will necessarily need to meet in order to stay afloat; nevertheless they do not constitute the only reason for drastic changes in the traditional construction process. Due to the high initial investments for the construction of buildings, the latter are built to last for a very long period (at least 30 years) in order to pay back the large costs; furthermore, the life cycle and end of life of buildings should be reviewed. In fact, traditional constructions usually end up being demolished in a time, money and energy consuming process that is disadvantageous for both the environment and the final profit of investors. We currently live in a society that keeps evolving at a faster and faster pace, changing our needs, standards and requirements at the same rate; the traditional, rigid, building industry doesn't seem to be able to keep up with this pace and needs to evolve so that modern buildings can finally get rid of the afore mentioned flawed processes.

PREFABRICATION

A huge step towards the optimization of the building process would be to follow the path that other successful industries have already gone through: industrialization. Prefabrication of buildings has already been tested since the industrial revolution, when the casting of iron components enabled the prefabrication of entire buildings which would then be shipped to British colonies. In 1833 the Balloon frame system was introduced in America and is still largely used throughout the country (fig.0.1), constituting one of the first and perhaps most successful examples of efficient prefabrication. The modernist movement, with influential architects



Fig.0.1 *The balloon frame system used in a modern project by the University of Lausanne, Switzerland; the building system was introduced in the 1930's by George W. Snow and has fostered the construction of entire American cities in the 20th century: "In the second half of the 20th century 60-80% of the whole US housing stock was based on the balloon frame system". (Vogler, A., 2015)*

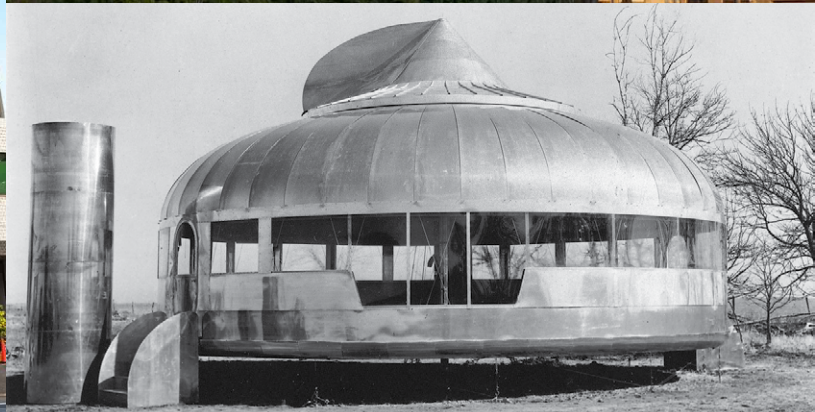


Fig.0.2 *On the left: Nakagin Capsule Tower by Kisho Kurokawa, Tokyo, 1972; in 2006 when demolition was being considered, it was estimated that renovation would require around 6.2 million yen per capsule. Top right: Habitat '67 by Moshe Safdie, Montreal, 1967; despite its problems, Habitat's fame and success made Safdie's reputation and helped launch his career. Bottom right: Wichita house by Buckminster Fuller, Wichita, 1947; the house is fully restored and permanently displayed in an indoor environment at the Henry Ford Museum in Dearborn, Michigan.*

like Van der Rohe, Gropius and Wachsmann, also focused on the prefabrication of buildings until WWII broke the cultural and technological development of an entire continent. The US then witnessed a period of massive prefabrication of houses, right after the second world war, when soldiers were coming back home from Europe. Many other studies and examples have subsequently been developed, buildings such as the Wichita House by Buckminster Fuller (1947), Moshe Safdie's Habitat (1967) or the Nakagin Capsule Tower by Kisho Kurokawa (1972) represent the attempts to experiment with extensive prefabrication in a period in which the architectural academy was deeply interested in the subject, trying to imagine futuristic scenarios of an ever increasing industrialized world; another extreme example is the Plug-in city project by Archigram, where the whole urban environment can be programmed and structured for change. "The steel mega-structure supported a series of detachable living and working units that could be maneuvered by cranes and responded to a hierarchy where the parts of the building that would need to be serviced and replaced more frequently, were most accessible" (Cook A., 1972).

Nevertheless, these pioneering projects were never more than mere experiments and the traditional building process never really left place for the industrialization of buildings to fully flourish.

CURRENT MARKET

The building's prefab market is nowadays experiencing different phases and grades of success according to the context: The US have a well established market mainly based on fully

prefab wooden movable houses, Japan is also a context in which prefabs have been able to affirm themselves thanks to a largely automated process as well as a homogeneous market; on the other hand, Europe still constitutes a very diverse market in which mainly small, national industries are able to establish themselves, and usually stay confined by their national borders. The diversity of customs and requirements of each European country prevents the development of any centralized European Prefab industry with standardized regulations, materials and customs.

Another conflict that one might think could disrupt the full integration of industrialized buildings is the possible fear of designers to remain job-less due to an extended standardization of products. Vogler A. (2015) states that: "talking about industrialized buildings, it does not seem that the conflict between architects and the industry is the problem. No single profession has been promoting industrialized building like the architects. No other profession has been blaming itself for the poor design quality of the environment like the architects either. However, architects would not lose much business, if houses were industrialized. Less than 5% of the 150.000 detached and semi-detached houses built annually in Germany are planned by an architect. The market does not want architects."

In an industry that struggles to accept changes but dramatically needs them in order to be able to satisfy regulations and ever changing market's requirements, FabField is yet another effort to promote a building system that approaches the design and construction of buildings differently,

implementing processes that traditionally belong to the manufacturing industries rather than buildings', in order to increase efficiency, quality and sustainability. The struggle to improve the traditional building process through industrial methods has been done many times in the past and is still being experimented in a myriad of different approaches that vary in scale, materials, context and goals.

FABFIELD

The FabField system is based on the CNC milling of OSB elements into specific shapes that allow to form box-like components, filled with insulating material, making up the four main components of the building system: beams, walls, roof and floor. The concept has been ideated by Pieter Stoutjesdijk and has been updating ever sincethrough further studies and theses which have been analyzing and developing the structural connections between components and the technology for CNC milled, demountable facade panels; this thesis focuses on the development of a system that integrates the required building services in FabField, perpetuating its core characteristics, namely modularity, short construction time, low-costs, efficiency, light-weight components and demountability through digital fabrication methods considering life cycles of different components and end of life strategies for the latter.

PROBLEM STATEMENT

A building system is provided; it is based on digital manufacturing techniques that make it sustainable,

cheap, safe and easy-to-build as well as modular and accurate in the production. Nevertheless, a system to efficiently integrate the required building services still needs to be developed for the latter building system. In 'traditionally' procured construction projects, building services and architectural design are not integrated. In most cases construction is well under way before any thoughts are given to the building services design. Building services engineers are often not provided with an up-to-date structural design and this leads to delays, errors and changes in the services design due to restricted spaces. The ideal scenario would be for the architectural, structural and services' design to work in parallel, with equal priority and with as much integration as possible; still, this does not correspond to the current situation and needs to evolve as soon as possible in the traditional building industry.

By moving the building services design in the front-end of the design process, forcing the strict collaboration between architect, engineer and services engineer, the issue can be tackled.

SUB-PROBLEMS

The main problem can be divided as two sub-problems:

- Traditional construction and design processes force most of the decisions regarding the distribution of building services to be taken on site, which lead to often destructive operations in order for the services to flow with consequent losses of time, energy and final quality of the outcome. Ducts, pipes and cables are also placed without any previous direction, often leading to situations in which the workers



Fig.0.3 The images above display the CNC milling machine used to process the building elements into the building components which are fully assembled at the factory; later transported on site and assembled by hand without the need of any crane. (own illustration)



Fig.0.4 The FabField building system has been tested in the construction of the PDLab, currently exposed just outside BK city (Bilow M., 2017).

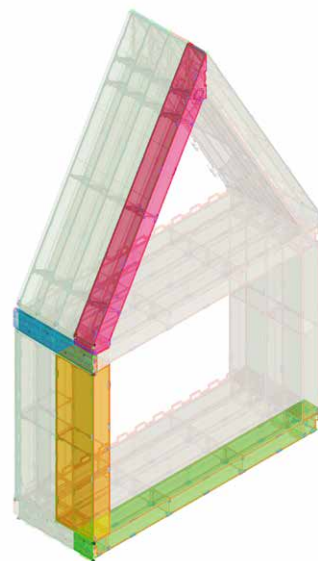


Fig.0.5 The scheme shows the four main building components of the system: floor, wall, roof and beam component (own illustration).

themselves make design changes in order for the latter to fit in the available space. The integration of cables, ducts and pipes through the building system is still required, especially since the prime objective of the FabField is to solve most of the problems in the early design phase in order to reduce construction time and ensure quality of the final product.

- Traditionally the structural part of the building is dramatically divided from the services' part. Furthermore, the finishing layers of traditional buildings are also independent from the latter parts and are, in most of the cases, impossible to disassemble without destructive operations. Digital fabrication techniques along with extensive early design considerations about the integration of structural, services and finishings aspects can lead to buildings in which all layers are integrated.

OBJECTIVE

The final objective of the graduation project is to tackle the lack of a system that integrates building services design in the FabField; special attention will be given to product development and digital manufacturing aspects in order for the final result to be in line with the overall concept developed by Pieter Stoutjesdijk, perpetuating the goals regarding off-site approaches, easy assembly and disassembly of components, digital fabrication techniques and end of life strategies.

SUB-OBJECTIVES

The main objective will be pursued by dividing it

into three sub-objectives:

- The design of a system for the methodical distribution of cables, ducts and pipes through the building system, maintaining its previously mentioned core aspects.
- The re-design of the already existing building components in such a way that they can flexibly accommodate cables, ducts and pipes for small family housing scenarios.
- The display of possibilities for the interior finishing layers of the building that can facilitate the assembly/disassembly of the latter, reducing times on site and embedding final interfaces of building services.

RESULTS

The results comprise:

- Design and methodology research and conclusions
- Study of precedents and subsequent determination of a representative case study
- Market survey and subsequent determination of most suitable energy producing technologies for the building system
- Study and determination of a commodious distribution system which suits different sizes and arrangements of the building within the function of small family housing
- Re design of the main components for the distribution of cables, ducts and pipes through the building system
- Directions for the design of partitioning walls for the distribution of cables, ducts and pipes through the building system
- Directions for the design of the interior

finishing layers for the flexible integration of final interfaces of building services and appliances (flush boxes, plugs, air vents, ventilation units, TV etc.) with the latter

- Prototyping

BOUNDARY CONDITIONS

The building system already exists and this already constitutes a major constriction for multiple aspects:

- The design of the basic components has already proved to work, therefore the possibility of major changes in the design, manufacturing process and materials of the latter will not be considered in order to keep the final scope feasible in the given time.
- The digital fabrication method used by Pieter Stoutjesdijk in the lab makes use of a CNC milling machine, the tests and prototypes are carried out with the same machine which is therefore considered as a boundary condition for manufacturing components.
- The building system has some shape constrictions given by the manufacturing method, design and materials used, such as the fact that curved walls or roofs are not yet envisaged.
- The size and connection between building components has been previously determined. Recent thesis by K.Gunawan further studied it in detail and concluded with a final design based on structural calculations which will be hereof considered as fixed.
- The whole concept of the FabField is based on certain core aspects that necessarily need to be kept and considered as boundary conditions,

namely weight limitations of components, demountability aspects, flexibility, modularity, end of life strategies and short construction times.

- Both global and local regulations are clearly heading towards a sustainable future, reason why only the most sustainable energy producing technologies will be considered, leaving out of the scope gas fueled boilers and coil based technologies in general.

Size, location and climate also had to be restricted in order for the subject to be treated properly in the given time:

- Gunawan's thesis focused around the structural flexibility of the system, analyzing the size range of the building in height, width and length, concluding that the current system should not go higher than 2 floors.
- The maximum width of the building is restricted by the current production method: the CNC milling machine cannot process elements longer than 5200mm, which is hereby the maximum width considered.
- Location affects climate, which in turn affects building services requirements; in order to restrict the scope the climate considered will be the Northern European climate, which leaves out of the scope cooling systems.
- The function of the case study will be single family housing. The decision is based on the small size that the system allows and a brief market research that demonstrated the sprouting and increasing demand of this typology in the Netherlands.

RESEARCH QUESTION

How can building services be integrated in the FabField building system in such a way that the core values (digital fabrication, low-costs, high accuracy, light weight components, demountability, end of life strategies and short construction times) are perpetuated?

SUB-QUESTIONS

The main research question will be answered through three sub-questions:

- What is the best way to distribute building services such as cables, ducts and pipes through the FabField building system in a small family housing scenario?
- What is the best way to integrate cables, ducts and pipes in the components of the FabField system, maintaining its already mentioned core aspects?
- What are the possibilities for the interior finishings of the building so that the latter can integrate services' final appliances, reduce time on site and facilitate assembly and disassembly?

In order to answer these questions, some background questions are suggested:

- What is the state of the art of the building services industry?
- Is it possible to assess the best energy producing technologies for varying contexts in

the FabField building system?

- What is the best way to distribute services (cables, ducts and pipes) through a modular building system?
- What is the best way to integrate cables ducts and pipes in the pre-designed components as well as in partitioning walls of the FabField building system?
- Can interior finishes be designed in such a way that services and appliances can be integrated in them?
- Can some principles by manufacturing industries such as automotive, aircraft, IT and shipping be borrowed and exploited in the building services design for the FabField system?
- Is it possible to consider all the building services design in the front-end of the process so as to dramatically reduce times on site and facilitate the building process?

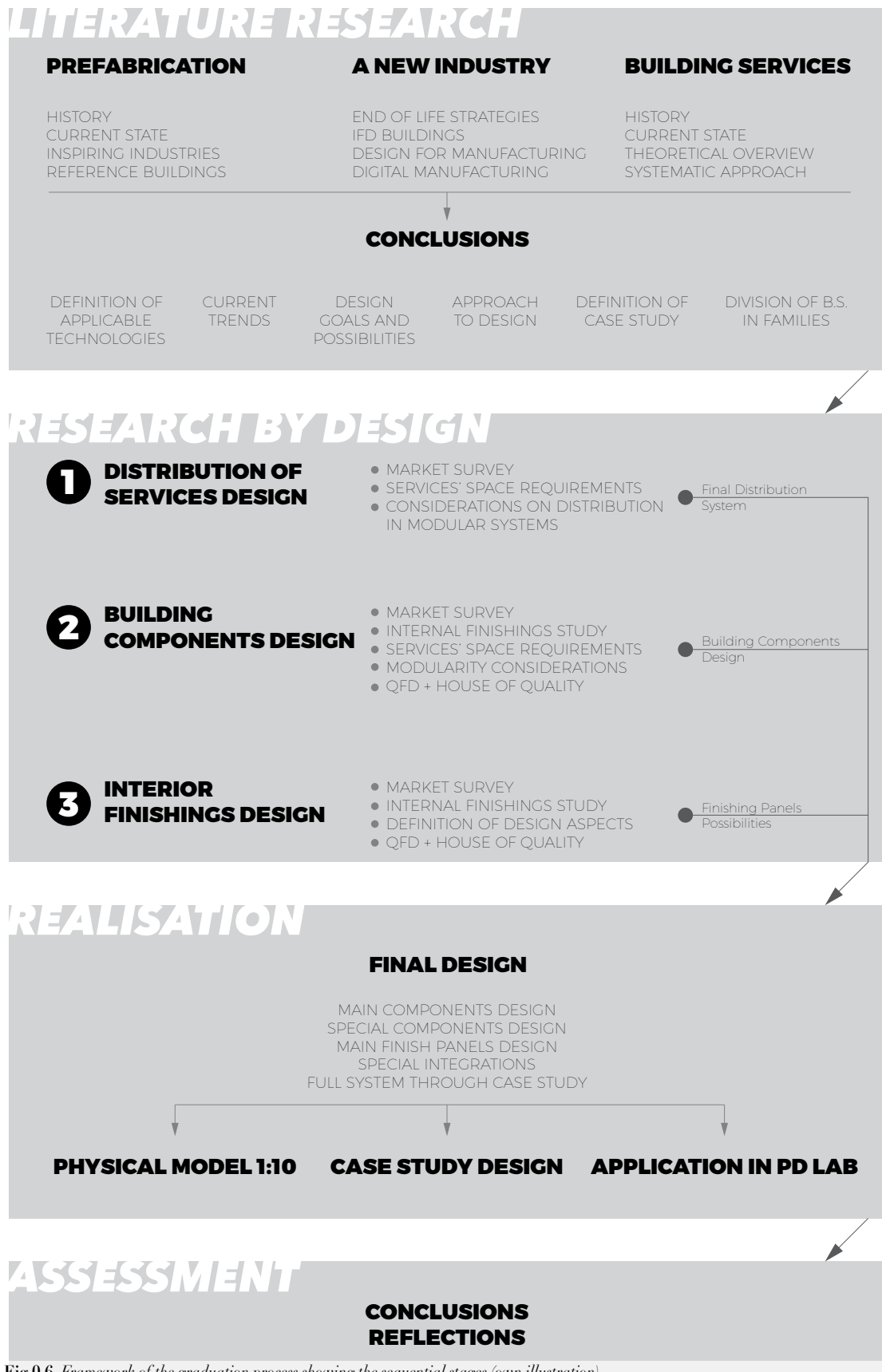


Fig.0.6_Framework of the graduation process showing the sequential stages (own illustration).

PREFABRICATION

The benefits of industrialization and prefabrication of buildings had been misunderstood and restricted to cost savings and fast construction, without considering the possibility of flexibility, future modifications or end of life scenarios, aspects that are becoming more and more important as nowadays' expectations for a building have largely changed: sustainability, energy efficiency, spatial flexibility and future uses are aspects of great importance in modern architecture. Understanding the true potential of industrialized building would bridge the gap between human prosperity and environmental efficiency, which is the essence of a sustainable future. Many outstanding architects such as Fuller, Gropius, Wachsmann, LeCorbusier etc. have tried to lead the way towards the industrialization and serial production of housing in the 20th century, unfortunately none of them succeeded in the task for different reasons, comprising the alteration of the social context, economic problems and even simple misunderstandings with their contractors.

Even nowadays, if one was to look at modern row single family housing, the thought that they were factory made would certainly pop into one's mind. However, they are all actually built on site, with all the disadvantages that come with it: weather dependency, high costs, time-consuming and subject to risks, defects and delays. Most successful products such as cars, ships, planes, computers, phones and so on, owe their prosperity to the perks of manufacturing methods; why doesn't the construction industry exploit the same advantages? Most of the prefab housing industry was established in the 1960's but none of the companies has a grade of industrialization comparable to the one of cars,

computers, planes or ships. We still build and live in houses through an obsolete on-site process that creates final products which are, qualitatively speaking, not even close to what we could achieve through serialization. Of course this would revolutionize an entire industry that has proven to be extremely resilient in the past years, decades and centuries, abiding numerous crises throughout history. Such transformation would require the collaboration of subjects that, historically speaking, have not been proven to get along with each other very well: designers and industries. "Observers of current and future trends predict that the 21st century is the beginning of an era that will be defined by temporary, multi-functional, and virtual organizations. The nature of working and living will change drastically such that society will require completely new types of structures" (Durmisevic, E., 2006).

Now more than ever the traditional building industry needs to finally shift towards the future to solve many problems, like housing for the poor, rising immigration waves, energy efficiency, sustainability and re-use of materials; I believe the past has proven that a step towards a solution could be the integration of production chains with architects to create high quality buildings that are flexible in uses and functions, easy and fast to build and transport and can even have a second life after their first purpose has been carried out.

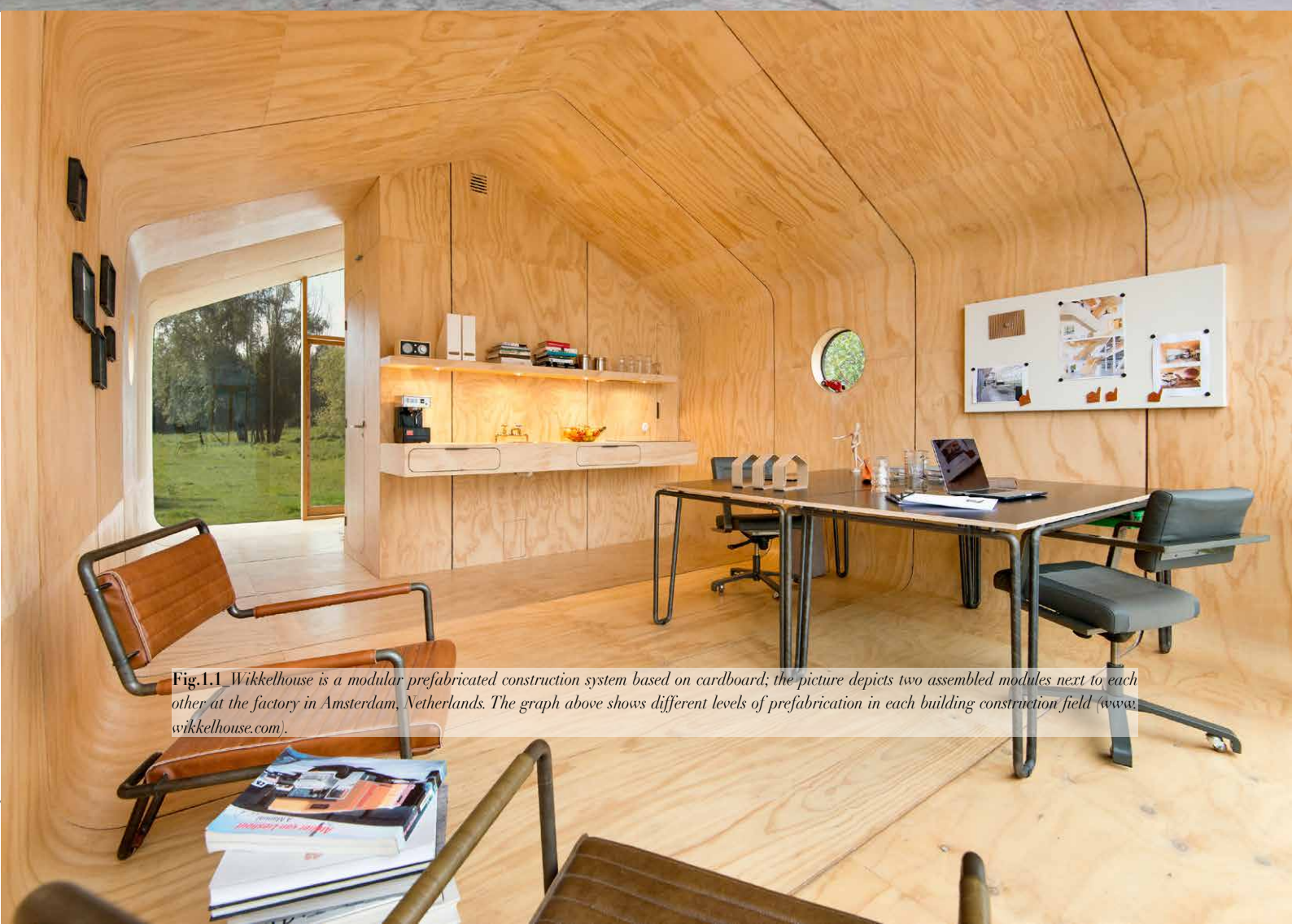


Fig.1.1 Wikkelhouse is a modular prefabricated construction system based on cardboard; the picture depicts two assembled modules next to each other at the factory in Amsterdam, Netherlands. The graph above shows different levels of prefabrication in each building construction field (www.wikkelhouse.com).

1.1 ORIGINS OF PREFABRICATION

The Merriam Webster dictionary defines the term “prefabrication” as: the fabrication of parts at a factory so that construction consists mainly of assembling and uniting standardized parts. If we neglect the part that restricts prefabrication taking place at factories only, then the first examples of the practice dates back 400.000 years ago, when humans could still not settle in a fixed location but had to keep moving in order to find food and escape from rigid weather conditions. “To avoid having to search for the required building materials after each and every change of location, the nomads collected materials which could be quickly and easily assembled, after a time dismantled and simply taken with them” (Staib, Dörrhöfer, Rosenthal, 2008). The chosen materials had to be obviously light, the elements reasonably modular and excessively small pieces had to be avoided.

With the advent of cropping men were finally independent from hunting and the first fixed settlements started to appear; architecturally speaking, a huge event was brickwork: wooden forms were used as form-work to pour clay into, which would subsequently dry in the sun and form the first examples of bricks, which can in turn be considered the first artificial, standardized building blocks (Fig.2.3). Stone also played an important role in standardization: in building their temples, ancient Greeks applied mathematical rules to maintain certain proportions from the building scale to the single stones, which were processed with such precision that they could fit together with razor sharp accuracy and then connected with bronze or iron clamps.

Romans would also use stone, as well as bricks and

concrete, to build their buildings; the empire was so vast that they had to set precise rules according to which the most representative buildings would have to be built throughout the empire. The Ten Books on Architecture by Vitruvius, from the first century B.C. established themselves as the foundation for the development of construction and contained instructions for modular building systems employing stone elements, which could be used to build temples in farflung colonies. (Staib, Dörrhöfer, Rosenthal, 2008)

Wood has also had a major role in the history of standardization. The first systems were very simple and consisted in leaning two logs against each other and cover them with stray or similar materials, over time these systems evolved to turn into the frame system, which had many variables according to the context but nevertheless survived until modern days. In fact, one of the first examples of “modern” prefabrication is the “balloon frame system”, introduced in 1832 by George W. Snow. It was an upgrade of the already-existing timber framework structures, the main difference being the replacement of posts and beams with timber studs placed at close distance from one another (Fig.2.4). The cross-section of the elements was standardized, the nails used for connecting them were industrially produced and the logs were easily reproducible with simple saws; these reasons contributed at making this system so popular and still being adopted nowadays in the United States. In 1855, The New York Tribune reported that without the balloon frame system, neither Chicago nor San Francisco would have been able to grow from villages to cities within one year; estimates say, that in the second half of the 19th



Fig.1.2 Ancient clay bricks can be considered the very first examples of modularisation and prefabrication of history; wooden frameworks were used to pour clay and subsequently let it dry in the sun to create solid construction elements (www.pinterest.com).

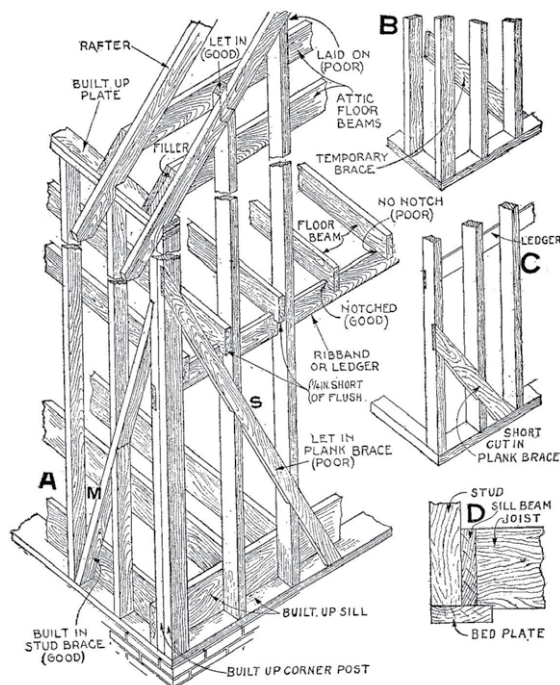


Fig.1.3 The image shows a schematisation of the balloon frame construction system which sprouted in the United States in the first half of the 19th century and is still widely used nowadays. (www.wikipedia.com)

century 60-80% of the whole housing stock was based on the balloon frame system. (Vogler, A., 2015) In traditional Japanese housing wood was also largely used as structural material: all wooden elements were standardized according to a unit called shaku, which was the base for building elements, shape and size of the rooms as well as the overall layout of the building. The Japanese housing system is a great display of standardization, unitization and modular arrangement in architecture.

The military and colonial expansion that took place in the early 19th century caused unitized modular construction systems to fully flourish during that period. The flourishing of the iron industry resulted in the prefabrication of building structures in England, which due to the high weight were not as easy to transport as wood; nevertheless, the invention of corrugated iron sheets originated a boom in the business: for the first time a durable, economic, fire-proof and light-weight material was available. The iron substructure would be easily and rapidly clad by screwing the corrugated sheets, galvanized on the outside to withstand rain. Portable iron buildings were produced and shipped to Australia, all kinds of functions were covered: houses, schools, police stations, stores, churches, banks, barracks and so on. John Manning, owner of a prefab housing industry, stated in 1830: "Gentlemen emigrating to the New Settlement, Swan river, on the Western Coast of Australia, will find great advantage in having a comfortable dwelling that can be erected in a few hours after landing, with windows, glazed doors, and locks, bolts, and the whole painted in a good and secure manner, carefully packed and delivered at the Docks, consisting of two, three, four,

or more roomed houses, made to any plan that may be proposed”.

During the 19th century the world witnessed yet another application of prefabrication, this time in a larger scale. The progress of prefabricated iron construction was so constant that multiple building projects can be found during that period in several different locations. One in particular shows the real potential of prefabrication: glasshouses. Exotic plants from far away colonies were constantly brought back to Europe and needed proper places with specific climate conditions to survive; the “buildings” that were supposed to accommodate them had many requirements in terms of flexibility and indoor climate control, on the other hand they demanded no specific styles or architectural meanings. The first unitized systems were designed for such purposes, to foster solutions for rational problems involving technical, structural and climate aspects. The most famous archetype of this type of building is the Crystal Palace, designed by Joseph Paxton for the 1851 Great Exhibition in London (Fig.2.5). Although the Crystal Palace measured 564m by 124m with an overall height of 40m, there were only two different forms of column for the ground floor and two for the first floor, and the trusses were of consistent depth despite the different distances apart (Staib, Dörrhöfer, Rosenthal, 2008).

The last but surely not the least important material which was part of the prefabricated scene in the late 19th century is reinforced concrete. Joseph Monier had the brilliant idea to put wires inside cement to make his vases more resistant, after noticing how effective it was he kept experimenting and testing it,

finally creating iron reinforced concrete.

By the end of the 19th century the world witnessed the first examples of prefabricated, modular reinforced concrete buildings: designed by Francois Hennebique in 1896 and used as signalmen huts throughout the french railway system, this little huts were built off-site and brought right on the spot by train, they represent the very first example of concrete modular units.

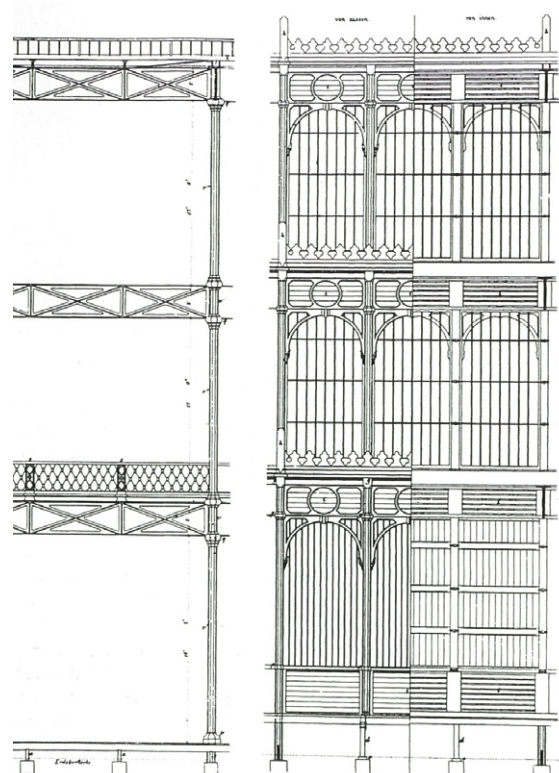


Fig.1.4 *Frame structure of the Crystal Palace, Joseph Paxton, 1851; after the Expo the building was completely dismantled and reconstructed within two years. It stood there until a fire destroyed it in the night of the 30th of November 1936 (www.sustpractice.files.wordpress.com)*

1.2 PREFABRICATION AS AN ARCHITECTURAL EXPRESSION

In this first “era” of prefab buildings, the involvement of architects was null, everything was proposed and done by manufacturers; this changed with the sprout of modern architecture. Even though WWI would shortly stop the cultural development of the whole continent, Walter Gropius had already proposed in 1910 the concept of an industrialized house made of “components”. At that time he stated: “Of objects there exists a choice of designs in different execution and pricing level, but in identical size. All parts fit without exception since they have been produced according to one and the same standardized size, and thus can be exchanged at will. The builder now can compose a house after his own personal taste from this wealth of material and diverse forms”.

Shortly after, LeCorbusier followed Gropius’ path stating in 1923: “A great new epoch has begun. There exists a new spirit. Industry, overwhelming us like a flood which flows on towards its destined end, has furnished us with new tools adapted to this new epoch, animated by the new spirit. We must create the mass-production spirit. The spirit of living in mass-construction houses. The spirit of conceiving mass-production houses”.

LeCorbusier’s statements did not add anything to what Gropius had already postulated previously, the main difference between the two was the major impact that LeCorbusier had on the scene thanks to the power and boldness of his images and ideas. Eventually LeCorbusier was contacted by an altruistic industrialist from Bordeaux who believed and wanted to invest in his ideas. He had finally the chance to translate his concepts into design and initiate the necessary production lines for the components. Unfortunately, after the houses in

Pessac were finished, they remained unsold for more than three years because of the bad press given by local architects; eventually, the government had to turn them into houses for the poor, which meant that LeCorbusier’s first experiment in factory-made houses was a complete failure (Fig.2.6).

On the other hand, Walter Gropius and his Bauhaus succeeded in pursuing the concept of industrialized housing as a tool to improve the middle class conditions, basically trying to improve the quality of commonly used hand-made goods by the means of mass-production. Affordable housing was a major social issue, especially in post-war German cities, and the Bauhaus was trying to tackle that problem through prefabrication.

During this period, up until the mid 20th century, the industrialization of houses was strongly promoted by many modern architects mainly due to the high need for new housing for the working class, especially in cities. In America, however, the housing crisis came about a decade later than in Europe; when the great depression struck in 1929 the housing market was still booming, during the following decade it declined dramatically, later presenting the urgent need for a strong housing stock. Catherine Bauer, prominent public housing advocate and educator of city planners and urban planners, stated in 1934: “Throughout the country, then, there are not more than twenty thousand dwellings erected since the war on a permanently nonspeculative basis, and with any pretensions to large-scale planning or fundamental change in the quality of house production and neighborhood environment. Twenty thousand to set against 4’500’000 in a section of Europe with only slightly

more population than that of the United States. Moreover, not more than half of the twenty thousand really achieve a degree of permanent amenity and freedom from congestion which is the minimum working standard for 'modern housing' in Europe.

By 1935, some 33 prefabricated systems were offered on the US market. Nevertheless, the housing crisis kept on rising so much that the US president Truman had to initiate a program called the Veteran's Emergency housing system in order to stimulate the market to provide for the rising demand. As a result, after being exiled from Europe from the Nazi regime, two genius modernist architects Gropius and Wachsmann got funded for the realization of their innovative ideas in 1943, by 1947 the General Panel company, based in California, was ready to produce over 30000 houses per year. The modular timber construction system consisted in elements already containing all the required building services such as wires and pipes in them, a whole building could be easily assembled by unskilled workers in 36 hours. Furthermore, the system was very flexible in terms of design possibilities, it allowed for all kinds of sizes and one or two-storey buildings. Unfortunately the company sold only 200 units until 1951, year in which it was liquidated and shut down.

Another key figure for prefabrication was Jean Prouvé, French engineer and constructor that was deeply fascinated by modern materials like aluminum, metal sheetings and plastics. Le Maison du Peuple in Clichy is probably his most recognized work; it was mostly built out of elements in wide, all of which could be moved. Nonetheless, the most interesting part was the facade, made of



Fig.1.5 *Cité Frugès in Pessac, LeCorbusier, 1926; the bordeaux industrialist Henry Frugès was thrilled by LeCorbusier's postulates and funded him for what is considered to be his first realisation (www.aquitaine.culture.gouv.fr)*

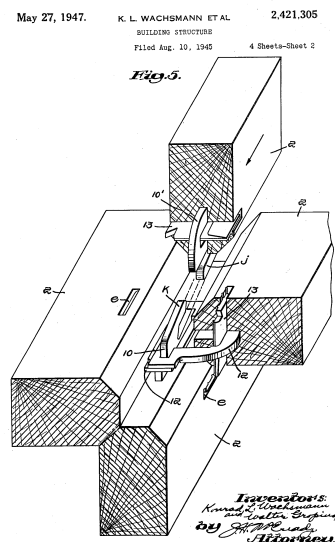


Fig.1.6 *Patent drawing by Wachsmann for the connection proposed in the General Panel Corporation, 1947 (patentimages.storage.googleapis.com)*

two aluminum sheets welded and folded together and connected to a structure that would then be patented in 1950 and is still considered the base for the modern post-and-rail system. “Like Buckminster Fuller, Jean Prouvé played a key-role in 20th century architecture and inspired architects like Renzo Piano and LeCorbusier” (Staib, Dörrhöfer, Rosenthal, 2008).

The next trend setter that needs to be pointed out is the above-mentioned Buckminster Fuller. “Bucky”, as he liked to be called, was a very inventive character, particularly interested in geometry and spatial structures with which he experimented a lot throughout his career. At one point of his life he decided to tackle the problem of housing, he thought that the traditional industry was not efficient enough and could have been improved if houses were treated as serial products instead of unique, on-site built elements. His biggest contribution to the cause was the Dymaxion housing system, (dynamic (max)imum tens(ion)), for whose production he exploited the Beech aircraft company in Wichita, Kansas. In fact, during the post war years, in America as well as in Europe, many factories that were highly involved in the production of war “products” found themselves without any good to produce. The Dymaxion house was a circular building of 74m² that only weighted 3500Kg overall. All the services such as heating, electricity, ventilation and water disposal were located at the center of the building, the modules for kitchen and bathroom could then be located anywhere around the central technical core. These modules were in fact very flexible and could be assembled and applied anywhere, not only in the Dymaxion house. The bathroom module for example, could be installed in just three hours and

it was complete with toilet, sink, shower and tub.

In general, every building component weighted a maximum of 5 Kg so that a group of 6 people could easily assemble the whole house in one day as well as a single man could assemble it in six days. Unfortunately this is another failure in the history of prefabrication: the production line was set up and ready to produce 200 houses per day, no less than 37000 orders were already received by the company. Nevertheless, only two prototypes were built, one of which was the famous Wichita house in which Buckminster Fuller himself lived for a period.

The 1960’s were then a period of sudden growth after the war, the expansion of the suburbs in the outskirts of cities along with the general rising wealth created a very high demand for detached houses, which wasn’t present in the decades before. The traditional housing market was not ready to withstand such a high demand, therefore the cheaper and fast-to-build prefab houses experienced a very high demand. Furthermore, the economic growth also meant higher land prices which would result in less budget for the building itself; people would then have to decide between a cheap housing or a lower quality detached house. The world was finally ready for prefab houses which were not only perceived as houses for the poor but also acceptable solutions for the middle class. As a result, many successful prefab companies were established during that period and still stand nowadays.

Eminent examples from this years are the Futuro House by Suuroen and Ronkka, an 8 m circular house with round curves that were finally achievable thanks to plastic molding and looked extremely futuristic and desirable at that time; a very similar

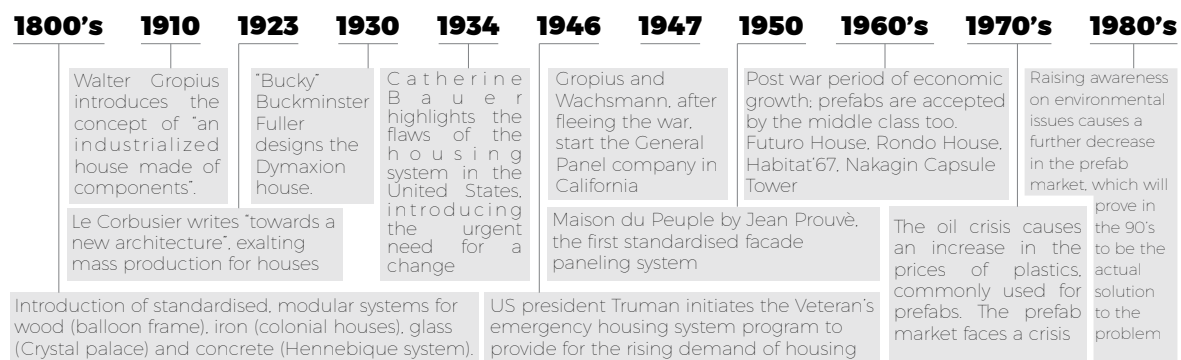


Fig.1.8 Timeline of the main events concerning history of prefabrication since the 19th century

design was the Rondo House by Casoni and Casoni in 1968 in Basel (Fig.2.8).

The 60's also witnessed the trend of Mega and Meta cities, which would have required a high level of prefabrication as well. In order to break the monotony of previous prefab designs some architects proposed solutions made of single prefab modules arranged in more complex and organic ways around a load bearing structure. Examples of this trend are the Habitat 67 by Moshe Safdie and the Nakagin Capsule tower by Kisho Kurokawa.

Even though the prefab house was finally starting to be perceived not just as the only solution for the poor but also as an acceptable living choice for the middle class, problems concerning noise and heat insulation, caused by the light building materials, would lead to prefab houses still being considered as lower quality alternatives. Furthermore, the oil crisis in the 70's and the rising environmental awareness in the 80's contributed to foster this negative image of prefab houses, even though in the 90's the same environmental awareness caused the industry to rise again from its ashes.



Fig.1.7 The Futuro house by Suuroen and Ronkka above, the Rondo house by Casoni&Casoni below; both of the designs are very similar and inspired by UFOs depictions from that time, clearly referencing the futuristic concept behind these designs. (Vogel A., 2015)

1.3 OVERVIEW ON NOWADAYS EUROPEAN MARKET

Europe is a very complex environment to analyze due to its internal diversity in terms of language, traditions and economical context. Materials, market profiles and construction practices differ a lot between different countries in Europe; the EU is a huge step towards unification but it still does not provide clear data as Japan and the United States, often a deeper focus on national level is required to get the whole picture on technologies and practices. The diversity is present also in terms of housing habits and stock: in some parts single family houses prevail whereas in others there is a distinct majority of families living in flats; some countries show a preference in house ownership whereas others tend to prefer rent, mainly due to the higher land prices. This high diversity seems to generate an ideal environment for the factory-made house industry.

Due to the market diversity, most of the prefabricated housing companies are fairly small, just like traditional building companies. The biggest company in Europe does not exceed 3000 houses per year, most of them are under 1000. The preferred material for prefabrication is timber thanks to the presence of monitored and certified forests, especially in northern Europe. Most of the prefabricated companies generally claim to use the latest technologies and state of the art in industrialization, at the same time they also brag about the quality of manual labor and craftsmanship, showing quite some misunderstanding in the terms industrialization and prefabrication.

Traditionally speaking European citizens are happy with the quality of their homes, houses represent a fairly safe long term investment and the average lifetime of houses is 76 years, which supports this theory.

1.4 INDUSTRIES THAT INSPIRE

As already stated before, most of the other industries have achieved over the decades a higher and higher level of prefabrication and industrialization; on the other hand, the building industry never fully automated the process and can still learn a lot from fields like automotive, shipping and aerospace. We ask ourselves: why can't a house be designed and built like any other product that is entirely built in factories and leaves them only when it is fully ready to use? Other than the obvious differences between the products at stake (mobility vs stability to mention one), all the previously mentioned industries are not as old and established as the building industry, which over the centuries kept its habits and has always been hard to innovate. Since the first industrial revolution, there has always been a certain fear of machines and robots taking over jobs that traditionally have always belonged to men; in this case the building industry is so well established that it seems to be the only one that still stands the attack of automation. Nevertheless, the positive effects of industrialization overcome by far the fear of innovation, this is a step that will need to be done sooner or later for the building industry not to become obsolete. In the following pages, an overview of the main industries from which the building industry could learn a lot is displayed briefly, after which the characteristics of any industrial product and process will be analyzed.

1.4.1 INDUSTRIAL PREFABRICATION

Prefabrication of elements has been possible since the 19th century and, since then, the possibilities given by this principle have largely increased. Nowadays prefabrication does not only indicate entire houses built off-site, it rather comprises also the production of building products in factories. We have been mentioning previously how prefabrication should be more part of the building process as if it was not present at all in traditionally built architecture. The truth is that if we consider all the factory made products, traditional buildings are 50/60 percent prefab. Prefabricated beams and columns as well as other structural elements can achieve much higher performances thanks to processes like pre-stressing. Prefabricated facade elements allow huge buildings to be clad in very short time and with the guarantee of high quality insulation, water tightness and free of defects. The practice currently mixes prefabricated elements with built-on-site elements to form complex building structures. The continually increasing demand for better quality and the efforts to shorten the design and construction periods encourages the development of industrial prefabrication in the building industry. Computerized, automated production techniques and equipment, for example CNC milling and specialized robots, enable the manufacture of highly complex building elements (Staib, Dörrhöfer, Rosenthal, 2008).



Fig.1.9 *Precast concrete beams and columns; this approach reduces risks on site and ensures structural characteristics of the elements. Furthermore it reduces time on site usually used to wait for the concrete to completely dry (www.keyconcrete.com).*



Fig.1.10 *Prefabricated facade panels can be found of nearly any dimension, color, material and complexity; this system is used for either modular or huge buildings that have a great external surface to cover. Advantages comprise reduction of risks and weather dependency and well as a perfect quality of the final product in a delicate layer such as the facade (www.keyconcrete.com).*

1.4.2 AUTOMOTIVE INDUSTRY

Automotive and building industries were mainly affected by a common factor: salary costs. The difference between the two is their reaction to the problem: since its establishment the automotive industry has dramatically increased its level of automation, a car can now be produced and assembled in 10 hours.

In the first half of the 20th century, when most of the automotive companies sprouted in the US and Europe, the latter were not only focused on car production, on the contrary the tendency was to diversify the production. Companies like Ford, which also produced tractors, or General Motors that was also involved in the production of railway locomotives and Rolls Royce, parallel producing jet engines.

However, this tendency decreased over time and all major car producers started to focus only on that, as well as outsourcing many tasks to other companies. The automobile industry is probably the one that influenced all the others leading the way in modern production methods like mass production, introduced by Ford, and lean production later introduced by Toyota.

Mass production was introduced by Henry Ford in the very beginning of the 20th century, when he pursued his dream of creating “a car for the great multitude”. The Ford model-T was designed to withstand the rough American roads of that period, therefore repairability and durability were the main attributes, after which the need of a quicker production was considered. Thus the creation of the assembly: a conveying belt would move the elements through the production chain and every worker would be limited to a repetitive task. Nowadays

most industries still rely on the same principle, even though the workers are preferably not restricted to a single repetitive task and the techniques have been largely refined over the years.

On the other hand, the origins of lean production can be found in the 1950's, when Toyota, after analyzing the flaws in American mass production lines, decided to improve the technique by getting rid of all wastes of space, time and products.

Although the American system had an impressive output, Toyota found it too wasteful and did not like the combination of unskilled workers and expensive, single-purpose machines. They combined some advantages of craft-work with those of mass production, avoiding high costs of craft and rigidities of factory systems. The result was the evolution of Toyota's lean production system, which employed teams of multi-skilled workers at all levels of the organization and highly flexible, automated machines to produce volumes of products in enormous variety (Gann, 1996). The time from the market survey to the placement of the car on the market was roughly 5 years, this resulted sometimes in a shift of customer's needs and subsequent under-selling of the final product. Thus, attempts have been made to reduce this time which has reduced to only two years in most cases, thanks to the so called concurrent design, where different subjects (engineers, designers, marketing managers etc) create a team responsible for all engineering, designing and marketing decisions.

Regarding the manufacturing process, the tendency is to accurately monitor the flow of materials and elements in the production chain, so as to make sure that there is always only the required amount.

The assembly is quite uniform and revolves around the mounting of the main two parts of the vehicle: body and chassis. The body comprises doors, windows and outer panels, the chassis comprises structural frame, wheels, gear and power train. The two parts are assembled in parallel and the moment when the two production lines merge is known as “marriage”. After that point only tests and inspections need to be carried out.

The rapid need for innovative and more captivating designs is causing the rise of the platform design, in which different models share the same structural parts and the only changes in the production chain need to be done for the final aspect of the new models, thus reducing time and costs.

To conclude, the automotive industry owes its success to its reaction to the initial problem, salary costs, which led to a dramatic increase of automation and reduction of wastes through lean manufacturing methods. Such evolution seems to be happening in smaller scale to the building industry as well. If the outcome will be the same as it has been for the automotive, the building industry will have a bright future by taking the same path.

1.4.3 SHIPBUILDING INDUSTRY

The shipbuilding industry is probably the largest of the ones considered in terms of size of facilities and final product. Regarding the end result, the industry ranges from small boats to huge cruisers and carriers; furthermore, the typologies can be divided into military, transportation and leisure.

The establishment of the shipbuilding industry dates back centuries ago; in the early ages ships

were built using overlapping planks to form the keel which would then be riveted together. The principle was very simple and the level of prefabrication was obviously null during those times. Nowadays, along with other industries, shipbuilders recognize the advantages of building large parts of the overall ship in covered facilities and assemble them together later on a slipway. The technique follows the principle of the modular or block construction, according to which different units, assemblies and components are gradually mounted together to form large prefabricated sections. Modular construction method was introduced in the shipbuilding industry mainly to shorten or improve the construction timeline. Basically, modular construction in shipbuilding can be defined as an engineered assembly that contains a set of predefined modules that would later form a complete ship (Siddiqui, 2008).

The production of ships happens in the shipyard, the main facility that comprises shops and assembly lines. A lot of different laborers work simultaneously in the shipyard. The production of ships is divided in several levels, from the raw materials and plates to units, sub-assemblies, assemblies, components and final product, which is finalized in the slipway, or berth, from which the ship will simply slide into water. Sub-assemblies and components are assembled together to form large parts of the hull, which are then transported to the berth and craned in place. Usually, this large parts are 5-6 storey tall, exclusively built out of steel plates and profiles; a big cruiser is generally made out of 18-20 of this blocks. Thanks to this work flow, tasks can proceed independently from weather conditions, under sheltered workplaces.

The raw steel structure is then complemented with the finishes delivered by third party suppliers which bring already fully equipped bathrooms and cabin interiors. As an example, the German company EMS PreCab, provide high quality cabins for cruises which are fully finished at their factory, comprising finishes, plumbing, wiring, tiling, carpets etc. The cabins can then be transported to the shipyard and craned in place in a very reduced amount of time, after which they're ready for use.

To conclude, Shipbuilders are less exposed to construction delays, as time constraints always represent their major concern in order to maintain the production momentum and reputation of the companies. Undoubtedly, while still maintaining a good balance between cost, workforce and quality control, modular constructions are preferably the best technique capable of increasing the growth of the shipbuilding industry (Abdullah. A., 2011). The large scale of the final products (comparable to high rises) does not compromise the level of prefabrication which is carried out in many layers of components and sub-components later assembled to form the final ship.

1.4.4 AEROSPACE INDUSTRY

The aerospace industry is the most advanced out of the three in terms of materials, technology involved and requirements for the final product due to the condition that it has to withstand under extreme conditions of temperature, speed, stresses, vibrations and noise. The production line is very complex and diverse since the parts that make out each subassembly are millions.

At the time of its establishment, the industry was

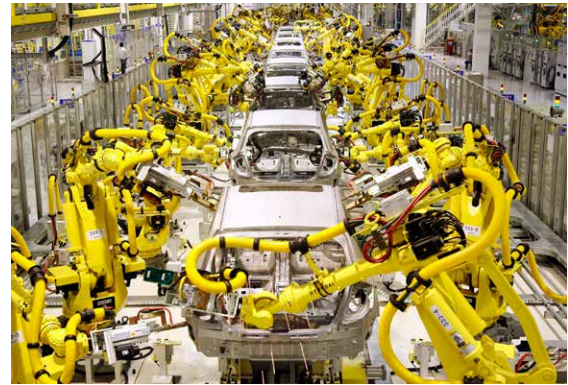


Fig.1.11_Modern assembly line in a Hyundai factory (Hyundai.com)



Fig.1.12_Assembly of a fully mounted dock and hull (Vögler A., 2015).



Fig.1.13_Final assembly lines of airplanes take place in huge facilities like none others in the world in terms of interior volume (www.rtec.my/wp-content.com).

more or less independent from outsourcing except for special parts like tires and engines which were provided by the automotive industry, Rolls Royce being the most eminent example. Over time the requirements and standards became more strict and the industry had to outsource the production of more parts that required different machines and skills. The second world war created a massive competition in aerospace technology, therefore production and design processes needed to be revised in order to overcome the enemy; more and more facilities were built, the already existing ones enlarged and more and more external companies were given the task to produce specific high quality parts. The 5.5-metre nose section of the Boeing B-29 bomber had more than 50.000 rivets and 8.000 different parts procured from over 1.500 suppliers. On the other hand, automobile-engine manufacturers were able to use existing skills to build aircraft engines along mass- production lines in already established factories (Vogler, A., 2015). Nowadays, since the parts to produce are so many and so complex, no single company in the world is built to carry out the task without outsourcing some components like mechanical components and electronic parts.

Regarding the design process, it strongly differs according to the final client: military aircrafts are designed as proposals that try to suit the strict requirements given by the client, which is usually the defense service of the country, whereas for civil aircrafts the aerospace company conducts a market study to analyze the current preferences and trends. After that they propose their design and solicit orders from airlines and such; if they reach a certain number of orders they can start the production

phase.

Traditionally speaking, the design of an aircraft starts from the preliminary design and moves forward getting more and more detailed; numerous iterations must be made before the final design is achieved due to the multitude of obstacles that are found on the way. The introduction of concurrent engineering has improved this process towards cost reduction just like it has done the same in the automotive. Concurrent engineering consists in the formation of diverse design groups that have to make design proposals taking into account all different aspects from aesthetics to performances, from safety to marketing and so on. This way, analysis that would have ran sequentially are now run in parallel. Computer aided manufacturing and computer aided design have also dramatically improved the design and production process by diminishing the necessity for prototyping and physical testing, which can instead be carried out virtually saving time and money.

As already stated before, from independent production companies, aerospace industries gradually shifted to highly diversified companies with many subcontractors. Assembly of aerospace vehicles at the prime contractor or systems integrator begins with the accumulation of sub-assemblies. Segments are taken to a facility where they are assembled together to form sub-assemblies which are then transported to the main assembly line, where they are joined together to form the final product.

1.4.5 BUILDING INDUSTRY

The traditional construction industry, even though still growing in terms of prefabrication, is still affected by flaws related to its on-site facet (Fig.2.17). Because of its intrinsic diversity given by ever changing regulations, habits and markets according to the country, the building industry is subdivided in many small-medium sized enterprises; the lack of centralization is preventing a strong research development and is keeping from innovations. In general, most buildings are managed by a main contractor which will then outsource different tasks to subcontractors, whose quality and performances are hard to monitor and check; as a result, the average quality of the final product is quite low. Another party involved in the industry is represented by big material producing industries, which are quite stable and generally not affected by the fluctuations of the market.

“The design is led by architects, that coordinate the activity of other specialists like climate designers, structural, mechanical and electrical engineers. Normally the construction of buildings is carried out by companies that had nothing to do with the design stage, with the exception of some very large companies that might have both a design and construction team” (A. Vogler, 2015).

The main problems identified with the traditional industry are the long and unstable duration of the building process, high costs and inconsistent quality of buildings, along with weather dependency and risks given by an on-site approach.

Prefabricated housing industry, on the other hand, have much more in common with advanced industries like aerospace, shipbuilding and automotive. The final products range in size and

level of finishing mostly according to customer's preferences, due to the fact that people still prefer to choose by themselves some aspects like furniture, fixtures, appliances and finishes. In most cases companies strive to offer a more or less high grade of customization to counter the negative, boring image that prefab houses got stuck with over the last decades. The quality of the final product is higher than that of traditional buildings, this because of the monitored, weather independent environment in which the product is assembled; furthermore, the price is roughly the same as traditional houses, whereas the main perk is the fact that the whole design, production and assembly is carried out by a single company, making the whole process more stable preventing risks and delays with subsequent money savings.

Compared to the reference industries, the prefab industry does not either invest nor rely on style and design; in fact, architects design less than 5% of newly prefabricated houses (Hoffmann, 2003). The design of prefab houses mainly tries to blend with traditional houses rather than innovating and trying to stand out from them; as a result, prefab houses are distinguished by a boring, sluggish design that prevents architects from having anything to do with the business. The brand of the companies is also widely neglected if compared to other industries previously analyzed, their names are usually just the name of the family and their logos are quite cheap and outdated, not trying to communicate any elegance.

The production is mainly carried out in facilities where the components are assembled together; there are 3 main levels of prefabrication in the

industry:

- Large scale wall and roof elements, transported and assembled on site to form the building
- Plug and Play modules, again transported and connected on-site
- Fully finished houses

The most adopted approach is the first one, followed by the second modules approach due to the fact that fully finished products are hard to transport by truck. Discarding one approach in favor of another one is a choice that affects the ease of transportation rather than the simplicity of on-site operations. A fully finished building will be quite hard to bring from factory to site but it will also require less time on site from the arrival of the truck until the house is habitable; on the other hand, wall and roof elements will be very convenient to bring on site but will also require a larger amount of operations on site to assemble the elements together to form the final product.

The degree of automation in prefab housing assembly lines is very low, mostly following traditional methods with the only difference of being in a monitored, sheltered environment that ensures a higher quality and lower risk of defects. CAD and CAM technologies are recent key players in the achievement of flaw-free products.

Concluding, the prefabricated building industry can be best compared to the automotive industry in terms of end users, they create in fact both end user products. The prefab industry should absorb from the automotive industry the way they invest on design and branding in order to make their product more desirable. In fact, prefabs still did not show the courage to stand out from traditional buildings

instead of blending with them.

Another aspect that could be improved in the industry is the full implementation of digital manufacturing techniques which, along with CAD can really ensure products free from any kind of undesired/unpredicted defect.



Fig.1.14 *High risks, material wastes and construction mistakes are just a few of the consequences of the current on-site based building industry: (www.dhclegal.com/wp-content.com)*

CA 2001	EUROPE (EU-25)	UNITED STATES
Population	437 mio	281 mio
Existing Housing Stock	201 mio [est]	119 mio
Housing Starts	1,7	1,7 mio
Housing market	Booming to shrinking	Booming
Value of Housing Market EUR	320 mio [est.]	360 mio
Percentage of detached houses	55% [EU-15]	66%
Traditional Construction	Brick-Stone	Timber-Frame
Life-time	75	44
Average sqm [existing]	100 [est]	162
Average sqm [new]	120 [est]	211
Median Price	130.000 EUR [UK]	120.000 EUR
Average House Quality	High	Medium
PREFAB		
Market share	15% [est.]	15% [average trend downwards]
Target Market	Lower-medium	Low end
Output of largest companies	3.000 units/year	20.000 units/year
Main construction	Timber-frame	Timber-frame
Automation	Medium-Low	Low
General Character	"Advanced building site under a roof"	"Building site under a roof"
Production Character	Serialised Variety Production	Serial Standard/ modular Production

Fig.1.15_The table above shows the comparison of the three major global prefab housing markets as per 2001 (Vogler A., 2015).

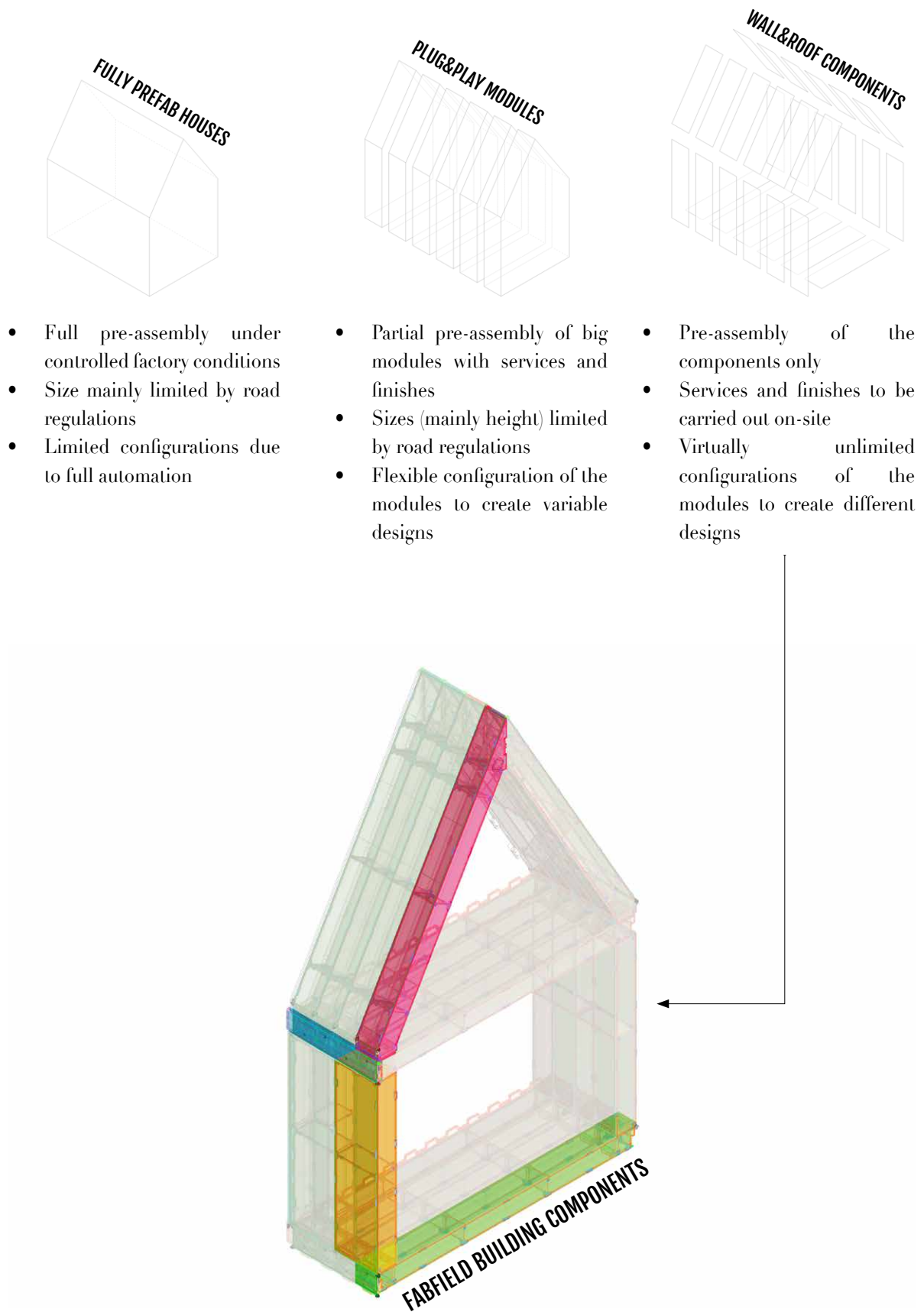


Fig.1.16_The three main grades of houses prefabrication offered by nowadays' market; FabField belongs to the "components" class.

1.5 REFERENCE PROJECTS

As already stated in the previous paragraph there are mainly three different levels of prefabrication for buildings, differing according to the size of the prefabricated components. It is considered of value to analyze some modern references of prefabricated houses to gather insights on the concepts behind it, the issues related to the different grades of prefabrication, the plan distribution and much more. Prefabrication not only concerning the buildings but also the services inside it, which have been an inspiration for the final solutions adopted.

The following pages are dedicated to the brief analysis of the most representative designs from different parts of the world, facing different challenges and market conditions, customer targets, sizes and grades of prefabrication, the only thing in common being that each one was of some kind of inspiration for me; as a final example, the FabField building system will be briefly introduced in its main components, driving philosophy and main flaws. Some other inspirational designs can be found in Appendix A at the end of the book.



KODA BY KODASEMA



**WIKKELHOUSE BY
FICTION FACTORY**



**CONCEPT HOUSE BY
TU DELFT**



**FABFIELD BY
THE NEWMAKERS**



APH BY ABATON



KASITA BY JEFF WILSON



VIPP SHELTER BY VIPP



HONOMOBO



WOODY'S HOUSING



BOKLOK BY IKEA



**PRET A LOGER BY
TU DELFT**

KODA BY KODASEMA

Koda is a project by Kodasema, an Estonia based company. It is designed to be relocated infinite times thanks to its ease of transportation; in fact the whole house is transportable by a single lorry so that the house can move with its client wherever he/she wants. The house comes fully furnished and finished, it doesn't need any foundation and it is ready to be used in one day.

The design focuses a lot on internal comfort, so much so that all finishing materials are natural and non-toxic, CO2 levels are constantly monitored, LED lights are built-in and external noises are minimized. Sustainability is also a key aspect for Kodasema which is a plus energy house thanks to its solar panels array on the roof and an extremely high thermal insulation. The facade is made out of concrete panels which are claimed to be waterproof, UV-radiation proof and maintenance free. Kodasema also claims that by the end of life of the building all of its components can be easily disassembled and reused.

On the company's website it is stated: "Imagine your computer or car being built in the rain ...in November... Why should your house be? KODA houses are produced off site with high-precision and uncompromising quality. The full process - from developing an extremely resilient, waterproof and maintenance free concrete panels, casting the concrete, the infrastructure and automation works, finishing surfaces, to assembling - every detail is under the control of the Kodasema team. Our technology for mass production of innovative concrete modules can be applied for different type of architectural solutions. Our moving factory concept allows it to be where the demand is".

The website also shows many different interior arrangements for different functions such as retail, office, hotel and living; the renders depict light, comfortable, flexible spaces that can truly be moved and used in many different ways, making Koda an excellent example of fully prefabricated, sustainable, multi-functional design.



Fig.1.17 *Koda is brought by a lorry on site fully finished and can then be easily relocated infinite times; no foundations needed. (www.kodasema.com)*

WIKKELHOUSE BY FICTION FACTORY

Wikkelhouse is a captivating modular design created and produced by Amsterdam based company Fiction Factory, it is based on the afore mentioned principle of plug&play modules assembled on site. The modules are 1.2m wide, weigh 500Kg each and are completely made out of cardboard which is wrapped around a metallic rotating frame, ultimate reason for the name that translates from dutch as wrap house

The modules have the profile of a typical house and can interlock together infinitely so as to form buildings of whatever length one might desire; it was already mentioned in the previous chapter that the main reason for plug&play modules is that they allow more flexibility along with an easier transportation, main disadvantage being the partial weather dependency during the connection of the modules. The thickness of the modules consists of 24 cardboard layers glued together with eco-friendly super glue that create a highly insulating shell.

Wikkelhouse is what you get when an everyday material finds a groundbreaking purpose," said Fiction Factory, a group of artists that has previously worked together to design interiors, fair booths and furniture.

"Using cardboard as its main building material, Wikkellhouse is a cutting-edge sustainable house with a beautiful design and exceptional constructive strength." After the 24 layers of cardboard are wrapped and glued on each other a waterproof, breathable layer is applied and later covered with the exterior, wooden cladding boards.

The building does not require any foundation, therefore it can be placed on site and ready to use within a day; the basic modules comprise the outer shell only, nevertheless slot-in sections are available and comprise shower, bathroom, kitchen and even a chimney. The structure is made only from recyclable material and designed to last for at least 50 years.

"Wrap House meets the criteria for temporary or permanent housing," said the designers. "It is as much as three times more durable than traditional construction and has an expected life of at least 50 years. You can move the house to different locations if needed, or extend your floorspace by adding one or more segments."



Fig.1.18 The Wikkelhouse modules are produced in the factory by wrapping 24 layers of cardboard with a special machine. (www.wikkelhouse.com)

CONCEPT HOUSE BY TU DELFT

An example of “smart” building services is in the Concept House “Delft” prototype, a single apartment of a not yet realized urban villa which consists of 16 apartments and 4 floors made by stacking the basic module apartments on top of each other. The prototype shows the characteristics of industrial production with a very low ecological foot-print and energy positive use. The building technical composition shows an assembly of floor, roof, wall and facade components and a central sanitary unit which concentrates all services of the apartment. The extreme level of prefabrication of the concept leads to the integration of all cables and service elements in the building components. The sanitary unit is furnished with all installations and is hoisted completely furnished, which enables an extremely short building time; the latter is the main reason for this project to be used as a reference: it shows in detail the plug&play approach applied to building services design.

The whole central module was built off site and integrates all necessary installations; the structure is a wooden frame which was erected at the factory; subsequently, all the pipes and ducts were embedded in the wooden frame and the energy sources installed. The central core was then transported where the rest of the building was and simply connected through plug&play systems that allowed all services to be active within one day.

The approach used in this case was to embed all services by cutting out the required sections from wall panels and floor and ceiling studs; the images show the complexity of the central core, which concentrates all the services of the house.

“The installation cluster is developed as one central ‘beating heart’ according to up to date BIM techniques, prefabricated and attuned. The installation cluster, equipped with preparatory and installed facilities (heat pump, boiler, converters, fuse box, ventilation system) and a completely furnished and finished sanitary unit (and triple waste water separation according to ‘quality’), separate lavatory and kitchen connections, also makes it possible that all connected, sustainable systems (PC systems, waste heat recovery from ventilation air, heat pump, etc.) can be used within one day after placement”. (Eekhout, M., van Timmeren, A., 2015)

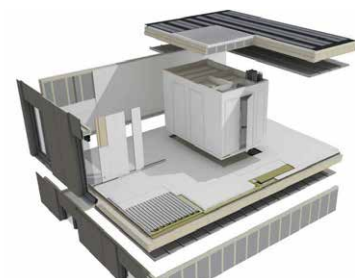


Fig.1.19_The Concept house was built and exposed in Rotterdam until 2016; it represents an important reference of a fully industrialized building.

FABFIELD BY THE NEWMAKERS

FabField is the building system created by Pieter Stoutjesdijk to trigger what he calls the "new digital revolution"; the building system is based on the principle of large scale prefabricated roof, wall and floor components which are produced and assembled in factory under a controlled environment and later put together to form a building on site. As it was previously mentioned, this approach has the advantage of allowing virtually infinite configurations but delivers a product that has to be finished and furnished on site with all the drawbacks that come with it. Pieter's mission is to keep improving this system so as to make it as efficient as possible in terms of prefabrication while maintaining and even improving the current flexibility.

Once one closely analyses the differences between the "large scale components" approach and the "fully prefabricated" approach, some improvements can be made in order to tackle the disadvantages of one approach and strive to turn them as much as possible in advantages. An aspect that creates a strong disparity is the fact that services and finishes have to be carried out on site with the FabField system, and that usually means delays, inaccuracies and higher costs. My thesis will try to turn this aspect in an advantage so that both services and finish layers can be carried out on site in safety, accurately and without the risk of any delay, maintaining the higher flexibility of the system compared to fully prefabricated ones.

The FabField building system borrows most of its basic principles from more evolved and flexible industries, making use of digital fabrication methods (CNC milling) to produce all components that constitute a building. Its main goal is to "upgrade" the construction industry by exploiting principles from the manufacturing industry. FabField combines traditional prefab modular principles with innovative digital fabrication methods, thanks to which construction times, costs and risks are reduced, while the quality of the final product is increased by a thorough design process and the accuracy of digital fabrication methods.

The system consists of 4 main building components which can ideally vary in size according to needs, the main restriction being the size of the CNC milling machine that has to process the 18,3mm thick OSB panels (1200x5200mm); all components are made out of a simple OSB panel which is processed by the CNC milling machine to be shaped as required by the design. As already mentioned, the 4 main components make up the whole modular structure:

- The Floor components are 300mm wide and have a protruding notch on each end to ensure their connection with the wall components
- Wall components are 600mm wide due to their reduced length; this ensures that each component weighs a maximum of 50 kg so that assembly is possible within 2-3 people. Each component has 4 holes on the top and bottom to allow the notches from floor components and Beam components to enter and ensure the friction fit connection.
- The Beam component is 1200mm long and ensures the longitudinal connection between walls, floor components and roof components.
- The roof component is 300mm wide and is fastened at both the base and the ridge of the roof, where it meets its "twin".

All components are easily demountable; faces of components facing the outside are clad with waterproof chipboard panels to protect them during outside assembly. The chipboard is then covered by aluminum composite panels that form the facade of the building system.



Fig.1.20 The FabField building system has been tested with a building prototype, the PD Lab, currently exposed outside BK. (www.thenewmakers.com)

CHAPTER'S RECAP

HISTORY

- Prefabrication is the fabrication of parts at a factory so that construction consists mainly of assembling and uniting standardized parts
- The brick can be considered the first artificial example of standardised building block
- The Balloon frame system (1832, Snow) is the most successful standardised system, still being used for most american houses
- 19th century's colonial and military expansion caused the prefab buildings industry to fully flourish along with the iron, steel and reinforced concrete industries
- Early 20th century is when architects start being involved in the prefab buildings industry (LeCorbusier, Gropius, Wachsmann, Fuller, Prouvé)

CURRENT MARKET

- Europe is a very diverse market in terms of housing requirements and habits due to its long history
- All prefab companies are small, producing less than 1000 units per year
- The material mostly used for prefabs in Europe is timber, due to the large number of forests

INSPIRING INDUSTRIES

- Traditional building industry is very rigid and well established in using the same old methods
- 50/60% of traditional buildings' parts are currently made of prefabricated elements (beams, columns, facades etc)
- Automotive industry introduced the assembly line (Ford) and Lean Production process (Toyota)
- Automotive industries have been constantly increasing their level of automation
- Shipbuilding industry is the most diversified in terms of size of end product, it's also the oldest one, it outsources a lot and has a lower level of automation
- Aerospace have to outsource a lot of elements due to the high complexity of the end product, the design process differs a lot between civil and military aircrafts
- In traditional building industry the diversity of the market prevents centralisation which in turn slows research development and standardisation
- Traditional building industry has the lowest integration between production, design and construction processes
- Building industry requires the most time spent on site due to the nature of the end product
- Architects currently design only 5% of prefab houses: style is not a key factor
- There are 3 main approaches for prefab buildings: Fully Prefab - Plug&Play Modules - Prefab Building Components

TOWARDS A NEW INDUSTRY

So far the concept of prefabrication has been introduced focusing on its history, current state, inspiring industries and different grades of prefabrication in buildings. The references that have just been presented in the previous pages are meant to give a practical overview on the most successful and modern designs currently in the market but also to display the variety of the latter. The last reference presented can also be seen as an informal introduction to the FabField building system, object of this graduation thesis, FabField will be analyzed more and more in the next pages.

The new building industry is already sprouting mainly through small-medium companies that follow different concepts but all seem to be driven by some core concepts that should be more and more implemented in the “mainstream” building industry so as to make a global change finally happen.

The next section intends to present some of these key concepts on which FabField and most innovative companies are based upon, namely the consideration of End of life scenarios during early design phases, digital manufacturing aspects, IFD buildings and design for manufacturing. These are aspects that should always be considered in the future building industry, reason why specific paragraphs were written to give a clear idea of what they represent.

2.1 END OF LIFE

“Disassembly in the building industry usually involves a few bulldozers and some explosives. In this way, materials and energy brought into the construction of built structures are often thrown away at the end of the building’s life cycle, together with tonnes of non-recycled materials, which go into landfills or incinerators. The reason for this is that buildings are not designed to be demountable. Their components are not designed to be reused and reconfigured, and materials that are often composed of composites are not designed to be recycled” (Durmisevic E., 2006).

End of Life scenarios have been considered for quite some time already in product design so that the actual product could be shaped accordingly; the reason for this relatively new practice does not only concern sustainability aspects but also costs as many products could be recovered and recycled into new valuable ones without acquiring more material, therefore saving considerable amounts of money.

“Investments in certain design improvements can offer financial gains when evaluated over the total product lifecycle. For instance, different design improvements can significantly reduce disassembly costs and increase revenues through retrieved materials” (Peeters R., Dewulf K., 2012). Furthermore, another aspect that drives companies into considering end of life scenarios is brand image reputation: most of the population is now well aware of the impact of pollution and wastes in industries, therefore base their choice over products on the impression of sustainability they have.

WASTE HIERARCHY - LANSINK'S LADDER



Fig.2.1 The Lansink's ladder, part of the European WEEE directive.

End of life scenarios should ideally be always considered in the so-called front-end design, the very initial phase where risks and costs of changes are the lowest. Nevertheless, it is still a practice that has no well defined boundaries and designers often are not fully aware of what it takes to consider such scenarios; the Lansink's ladder (fig.2.28) is a useful tool to think of a hierarchy of ecologically preferable EoL solutions. Nevertheless, these are not the only EoL strategies one might consider in product design: fig.2.2 gives a broader overview of all options and crucial steps in the end of life treatment.

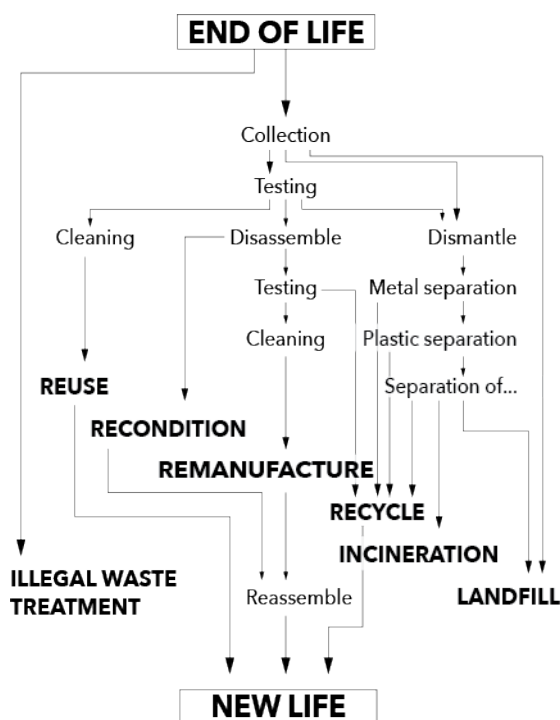


Fig.2.2 There is a wider range of actions that designers should consider in the front-end design to assess EoL strategies (own ill.).

As already mentioned before, end of life strategies are a common practice already in the product design process but they should also be implemented into the building industry so as to tackle the problem of material wastes, pollution and reuse of building materials and components; this requires the re-thinking of the whole building process and a strive to re-design our buildings into components and sub-components to promote new life-cycles and disassembly of the latter.

Observers of current and future trends predict that the 21st century is the beginning of an era that will be defined by temporary, multi-functional, and virtual organizations. The nature of working and living will change drastically such that society will require completely new types of structures (Durmisevic E., 2006).

A common conviction is that the life of buildings can be increased just by using more durable materials, on the contrary there are other factors at play

when it comes to buildings life-time. Firstly, the difference between the technical life cycle of single materials and the use life cycle needs to be pointed out, the latter is often shorter than the technical life cycle; The substructure of a specific type of facade may guarantee a technical life cycle of 100 years but, if another part of the same facade, which is not designed to be disassembled from its substructure has a shorter technical life, as a result the use life cycle of the substructure will be much shorter than its potential technical life cycle. When materials are integrated into fixed assemblies, the substitution or shorter life of one involves the substitution of all the others which are assembled in the same component. Industrial products have already long started to be designed with a special focus towards the disassembly procedure rather than the simple traditional disposal. This new approach has proven to have a positive environmental impact.

Durmisevic E. (2006) explains that the performance of a particular configuration with respect to disassembly (and transformation of the structure) can be measured by two criteria for disassembly: independence and exchangeability of materials. In other words, a building product can be dismantled if it is defined as an independent part of a building structure and if the interfaces with other parts are demountable. Sub-assemblies are non other than clusters that have independent production, assembly and disassembly.

We can take as an example a building which is clad with prefabricated facade panels; the facade panels can be seen as the lowest subassembly, having independent production, assembly and disassembly. Nonetheless, if part of the facade panel needs to be

replaced causing the whole panel to be replaced than we are talking about a closed system, whereas if the facade panel can be further divided into independent sub-assemblies then it can be considered an open system. This way of thinking can be done in all different scales and for all kinds of components. Closed systems are designed and produced following principles that favor the assembly process: integration of parts, creation of modules, standardization of system levels. Open systems are designed in such a way that different requirements can be satisfied during a system's life-cycle. they are simply more flexible providing separation of functions, open assembly and flexible production processes. Accessibility, variation, reuse,

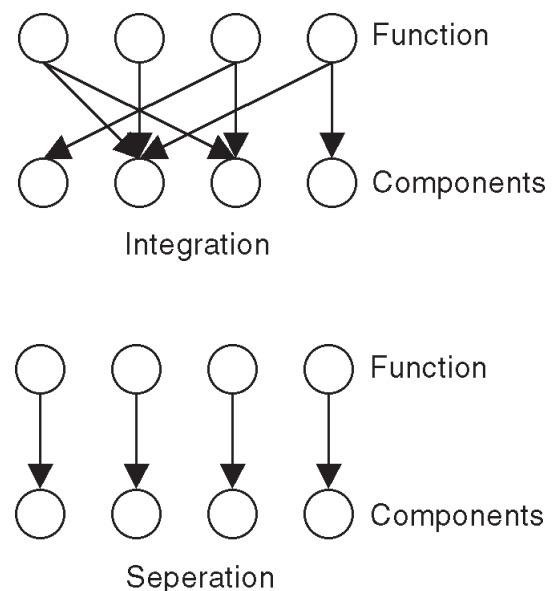


Fig.2.3 The scheme summarizes the different levels of dependency of closed systems (above) and open systems (below) (Durmisevic E.,2006).

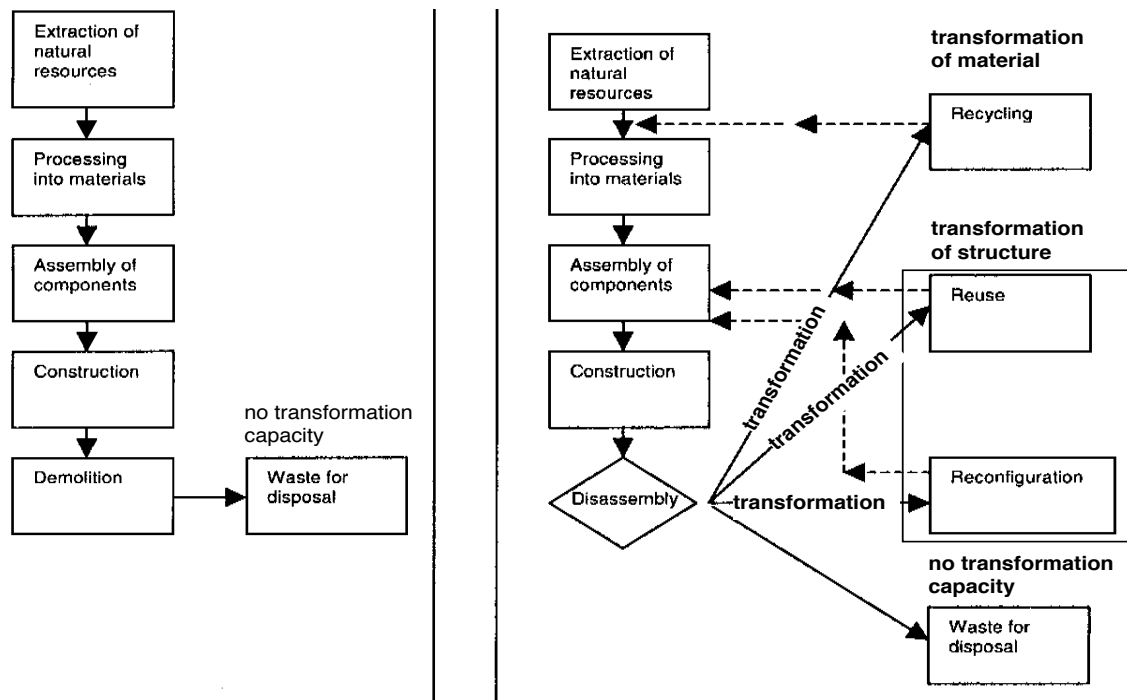


Fig.2.4 Current linear model of life cycles of materials and components on the left, versus the life cycle for improved sustainability on the right (Durmisevic E., 2006).

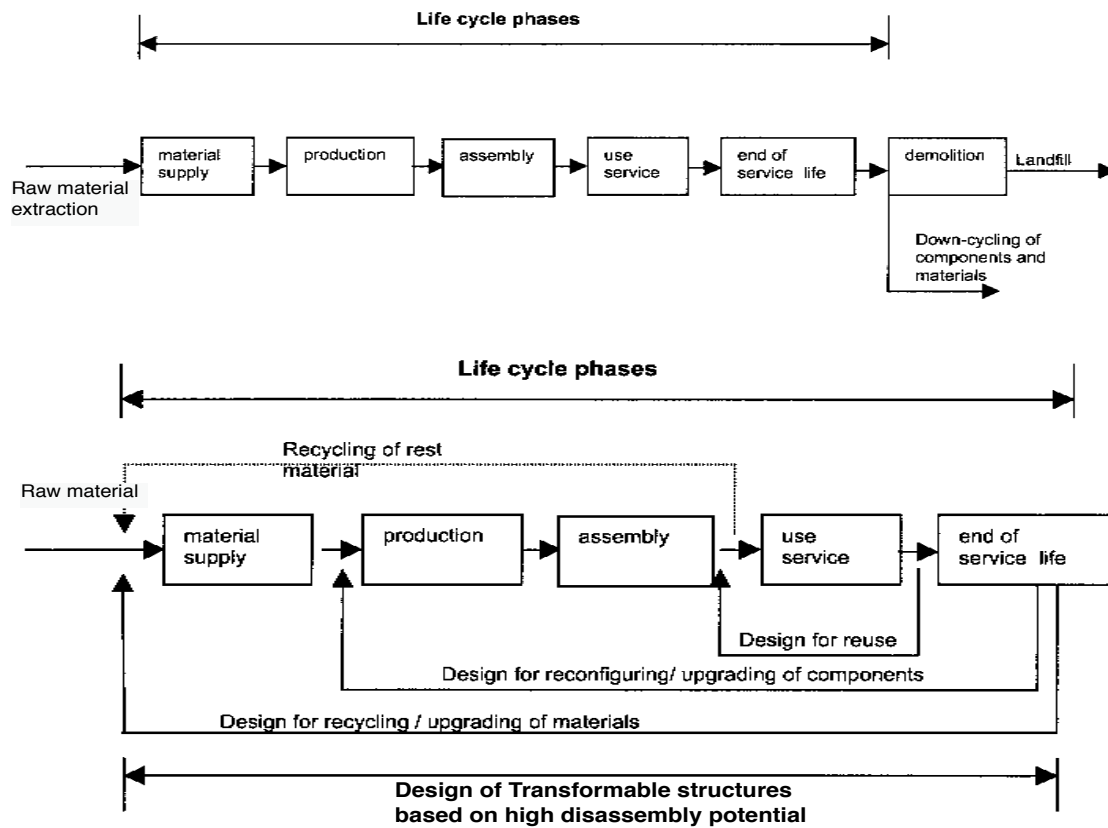


Fig.2.5 Processes that stimulate transformation of materials on all levels should be considered to overcome the linear model and end with a cyclic material flow (Durmisevic E., 2006).

repleceability, reconfiguration and recycling are the main key points to design open systems.

Disassembling means separating a product into subassemblies, product designers are already addressing this aspect through the design criteria known as DfDs (design for disassembly and serviceability). Disassembly of products or structures can be carried out either by an unfastening action or a destructive action, the latter being the least desirable in DfDs approaches as it takes out of the scope repair and serviceability.

Traditionally, product disassembly was only done to service or repair a part. But the disassembly of a product at the end of its useful life is slowly growing into a common and worthwhile industrial practice. End-of-life disassembly facilitates part re-use and more efficient material recycling, and thus helps reduce the environmental and ecological detriments associated with product disposal (Sodhi R. et al., 2004). Even though disassembly does not require any special skill from the workers it is still a time consuming process and it does not create major revenue streams, as a result it is quite a fragile process that not all product developers currently follow.

Demolition of buildings has a negative impact on the environment and generate considerable amounts of waste materials, thus every building should be designed and constructed considering the transformation capacity of its subassemblies. Life cycle design is a way of designing that needs to be supported by certain principles in order for it not to be only theoretical; the main criteria used for it are LCA (life cycle assessment), which measures the impact of building materials throughout their whole life, and LCC (life cycle cost), which only takes into account

their impact in the building's life cycle.

The afore mentioned criteria represent nothing more than a prediction of until what point a material or component starts to decay, what will be the environmental impact of its removal or maintenance and what effort will it require to be disassembled/removed.

Society is going through major changes in habits as well as in living standards; we no longer live in a stable world where conditions might stay the same for long periods, it now seems like what we predict today might completely change in a matter of months. Jobs are more flexible, travelling has become cheaper and easier and housing should also reflect this by making buildings more flexible and the house market more affordable and less rigid. Short-term solutions are no longer favoured by today's society. "We communicate and travel faster, further, and migrate more times in our lives. This desires access. Access requires physical improvement that has dramatic implications on architecture. It also demands political and societal flexibility -in planning, real estate, urbanism and architecture. It requires changeable buildings, changeable urbanism and changeable real estate. Such a package can turn the world into an exhilarating, accelerating space" (Berlage Institute, 2002).

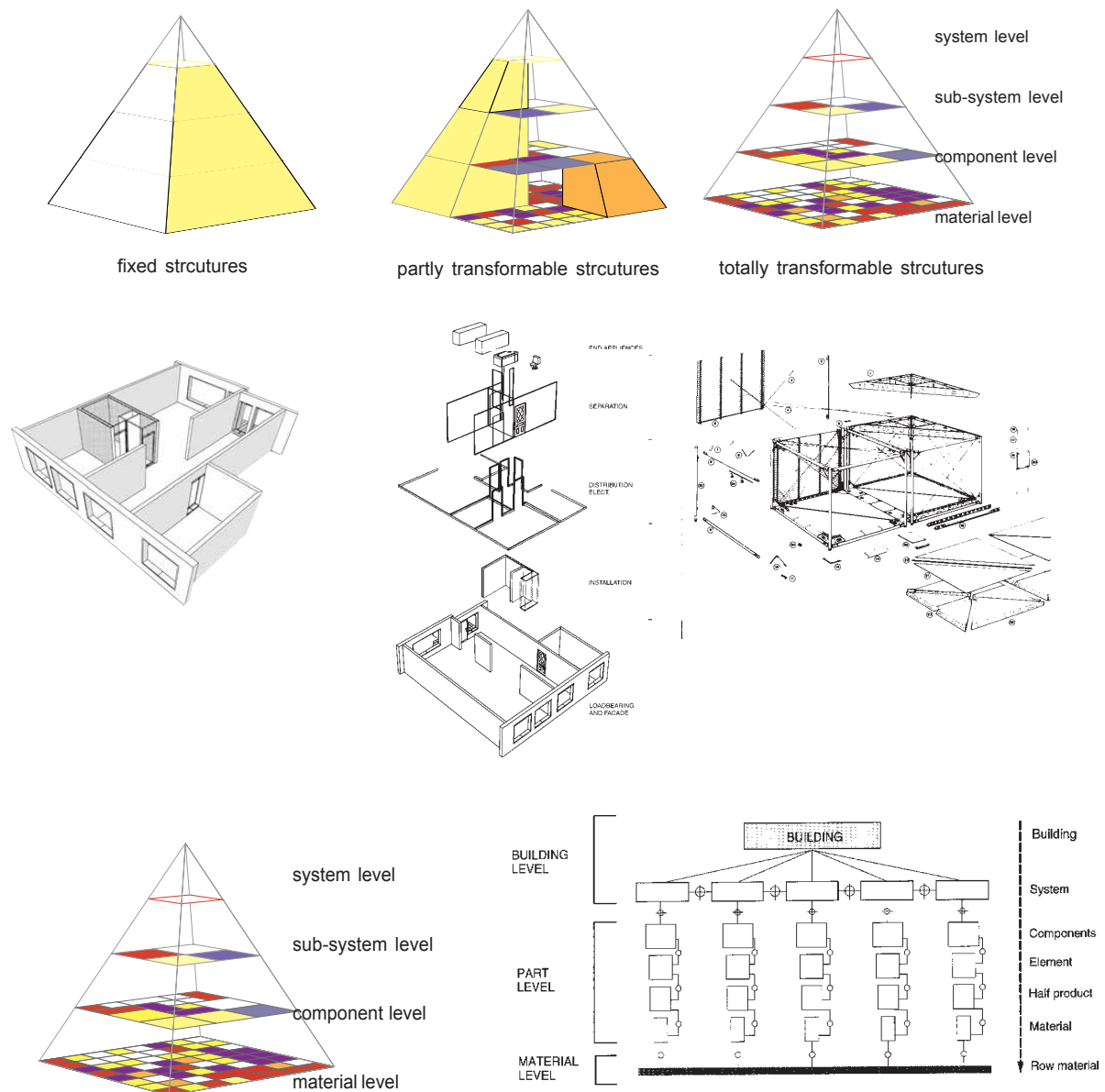


Fig.2.6 Design for disassembly means that every level, from system to material, is independent and replaceable without affecting the rest of the building. (Durmisevic E., 2006).

2.2 IFD INDUSTRIAL, FLEXIBLE, DEMOUNTABLE BUILDINGS

An interesting program that fosters prefabrication and industrialisation in the building industry is represented by the so called IFD building system.

IFD buildings (Industrial, Flexible and Demountable) have been introduced and funded by the Dutch innovation programme by the end of the 1990s as a consequence to the shift between a supply driven market to a demand oriented one. The concept that the name stands for is that buildings now need to be more industrial in order to improve the production process, flexible so that the user can have a wide choice in terms of functions and can change in the future when required, and demountable so that waste materials are reduced and, as a result, the environment can benefit from it. An IFD building is flexible now and in the future- its components are interchangeable, expandable and replaceable to meet future user needs. This prevents the building from becoming obsolete (van den Brand, 2004).

The aim of the program is to balance all currently involved stakeholders from the construction industry. The consumer benefits from the flexibility and better quality of the final product, the construction

industry itself benefits from lower production costs and increased customer satisfaction, society in general profits from a more sustainable development given by the IFD approach.

IFD buildings share the same features and reputation as prefabs, thus being a generally accepted choice when the market requires a fast response for a pressing demand for high volume requirements whereas it has been less appreciated in a “normal state” market where clients prefer customisation instead of standardisation. The solution to the issue can be found by developing the system towards basic modules that can be arranged and finished in different ways as well as having certain options between the client can choose, so as to foster customisation through standardisation.

Developments toward this objective are hard to pursue considering that the construction sector is fragmented by nature and each small/medium company tends to focus only on lowering the costs, neglecting the R&D phase. A successful integration of the IFD concept would require a change in traditional roles from the building industry: the final

	<i>Characteristic</i>	<i>Explanation</i>
<i>Industrial</i>	<i>Assembly</i>	<i>production preparation in the factory, on site only assembly, no improvisation on site.</i>
	<i>Project independent product development</i>	<i>Repetitive use of developed product, re-use of knowledge and experience.</i>
	<i>Weather independent</i>	<i>Building progress does not depend on weather and wind</i>
<i>Flexible</i>	<i>Freedom of choice</i>	<i>There's enough attention for freedom of choice of first-use users.</i>
	<i>Adaptability</i>	<i>Successive users adapt the building to their specific needs</i>
<i>Demountable</i>	<i>Building re-use</i>	<i>Buildings can be adapted to new functions</i>
	<i>Recycling</i>	<i>Building components or parts are suited for worthwhile re-use</i>
	<i>Waste reduction</i>	<i>The production of waste is reduced</i>

Fig.2.7_The table summarizes how the IFD concept is realized through some key factors such as the considerations of future and EoL scenarios as well as the production of components and subassemblies (van den Brand, 2004).

user would have an active role in the production process as opposed to the current passive role; the architect is no more just a designer but has to also mediate as some sort of industrial designer, formulating not only the spatial arrangement of the building but also proposing production scenarios, always taking into account the DFM (design for manufacture) aspects; the building contractor should take care of the product development assembly, be much more involved in the manufacturing process rather than being the traditional builder/site manager; the government's task would no longer be to approve a myriad of distinct projects, instead it would be the approval of several systems by certification, after which a certain system is just free to produce as many products as needed under the certification allowance.

An example of IFD is the office of Damen Bouwcentrum and ABT in Delft, which was one of the granted projects in the first selection round; its focal points were long life, loose fit, low energy and less waste. Some characteristics that make this building IFD comprise a redundant parking that could easily be turned into office space; a load bearing structure that could be reinforced in future when, if needed, an additional floor is added on top of the building; prefabricated demountable steel and concrete beams and columns and prefabricated concrete floor elements. van Gurchom (2002) claims that "the process can be evaluated as partially successful. However, the construction process itself took more time than originally planned (+50%). In addition to this, the mutual collaboration in the design phase of the project was dysfunctional. The result was a change of contractor in the building team". Even though

there were some issues in the process, it can still be seen as a step forward in the integration of IFD in the construction industry.

To sum up, the rising expectations from the clients in terms of quality, construction times and guarantees requires the traditional market to find new solutions and alternatives from the classic construction process; IFD contributes to this modern demand by making use of modern industrial production processes. However, the current organisation of the construction industry seems to be very rigid and hard to evolve due to the fragmentation and the low-cost oriented strategies of most of the construction companies.

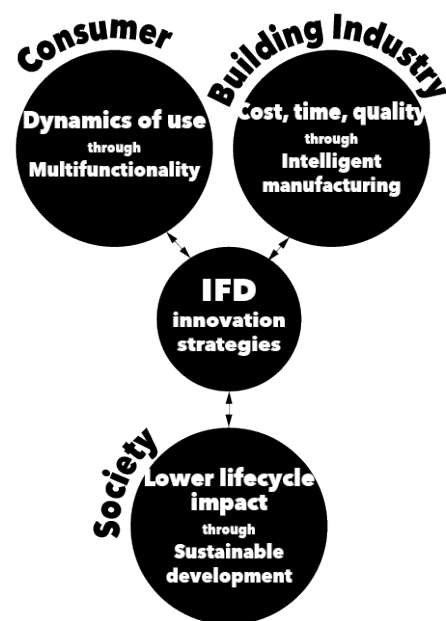


Fig.2.8 Balance between consumer, building industry and society can be brought by IFD. (own illustration)

2.3 DESIGN FOR MANUFACTURING

Digital manufacturing technologies and the development of IT are bridging the gap between design and production, but there is yet another sub discipline that strives to do so: design for manufacturing (DFM). DFM is the practice according to which manufacturing considerations are taken into account in parallel with the design process. This is very useful as, once again, it shifts the approach that has always been followed so far; instead of repeated iterations between design of products and their production, or even worse the adaptation of the production process only according to design choices, DFM enables to consider the two aspects in parallel so that all manufacturing aspects (production time, costs, product requirements and quality etc.) can be considered in parallel.

DFM comprises empirical guidelines based on good design practices. It involves the simultaneous consideration of design characteristics and constraints, some of them imposed by manufacturing. It demands an understanding of the technical limitations and capabilities of the manufacturing processes, and how they affect design solution characteristics (Ferrer, I et al., 2008)

Process modeling based on guidelines, empirical data, statistical data and physical models can be used to perform the manufacturing process selection (Shercliff and Lovatt, 2001). Additionally, computer aided engineering applications can be used to simulate manufacturing processes and predict their performance, and to evaluate manufacturability aspects of the part to be processed (Altintas et al., 2005).

Design for manufacturing is not easy to take into account for any professional figure; many aspects need to be taken into account, some of them are so quick at changing that an integrated IT needs to be developed to keep track of them. The empirical data on which choices are made comes from years of experience in the field which may still not be enough because new manufacturing processes are nowadays still being developed and some others might subsequently become obsolete over night.

When DFM is applied in IT, there is a broad variety of data associated with each production process but it's still not clear how it can be best arranged in a methodical, intuitive way. Furthermore, there are so many different sources and formats that the trend among companies is to develop their own guidelines instead of trying to develop a common one.

It is still debatable when the DFM should start in the design process; some say it should already start in the conceptual phase, when functions and specifications of the product are determined (Ulrich and Epping, 2004), some in the embodiment phase and some others consider it part of the process selection task (Ashby, 2000)

Concluding, DFM is a complex aspect that gathers multiple criteria and requires deep knowledge and experience in the manufacturing industry to be properly applied; the proper moment when it should start to be considered is not agreed by all and seems to be quite subjective. Some useful softwares have been developed (CES) but integration between criteria and data related to production processes is still lacking, making it difficult to develop a universal IT platform.

2.4.1 DIGITAL MANUFACTURING

Digital manufacturing tackles the increasing demand for customization along with the expectation for reduced development and production times in the manufacturing process. The main idea is to seamlessly connect data from every field and discipline so that the latter is immediately reusable by a different discipline. The fields of application spans from machining to manufacturing planning and control support. One of the first examples of integration of IT in manufacturing is CIM (computer integrated manufacturing), introduced in the late 80's to foster efficiency, performance, product quality and time response to market changes; at that time the industries were not fully ready and equipped to exploit the benefits to their full extent. The lack of integration between softwares complicated the use of IT in industries, this changed with the maturity of certain softwares, the advances in microprocessors and the general integration among diverse software applications during the last decade, which made the application of IT in the environment of manufacturing systems very common.

Miller E. (2006) declares that by exploiting digital manufacturing, manufacturing enterprises expect to achieve the following:

- (a) shortened product development
- (b) early validation of manufacturing processes
- (c) faster production ramp-up
- (d) faster time to market
- (e) reduced manufacturing costs
- (f) improved product quality
- (g) enhanced product knowledge dissemination
- (h) reduction in errors
- (i) increase in flexibility

The most widely used and appreciated Computer aided technology is probably CAD (computer aided design) which is nowadays indispensable for most manufacturing industries. It dramatically reduced product development times and boosted productivity; however, the first application of CAD were fairly hard to utilise due to their text-input interface. Currently the market offers much easier softwares with intuitive interfaces that even create real time 3D feedbacks of the design, finite element analysis, dynamic analysis, climate analysis and so on. Over the years CAD systems have become more and more integrated with the manufacturing machines, reason why now they are considered essential for the industrial production. CAM (computer aided manufacturing) enables mass production and customisation at the same time, revolutionising the whole industry. The best example is the introduction of CNC (computer numeric control) machines, true connection between the three dimensional environment and the production process.

In the 1990's the automobile and aerospace industries launched the AIT (accessible information technology) program to foster the competitiveness of industries by adopting IT in both design and manufacturing. The automotive industry has ever since led the research and development of digital manufacturing. Eminent examples comprise BMW, which thanks to simulation of the production processes at early design stages achieved 50% fewer faults per vehicle, Opel achieved a very fast production launch through the utilisation of three dimensional simulation environments for the production process; Chrysler, General Motors, Volvo and Ford are other companies that largely benefited from digital manufacturing methods lately.



Fig.2.9_A CNC milling machine is one of the types of computer controlled tooling that are essential to digital manufacturing (www.glacern.com).

2.4.2 3 AXIS CNC MILLING

The quality and manufacturing cost of the final product are determined again in both the design and production phases. This demonstrates that there is a significant need for a bridge to be built between the production of development and the real production; digital manufacturing aims to play this part (Chryssolouris.G. et al., 2008).

Digital manufacturing needs to be further exploited in order to close the gap between the product definition (configuration of components and required manufacturing processes) and the actual manufacturing production activities within the enterprise (Miller E. et al., 2006).

CNC milling is a digital manufacturing technique that enables many industries for rapid prototyping as well as the production of mass customized products. It allows to create physical models from detailed three dimensional computer models, which make virtual models even more essential in nowadays industry. It has to be pointed out that three dimensional nor physical scale models can really substitute the immersive experience of real architecture, which can only be mimicked by modern immersive techniques such as virtual or augmented reality.

As already stated, CNC milling is strictly connected to computer models. However, it does not imply

the fact that the production of physical models or components can be carried out by simply pressing a button, regardless of different materials and geometries. It is actually a technique that requires some modern crafting techniques in the sense that a lot of knowledge and experience should be acquired in order to be able to really master each milling technique. Some materials such as rigid foam indeed do not require any special level of expertise, but when it comes to wooden materials then every different shape, thickness and wood type demands different bits and rotational speeds which are nowadays still not clear and very much based on experience.

3 Axis CNC routers have various capabilities, Aitcheson et al. (2005) list them as follows:

- 1) Cutting large sheets of material such as plywood sheets. In this sense the CNC router is like a powerful laser cutter but the CNC router has the added advantage of being able to cut special edge profiles rather than just vertical cuts.
- 2) Milling large terrain models. Such models generally have large widths and lengths but relatively small elevation changes compared to the length and width.
- 3) Half-rounded objects are easy to machine because the cutting tool in a 3-axis machine can only machine from one side.
- 4) Fully round objects. This is accomplished by rotating the piece to be cut so that cutting can be accomplished from more than one side (one of the case studies below involves two-sided cutting. It is, of course, possible to mill from more directions with a five-axis milling machine where the cutting tool can move in five degrees of freedom, usually accomplished with a tool that can

move in three directions (x,y,z) and a table that can rotate and tilt.

The CNC milling process requires at first to create a virtual model that should then be exported in a different softwares that creates so-called tool paths, which are basically the directions that tell the tool how to move in the physical world. The final instructions for the CNC router come in G-codes in form of text formats. The physical panel is generally referred to as the stock.

In order to avoid costly mistakes it is common use to run tests with inexpensive materials such as foams first, secondly it is also advisable to run a second test on a small part of the final model with the actual material so as to confirm feeds, cutting strategies and speeds.

Rigid insulation may be cut at high feed rates (the rate at which the cutting tool moves through the material to be cut) and high rotational speeds of the tool, whereas different kinds of wood each have a speed limit depending both on how fast the cutter can remove material as well as the heat produced (which can produce burning) and the type of finish produced (Aitcheson et al., 2005).

It is still very hard to fix these values according to each case, therefore they must be determined according to one's experience. Another experience based decision in CNC milling and probably the most influential one time-wise is the selection of the right set of tools and paths that can achieve the desired shape and quality in the least amount of time; by choosing a really small bit rather than a bigger one to achieve better quality might not always be the best solution as often high quality can be achieved even with bigger bits whereas

small ones can prolong milling time even for days in big models. Luckily, softwares can actually simulate milling times before the process actually starts so that the user can always choose the most suitable trade off between quality and milling time. Determining the most appropriate tool paths is one area where creativity is involved.

FabFac stands for Fabrication Factory and it offers to the public the possibility to rent a 3 axis CNC milling machine for all purposes and many different materials spanning from regular wood to sheet materials, ECOboards, MDF and different kinds of sandwich panels. The machine is available to produce prototypes and test them in an iterative process thanks to which the built designs are further assessed. Many performance flaws as well as assembly difficulties can in fact be only detected once a physical model is built.

2.4.3 FABFAC'S CNC MILLING MACHINE

FabFac features a SCM Record 220 milling machine with NUM1040W control, the milling bed is 5200x1200mm, it allows for stocks up to 300mm thick to be processed, the latter is kept in place by two vacuum pumps. The accuracy of this specific machine is a hundredth of a millimeter.

The max speed at which the head can move in the x and y axes is 40 meters per minute, the max milling head rotation is 18.000rpm or 300rps; an automatic tool changer allows for up to 10 milling heads to be automatically changed during the milling process. The dust created during the milling is extracted by a big vacuum placed around the milling head.

The machine enables for simple drilling, engraving, outlining, slotting and even landscaping. The three axis correspond to the x,y and z axis, that as we all know are enough to identify any point in space; on the other hand, there are also other axis that allow to process more complex shapes, the rotational axis around x,y and z, respectively named A, B and C. CNC milling machines that use more than the three axis allow for results that are basically comparable to the ones achieved with 3D printing, which is currently animating the debate over the best approach between additive manufacturing and subtractive manufacturing. The 3 axis CNC milling machine therefore allows to process panels using bits that only perform transitions over x,y and z. The two vacuum pumps that hold the panels in place also prevent to safely cut small elements without the risk of the latter to move from their original position.

There are some technical aspects that need to be taken into account when producing a digital file for CNC milling. Slots and cutouts, for example need to be drawn considering the thickness of the head used as well as multiple slots and cutouts next to each other, which need to be apart at least the same length as the head thickness.



Fig.2.10_FabFac's CNC milling machine with which the PD lab was produced and some of the bits for the different operations required (own ill.)

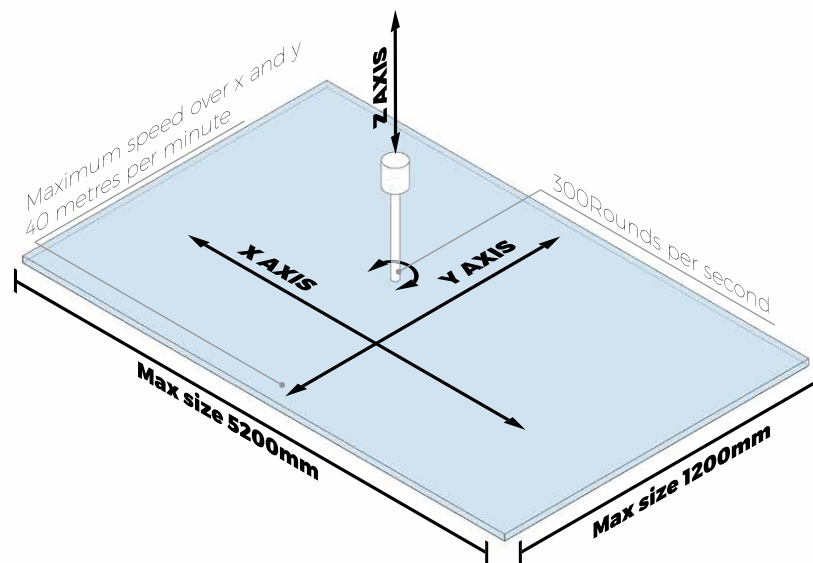


Fig.2.11_The drawing displays the 3 axis on which the CNC milling machine can operate, the maximum speed and the maximum size of the panels that can be processed by it (own illustration).

CHAPTER'S RECAP

END OF LIFE

- End of Life approaches don't only concern sustainability but also reduce costs and improve the brand image of the company
- The understanding of technical life cycle and use life cycle of components is the basis for End of Life strategies
- Independence of assemblies and sub assemblies in buildings promotes disassembly and reuse rather than demolition and disposal

IFD BUILDINGS

- IFD buildings are flexible now and in the future, its components are interchangeable, expandable and replaceable to meet future user needs. This prevents the building from becoming obsolete
- Successful integration of IFD buildings requires a change in the tasks of all traditional subjects involved (client, architect and contractor)

DESIGN FOR MANUFACTURING

- DFM fosters the integration of all manufacturing aspects (production time, costs, product requirements and quality etc.) in the early design phase to boost the efficiency of production and prototyping
- Integration of DFM requires an understanding and constant update of all possible production processes, reason why it should be implemented in the companies' IT
- It is still debatable when the DFM should start in the design process

DIGITAL MANUFACTURING

- Digital manufacturing tackles the increasing demand for customisation along with the expectation for reduced development and production times in the manufacturing process
- The development of CAD technologies has allowed its integration in manufacturing techniques, boosting the design and production of all industries
- CNC (Computer Numeric Control) milling is a digital manufacturing technique that enables many industries for rapid prototyping as well as the production of mass customised products

BUILDING SERVICES

3.1 OVERVIEW

The history of building services engineering is long and convoluted. The beginnings can be even found in ancient Greece and Egypt, where architectural structures were oriented taking into account the course of the sun during the day to optimize sunlight while monitoring solar gain. The true masters of building services were without a doubt ancient romans, which invented the first sewers, public fountains and baths as well as an incredibly long and thoroughly engineered system of aqueducts that spanned throughout the empire to finally bring water to Rome. In public baths and noble houses they also developed the hypocaust, an ancient yet innovative floor and wall heating system; a substructure made of pedestals allowed hot steam to flow under the actual tiles, heating the latter. These first applications can be considered the genesis of building services engineering, even though the real beginning of this discipline only dates back a couple of centuries ago; the concept behind building services is to build constructions which can be comfortable independently from outside conditions. The very first written example of this study is a paper by a German vicar dating 1720, titled “calculation of the heat demand in buildings”. Still in Germany, in 1856, the Verein Deutsche Ingenieure (association of German engineers) was established and went more in depth into the subject leading to a study titled “heat loss due to transmission and ventilation”. It was Rietschel in the end of the 19th century that wrote the basis for what then became modern building services engineering; the field kept developing with further studies, all focused mainly on the heating demand of buildings. Ventilation and cooling were still not considered worthy of specific studies for the improvement of

indoor environments.

By the 1940's architectural faculties worldwide started to implement specific subjects to teach next professionals the basis of technical installations required in modern buildings. During those years air conditioning systems started to be integrated in many buildings of developed countries, especially in the United States. These systems caused a dramatic raise in the energy demand of buildings. As a result, the 20th century witnessed the first claims to lower energy consumption due to excessive costs, ecological/environmental motivations were still not taken into account though. Availability of fossil fuels became abundant during those years and building design responded with mechanical and electrical systems which often consumed too much fuel. Large single glazed areas caused over heating, glare and discomfort during summer; combined with draughts and heat losses in winter. The control was rudimentary and simply represented by opening or closing windows according to one's needs.

The first global introduction of sustainability after the ecological movements that took place during the 70's was the Brundtland report in 1987, also known as “Our Common Future”, with which the WCED (United nations world commission on environment and development) initiated the world to the concept of sustainable development, claiming that global development was indeed possible but it had to be sustainable, meaning it shouldn't compromise the future of next generations. Sustainability is the base upon which a completely new approach to building services engineering, and more in general towards the modern designs of the built environment was taken. New sustainable technologies based on

renewable energies started to sprout and are still nowadays booming more and more thanks to local, national and international funds and grants that foster the use of green energy sources.

At the end of 2009 the EU passed an amended version of the directive concerning the energy performance of buildings, according to which, as of 31 December 2020, all EU member states must ensure that all newly constructed buildings produce as much energy as they themselves consume (Lenz B. et al, 2011). The latter directive defines a net-zero energy building as a construction in which the very high energy efficiency causes the overall annual consumption not to exceed the energy production from energy sources on site.

The FabField building system, as already mentioned in the previous chapter, embeds this sustainable approach from the very first concept. The building is made out of OSB which is a non toxic, low footprint, economical type of wood; the design and production process is based on industrial, digital manufacturing methods in order to make the whole process as efficient as possible, reducing waste material and improving accuracy and safety during both production and assembly. Furthermore, it is a modular, flexible, demountable system that takes into account re-use and end of life scenarios so that life of components does not end with the end of the building but can continue in other forms or functions of the original material or component. In order to pursue the same sustainable approach in building services as well as in the building itself some restrictions need to be considered:

- The design process will rely partly on the product development of the OSB building components but it will also partly depend on commercially available products such as boilers, panels, heat pumps as well as pipes, ducts, wires and so on.
- Some building services, especially the ones belonging to energy production, rely on sources of energy which are going to be discarded as not in line with the overall FabField approach to sustainability. The final goal is to use energy sources which are clean and flexible.
- To restrict the scope of the thesis the location will be bound in the Netherlands, therefore cooling requirements will be neglected for the case study.
- The market offers a myriad of solutions for each different scenario, context and requirement; nevertheless, this is not meant to be an encyclopedia of market solutions, rather a collection of the ones considered the most suitable for the FabField building system in terms of size, energy source, installation complexity, space requirements, maintenance and demountability/second life.

3.2 THE INDUSTRY: TRADITION vs INNOVATION

The building services industry is founded on engineering principles which are applied on the built environment, they are under many aspects responsible for the artificial environment we live on as well as the current environmental condition of our planet. It is a vast industry in terms of the diversity of professions that encompasses.

The industry is generally divided between design and installation. Design is taken care of by specialist contractors which are sub-contracted on site by the main contractor for the construction. Nevertheless, some design and installation practices exist, which simplifies contractual and communication relationships. Other than that there is a market with an abundance of companies which design and manufacture the different products spanning from snap-fit plastic water pipes to high capacity CHP stations.

Building services play a central role in contributing to the design of a building, not only in terms of overall strategies and standards to be achieved, but also in façade engineering, the weights, sizes and location of major plant and equipment, the position of vertical service risers, routes for the distribution of horizontal services, drainage, energy sources, sustainability, and so on. This means that building services design must be integrated into the overall building design from a very early stage, particularly on complex building projects such as hospitals. Whilst it is usual for a building design team to be led by an architect, on buildings with very complex building services requirements a building services engineer might be appointed as the lead designer. The detection of clashes between building services and other building components is a significant

cause of delays and variations on site, not just in terms of the physical services themselves, but also access to allow the builders work in connection with those services. The use of 3D computer aided design (CAD) systems and building information modelling (BIM) should help reduce the occurrence of such problems. Increasingly, building services engineers are central to the design and assessment of sustainable systems, assessing the life cycle of buildings and their component services to minimise the resources consumed and the impact on the environment during fabrication, construction, operation and dismantling.

Alternatively to the classic approach of building services design and installation there is a fairly modern approach which is trending more and more due to the numerous benefits it provides.

Since the mid-1990s, several articles have appeared, describing off-site (or modular) construction of building services, and the projects that this methodology has been applied on. Building services are a major economic factor in the construction industry, they can make up to 30-40% of the total project value and, in turn, can be one of the biggest economic losses of the latter. In order to reduce risks and guarantee the final quality of building services, similarly to the whole construction industry, installations should evolve from the traditional process and implement as much from the manufacturing industry as possible.

In ‘traditionally’ procured construction projects, building services and structural design are not integrated. In most cases construction is well under way before any thought is given to the building services design, whereas all aspects of construction

should be in line and integrated in order not to have any risks, imperfections and time delays which coincide with money losses. Construction quality is indeed a major issue for traditionally procured building services. The services system is the last major part of construction and installation. The space within which the services are installed is restricted, and often cramped with more than one trade completing its part of the works. Due to a lack of full design and layout information there is little order to what occurs within the service voids. Consequently, the quality of workmanship suffers. Through the “off-site” approach, information regarding all fields of a design is made available and constantly updated; building services are carefully designed, produced and installed on factory rather than on site, ensuring the final quality of services. However, it is still very difficult to have such a fluid flow of information in the design, especially if the building services design is the only field to follow such approach. In an ideal scenario, all fields involved in the design of a building should be in line, so that the design part is carefully integrated and carried out by all subjects involved and the subsequent construction is much more safer and faster.

Bob Hughes (2013) declares: “Offsite fabrication of modular pipework systems is emerging as a mainstream approach because it addresses many, if not most, of the key challenges facing the industry today. In terms of costs, our experience over the past years shows that reductions of 10 to 20% can be achieved, compared to a traditional approach involving pipework installation on site. Another important benefit is time certainty. Working in factory conditions removes uncertainty – it is

guaranteed to deliver on time, every time. Projects are no longer at the mercy of the vagaries of the weather or manpower availability.”

The difference in efficiency on-site between the two approaches is drastic: 35-55% efficiency for traditional projects and 85-90% efficiency for the off-site approach.

The industry pushes towards prefabrication of building services, mostly for complex projects that require very high quality and precision as well as a high degree of time certainty. Prefabrication in this discipline requires even a larger effort upfront during the early stages of design process, therefore it is still not trending in small scale projects or all functions that do not require a huge volume of services like hospitals do. Some exceptions of course exist and are mainly focusing on the prefabrication of a central module containing all necessary installations from which pipes and ducts can later be connected. Not many examples were found concerning the prefabrication in the distribution of services through buildings.

In the following pages, a theoretical overview will be given to the main energy producing technologies currently trending in the market, analyzing which of the latter could be adaptable to FabField in terms of energy source, size and flexibility. After that, a first analysis on the adopted approach for the integration in the system will be given, followed by the summarization of the market research carried out to gather technical data from building services companies.

3.3 BUILDING SERVICES FAMILIES: A SYSTEMATIC APPROACH

At this point, for the sake of clarity it is necessary to structure and divide building services into families.

The three families are divided according to the medium they are dealing with (water, air, power).

This is specially done for the fact that the family “heating” doesn’t take into account running water, which is still a fundamental aspect that the design will have to deal with. Thus, the family water will comprise hot and cold water as well as heating and domestic hot water.

These three big families can be further divided into three more groups according to the function they carry out and their spatial requirements in the construction of the building. Some appliances do not stretch throughout the plan of buildings, they are rather compact objects placed in fixed locations that might produce or supply energy; some other building services snake inside walls, ceilings and floors to take the medium from one place to another. The services responsible to bring energy from one place to another are air ducts, water pipes and electric cables and wires. This big family of services will be referred to as “*distribution*”. In the traditional industry the distribution of services is not planned thoroughly during the design phase, the smaller the building the less time they will be given. It is also the family that creates the most clashes and problems on the building site; laying cables, ducts and pipes is very time consuming and often different sub-contractors overlap in the same place and can hardly proceed with their tasks without clashes.

Multiple variables are related to the distribution of services, a myriad of products with different sizes, specifications and materials, many different habits

and regulations for each country. i.e. some countries prefer to group electric cables on ceilings whereas some others on walls. It is also not just a matter of habits and traditional way of working, the result widely differs also depending on the function and structure of the building. All these data will be later taken into account, some as variables, some as fixed conditions.

Distribution may be the most complex group but it is certainly not the only one; as already stated previously there are services represented by physical objects placed in fixed places, which therefore do not require any planning in the way they stretch throughout the building. These products are designed to either produce energy, or be the final interface that the customers will interact with, the only visible part of a wider network mostly hidden behind walls, floors, ceilings and technical rooms.

We are gonna refer to these two groups as “*sources*” and “*final appliances*”. Sources, as the name might suggest, are all the physical products that use one form of energy and turn it into another through any process; this family comprises boilers, heat pumps, solar systems, PV panels and many more, according to the type of energy they are fed with and the one they supply. In terms of spatial requirements, these products are the bulkiest and need to be placed in strategic locations in order to be as efficient as possible while working silently and safely.

The context, function, size and location of the building strongly influence these set of services which are impossible to work everywhere regardless of external conditions. A heat pump will only work efficiently when outside temperatures remain


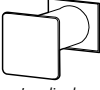
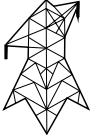

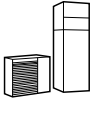




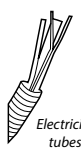





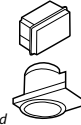
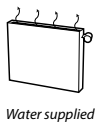


	AIR	POWER	WATER
SOURCE	 Centralised mechanical ventilation  Localised mechanical ventilation	 Main grid  Photovoltaic	 Heat Pump  Pellet Boiler  Solar Thermal
DISTRIBUTION	 Round ducts  Flat ducts	 Electricity tubes  Columns  Skirting ducts	 Ø15-19 mm copper/plastic pipes
APPLIANCES	 Wall-ceiling-floor vents	 Lights and flush boxes  Recessed lights and flush boxes	 Water supplied heating appliances  Toilets  Sinks

Fig.3.1_Systematic division in families of building services (own illustration).

above a certain limit, after which the pump will not be able to reach acceptable temperatures. A PV array will only make financial sense when the building, geographic location and surroundings allow for a proper sun exposure, otherwise the power production would not be appreciable. Design wise, technical data needs to be gathered especially regarding their size, proper location, efficiency and fuel kind.

Final appliances is a very diverse group of appliances which comprise user interfaces (plugs, switches, monitors etc.) and energy destination points (lights, air grills, radiators etc.). All these products are nevertheless grouped under the same family for a specific requirement: they all affect the building's finish and they are usually the only tangible service that the user can actually see and interact with. Therefore, the data that needs to be gathered is related to their finish quality, the thickness required and the level of integration within walls, ceilings or floors. The same service can be placed in multiple spots, like lights or air grills for example, which could be on walls as well as on ceilings or even floors. Thus, this group requires some technical data gathering followed by some restrictions, without which the methodical approach would simply be too wide.

The last group is actually a non-group, gathering all those services which do not belong to neither of the families mentioned above. In fact, there are some products that are not placeable in sources, distribution nor final interfaces; furthermore, these objects are not indispensable in buildings, even though they can be interesting appliances in some specific cases. For these reasons, the group is called “add-ons” and consists of power storage, solar tubes, home automation systems and so on. These products came out after the research was carried out, their characteristics did not allow them to be part of the other families but their integration can be really beneficial in some cases; their characteristics were gathered anyway and a special family was created so that after choosing the basic energy concept for a building, one could still integrate some add-ons to it depending on the circumstances.

To sum up, building services can be divided depending on the medium they administer: water, air and electricity. Furthermore, they can further be grouped according to their function and spatial requirements: sources, distribution, final appliances and add-ons.

3.4 THEORETICAL OVERVIEW: HEAT, AIR AND POWER

3.4.1 HEAT SUPPLY

Condensing Boilers

These boilers offer the greatest efficiency among all other generators (95%). They make use of the latent heat contained in the steam through a condensing process. The big downside to this technology is that it is fueled either by gas or oil, which is in conflict with today's aim to avoid fossil fuels in heat generation and use renewable energies instead, reason why this technology is described but already discarded from the possible design choices.

Biomass Boilers

All organic material produced by animals or plants is referred to as biomass. These systems are extremely sophisticated and, most importantly, energy neutral, therefore able to offer a sustainable heating source in buildings. These kind of boilers require specific design conditions such as a storage room and a fuel delivery space, reason why they need to be set at an early design stage so that the structural and architectural design can be adjusted accordingly. The most commonly used kind of biomass boilers are wood-chip boilers, which are fueled by leftovers from wood processing, and pellet boilers, that use compacted, very dense wood with a high energy content. The fuel for these boilers is cheaper than oil but less efficient (70-75%). In small buildings they can be either automatically or manually fed, whereas in larger buildings they are exclusively automatically fed.

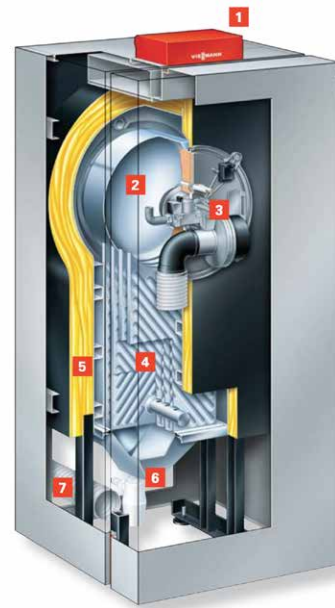


Fig.3.2_ Condensing boiler Vitocrossal 300 (www.viessmann.com)



Fig.3.3_Pellet boiler Vitoligno 300C (www.viessmann.com)

Heat Pumps

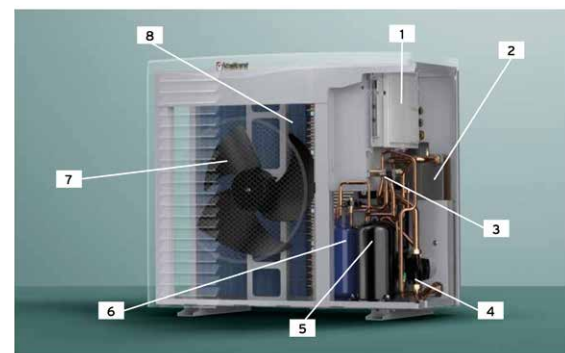
Heat pumps work in a different way than traditional heat generators: they convert anergy (unusable heat) into exergy (usable heat). The heat absorbed indirectly by the sun is stored in water, ground and air and can be converted by heat pumps into either cooler or warmer air. The most frequently used source is outside air, even though it has the lowest energy density. Ground water as a source offers a stable temperature throughout the year but requires a larger investment. When using near surface ground heat the nature of the soil has to be studied in advance, which makes it unfavorable for a standardized solution.

When we talk about heat pumps, the term efficiency is not applicable anymore, instead the term COP is applied (coefficient of performance) which indicates the performance of the refrigerant cycle. This kind of technology is best used with a low temperature heating system such as underfloor heating.

Heat pumps are powered by electricity, it does not necessarily mean they are more sustainable than traditional fossil fueled boilers, it actually depends whether that electricity comes from a renewable source or not. This means that in our case, a heat pump should be coupled with a PV panels array in order for it to really be Eco-friendly.

CHP (combined heat and power generation)

This kind of technology produces both heat and power like the name suggests; it is a very efficient energy production method with a combined efficiency that ranges between 80 and 95%. This kind of plants must be designed only for base loads as they have to work for sustained periods of time, therefore they usually require additional supply



Key:

1. Electronic box
2. Condenser
3. 4 way valve
4. CH pump
5. Compressor
6. Gas buffer (refrigerant heat exchanger)
7. Fan
8. Evaporator



Fig.3.4 Heat pump external compact unit (www.vaillant.com)

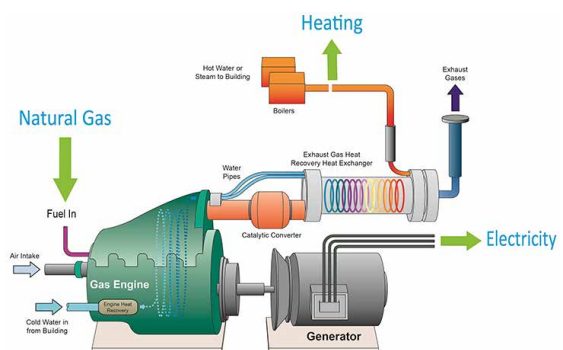


Fig.3.5 Scheme of the functioning principle of combined heat and power plants (www.regen-uk.co.uk)

systems for peak loads. Furthermore, they are usually very big plants which would not be suitable for a small single family housing building; nevertheless, MicroCHP exist as well especially for smaller scale requirements, even though the initial investment is still very high. In conclusion, it is an interesting technology which, due to the high costs may not be the best solution for the FabField system.

Solar Thermal Systems

Solar thermal systems are modules that usually comprise a collector, a heat transfer medium, transport equipment and a heat storage facility. Mainly 4 different kinds are currently available on the market, they vary in technology, cost and efficiency:

- **OPEN ABSORBERS** are the simpler and less efficient kind (40%), commonly used for swimming pools or as a heat source for heat pumps, the water is heated up to 30-40°C.
- **FLAT PLATE COLLECTORS** are the most widely used, especially in housing; they reach efficiencies of 65-70% and the exiting water is 40-50°C.
- **AIR COLLECTORS** are used to heat up air rather than water, reason why they are not widely used; efficiency 60-65% and exiting medium at 60- 90°C.
- **EVACUATED TUBE COLLECTORS** are the most advanced type. They reach efficiencies of 80-85% and the water reaches 70-130%; nevertheless they are very expensive.

Solar thermal systems are generally used for the production of domestic hot water. A way for them to be really effective is to pair them with inter seasonal storage tanks which store the excessive heat from summer and use it in winter; however, this type of

storage only makes sense in large projects, which makes it unsuitable for the case study.

Concluding, the most efficient way to heat a building is strongly dependent on the infrastructure built around it, if there's an already existing heating network it makes perfect sense to connect it to the grid, from an ecological point of view as well. Even if at the time that the building is connected the central source is not as sustainable as a decentralized independent one could be, the latter will sooner or later be replaced by a more sustainable one due to the large number of buildings connected to it. The final aim is of course to rely as much as possible, and eventually fully, on renewable sources available in each context such as ground heat, solar radiation, wind and so on. Nowadays, solutions like heat pumps and solar thermal systems are booming thanks to the development of the technologies that occurred in the past decade as well as European and national funds and grants that made them favorable for almost any condition and context. If local renewables are not available or insufficient and the grid is not conveniently close to the site an alternative clean source of energy can be biomass (wood chip or pellet).

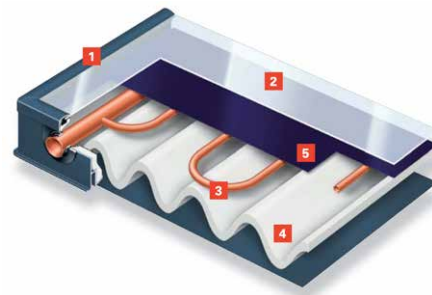


Fig.3.6 Flat plate collectors for solar thermal heating (www.viessmann.com)

3.4.2 AIR SUPPLY

In addition to oxygen supply, the principal aims of building ventilation are to remove pollutants and smells from rooms within buildings. The main factor though is the amount of CO₂; a person in sedentary condition consumes on average 0,0047 l/s CO₂. Some reference values are useful to get a grasp:

- 1000ppm are usually the maximum concentration of CO₂ allowed in a room.
- 300-400ppm is the average concentration of CO₂ of outside air, obviously varying from place to place.
- In offices the concentration can easily reach 600-800ppm, which is clearly very high.
- In classrooms it can easily reach values of 1500ppm

An excessive concentration of CO₂ can lead to tiredness, headaches, dry throat and lack of concentration.

Another important factor is the relative humidity, which must be kept under control to prevent the formation of mold, bacterias and fungi. The comfort value ranges between 30-65%, with higher concentrations the growth of germs is favored, lower values can cause high ozone concentrations.

When designing and dimensioning a ventilation plant, it is important to previously set the required room quality, usually a value of 30m³/h per person is the applied value for the exchange rate, mainly for energy saving reasons as high room quality is ideally achieved only with a value of 36m³/h.

Natural ventilation

Natural ventilation systems require openings in the building's envelope to exploit naturally occurring pressure differences given either by wind pressure

or temperature differences between inside and outside.

Window openings are deeply affected by their height or height difference between two openings as well as their cross sectional area. In this type of natural ventilation the depth of the room should ideally not exceed 2.5 times the room height, in case of cross ventilation, the depth of the room connecting the 2 openings should not exceed 5 times the height. Updraught systems are another kind of natural ventilation which exploits the variation of air pressure with height. An opening is placed at a high point and if there is enough temperature difference thermal buoyancy will occur and provide for ventilation. Since the case study for the FabField system is a small single family housing, a minimum height is not granted for updraught to work efficiently.

Wind catchers can also be used for natural ventilation; they exploit negative and positive pressures on the sides of a building to ensure ventilation. Nevertheless, it is very hard to ensure an even ventilation with these systems as obviously wind varies in direction and pressure. It practically consists of a shaft with one or several openings in the upper part; to integrate it in the FabField system, some adjustments in the overall design would have to be made but it would surely be useful as a cool air supply for the main ventilation system.

Mechanical ventilation

In contrast to natural ventilation, these systems can be provided with a control mechanism, a filter and even heat recovery. The downside is obviously the need of energy for them to operate the fans. Mechanical ventilation systems can be differentiated in central systems and local systems. The first ones require ductwork to distribute and exhaust air from the building, which makes them quite costly and complex. Local systems are placed in openings in exterior walls and do not require any kind of ductwork, which makes them very flexible for the Fabfield system. They consist of a heat exchanger and a small fan which is integrated into a penetration in the exterior wall, each room should be equipped with a unit. The functioning principle is based on cross ventilation: half of the units draw fresh air in while the other half removes exhaust air in intervals of one minute. The size required for each opening is circa 20x20cm.

Obviously there are many other technologies for supplying air in buildings, such as earth pipes, ventilated thermo active building systems (TABS) or night time ventilation, but they haven't been analyzed further since they are not in line with the scale of the case study, nor with the location as for the night time ventilation.

A good air supplying system is essential for internal comfort, even though we give it for granted as it is probably the least tangible family of building services. In the past, especially residential buildings did not include nor require a mechanical ventilation system since fresh air was supplied by the innumerable leaks present in the building's skin and openings. However, current technologies

made common residential buildings almost air tight, subsequently raising the need for ventilation systems for these functions as well.

Natural systems are hereby discarded for the high energy losses they cause in a building; highly context-dependent ventilation methods are also neglected due to the strive to find solutions that can be efficient anywhere, regardless of the site, context and surrounding infrastructure.

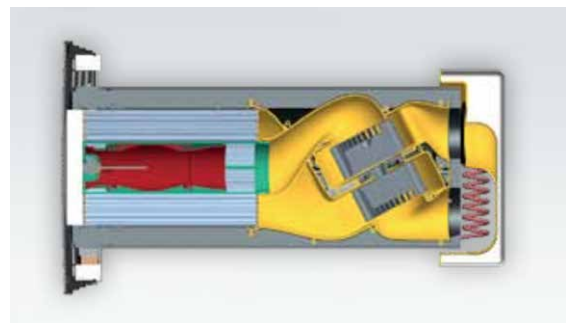


Fig.3.7_Localised air ventilation unit brink air 70 (www.brink.com)



Fig.3.8_Centralised residential ventilation unit (www.vaillant.com)

3.4.3 POWER SUPPLY

Electric consumptions are rising due to the increase of appliances that we use in our everyday lives; lighting, air distribution, electrical devices, electric cooling/heating cause consumption levels to be generally really high, especially in non-residential buildings. The final aim in this case is to produce the whole electric demand on site, creating self sufficient buildings electricity-wise.

The already mentioned sustainable global goals are, during these years, bringing an unprecedented change in the electricity industry. The promotion of decentralized renewable energy production requires the mains grid to fulfill the task of coordinating the balance between supply and demand as well as distributing power from central stations. It is therefore necessary nowadays to examine whether and to what extent a building can become a power generator. In contrast to the numerous possibilities for heat generation, from a building planning point of view, the opportunities for a building to produce electricity from a sustainable source are limited to PV panels and CHP plants; the latter are out of the scope due to the very high initial investment and large size which makes them unsuitable for small family housing. Photovoltaic technology is a method of generating electrical energy without mechanical wear and tear, emissions or noise. Apart from producing energy they are also often used in buildings for weather and sun protection as well as visual screening. Architectural applications of photovoltaics begun in the early 80's and has increased ever since; nowadays they are widely integrated in buildings as facade elements or more

simply on rooftops. Solar radiation on vertical surfaces is 30% lower than that of inclined but, the application of PV modules in facades can replace other expensive finishing materials finally bringing both energy and economic savings to the building. Nevertheless, the correct orientation of the panels is fundamental in their application as their efficiency drops considerably when not correctly exposed, as opposed to solar thermal systems which can still be very efficient even under not optimal conditions. The modules need to be therefore carefully placed in order not to cast shadows to the closest one.

Solar cells are the basic element of PV, they differ in structure, efficiency and base material. The two main categories are crystalline, further divided into monocrystalline and multicrystalline cells, and thin-film cells which are coated with a silicon material. An assembly of many solar cells is called a PV module, commonly known as PV panel, more modules form a PV array. Pv technology produces direct current, which then needs to be converted into alternating current in order to be sent back to the grid; every PV array is thus integrated with an inverter to carry out the conversion.

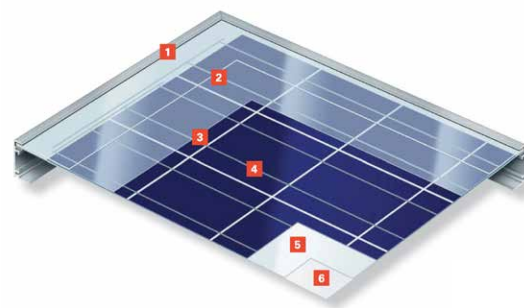


Fig.3.9_Photovoltaic panel Vitovolt 200 (www.viessmann.com)

CHAPTER'S RECAP

HISTORY

- The first building services were introduced by romans, inventors of sewers, public fountains, aqueducts and heating systems integrated in buildings
- The concept behind building services is to build constructions which can be comfortable independently from outside conditions
- Architectural faculties implemented building services in their studies in the 1940's
- Lower consumptions and sustainability are issues that have started being considered only by the late 20th century

CURRENT MARKET

- The building services industry is generally divided in design and installation, with the exception of some design and installation practices, which simplify contractual and communication relationships
- Building services play a central role in the final aspect and performance of buildings, nevertheless their design is usually overlooked and not integrated with the architectural and engineering
- Alternatively to the traditional approach, a new trend is the off-site approach, which focuses on prefabrication and reduction of time spent on site with consequent increased quality of the final product
- Prefabrication of BS and integration of their design in the front end phase is rare and mainly happens in big, complex projects like hospitals or public buildings

THEORY

- Sustainable sources are the only one to be considered; fossil fuels have been deliberately left out of the scope
- The most efficient way to heat a building is strongly dependent on context and climate as well as on the infrastructure already present in its proximity
- The future aim is to have as many buildings as possible relying on clean renewable energy sources only
- Green solutions like heat pumps and solar thermal systems are nowadays booming thanks to the increased impact on the market of sustainable aspects
- In addition to oxygen supply, CO2 removal and humidity control, the principal aims of building ventilation are to remove pollutants and smells from rooms within buildings
- Ventilation can be divided into two big families: natural ventilation and mechanical ventilation; the latter is often required to reduce heat losses to the outside
- Mechanical ventilation comprises two main systems: centralised systems (with a central unit and an extended distribution system) and local systems (compact flexible all-in-one units)
- It is fundamental nowadays to analyse if and to what extent a building can become a power generator
- Power can either be supplied by the existing grid or generated by renewables such as PV panels

B.S.FAMILIES

- Building services can be divided according to the type of energy they deal with: Air, Power and Water
- Building services can be divided according to their space requirements and functions within the building: Sources, Distribution and Final Appliances
- A fourth group called "Add-ons" gathers all the products that do not belong to neither of the previously mentioned; examples are power and water storages, home automation systems and tubular skylights

METHODOICAL APPROACH

4.1 METHODOLOGY FOR PRODUCT DEVELOPMENT

Between the two phases of literature research and design a methodical approach was built to systematically find the best design solutions for such complex design task. The design problem comprises many variables that influence the final result in different scales: the choice for the best distribution of services will deeply affect the design requirements of the single building components which will in turn affect the final appliances that can be integrated within the components. For this specific reason it was deemed necessary to divide the design in three phases which represent some sort of design checkpoints. Just like the main design question was divided into three subquestions, the design was also divided into three sub-designs which answer the three sub-questions in order to find the answer to the main question. Each phase gives a design conclusion upon which the next phase bases its initial assumptions. The process starts from the services' distribution design, followed by the building components' design and finally the finishing panels' design.

The distribution of services bases its initial assumptions on a research that was divided in two parts: the first one very experimental, comprising multiple assumptions and investigations on generic flows of lines in modular building systems, the second one more practical, gathering current methods of distribution as well as typical locations of appliances and thicknesses required for commercial products. The study began by making very generic and experimental assumptions which then started to also take into account practical aspects as the study proceeded. The final distribution system is therefore a good mix of experimental and practical

approach. The method used can be described as a trial and error procedure: different studies and trials were carried out not to find a final solution but rather to gain additional knowledge after each one. The third investigation concludes with a final distribution system which is based on the knowledge and data acquired from the previous studies too.

The second and third phases are fully based on the same method already used in previous theses by Jeroen van Veen and Nick van der Knaap which were in turn based on the "house of quality" as well as other assessing practices borrowed from industrial product development. Most of these design practices are commonly used by the industries that were analyzed in the first chapter about prefabrication (automotive, aerospace and shipping just to name a few).

The whole methodology for the building components' design and finishing layers' design is based on the definition of so called "criteria" that define each and every aspect of the final product, from the design phase to production through use until end of life. These criteria when summed up define the overall quality of the product; the latter can be defined as the achievement of the maximum amount of customer satisfaction with the least amount of waste during design and production. In the case of FabField and its new approach to building services design, the "exciting qualities" that it might provide are related to the lesser amount of time spent on site for the installation of building services which is directly related to the drastic reduction of risks, money saving, improved quality and efficiency of the overall "house product".

4.2 QFD AND THE HOUSE OF QUALITY

QFD is a multi criteria decision making process that helped numerous companies integrating customer requirements into products; it was created in 1972 by Mitsubishi's designers and has gained popularity ever since. The final goal of the tool is to help the designers understand customers better than they understand themselves, it tries to predict how customers will judge a product value, it helps to obtain cross functional agreement and buy-in on the customers needs and translate customer's needs into development goals and technical capabilities. Overall it provides logic and structure to the front end of product development, it prioritizes resources and customer's requirements in order to achieve a greater product quality. It basically helps to make the design process more proactive by spending more time and effort upfront rather than towards the end of the process, which is exactly what

it's needed for the final components' design. It helps saving resources by focusing on customer's perspective, communication and teamwork. QFD's main advantages are a much improved product definition and overall communication and efforts more strategically prioritized.

Typically QFD happens in four phases:

- 1- Analysis of the customer's requirements and demands and deployment of the latter into product characteristics
- 2- Translation of product characteristics into component parts and systems
- 3- Planning of required operations to produce components parts and systems
- 4- Choice of the control steps that ensure the reliability of the final product, its component parts and systems

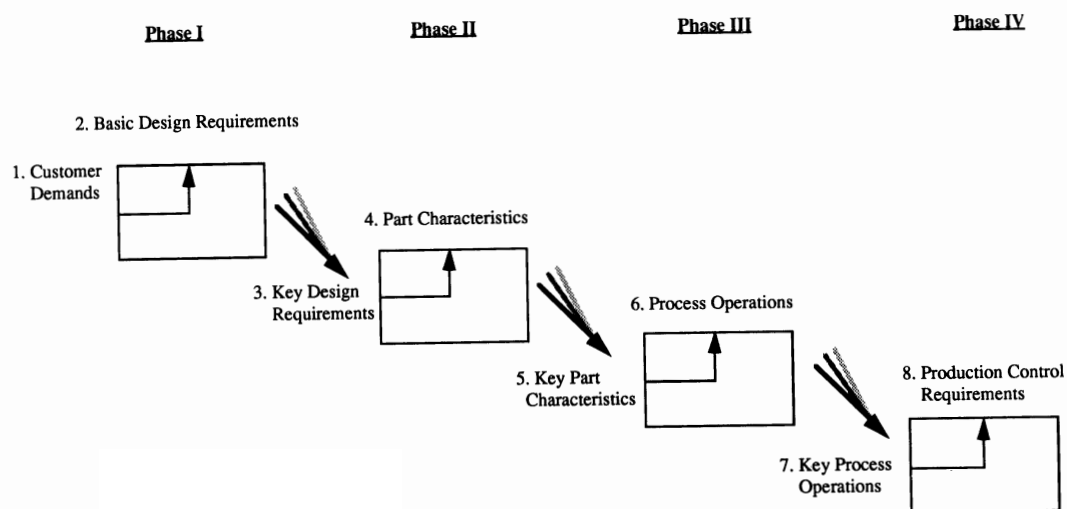


Fig.4.1_The four phases of the QFD analysis: deploying the voice of the customer (Hochman D., 1993).

The most crucial and complex part of the QFD is the very first phase, when the design team tries to predict and take into account all existing and latent demands before the product is actually manufactured; this is also the main feature of QFD, the strive upfront rather than in the end of the process.

The main “matrix” used to structure the gathered data is the so called “house of quality”, shown in the image on facing page. Customer’s needs are usually gathered through surveys and interviews; note that most of the time people don’t know what they actually want, thus the questions in the surveys have to be strategically planned in order to get the most useful data out of them. The customer may also express his needs in form of negative statements, which have to be translated into product characteristics by the interviewer during the next stage of QFD. The survey does not only gather primary and secondary product requirements but also helps defining their importance; the customer is asked to give a grade from 1 to 5 to each requirement.

Each customer demand will then be translated into at least one technical characteristic; the reality is that one characteristic may have impact on more than one demand, these relationships are critical and they are analyzed in the central part of the house of quality giving a score of 9 for strong relations, 3 for medium and 1 for weak ones. This part gives insight on where resources are more important as they may tackle more than one demand.

The right part of the house of quality analyses each demand by comparing the relative performance of the main competitor of a given product. When

a requirement scores low on a product and, simultaneously a competitor is scoring a high grade, that means that requirement needs to be improved in order to keep the pace of the competitors. On the other hand, when a requirement scores low on both products, that means the market is offering an untapped source of customer value.

The so called “technical importance rating” is obtained by multiplying each grade for the given weight, the resulting rate helps defining how aggressively each aspect needs to be pursued and what proportion of its resources to devote to improvements or innovative breakthroughs. The last section of the house of quality is the roof of it and it’s dedicated to identifying conflicts or synergies between characteristics. If major conflicts are identified at an early stage, the process will not incur in costs of redesign due to hypothetical clashes. With this chart, choices can be made towards spending more time on technical innovation or compromise customer satisfaction.

This approach is the reference for the methodology used in the assessment of building components as well as the one used for the assessment of finishing panels, which will be displayed in the next chapter. The next phase, it being the first phase of the assessment, is the listing of criteria deemed important for the overall design.

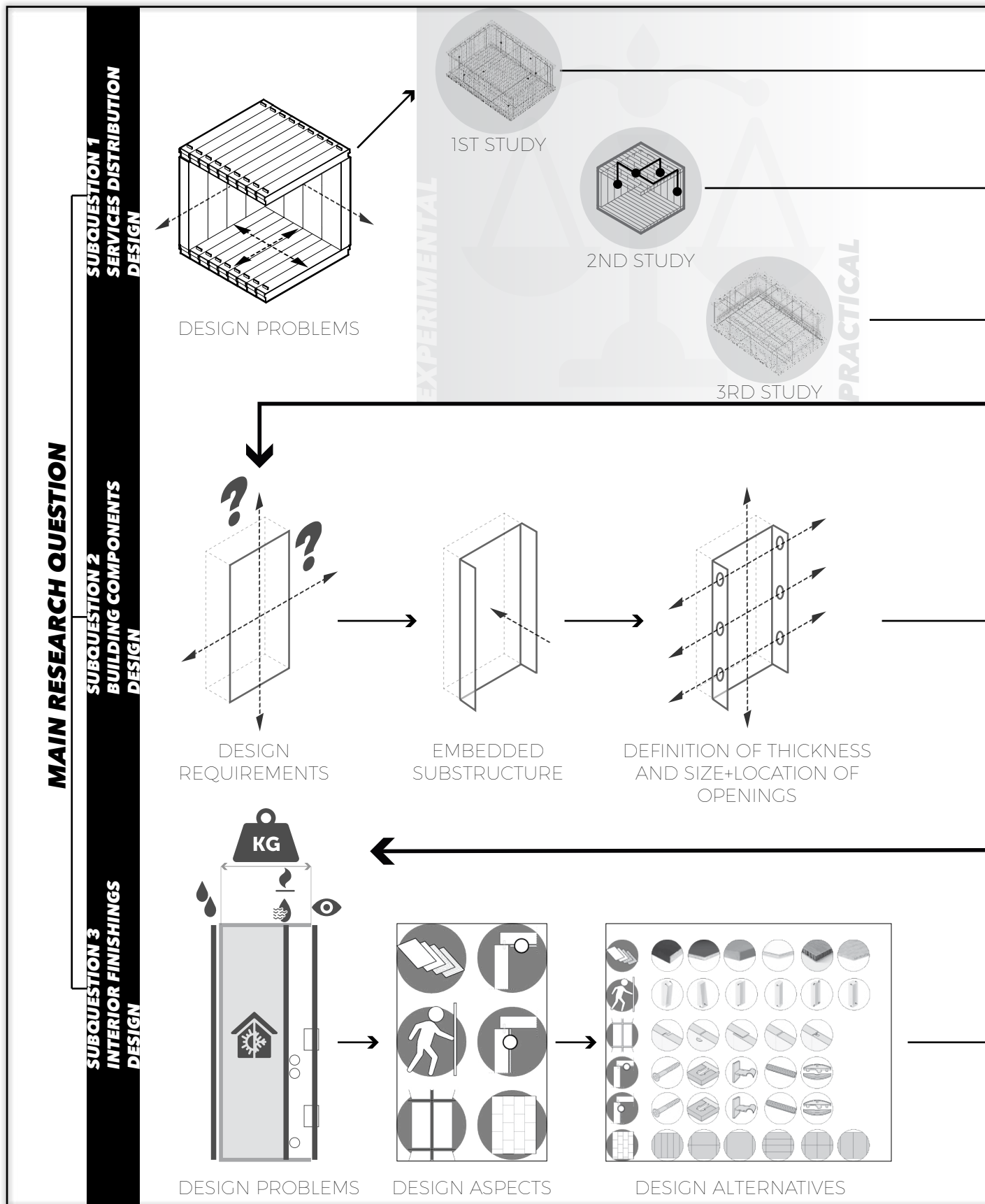
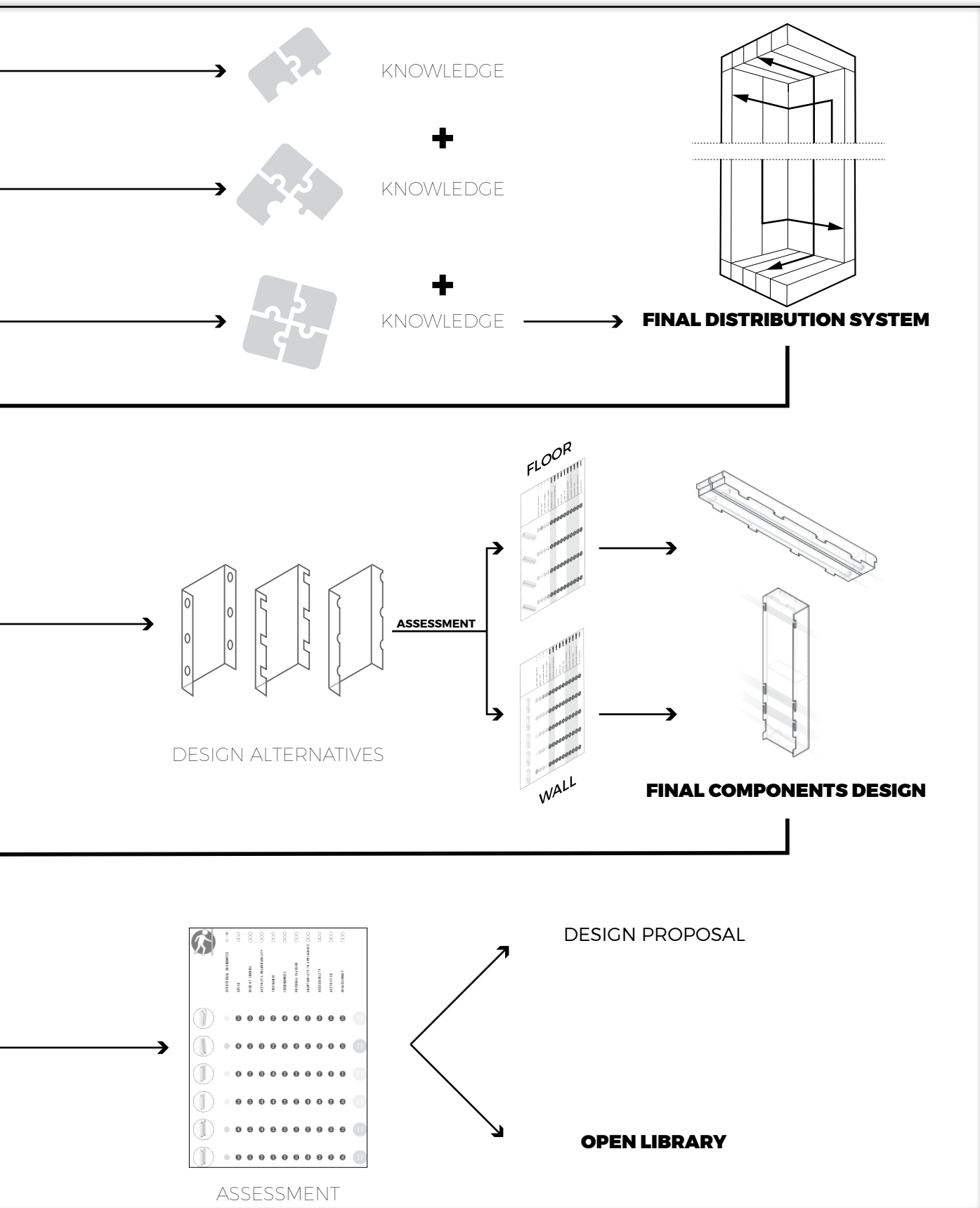


Fig.4.2 The scheme shows the methodical approach adopted for the design problem; the main research question has been divided into 3 subquestions, each one answered in a different design phase and using different methodical approaches (own illustration).



DISTRIBUTION OF SERVICES

What is the best way to distribute cables, ducts and pipes through the FabField building system?

As already mentioned in the previous section, the three big families of building services were divided according to their functions and requirements in a building. Each family also has a certain size and weight range, materials and demands. By looking at the family of “sources”, for example, we notice that the latter are mainly large products, that after being fed by a certain fuel source are able to convert it into usable energy, either electricity, heat or air flow. The integration of this products in buildings usually requires a certain space where the machines can be installed; this space could either be the roof in the case of solar thermal systems and PV panels or a technical room strategically placed in such a way that the noise does not cause too much disturbance and the “distribution” snakes as shortly and freely as possible throughout the building to the final appliances.

On the other hand, the remaining two families require a completely different kind of integration in the system. The space requirements for distribution are much different, these kind of services demand a deeper study regarding the way they can snake around the house; what are the most convenient routes to connect sources and the related appliances? What are the pros and cons of each possibility? What materials and thicknesses can be used for each of them?

Moreover, for these services, finishes of the interiors become crucial for the final design. The “final appliances” (switches, plugs, electricity boxes, lights, water outlets and so on) family is especially affected by the level of finish: if we think about vents, flush boxes or plugs we immediately notice that they only require a certain thickness within the wall, reason

why finishes are so critical for this family.

Research and design for the sources becomes secondary at this point, the choice of the most suitable energy source is mainly up to the client or builder. The research carried out so far is solely intended for gathering their requirements, verifying the possibility of their application in the building system, on the other hand the next phase will focus mainly about the integration of “distribution” and “final interfaces” related to them.

Each product detected in the previous chapter regarding the general research of commercial building services currently available on the market has specific spatial and functional requirements that have to be met for their integration in the FabField system. The main requirements for products belonging to the “distribution” and “final appliances” families comprise the thickness and the typical path that they follow in the building. As already stated before, appliances usually just require a variable thickness in specific spots such as walls for switches or ceilings for recessed lights. Nevertheless, services made for the distribution of energy also require some considerations about the best route to transport the energy from source to final appliance. The next pages display the process through which different cases of services distribution have been assessed leading to the proposal of the most suitable distribution system for FabField.



5.1 FORETHOUGHTS ON MODULARITY

As already stated before, this section investigates the distribution of services through the building, meaning the way cables, ducts and pipes flow behind the finishes of walls, ceilings and floors. There is no predefined, perfect way that works for every situation and every country and the variables at play are many: the size and number of floors of the building affect the dimension of services, the function affects the requirements in terms of sources and also the flexibility. Office buildings often make use of flexible systems such as raised floors, suspended ceilings and drywalls in order to be able to vary the position of the final appliances over time for different internal arrangements, houses tend to prefer more rigid systems as they provide more internal comfort and aesthetics but less flexibility, which is generally not the main requirement in the current housing sector; this being the main issue that FabField strives to tackle. There are also some intangible factors at play such as different customs generated over time in different countries for different reasons: in the Netherlands for instance the main electricity distribution flows in ceilings and the cables are cased inside rigid plastic tubes whereas in Italy the main electricity lines are generally embedded within the floor thickness and are cased in corrugated tubes that allow for more flexibility and easier changes of direction.

That being said, there are some aspects that they share and this is the lack of integration with architectural and engineering design: the current building services sector tends to have to figure out many aspects directly on site, drilling holes for cables to pass through, cutting through wall parts for the installation of switches and plugs and so on.

The integration of building services in a modular building system requires a totally different approach and some boundaries need to be defined beforehand. The problems that are traditionally solved on site directly by the labor workers should be hereby considered in the so called “front end” design, allowing the system to have enough flexibility for every scenario.

As already mentioned earlier, FabField features 4 main components: Roof, Wall, Floor and Beam.

The most important ones in terms of interior distribution of services are the Floor and Wall components, accommodating the main appliances and distribution. The scheme in the facing page displays the intent to approach the issue of distribution by allowing only certain movements within the building components. If cables normally run also diagonally in traditional buildings, the nature of wall and floor components and their assembly allows only for parallel-to-component and perpendicular-to-component movements.

Image 2.2 shows how in this way, the possible connections between two generic points A and B is limited and needs to be assessed to understand which is better. Underlying image 2.3 highlights all pros and cons of each movement and the related effect on the building components.

On the following page the effect of different movements on components is analysed for each family (air, power, water and water disposal) so as to gather more understanding of the requirements of the components.

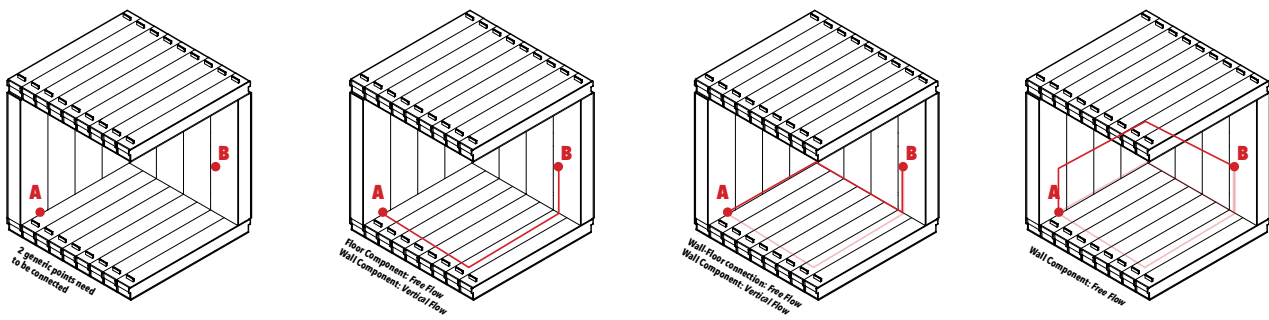


Fig.5.1 The distribution of services was tackled at first by analyzing the possible movements that a modular system could allow (own illustration).

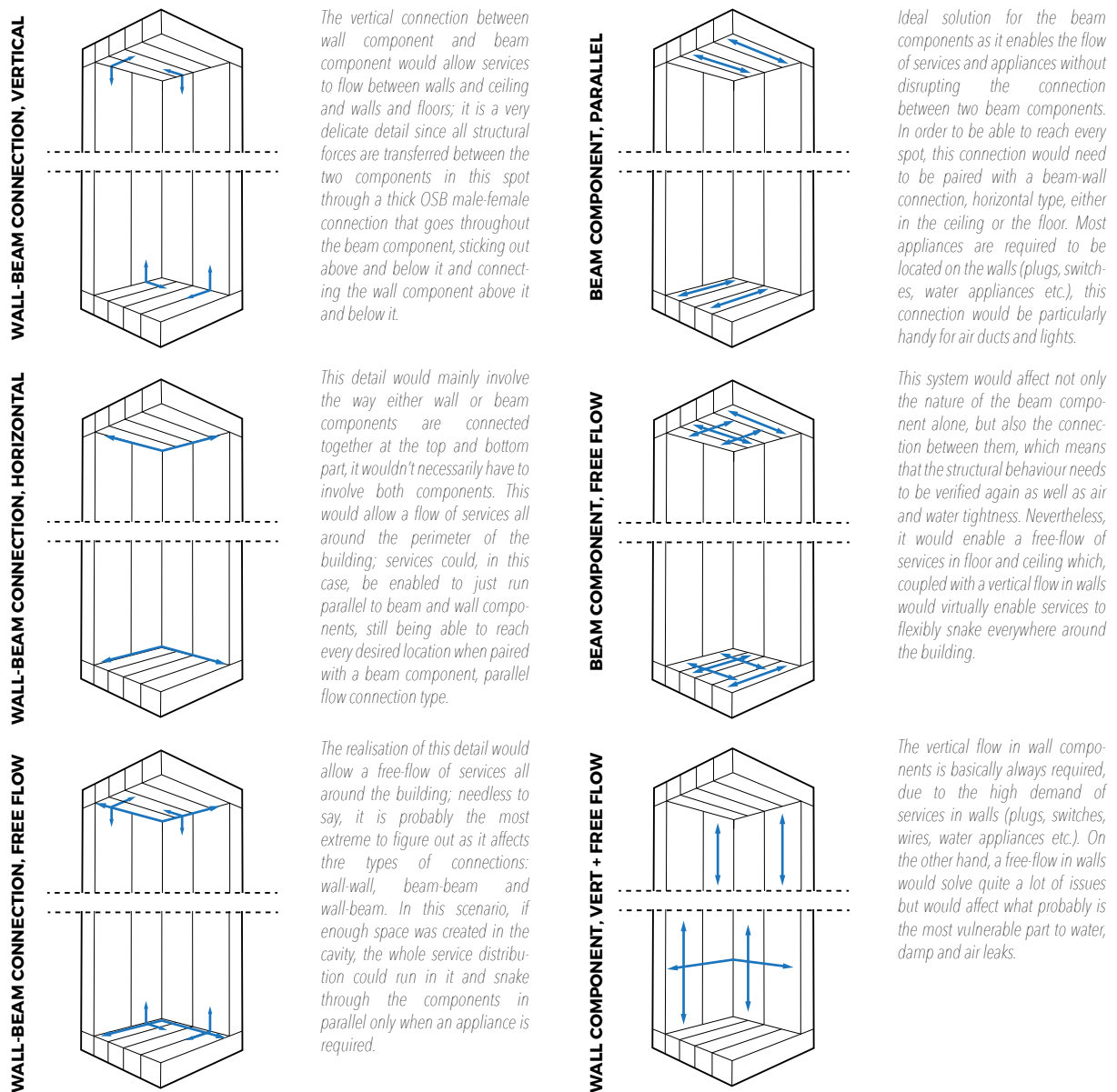


Fig.5.2 First considerations on the effect of different movements of services distribution on the requirement of building components and the connections between them (own illustration).

5.2 30 CASE STUDIES ON DISTRIBUTION

A on wall, B on ceiling

A on floor; B on wall

A on ceiling, B on floor

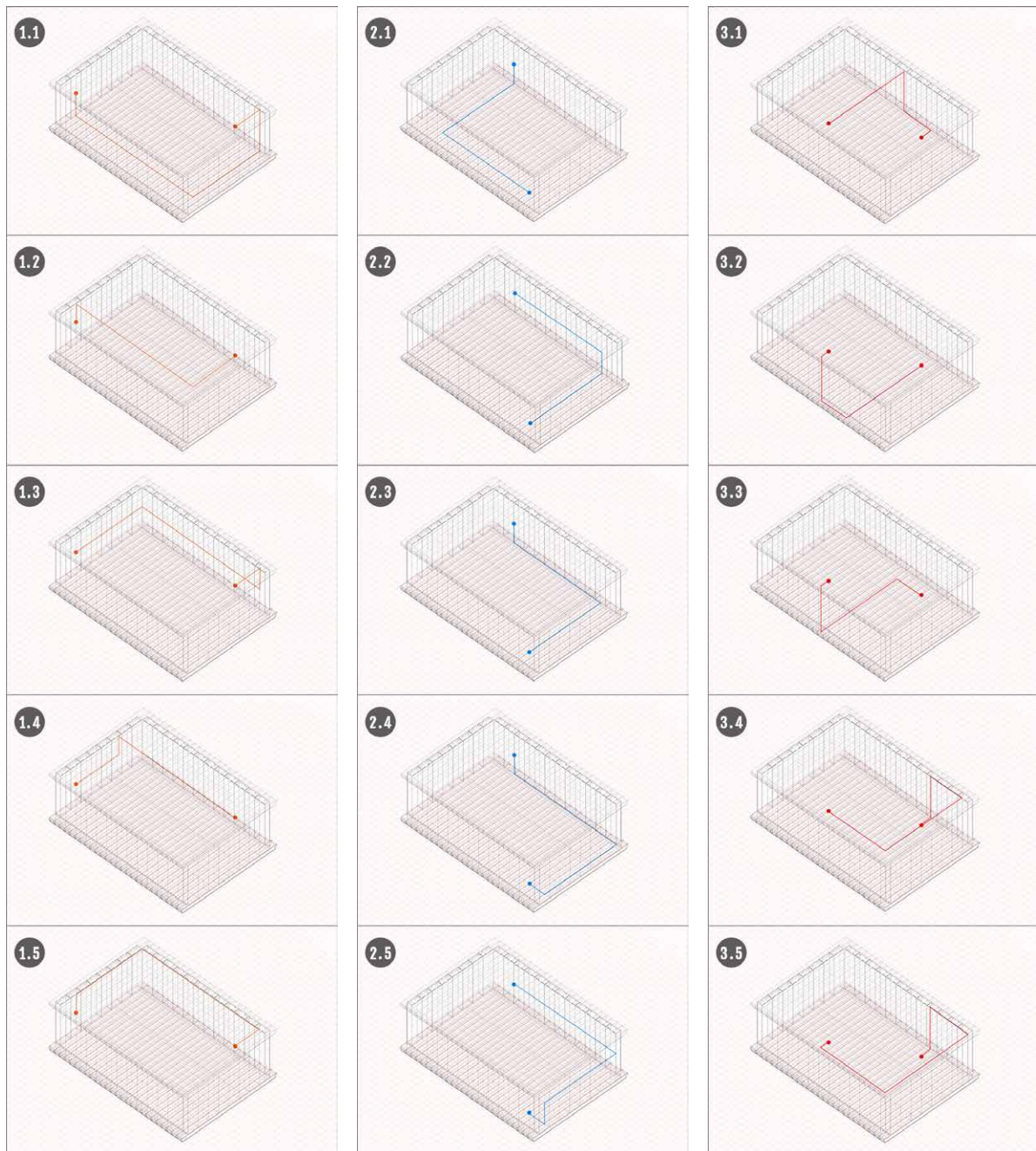
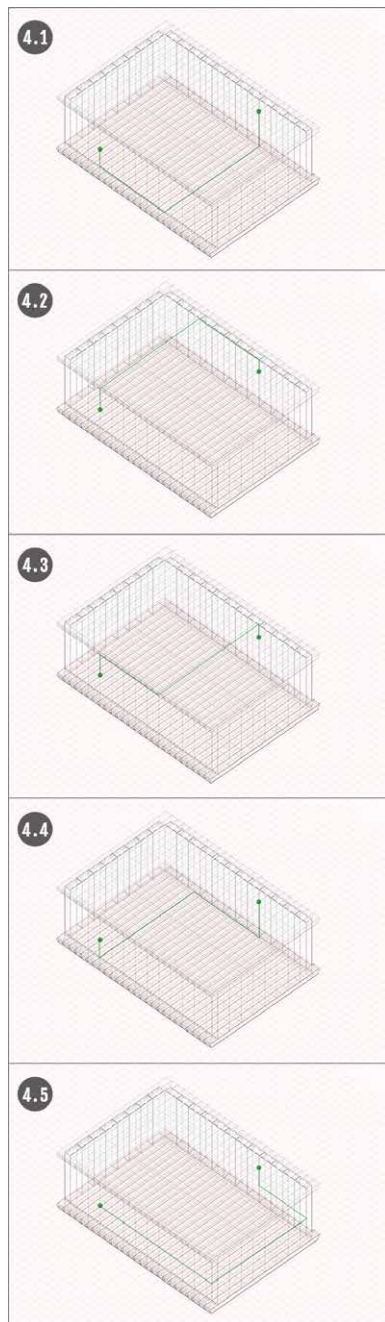
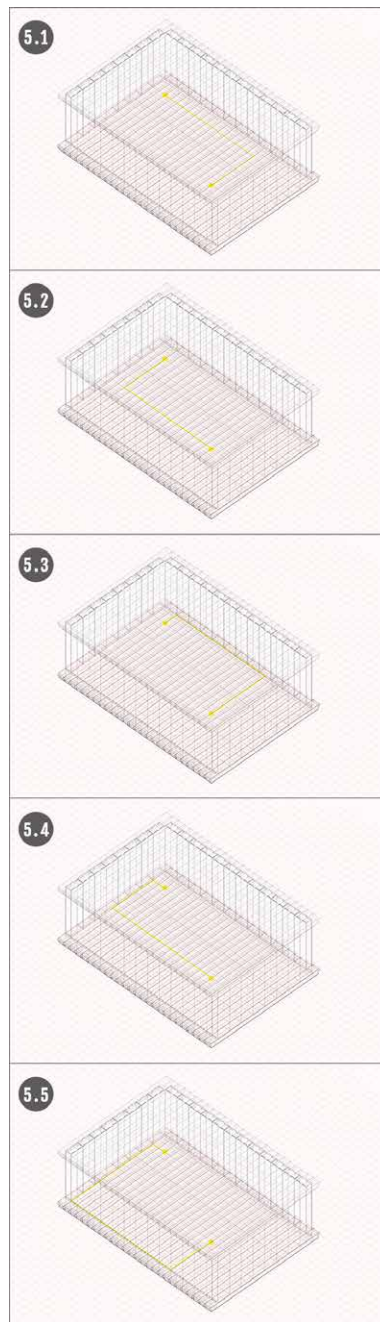


Fig.5.3 For each of the 6 case studies, 5 different paths to connect the points are represented in the schemes and later analyzed (own illustration).

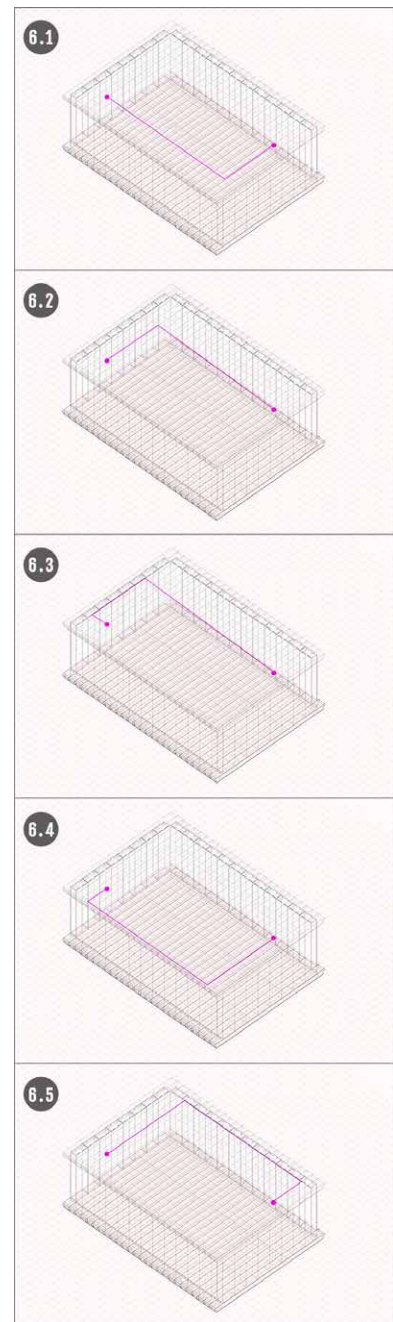
A and B on wall



A and B on floor



A and B on ceiling



The previous page shows the illustration of six simulations carried out in order to gain further knowledge on how two generic points can be connected in a modular grid system and what kind of movement would the components have to allow for the two points to be always connected. First of all, there are three main surfaces on which services may run in the FabField building system:

- Interior side of Wall components
- Bottom side of Floor components (ceiling)
- Top side of Floor components (floor)

This leads to the conclusion that there are 9 possible different combinations for point A to reach B, the graph below shows these combinations. It is noticeable that there are 3 pairs that can be considered equal (1-4; 5-8; 2-7) as the only difference is the direction of the arrow which does not influence this study in any way.

This leaves us with only six case studies, which are the ones displayed in the illustrations:

- 1_Wall to Ceiling
- 2_Floor to Wall
- 3_Ceiling to Floor
- 4_Wall to Wall
- 5_Floor to Floor
- 6_Ceiling to Ceiling

Each case connects two generic points, randomly located, following five different paths. The paths are simply drawn using common sense and instinct, at this point there are no fixed requirements on the paths and this is actually the output that this analysis should give.

The total number of simulations is 30, the table on the facing page gathers data about how each simulation affects the components and which movement they have to allow in order for A to reach B.

	CEILING	FLOOR	WALL
1	A •————→ B		
2	A •————→ B		
3	A ↔ B		
4	B ←————• A		
5	A •————→ B		
6	A ↔ B		
7	B ←————• A		
8	B ←————• A		
9	A ↔ B		

		WALL vertical	WALL horizontal	TOP BEAM parallel	TOP BEAM perpendicular	BOTTOM BEAM parallel	BOTTOM BEAM perpendicular	SKIRTS bottom
CASE 1_WALLtoCEILING	1							
	2							
	3							
	4							
	5							
CASE 2_FLOORtoWALL	1							
	2							
	3							
	4							
	5							
CASE 3_CEILINGtoFLOOR	1							
	2							
	3							
	4							
	5							
CASE 4_WALLtoWALL	1							
	2							
	3							
	4							
	5							
CASE 5_FLOORtoFLOOR	1							
	2							
	3							
	4							
	5							
CASE 6_CEILINGtoCEILING	1							
	2							
	3							
	4							
	5							

Fig.5.4 The table gathers the movements that had to be allowed by the building components for each one of the 30 case studies (own illustration).

The first output given by the illustrations is that the grid system allows movement only in two directions relative to the components, vertical and horizontal movements on walls, parallel or perpendicular to beam movements and through the edges of the building where beams and walls connect.

The table on the facing page lists what kind of movements should be allowed in each case of each simulation, the overall behavior gives some insights for future requirements.

To sum up, 30 simulations were carried out, 5 for each of the 6 combinations between components.

Here are some conclusions from the data gathered:

Walls 20 times the vertical movement was allowed, 5 times the horizontal movement, for an overall of 20/30 times in which wall components were involved for any kind of movement.

Beams 18 times the top side of beam components (floor) had to allow some degree of movement, 15 times it was parallel to the component, 9 times it was perpendicular. 17 times the bottom side of beam components (ceiling) allowed movements, 16 times it was parallel, only 6 times it was perpendicular.

Skirts These movement was adopted exploited 16/30 times. It's extremely interesting to point out that 12/16 times the use of skirting movement prevented the use of any perpendicular-to-beam or horizontal movements, which according to the test simulations and common sense are the most difficult to ensure.

In every case either 2, 3 or 4 movements were allowed for the connection between A and B; when

the two points lie on the same kind of component the movements allowed are 10 out of 15 times only 2. When A lies on wall and B either on ceiling or floor the usual movements allowed are 3, 8/10 times; the simulation in which A was on the ceiling and B on the floor always needed to allow 4 movements. This shows that the best and easiest way to connect two points is when they lie on the same component.

These data provides some interesting conclusions:

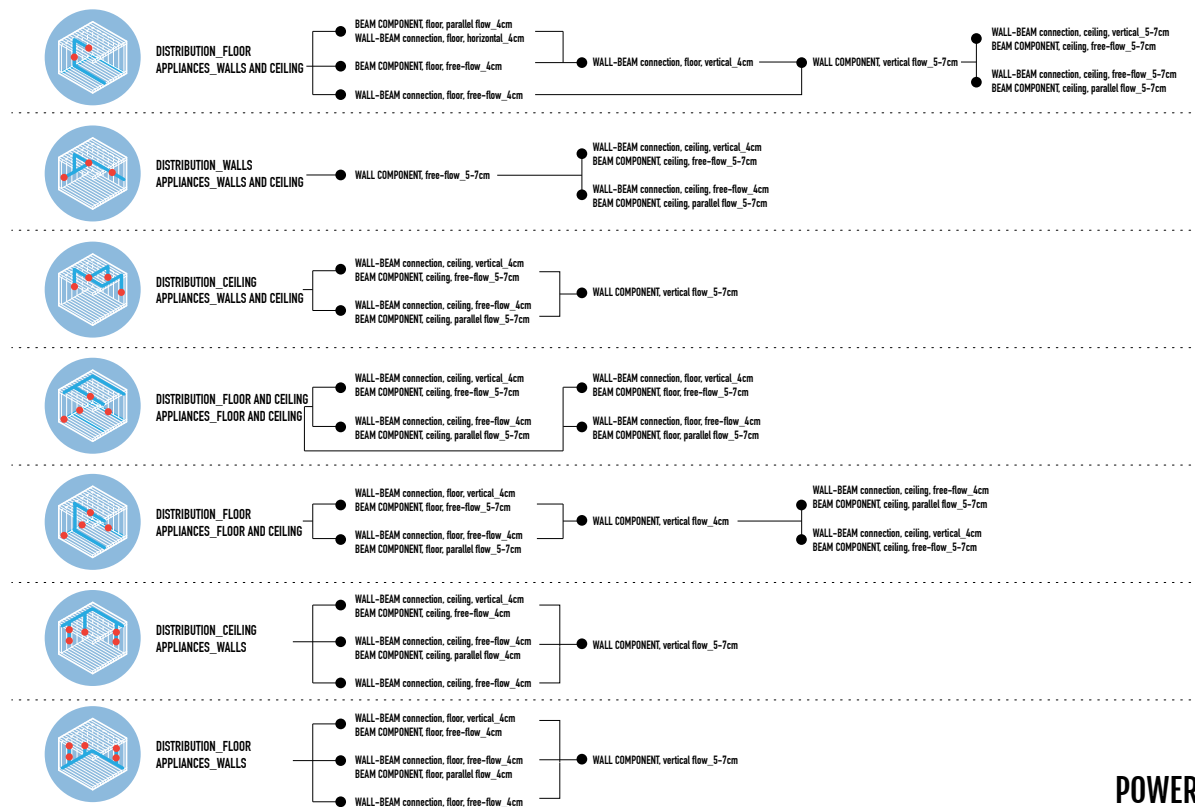
- Wall components are the most affected ones in general, which means that these kind of component will probably have to always provide some kind of movement. The only cases in which walls are not involved are floor to floor and ceiling to ceiling, which in reality never happens.
- There is almost never only perpendicular-to-component movement; when the latter is allowed, there is also a parallel movement. In these cases though, the parallel movement affects only one or two components whereas the perpendicular affects many.
- The best and simplest scenario is always to have distribution and final appliance lying on the same kind of component.
- In most of the 30 cases, at least one perpendicular-to-component movement had always to be allowed. The only exceptions were the cases in which skirts were adopted, in those scenarios perpendicular directions were avoided, concluding that skirting movement prevents the request for perpendicular-to-component movements.

5.3 EFFECT ON COMPONENTS

The second study is a mix between experimental and practical approach; for each one of the four families several scenarios have been carried out with the intent to investigate how different locations of distribution and final appliances would affect the design requirements of the different building components. The study is strongly based on thicknesses of commercial pipes and ducts that were gathered previously.

The 4 schemes stretch horizontally in some sort of parametric scheme in which the origin

and destination of each service can happen in different ways, each way concluding with different requirement for the distribution system. Only thicknesses of products adoptable for small family housing were considered so as to avoid products that would occupy more than the strictly necessary space. The scenarios have varying lengths, more movements to reach the final destination also mean more complexity for the distribution system. The image hereby shown is the study for power distribution, the complete study regarding all four families can be found in appendix C at the end of the book.



POWER

Fig.5.5 In the second study the actual thicknesses required by the different services were considered and analyzed for each one of the services families. (own illustration).

5.4 PRACTICAL APPROACH

In the previous paragraph it has been stressed how the way building services snake through traditional buildings is extremely variable and depends on many different factors. Nevertheless, it is still deemed necessary to investigate the nature of services that typically flow through walls, floors and ceilings, their typical dimension in case of small family housing, their direction in the related surface and the usual position.

The fact that FabField is a modular building system gives a lot of freedom in the decision making process of how cables should run through it, however it's still necessary to point out that the position of final appliances such as sinks, plugs, switches, lights etc. is not completely fixed but mostly follows common sense; there would be no point of having a water outlet for a sink on the floor of a building, at the same time it wouldn't make much sense to have light switches at feet height or above 1.50 m, it would be annoying for the user and lead to discomfort in the living environment. The table displayed on the facing page gathers all informations that need to be taken into account in order to study the FabField services distribution system in a free way but still relying on common sense. This table was then converted into an illustration which displays the encumbrance of each family on the three surfaces. It is important to state that this drawings only show the final appliances, whereas the distribution should be arranged accordingly.

The first image shows the burden that each family could have on the floor of a generic building. Water's only final appliance, shown in blue, represents the hypothetical space required by underfloor heating, which would occupy most of the available area and preclude the presence of any other service. Yellow represents power, in the specific case skirting ducts, very flexible solutions especially for offices, not so often used in residential buildings. The green space is air and it takes into account the possibility of having air vents for either supply or intake on the edge of the building.

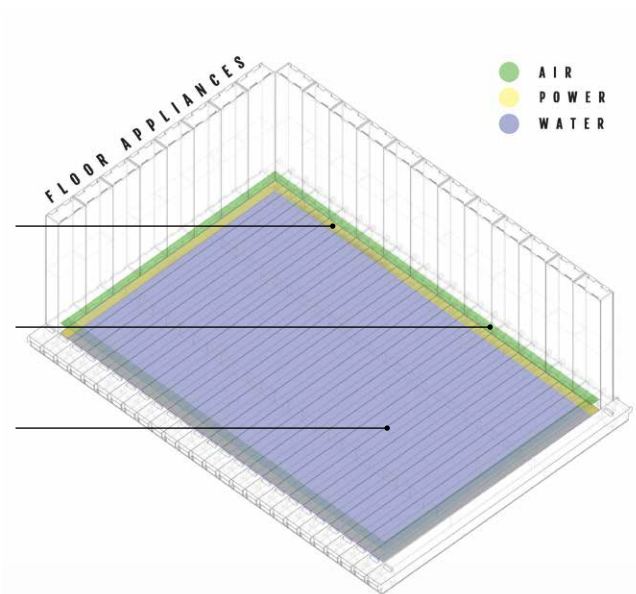
The second drawing displays the burden of final appliances on wall components. Water is only depicted by two lines and a square, which respectively stand for the two heights of water supply and disposal, and the manifold that would be required for water underfloor heating. The big power area stands for the normal height of plugs and switches in bathrooms, kitchens, bedrooms and so on; there is a smaller yellow line at the top which represents the possibility of having lights installed on walls at that height. Lastly, air shows two green lines at the top and bottom of the wall components which again depict the possible presence of air vents in walls, which would nevertheless take quite a large thickness.

Third image represents ceiling appliances; just like in floors, water and air respectively show the space for ceiling heating and air vents, the main difference being that ceiling heating does not preclude the presence of other building services. Power in this case stands for ceiling lights or electric heating panels.

skirting ducts can be used at the edge of floors, requiring between 50 and 100mm of depth for the wiring

air ducts and vents can stretch along the edges of the floor as well, requiring at least 50mm for ducts and 80mm for vents

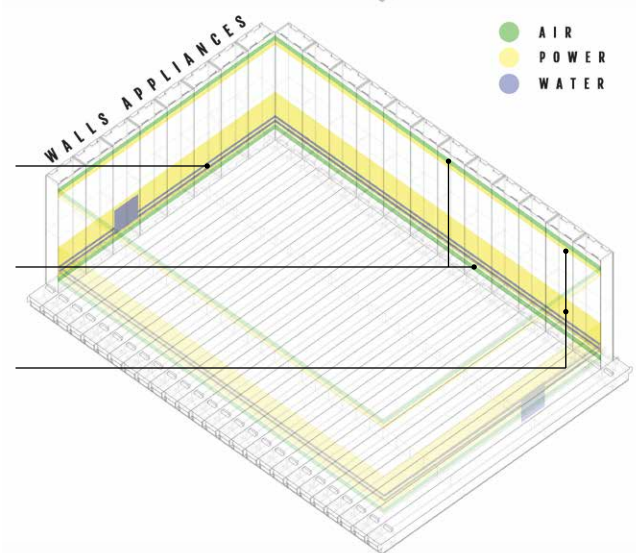
water appliances at floor level only comprise floor heating, which demands for varying thicknesses



water appliances in walls only comprise outlets for sinks, showers, toilets etc and the space for a manifold in case of floor heating

air vents can be placed at the upper or lower parts of walls even though the thicknesses required are quite large (80mm min)

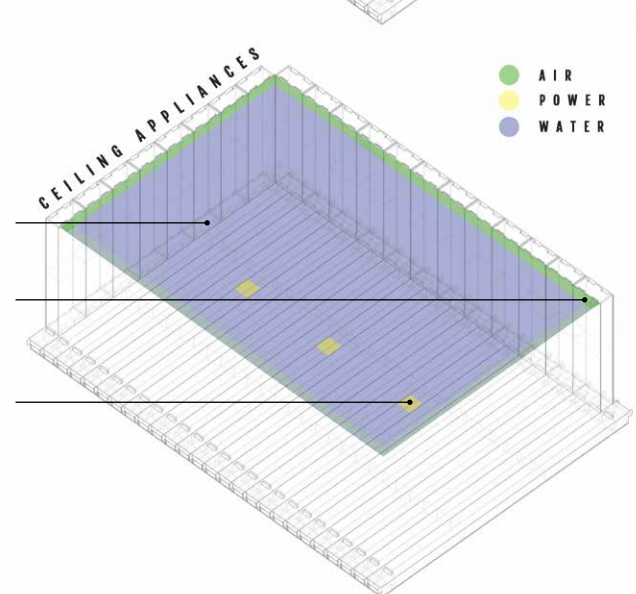
power appliances in walls comprise all plugs and switches as well as lights that could be placed on upper parts of walls



water appliances in ceiling are represented by ceiling heating but also the possibility of sprinklers

just like walls and floor, air vents and ducts can stretch through ceilings on its edges, even though the thicknesses are very large

the ceiling always needs to give the possibility to accommodate power appliances like lights and electric sensors of various kinds



5.4.1 DISTRIBUTION THROUGH FLOOR

At this point it is interesting to analyze the possibilities for the distribution of services. Sources are still very flexible and anyway not affected in this process. Final appliances are more or less regulated and based on user's habits, which this thesis takes into account and doesn't wish to modify. Therefore the main focus of this section is to gather as many informations as possible on distribution so as to set some distribution systems that can later be evaluated through the methodology assessment.

The drawing on the left shows an hypothetical free-flow distribution of services through the floor. The starting point, which in reality would be the source position, is hereby randomly positioned, whereas the end points are based on the traditional position of relative final appliances.

Water_ First of all water distribution comprises heating water, domestic hot water, fresh water from main and water disposal; all pipes for water supply are considered to be approximately $\varnothing 16$ mm, gray water disposal comprises usually $\varnothing 50$ mm pipes, even though there are space saving solutions in form of oval pipes of approximately H 30mm; all gray water disposal pipes must have a slope of at least 1%, enough for the water to flow naturally but slowly enough to carry away solid waste materials. Black water disposal happens mainly vertically through $\varnothing 100$ mm columns and it's therefore not even considered as distribution, its integration will be taken into account in a different section along with all other services with special requirements. Distribution of water can be through the floor, the main problem being the 1% slope required for its disposal, which limits the distance of supply

and main disposal water column, as the distance increases the thickness of the floor must increase as well in order to accommodate it.

As the image displays, the distance between distribution and appliances is never excessive since all water related appliances are located at the bottom part of wall components. This distribution does not allow for water underfloor heating; it is also not advisable in the case of water ceiling heating since the distance between distribution and appliance is definitely excessive and the power required to pump the water that high is purely a waste.

Air_ Distribution of air is usually located on floors or ceilings; a smart space saving solution for small buildings are flat plastic ducts that only occupy H 50mm. A typical location for the central mechanical unit is just below the roof, this due to the fact that intake and exhaust are usually located in the rooftop and the distance between the latter and the central unit should not be too large. If this could be taken as a fixed requirement also in the FabField building system, then the air distribution could easily be placed in the roof space without having to integrate it into the components or finishes. Otherwise floor distribution would be fine, the only issue being the large thickness required for the air vents (100mm)

Power_ The distribution of electricity is usually carried out by thin cables which are then contained by $\varnothing 15$ -19 mm plastic tubes. An alternative way would be through flat wires contained in skirting ducts, mainly used in offices. The typical location for electricity distribution in residential units varies from country to country. Nevertheless, floor distribution can be the right solution for generic

functions since the final appliances are not too far apart from the floor; the only appliance that could be too far apart is ceiling lights, which in this case are suggested to be replaced in favor of wall lights. Another aspect to take into account in this case is the distance of cables from water and safety in case water leaks get in contact with the latter.

To conclude, water and electricity distribution are both possible but not at the same time, mainly for safety reasons. Floor distribution in general can be easy to install but quite hard to maintain since the finish layer will then be overlapped by furniture and such. Air ducts could run under the floor but a method to allow flat duct bending has still got to be found. Water disposal through the floor is often used but the distance to be covered shouldn't be too large in order to keep the floor thickness acceptable. All 3 families would require connection to wall components since most appliances lie on walls.

5.4.2 DISTRIBUTION THROUGH WALLS

It was noticed previously how most appliances lie on walls, it was also concluded from the general “flow” analysis how the simplest way to integrate services in a grid based, modular building system for distribution and appliances is to be on the same kind of components in order for the path to be as short and easy as possible. For these reasons distribution through walls seems to be particularly promising for the FabField, it is henceforth analyzed more in depth.

Water_ distribution of water through walls is widely used in traditional buildings. The 1% slope required for the natural flow of gray and black water usually causes differences in floor height when the distance to be covered is excessive, on top of that it wouldn't make much sense to place the water disposal system on the ceiling. Most of water appliances are on walls (radiators, taps, showers, tubs, sinks, washing machines, dish washers etc.) at an height that can be averaged at 45cm for the sake of simplicity; the disposal of all the aforementioned appliances is considered to lie at an height of 30cm.

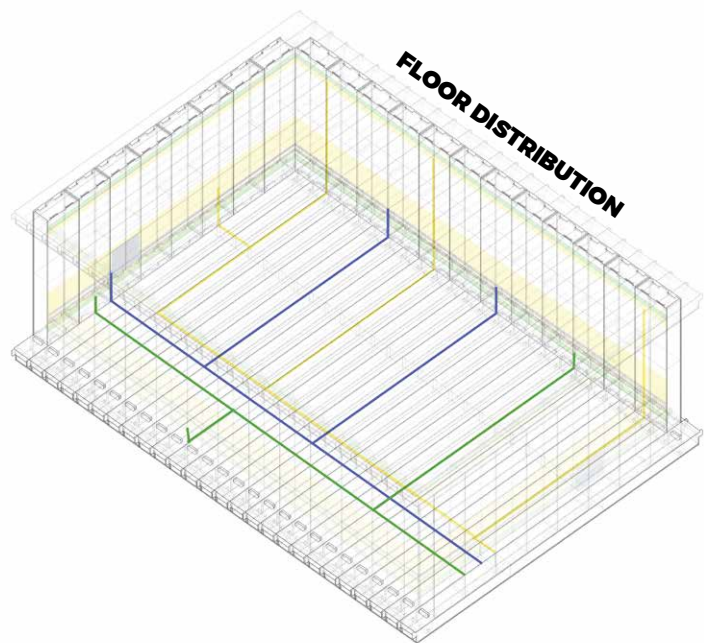
The only water appliances that are not in walls, yet are still best served when water distribution is on walls, are ceiling heating and underfloor heating. For all these reasons walls are considered to be the best choice for water distribution.

Air_ The ducts required for air distribution are among the thickest elements for the distribution of building services, even though only the thinnest products on the market were considered in this study. Traditionally ducts snake through ceilings and floors, they only go through walls when a final appliance is designed to be there, or when ducts

● **Water distribution through floor** would require space for $\varnothing 16\text{mm}$ pipes and $\varnothing 50\text{mm}$ for disposal of appliances, with an additional space to allow the 1% slope. In case of ceiling heating the length of distribution drastically increases.

● **Air distribution through floor** is possible and convenient thanks to the presence of commercial space saving ducts that only take 50mm of space; nevertheless the thickness for the air vents takes up to 100mm to allow the bending.

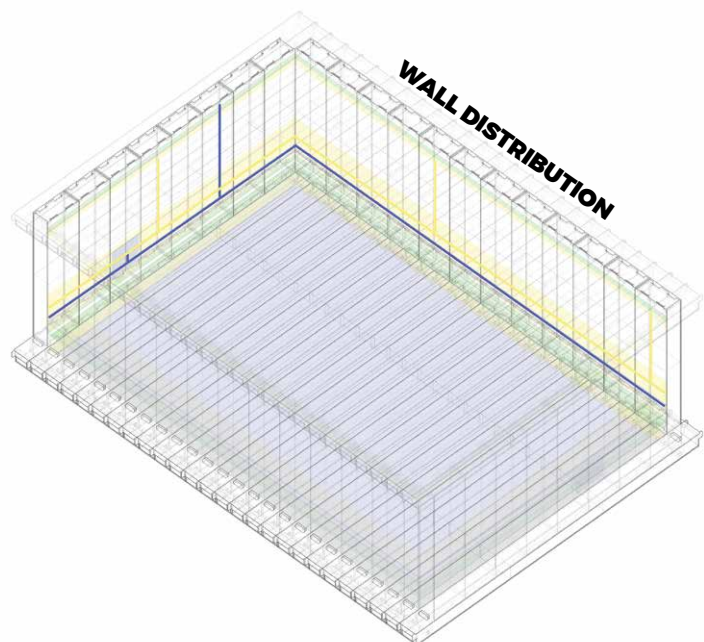
● **Power distribution through floor** requires a thickness of max 20mm for the plastic tubes that usually contain the wiring; the final appliances are mostly at the bottom part of walls, therefore not too far. The main issue is safety in case of water leakage.



● **Water distribution through walls** is convenient since most water appliances are on walls. The only appliances not lying on walls are ceiling and floor heating, still best served by water distribution through walls.

● **Air distribution through walls** is traditionally the least adopted solution. Air ducts take up a lot of space and air appliances do not necessarily need to be on walls, therefore most of the times they snake through ceilings or floors.

● **Power distribution through walls** is advisable for the same reasons as water distribution: most of the related appliances lie on the same component, which means leaving floors and ceilings free of encumbrance.



needs to go at a higher or lower level. It is possible, yet not used nor advisable to use walls as air's main distribution space.

Power_ Just like water, also power is usually distributed through walls as most of the related appliances lie on it; also similarly to water, walls are the best place to accommodate wires for the principle that the shortest distance between appliance and distribution is usually the most economic and easier to install. Walls could really accommodate all power related services, leaving ceiling and floor completely free from it if the design renounces to appliances like electric ceiling heating, ceiling lights and skirting ducts. Power seems to have a lot in common with water, with most of the appliances lying on the same level, similar thicknesses and similar flow; they also have a major problem in their integration, the simple fact that water should never get in contact with electricity due to the high conductivity of the latter; the two families can still lie on the same component but safety measures must always be taken into account.

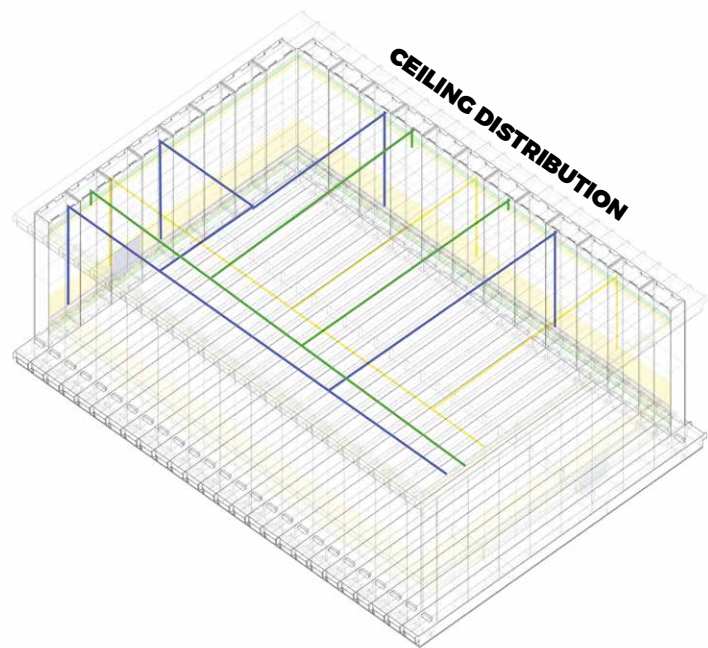
To sum up, wall components accommodate most of water and electric appliances and are therefore the main candidates to accommodate also their distribution, nevertheless their integration in the same components must come with all the required safety measures. Air ducts are probably the least favorable to run through walls since they occupy a very large space, up to roommm when the duct has to bend to allow air vents. Power could entirely be comprehended in walls, even though for functions like offices it's still recommended to use floors.

5.4.3 DISTRIBUTION THROUGH CEILING

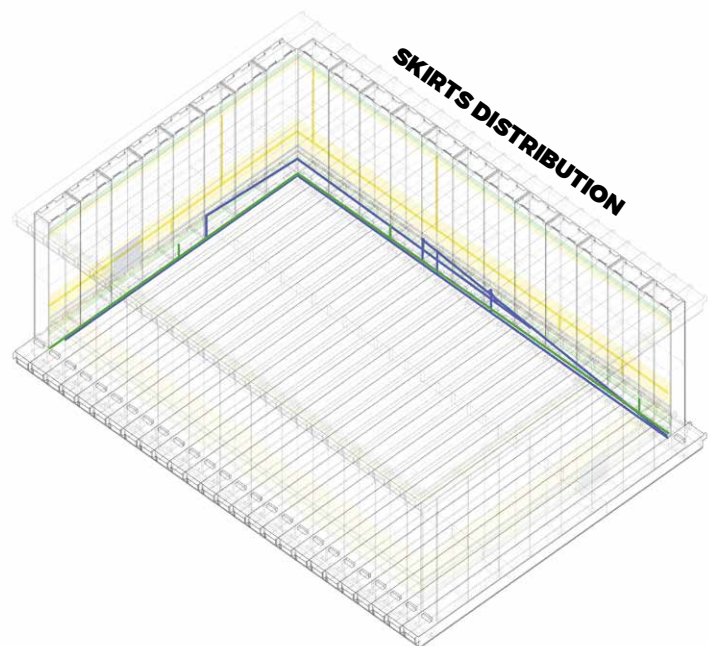
Ceiling distribution is traditionally used for electricity in order to connect appliances like alarms, infrared heating panels and ceiling lights; it is also used occasionally for water in public functions that need sprinklers in case of fire which we won't consider in such a small scale building that FabField allows. In the case of ducts it is widely adopted along with floor distribution. In buildings in which suspended ceilings are installed, the gap between slab and ceiling panels is usually exploited for all kinds of service distribution, leaving all other surfaces free of most of the encumbrances. This is actually the main choice for offices, which either opt for raised floors or suspended ceilings in order to make the whole environment flexible in terms of internal arrangement, which can in this case be easily later modified.

Water_ As already stated above, ceilings can usually service for water distribution in public functions where sprinklers are required by regulations. Nevertheless, having an extended water distribution grid running through ceilings is not advisable for many reasons: in case of leakages, water will start dripping on furniture, appliances and finally on the user's head. Most of water appliances occupy the bottom part of wall components, which means that the ceiling is the furthest component from them, thus the least desirable to host water distribution. The installation and maintenance of anything running through the ceiling is deductively problematic due to the high position of the latter. The last but not least reason is that water distribution comprises supply and return for heating, supply and disposal for DHW; this means that supply would run on the ceiling whereas half of pipes would have to run

- **Water distribution through ceiling** is usually used only for sprinklers, this has several explanations: in case of leakage, water would immediately be dripping on furniture and users, it is also the furthest surface from most water appliances.
- **Air distribution through ceiling** is often the solution adopted for extended ventilation systems, like in BK. Vents and ducts could be placed on the ceiling, the main issue is the large thickness required for the vents (100mm).
- **Power distribution through ceiling** is a flexible solution which is often adopted for improved flexibility, just like floor distribution of power. Nevertheless, appliances cannot be on ceilings, whereas they could be on floors, making this solution not desirable.



Water, air and power distribution through skirts is an interesting solution that requires the creation of wide spaces in the interior edges of the building to provide accommodation for all services. The principle is already used in offices, mainly for flexible power distribution. The skirts would be at the lower edge of the building, where walls and floor components connect, and they would benefit specially the easy distribution of ducts and water disposal. Nevertheless this comes with a waste of usable space and waste of materials used to create an additional void. Interesting solution to be avoided if not strictly needed.



through walls or floor in order for the 1% slope to be possible. To conclude, ceiling is the least favorable choice for water distribution, with the obvious exception of sprinklers.

Air_ For ducts it is common to snake through ceilings; in our case the main issue is the thickness requested in the points where air vents require a bend in the duct (100mm). Another issue is the fact that the ideal scenario for ventilation is to have the supply of fresh air at floor level and the exhaust at ceiling level due to the fact that stale air is usually warmer than fresh one and it naturally flows upwards. Mechanical ventilation can be in two forms: supply and exhaust or only exhaust. It's probably the best case for distribution to be closer to ceilings rather than floors.

Power_ It has already been pointed out that power distribution through ceilings traditionally happens in offices, schools, hospitals and commercial functions to keep the interior arrangement as flexible as possible, it is usually coupled with flexible partitions like gypsum walls. Another advantage of this solution is that it easily allows the installation of electric appliances like ceiling lights, which makes it slightly more desirable than floor distribution, even though it is a trade off between the latter and ease of maintenance.

5.4.4 DISTRIBUTION THROUGH SKIRTS

Skirts are the edges of the building, the horizontal line where beam and wall components meet, both at the top and bottom of the walls. It was deducible from the drawing displaying in-wall appliances that the latter are mostly located at the bottom of walls, it is also common sense to locate such elements at the bottom of walls for ease of installation and maintenance. For this reasons only bottom skirts are considered in this analysis.

The integration of services in skirts requires the creation of a space where wires, ducts and pipes can be accommodated, this could happen mainly in two ways: by addition or by subtraction. Nevertheless this is an aspect that is still to be neglected in this phase and will only be analyzed at a later stage.

It is also important to state that skirts can only provide limited distribution compared to the previously assessed components: only horizontal paths and in the perimeter edges of the building. Due to this limited distribution this solution only makes sense with a connection with walls and floors.

Especially convenient for water since it would easily enable the 1% slope for water disposal. Air could also be accommodated and be useful for supply, not so much for extraction which should be at higher levels. The integration of power would be convenient as well, the main pro being the easy installation, maintenance and accessibility. It is a promising solution that requires a further study that clears in what way it can implemented in partition walls and wall components.

The graph on the next page summarizes the data gathered from this second analysis and draws some interesting conclusions.




	WATER 	AIR 	POWER 
SOURCES	Fresh water from main, DHW and heating water supplied by boiler in technical room	Localised units embedded in wall components; when strictly necessary, central units placed in roof space	Electrical cabinet placed in technical room; all other products (inverter, power storage etc) also in technical room
FINAL APPLIANCES	Most of the appliances on walls (H 30-45cm). Ceiling for sprinklers or ceiling heating, floor for floor heating only.	Air vents can be placed on walls, ceilings and floors, they require a very large thickness to prevent noises.	Final appliances are mainly on walls (plugs and switches) and ceilings (lights and sensors).
DISTRIBUTION	<p>1. WALLS</p> <ul style="list-style-type: none"> - most of the appliances are located on walls as well - favours the 1% slope for gray water disposal <p>2. SKIRTS</p> <ul style="list-style-type: none"> - creation of a large exploitable space for all water distribution - close to all water related appliances <p>3. FLOOR</p> <ul style="list-style-type: none"> - increased thicknesses for 1% slope of water disposal - underfloor and ceiling heating not advisable for this solution <p>4. CEILING</p> <ul style="list-style-type: none"> - same limitations of floor but further away from all final appliances 	<p>1. WALL (local unit)</p> <ul style="list-style-type: none"> - easy, economic and flexible solution for reduced air volumes. <p>2. FLOOR (roof space)</p> <ul style="list-style-type: none"> - roof space edges are exploitable and "absorb" the large thickness required by the vents <p>3. CEILING</p> <ul style="list-style-type: none"> - closest surface to final appliances and source (roof space) <p>4. WALLS (ducts)</p> <ul style="list-style-type: none"> - not advisable due to the large thickness required by air vents 	<p>1. WALLS</p> <ul style="list-style-type: none"> - reduced thicknesses easy to integrate in wall components. - most appliances are on walls as well <p>2. CEILING</p> <ul style="list-style-type: none"> - good solution for improved flexibility - appliances like lights are located on ceilings <p>3. FLOOR</p> <ul style="list-style-type: none"> - good solution for improved flexibility - furthest surface from most of the final appliances <p>4. SKIRTS</p> <ul style="list-style-type: none"> - waste of usable space since power distribution does not require a separate void for it

Fig.5.6 _the scheme gathers the data acquired during the 3 studies and ranks the best components to accommodate each services' family: (own illustration).

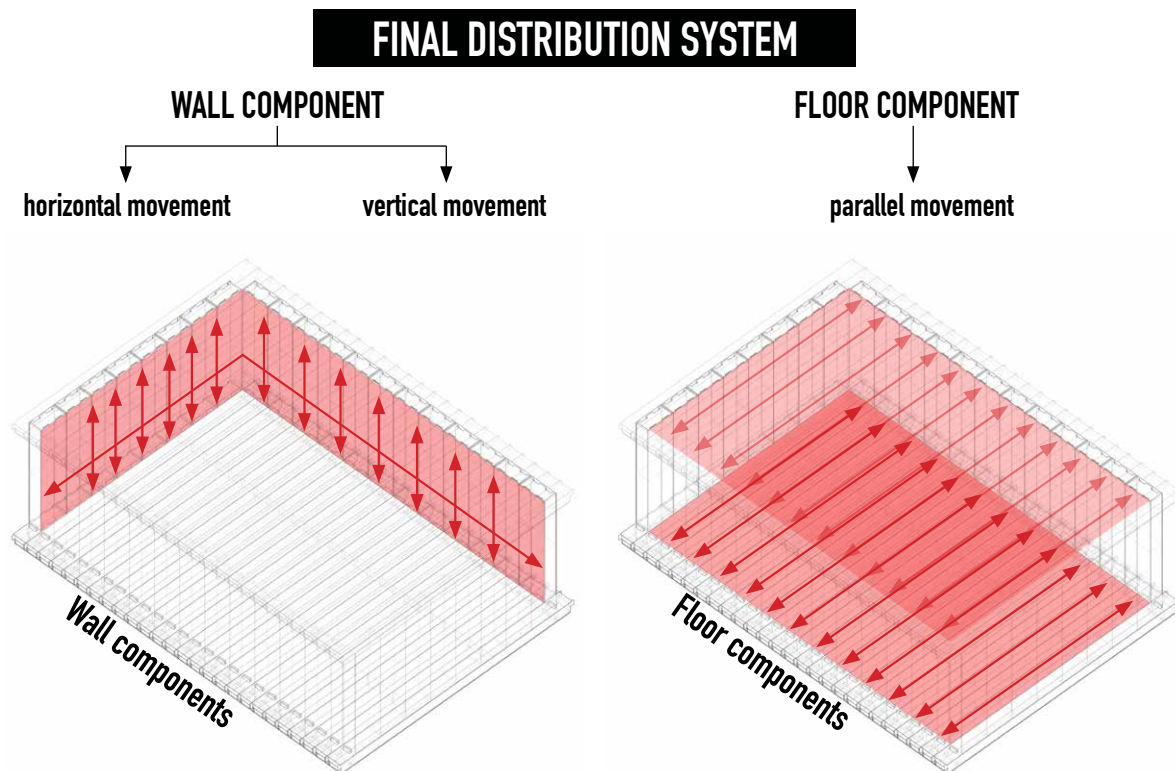


Fig.5.7_the conclusion of the distribution design is the starting point of the building components' design; wall components have to allow both vertical and horizontal flow of services whereas floor components only need to allow a parallel-to-component movement. The system is flexible enough to connect any combination of source-final appliance on the same floor and the requirements for the building components are satisfied in the building components design (own illustration).

CONCLUSIONS

The methodology used for the design of the distribution system was based on the function of family housing only. The maximum size of the building is restricted in both height and width by the digital fabrication process, which is limited by the size of the CNCmilling machine. The limited function and size of the building means that the research on the commercial products applicable for it was limited to products with small sections, therefore the distribution system suitable for small family housing in the PD lab should be reconsidered for other sizes and functions of buildings.

Parts of the study were carried out without considering the characteristics of the FabField building system, only taking into account the general characteristics of any standardised building system based on a modular grid. As a consequence, some of the conclusions might be valuable for all future studies on the distribution of building services in modular building systems. Nevertheless, the final distribution design is strongly based on the physical characteristics of the components of FabField and considered the difficulties in allowing certain movements of services in the already existing components; if the design was to be carried out by scratch, neglecting the already existing building components, the final outcome would most definitely differ as well.

Furthermore, the distribution design is the starting point of the building components design, which is based on the conclusions of the latter. If the concept for the distribution was different also the building components design would change drastically; it would be interesting for the future to apply different iterations in the distribution design to test also the different outcomes for the building components' design.

BUILDING COMPONENTS DESIGN

What is the best way to integrate services in the already existing building components?

The most suitable distribution system has been analyzed and set according to personal research results and data previously acquired; at the same time spatial requirements of services have been gathered and will now be taken into account to design the building components that will accommodate them. The main components that will be carrying this function will therefore be Wall and Floor component, with the Wall granting a free flow of services on its interior side and the Floor granting only parallel-to-component movements on its lower side (ceiling) whereas the upper side (floor) will be left as is for several reasons among which we can list: safety during on-site operations since it's always safer to walk on a flat, smooth surface; flexibility reasons as a flat surface grants the possibility to apply any kind of finish as well as any kind of service such as underfloor heating.

Of course if we talk about the integration of services in the components then we should probably take a closer look at the latter, even though they have already been briefly introduced in the first part of the thesis. FabField is entirely based on 4 components, namely Floor, Wall, Roof and Beam. The image on the facing page gives an overview of their size, structural role and aspect.

The Floor component has the structural role of a beam; the floor components at the lowest level connect and support the overlying walls whereas the ones above are supported by the walls and act as a stiffening element that keeps the walls from falling apart. The maximum length of the component is 5200mm and its limited by the size of the CNC milling machine that is currently used to produce

them. The component is 300mm wide and 250mm tall, it connects to the walls through a protruding notch at each side, it also contains 2 stiffening plates that prevent the elements from failing.

The wall component is 2400mm tall, 600mm wide and 300mm thick, it also contains a stiffening element at 1200mm of height. It has 4 rectangular gaps on the top and bottom to connect respectively 2 floor elements and 1 beam element for each side. The external element features a green, waterproof layer to temporarily protect the building before the facade is placed on it.

The roof component differs depending on what degree the sloped roof has, 30-45° or 60° are possible; the width is fixed to 300mm and the maximum length is also restricted by the maximum length allowed by the CNC milling machine. It features stiffening elements just like the floor component and connects to the latter at its bottom through a gap that accommodates the floor's notch whereas at the top it connects to the mirroring floor component.

The beam component has no real structural purpose if not connecting wall components with each other and the overlying roof components. It also temporarily protects the building with its outer waterproof layer. It is 250mm tall and 1200mm long which spans exactly for two wall elements.

All components are produced and assembled in the FabFac factory in Delft. They are all processed by the same CNC milling machine by milling 18.3mm thick OSB elements which are then connected together through glue, nails and mechanical connections.

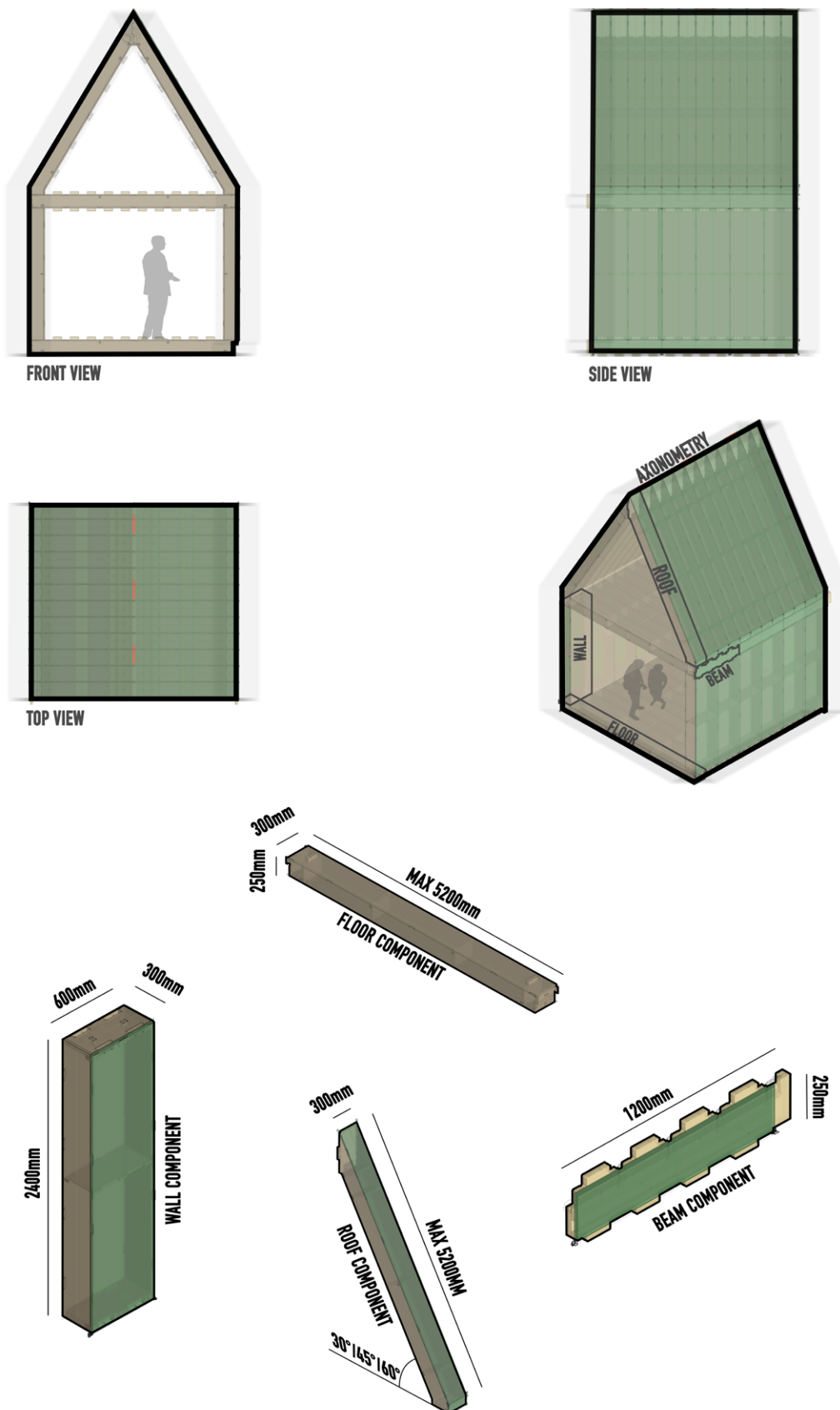


Fig.6.1_FabField is based on 4 building components with sizes limited by the production process (own illustration).

6.1 FORETHOUGHTS ON FINISHES

The first section concerning the distribution design concluded that the only surfaces being affected by distribution and final appliances are going to be the interior side of walls and bottom side of floor components, AKA ceiling. A further understanding of the influence of finishes on distribution and final appliances needs to be gained in order to integrate the latter in the building system. One of FabField's pivotal aspects is demountability, which so far only regards the structure and the facade, this thesis also strives to keep this aspect into account when it comes to building services, therefore every further application has to consider it too. In this brief section on interior finishings applicable in the FabField building system, only dry demountable systems will be taken into account for walls, ceilings and floors.

Finishings are a very important part of a building, they are what the final customer will see and perceive the building based on, therefore quality, durability and aesthetics are a very important aspect.

Interior finish consists mainly of the coverings of the rough walls, ceilings and floors; they provide a decorative skin to conceal building components like insulation, structural members, ductwork, pipes and wires. Finishes may be divided into two main categories: *self finish vs applied finish* and *wet finish vs dry finish*. Self finishes are all finishes that are inherent in the material whereas applied finishes need to be applied on site. As already said previously only dry finishes will be considered. Examples of dry finishes are plaster boards, timber paneling and carpeting; the main advantages of dry finishes compared to wet ones is the lack of dry out process and also the possibility to later disassemble/replace the whole layer.

Traditionally speaking walls and ceilings can host quite a variety of services within their thickness (belonging to distribution and final appliances). The usual practice is to cut out wall sections in order to accommodate the required services. Once the latter are installed, the wet finish layers can be applied. This is an inefficient process in which the position of services is not considered in advance, therefore a lot of material is wasted in the construction and subsequent destruction of the wall; moreover, traditional wet finish layers do not allow for maintenance or later demounting operations, reason why only dry wall finishes will be considered in this brief analysis.

The first finish analysed is drywall systems. Drywalls consist of a substructure, usually metallic, which is fixed on the walls and supports gypsum boards. This system is widely used for internal partitions thanks to its high flexibility and high performances in terms of fire resistance and acoustic insulation. The main issue with it is that gypsum boards do not constitute the last layer and should be plastered in the end. This last part is in contrast with the demountability concept around which FabField orbits. Nevertheless alternative methods to plastering are available, i.e. modern wallpapers offer the possibility to easily detach the paper from the wall when needed.

The second wall finish method considered is paneling, which follows the same principle as gypsum boards with the main difference being the fact that the panels don't need to be plastered and constitute the final visible layer of the wall.

Both drywall systems and wood paneling systems require a substructure of approximately 40-50mm, they both can be considered as "substructure" systems.

Substructures are traditionally not integrated with the main structure, instead they are installed only at a later time as a separate structure supported by the main wall. Substructures usually consist of U-shaped metallic profiles that run vertically through the wall from floor to ceiling, in this case building services can also only run vertically, when they need to run horizontally some holes need to be applied on the profiles. A big advantage with digital fabrication is that we can predict these circumstances in advance and solve them in the

design stage so that the installation phase can run more smoothly. A substructure system could be integrated in the design of the structure thanks to digital fabrication methods, considerably reducing installation time on site.

Similarly to walls, ceilings can also be finished with the drywall system by adding a metallic substructure to which panels are fixed and then usually finished with plaster, giving a smooth and even aspect to the ceiling. Nevertheless wet finishes are out of the scope for previously mentioned reasons.



6.2 SUPPORTING STRUCTURES FOR FINISHES

Previous paragraph introduces how interior finishes can affect the integration of building services. The possible approaches for the flow of services can be grouped into three common practices:

- Services fully visible and proudly shown throughout the building, usually backed by a wet, rough finish which could either be normal plaster or even the fireproofing layer. This approach can be seen throughout our faculty at BK.
- Services hidden behind a substructure which could then be finished with wood paneling or any kind of paneling which in turn could constitute the final finish depending on its aesthetic quality. This approach is very popular and flexible, it comprises elevated floors, drywalls and suspended ceilings.
- Services embedded in the wall structure which is usually cut out from the solid element to allow the related services to be accommodated in it. This system is usually finished with the paneling or tiling.

Among the approaches hereby mentioned the first one will be discarded from the study since it doesn't require any study for its integration. It is generally a sustainable approach as it simply leaves out the final aesthetic layer, sparing material and time on site; it will always be a possible approach for clients that desire it but it won't be included in this thesis.

The next two approaches are both interesting and allow for any kind of dry self finish on top of them.

The substructure approach has great flexibility and allows the free vertical flow of services between its structural posts, nevertheless, when horizontal movement is requested the structural elements need to be cut accordingly on site, wasting time and material. Another disadvantage is that it takes away precious space as it constitutes an addition to the thickness of the wall, without granting any structural function.

On the other hand the embedded approach, instead of adding thickness it reduces it by cutting out the desired material from the wall or ceiling itself. Its main disadvantage is the waste of that material which is usually cut on site leading to possible mistakes and risks as well as it being time consuming.

The two distinct approaches can be merged into a single one thanks to the integration of services design in the front end phase as well as digital fabrication methods.

The image on the facing page shows the concept: the thickness required for the services is not added to the current wall thickness, instead it is created by simply backing the front panel; this allows the required space for the passage of services without reducing the structural strength of the component since the resulting flanges are still part of the original structure. An extensive study on the required position of services in the components also allows the required material to be cut out directly during the production process, reducing time on site, risks and increasing the accuracy of the final components. Since this system is a fusion of the "embedded" and the "substructure" approach it will from now on be referred to as "embedded substructure".



VISIBLE SERVICES

building services are deliberately left visible in many buildings, sometimes playing an important role in the interiors architectural concept of buildings. This approach is out of the scope as it does not require any further study for its application



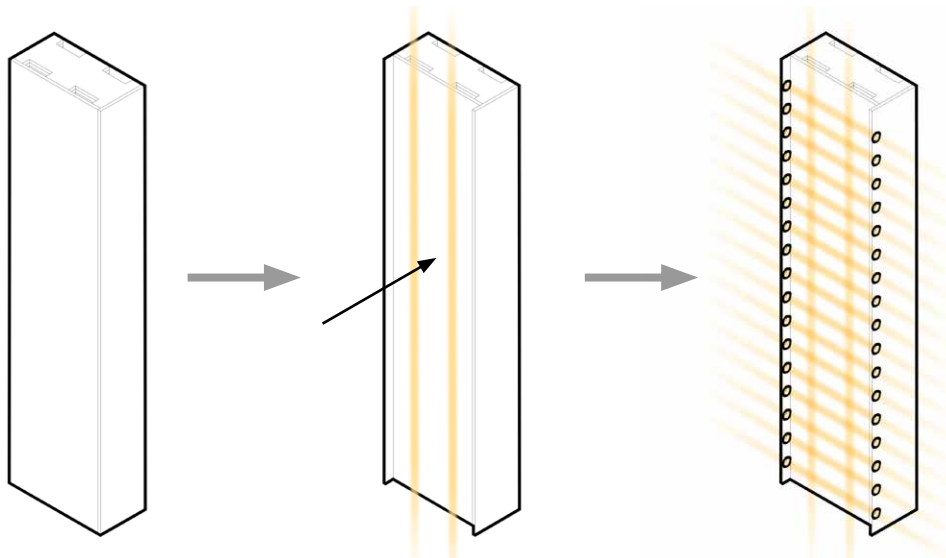
SUBSTRUCTURE CAVITY

very popular approach that allows great flexibility and demountability, especially used in office spaces. It relies on the addition of metallic posts and beams to create a cavity for services; the finish panels/gypsum boards are later attached to the substructure



EMBEDDED IN SUBSTRUCTURE

services are embedded in wall's thickness by cutting the required sections directly on site. no additional thickness is created but on the other hand a lot of time is spent on site and great amounts of material wastes are produced



1. CURRENT WALL COMPONENT

the structure of the current component does not integrate building services

2. WALL WITH SUBSTRUCTURE

vertical movement of services is allowed by backing the front panel, creating a substructure

3. EMBEDDED SUBSTRUCTURE

openings in the flanges allow the services to move horizontally as well, fulfilling the wall's requirements

6.3 SPACE REQUIREMENTS

The concept of the “embedded substructure” permits the flow of services within the wall thickness, the same concept can be easily applied to the bottom side of floor components as well. The thicknesses of typical substructures such as drywalls, elevated floors and suspended ceilings vary enormously depending on the space needed for the services, this because the substructure is structurally independent and does not affect the building’s structural capacity. In the case of the embedded substructure it does as the flanges constituting the substructure are also part of the structure of the component itself, affecting their structural capacity and overall behavior. For these reasons the gap cannot just be of any thickness but should instead only allow the necessary space for cables ducts and pipes.

The question that this paragraph answers is: what is the required thickness of the substructure so that all necessary services can be accommodated within it?

An important boundary condition that has already been stressed out at the beginning of the thesis is that the only function that will be considered in this application is small family housing; this is based on the assumption that the building components (especially floor) are limited in size and only allow for small buildings to be constructed. If the scope was to be enlarged to big offices for instance, the space requirements for electrical and ventilation systems would be much larger and the question above would lead to space requirements that would not allow the embedded substructure to work since its structural behavior would probably be compromised.

It needs to be pointed out once more that the expected services to be accommodated within the thickness of walls are only related to water distribution, electricity and partially water disposal, whereas ventilation distribution is integrated in floor components.

Water distribution gathers hot and cold domestic hot water and supply and return of heating water. The latter are constituted by 4 distinctive pipes which can be either made of copper or plastic multi-layered materials. The thicknesses that can satisfy the requirements of small family housing can be considered to be minimum 6.5mm and maximum 10mm depending on the pressure requirements. Nevertheless, these thicknesses should be oversized to allow for insulation for three main reasons:

- Insulation for hot water (both heating and DHW) should be allowed to prevent heat losses, subsequent inefficiency of the heating system and overuse of the boiler.
- Insulation for cold water pipes needs to be allowed to prevent condensation and subsequent dripping to occur. These would lead to the underlying surfaces to be wet and be fertile ground for mold. It also could cause the OSB elements to swell and/or deteriorate.
- Insulation should be always allowed to prevent the contamination of cold water with legionella. Legionella bacteria is commonly found in water. The bacteria multiply where temperatures are between 20-45°C and nutrients are available. The bacteria are dormant below 20°C and do not survive above 60°C. This is also the reason why hot water tanks store water above 60°C and

distribute it above 50°C, whereas cold water is always supplied below 20°C. In traditional buildings, the DHW is distributed separately from heating water, thus preventing cold water to be heated up by hot water pipes. In this case the distribution would happen in parallel, reason why insulation is required to prevent the risk of heating up cold drinkable water above 20°C from the constant heat generated by the hot water heating pipes.

If we consider the possibility of adding an insulation layer to the 19mm water pipes, the resulting maximum thickness for water distribution should be between 25 and 35mm.

As for water disposal the thicknesses are considerably larger. In fact this usually constitutes the largest space required as the main water disposal column sizes minimum 100mm of diameter and should run vertically throughout the building connecting the roof's pressure stabilizing intake to the main water disposal pipe. This pipe is always placed as close as possible to the toilet, all other water disposal pipes on the floor connect to the latter by a 1% slope. These pipes can be as narrow as 40mm of diameter. PVC is commonly used for this application for its durability and structural properties that can withstand extremely large pressures. The main problem with water disposal is no longer related to heat losses nor condensation or legionella. Instead noise and vibrations are the issue, reason why this pipes should be always fixed properly in order to maintain an internal comfort throughout the building's life. They do not require any insulation.

Electricity distribution is constituted of wires cased in plastic cases which can either be rigid or corrugated to allow more flexibility and easier installation. These cases size between 15 and 22mm and do not require any kind of insulation. They are traditionally fixed through clipping snap-fit connections. These tubes snake through walls, floors and ceilings and connect to all electric appliances through flush boxes inserted within the thickness of the wall/ceiling/floor. The latter flush boxes are rectangular plastic hollow boxes of varying sizes and thicknesses depending on the requirements. The depth required within the element spans between 40mm and 70mm.

Air distribution is usually the most encumbering and the size of the ducts can reach very large diameters depending on the internal volume to be ventilated and the number of people crowding it. Nevertheless, for small single family housing applications there are some interesting space saving products such as localized ventilation units. In case centralized ventilation is required, the smallest products available are flat flexible plastic ducts 50mm thick; the final interface of the air vents can take up to 80mm to allow the duct to turn without creating any buzzing sound which would disrupt the internal comfort of the building.

To conclude, the minimum thickness required for the accommodation of power and water related products belonging to distribution and appliances, taking into account some additional space for an ergonomic and fast assembly would be 60mm between the outer edge of the flanges and the exterior panel of the wall component.

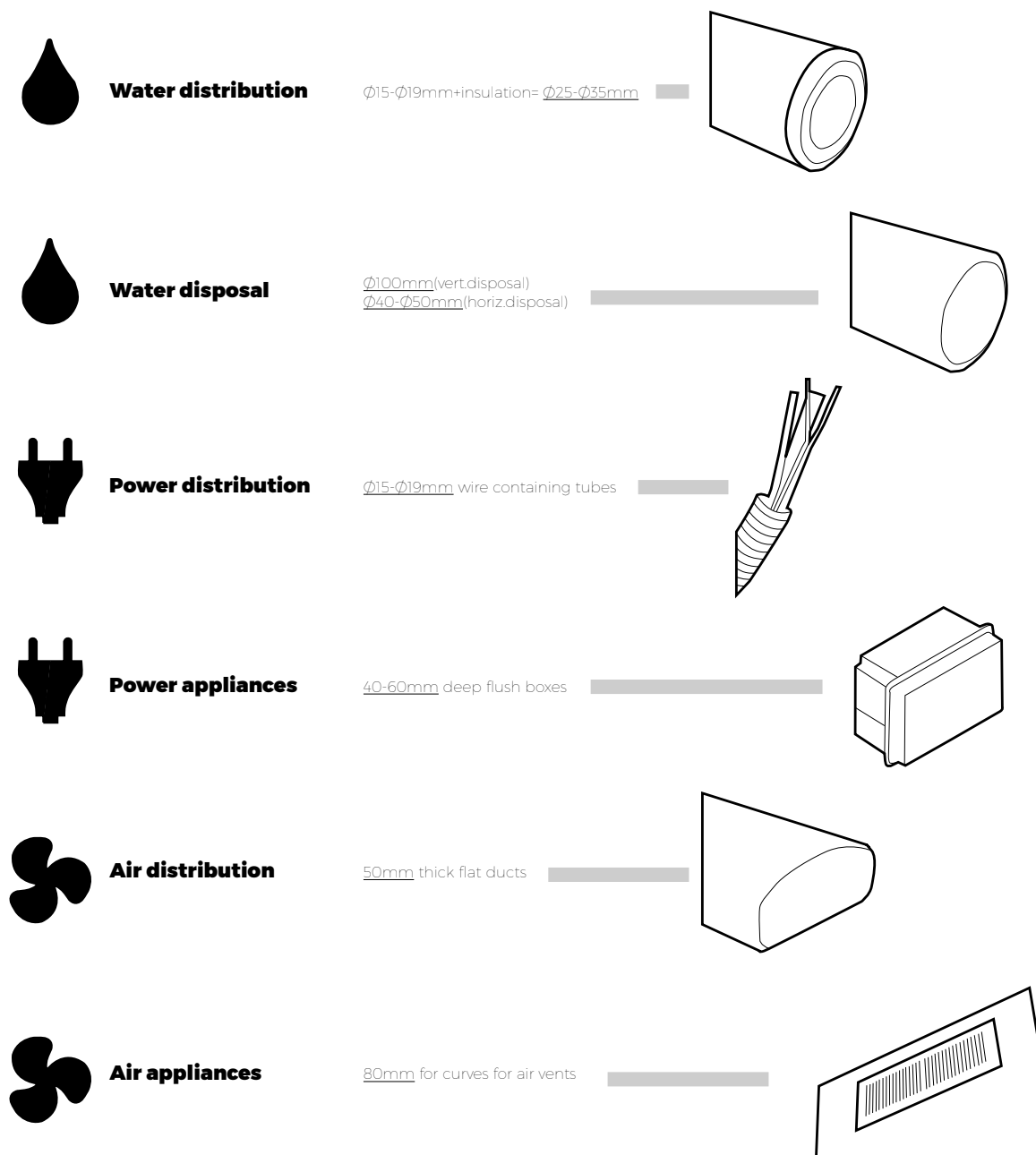


Fig.6.2_the scheme shows the maximum thicknesses considered for appliances and distribution of the three services families (own illustration).

6.4 STRUCTURAL CONSIDERATIONS

What is the current wall component's maximum loading capacity? Which one is the element that will fail first under compressive stress? How does the design concept affect the wall structurally?

These are a few questions that needed to be answered in order for the design concept for beams and walls to be feasible.

All building components can be considered rigid boxes since they are connected in multiple points with glue, nails and mechanical connections; the framing structure of FabField itself can be considered fixed in the connections between all components for the sake of this brief study. The connection between bottom part of wall and floor components is where the maximum bending moment can be found. Bending moment is a force \times distance which in this case is the distance between the bottom wedges of the wall; this means that by reducing the distance between the wedges, the force they have to withstand necessarily increases. The maximum axial stress is absorbed by the front and back elements of the component, which need to be verified against it. The structural calculations displayed in Appendix D show that the current wall component can withstand these stresses, also the new concept is verified by far against these stresses, proving to have a large redundancy.

As for the floor and roof components, the flanges are added to the already existing section instead of being subtracted; the structural effect of the protruding elements on the aforementioned components is therefore neglectable. Nevertheless, calculations on Appendix D proves how the parallel movement designed for the floor components is also

structurally advised since the flanges are the most important parts and should remain untouched. More insights and structural considerations can be found in Appendix D.

6.5 THERMAL CONSIDERATIONS

The design of the new components affects thermally only the wall component by backing the front panel, thus reducing the space for the insulation. The section of the current wall profile is confined in the exterior and interior by two OSB panels, respectively 18,3mm thick (thermal conductivity 0,13 W/mK for OSB 650Kg/m³) and is filled with 2 layers of rockwool of 180mm (thermal conductivity 0,035 W/mK). The actual gap of air between the two panels is 564mm, which are not thoroughly filled with insulation: the total thickness of the two layers of rockwool is 360mm, leaving 200mm of air inside the wall components. By backing the internal face of the wall component of 60mm the same amount of insulation would still be allowed, the only thing being reduced is the air gap inside of the component. If the latter was to be considered airtight it would also contribute to the overall thermal insulation of the wall component, just like the airtight gaps between window panes. Nevertheless, this is not the case and the overall thermal performance of the wall component remains untouched with the new design modifications.

The current and future U-value of the wall component is given by reciprocal of the sum of the thermal resistances of the 2 OSB panels (0,276m²K/W) and the two 180mm mats of rockwool (15,42m²K/W), which gives as an outcome 0,063 W/m²K.

6.6 FINAL APPLIANCES POSITION



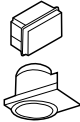


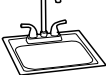
In the previous sections the minimum thickness to accommodate every service has been defined through an extensive research of current practices and commercial products; the latter thickness has also been reviewed in its structural and thermal behavior. If we take a step back and recall the principle of the embedded substructure we can conclude that the aforementioned studies have verified the substructural part of it. The next step is to understand how this can be turned into a fully functional, prefabricated embedded substructure wall component. The step that needs to be made in order for this to happen is to analyze the horizontal flow of services through the component. In fact the two flanges already allow the free flow of services in the vertical direction, but how do they flow from one wall component to the other in the horizontal direction? In order to answer the question it is first required to understand what walls usually accommodate in our homes and in what position these elements are usually placed. In the previous sections the systematic definition of building services has been given through a table that shows how the latter can be divided into families according to the medium they are related with (water, power or air) and their function and space requirements within the building (sources, distribution and final appliances). “Sources” have been thoroughly analyzed and their extensive description and space requirements can be found in the appendix of this book, “distribution” has been researched and studied in the previous chapter to define its flow and further investigated in the previous paragraphs to define its space requirements in terms of thickness of the embedded substructure.

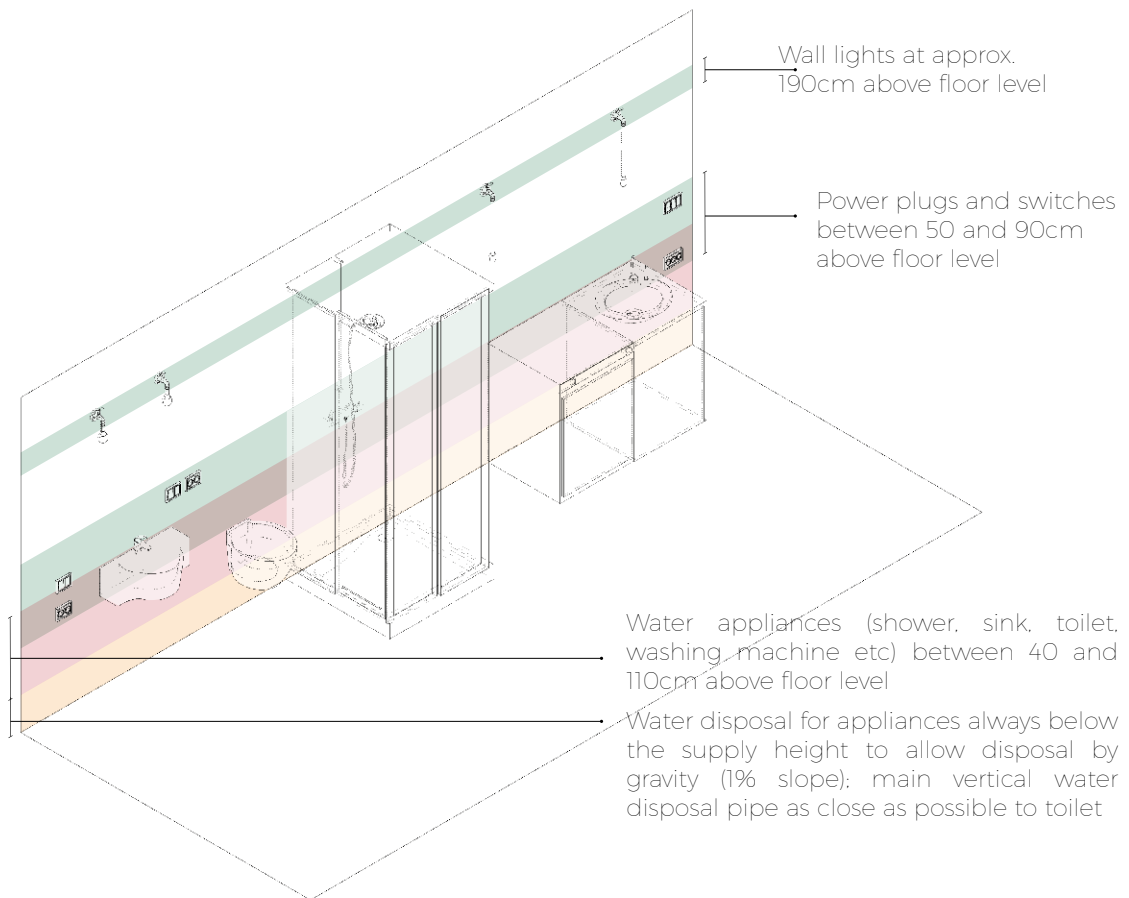
Now “final appliances” need to be reviewed in order

to understand their typical position so that the distribution can flow accordingly.

Most water related final appliances, with the exception of sprinklers which are not required in single family housing, are usually located in walls at varying heights. Most of the inlets for sinks, dishwashers and washing machines are placed between 45 and 70cm above floor level, for showers the intake is between 100 and 120cm. It is obviously important that the water disposal pipe is always located below the inlets since this is transported downwards by gravity; water disposal pipes have to be placed with at least a 1% slope towards the main water column which will then gather all black water and dispose of it out of the building to the sewers. Electricity lines do not follow any fixed scheme and vary enormously from country to country, as long as they reach their final appliances they can flow wherever through the building. It is entirely up to the building services engineer to decide the best way to reach the final spots, which are always either plugs, switches or lights. Lights can be placed on the ceiling or on walls, in the second case they are usually placed above eye-level at approx. 190cm above floor level. Switches and plugs differ depending on their application: low plugs for appliances such as TV or vacuum cleaners at 30cm, bedside switches at approx. 70cm, generic light switches at 90cm and plugs for bathroom and kitchen appliances usually at around 110cm.

Lastly, ventilation will be later described in a dedicated section. It is important to state that these heights are not restricted by any regulation but rather by common sense and comfort considerations.

	AIR	POWER	WATER
APPLIANCES	 <p>Wall-ceiling-floor vents</p>	 <p>Lights and flush boxes</p>  <p>Recessed lights and flush boxes</p>	 <p>Water supplied heating appliances</p>  <p>Toilets</p>  <p>Sinks</p>



HEIGHT OF HORIZONTAL OPENINGS

UPPER M10 BOLTS H 235cm
LOWER M10 BOLTS H 6,5cm

The necessity and position of the bolts have been set by previous structural analysis by Kevin Gunawan. They connect neighboring wall components and prevent them from tipping off.

UPPER POWER LINE H 220cm
LOWER POWER LINE H 80cm

Electricity is distributed at two different heights to improve design freedom and decrease the distribution length for ceiling appliances which can be reached easily from the upper line; appliances at 190cm are also reachable from the upper line whereas lower appliances at 110, 90 and 70cm are connected to the lower line.

**MAIN HOT AND COLD DHW AND SUPPLY
 AND RETURN HEATING WATER H 50cm**

The 4 main lines can run in parallel just below the overlying power distribution and every electric appliance so as to prevent any kind of dangerous leakages on the latter. The height has been determined according to the height of most water appliances which is approx. 40-60cm.

WATER DISPOSAL LINE H 30cm

The waste water from the appliances is connected to the main water pipe with a 1% sloped pipe of 40-50mm diameter which is allowed to sneak by the large space reserved (between H 30 and 10cm). This allows for distances as long as 24 meters, or 40 wall components, before having to reach the 100mm main water disposal vertical pipe.



We will leave air out of consideration for now since the thickness it requires is far larger than all other services, especially for the vents that require at least 80cm to turn without creating any buzzing noise. For this reason, the idea is that air could be supplied by either localized units or by distributing the ducts on the unusable space on the second level of the building.

The graph on the facing page shows a study of the wall components and electrical and water related services that could run through them within the embedded substructure. As already said, the idea is to create some cuts in the section of the flanges of the wall at predefined heights so that services can be accommodated easily in any case.

In darker blue are represented the main electricity lines that run respectively at around 220 and 80cm; the higher line is designed to reduce the length of the distribution for higher appliances such as light appliques (190cm), bathroom and kitchen switches and plugs (110cm) and especially all ceiling lights which can be easily reached by a space created between wall and floor component for the exchange of services. The lower electricity line is for all other low appliances that can be easily reached since they are located at 90 and 70cm; it is possible but not advisable to have electric appliances lower than the main water distribution simply because this could lead to clashes between cables and pipes but mostly because the goal is to protect electricity from water by only having cables placed above water level to avoid any kind of risk caused by the possible contact between water and electricity.

The space left free between the two main electricity lines is intended to allow window openings whenever deemed necessary.

The 4 main water pipes (2 for DHW and 2 for Heating) flow horizontally at 50cm above floor level since all water appliances such as sinks, dish washers, showers, washing machines and so on are all easily reachable from that level. Right underneath it the water disposal has 20 cm of space (between 30 and 10cm above floor level) to allow the 1% slope to run freely for as much as 25,4m and reach the main water column. It is deemed more than enough since a good design would always prevent longer distances by placing water appliances quite close to each other. In many cases, bathroom and kitchen share the same wall to drastically reduce the distance and encumbrance of water disposal pipes, this is obviously suggested in all cases when possible.

Lastly, at roughly 6,5 and 235cm above floor level a series of M10 bolts are placed in order to structurally connect walls; the necessity of the bolts emerged from Kevin Gunawan's previous thesis on the subject.

The case of air supply needs some further considerations in order for it to be integrated in the system, this because of its different distribution requirements in terms of space, paths and position on its final appliances.

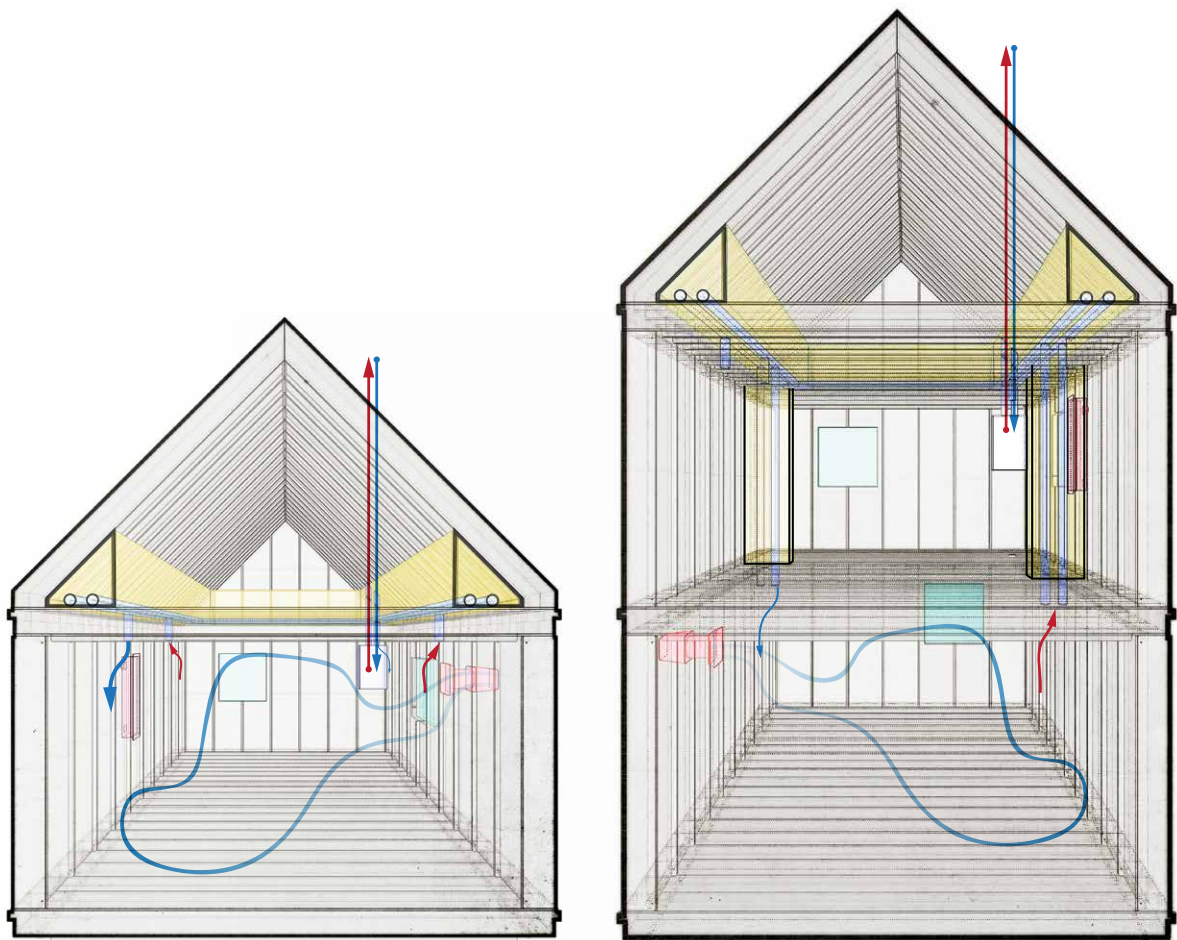
As already mentioned in the previous theoretical overview of building services, ventilation can be mainly divided into two categories: localized units and centralized units.

The first group comprises compact products that can be simply integrated in a single wall module by applying a hole of the required dimensions, connecting the inside to the outside simply through a duct. These devices can either provide fresh air supply and extraction of stale air or only extract stale air, depending on the requirements dictated by the case. This kind of solutions are optimal for small spaces that do not require large ventilation rates, they allow very high flexibility but are not the best choice for larger, more complex interior spaces. The most interesting products gathered during the market survey are Fresh-r by Vaventis and Air-70 by Brink, for which the integration in wall components is shown in the last chapter of the thesis along with other special integrations.

Nonetheless, integration for ventilation needs to be designed mainly for centralized ventilation units, which just like localized units can either only provide extraction of stale air or also draw fresh air inside the building. In this case the main difference between the two cases is that the amount of ducts required for the distribution is doubled, the requirements in terms of thicknesses or position of the ducts remain untouched.

The big aspect that affects the distribution lies in the number of floors of the building; if the building has a single floor the integration is fairly simple: the most convenient way to position the central unit is in the roof space, as close as possible to the rooftop, where fresh air can be drawn in and stale air expelled. The edges of the roof space cannot be considered a habitable space due to the steepness of the roof slopes which conspicuously reduces the height of the room, therefore it is a perfect position for the distribution of air ducts. The non-habitability of the edges allows ducts to run freely along them as a result. The edges will need to be appropriately covered by either furniture, finishing or partitioning elements. The best way to integrate this distribution system in the building is by using a floor component with a CNC milled gap that allows the services to go from the floor on the roof space to the underlying air vents.

In the case of two-story buildings (maximum height allowed by FabField) further considerations need to be done for the distribution to lower floors. Simple holes in the beam components are no longer sufficient, a special component allowing the vertical connection between floors needs to be implemented in order to supply both floors. This function could also be integrated in the same component that contains the main room water disposal.



The central unit is located in the technical room, the location of the latter is not restricted by particular requirements. Intake and exhaust happen on the roof, as well as the main air distribution which flows through the edges of the roof space, where the internal height is not habitable. Nevertheless, ventilation can also be carried out by localised units, displayed in red on the image above.

The central unit has to be as close as possible to both the intake and exhaust placed on the roof. The main difference between the single floor and double floor scenario is the necessary introduction of special components for the vertical distribution of air ducts between top and bottom floor in the two-storey building, whereas this is not required for single floor buildings.

6.7 FIRST DESIGN PROPOSALS FOR THE WALL FLANGES

Some design proposals were carried out at this point to assess their ease of production, assembly and sturdiness. The main way to check if a design works is to prototype it, nevertheless this was not the case yet as the proposals were still not detailed enough. Some models scale 1:10 have been made mainly to assess different shapes of openings into the wall flanges for the horizontal flow that was just explained in the previous paragraph. The position of the openings did not really matter at this point, therefore all openings were roughly placed at mid height of the flanges. Some more models were also made and are not hereby shown as not relevant to the final design.

Model number 1 is the current wall component used for FabField, 24cm high, 3cm thick and 6cm wide. All other five models display different proposals for the embedded substructure, in each one of them the substructure is 0.5cm thick (5cm in real scale) but they differ in how the flanges are shaped.

Model number 2 has a straight cut out of 5cm in each flange. It was later found that the CNC milling could not even process such stright cutout because of limitations caused by the round bit; nevertheless the principle is still the same; 90° angles are not ideal for because of the way they concentrate stresses around the edges, therefore some other shapes have also been studied.

Model number 3 shows 2 elliptical openings for each flange; the openings are roughly 0.3cm (3cm in real scale), leaving only 0.1cm of material to support. This was obviously a bad idea because it creates an extremely weak section of the element that

would sooner or later brake during transportation, assembly or use of the component. This is even more understandable when assembling a 1:10 model, in which the part broke and had to be glued back together.

Model number 4 applies an opening which is similar to the second model, nevertheless it has a round shape for the aforementioned principle of avoiding straight edges so as to distribute stresses more evenly.

Model number 5 proposes a series of smaller holes, each one should accommodate a cable, duct or pipe. The concept is similar to model number 3 but the section is much more solid because more round shapes can distribute stresses much more uniformly: the part of material 0.1cm thick is constantly sided by thicker sections of material that take up the stresses that the thinner section couldn't take.

Model number 6 lastly evolves the concepts of models number 2 and 4 by creating cut out parts which are double curved and distribute the stresses along the edges in the most uniform way.

Models 5 and 6 were the best performing in terms of structural stiffness, which means that during assembly, production and transportation the flange would behave much better than the other proposals. Nevertheless, some aspects of both designs were still flawed: model 5 lacks of flexibility and in case of disassembly of services it would probably be the most difficult. Model 6 is more flexible and it allows an easier disassembly of services but would requires some fixing elements for the latter to be placed.

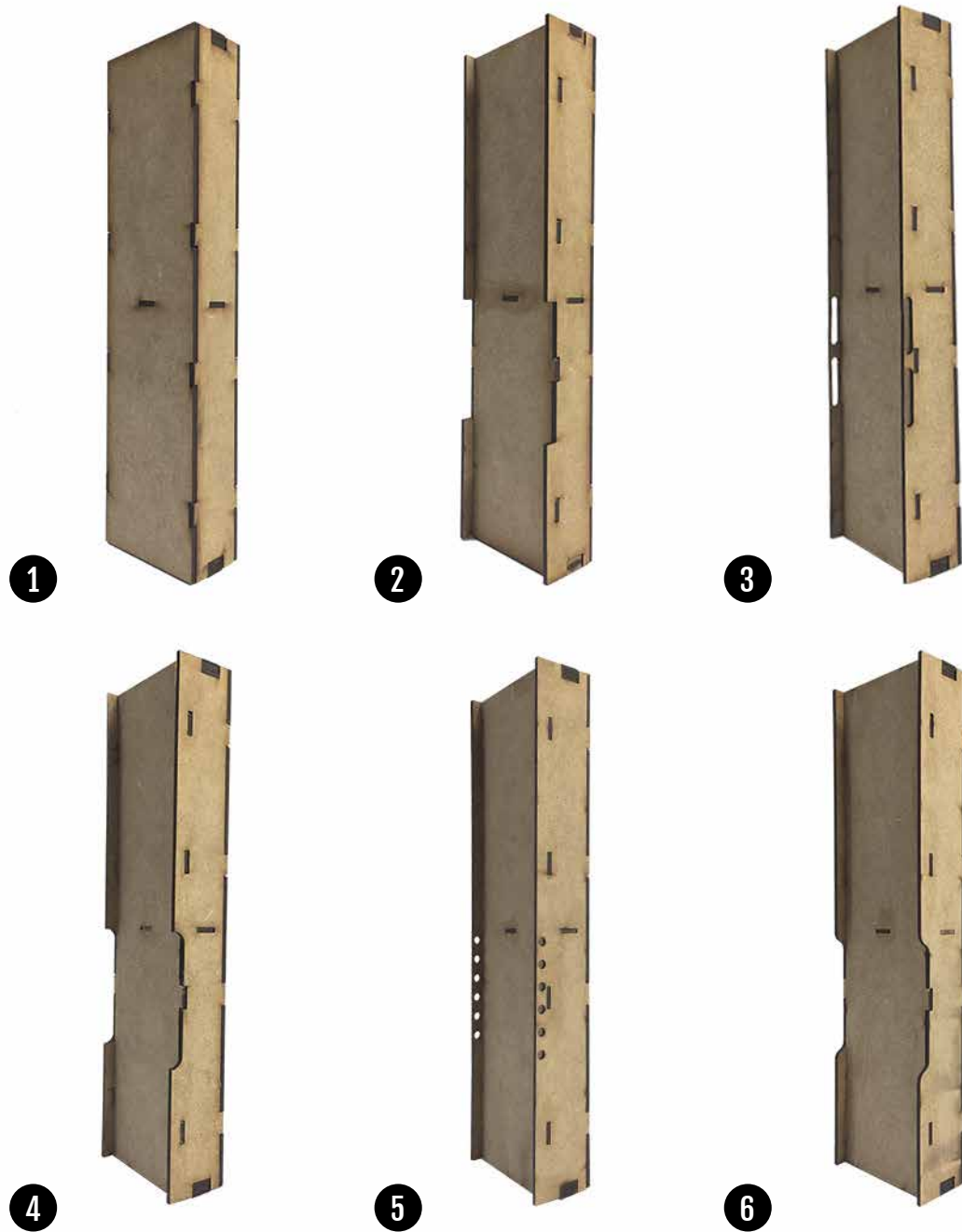


Fig.6.3_6 models 1:10 were laser cut and assembled in order to investigate on the fragility and effect on assembly difficulty of different shapes of flanges (own illustration).

6.7.1 STRESS CONCENTRATORS

The flanges of wall components are quite delicate yet fundamental elements as they have to carry out important functions such as supporting the internal finish layer of the building as well as air proofing the building. Thus they must be strong and resistant, especially during transportation, process in which components can be easily damaged. Furthermore, the allowance of horizontal movement makes the flanges even more vulnerable as a result of so called “stress concentrators”. Stress concentrators are areas that tend to magnify the stress level within a part. Stress that is higher in one area than it is in surrounding regions can cause the part to fail. If the radius of curvature in the notch tip is very small or if there is no radius, the stress level will be very high. Sharp corners are specially critical. (Structural integrity analysis, Stress concentration; Igor Kokcharov). Alternative number 1, where the space is created through simple 90° angles is the most fragile since no radius at all is provided and the corners are subject to high stress concentrations.

Alternative 2 is an evolution of the first one: the outer sharp edges are rounded to absorb impacts that might damage the flanges during transportation; the round edges also help to distribute stresses, making the flanges more resistant overall.

The third proposal has both corners rounded to smoothly distribute stresses throughout the section; this is the most robust section of them all.

Alternative number 4 provides small round openings to accommodate cables and pipes; this is quite a good method to distribute stresses, nevertheless, the thickness between the edge of the holes and the edge of the panel is too small, thus creating a large stress concentration in those points. This happens in the third design as well, where it's clear to see

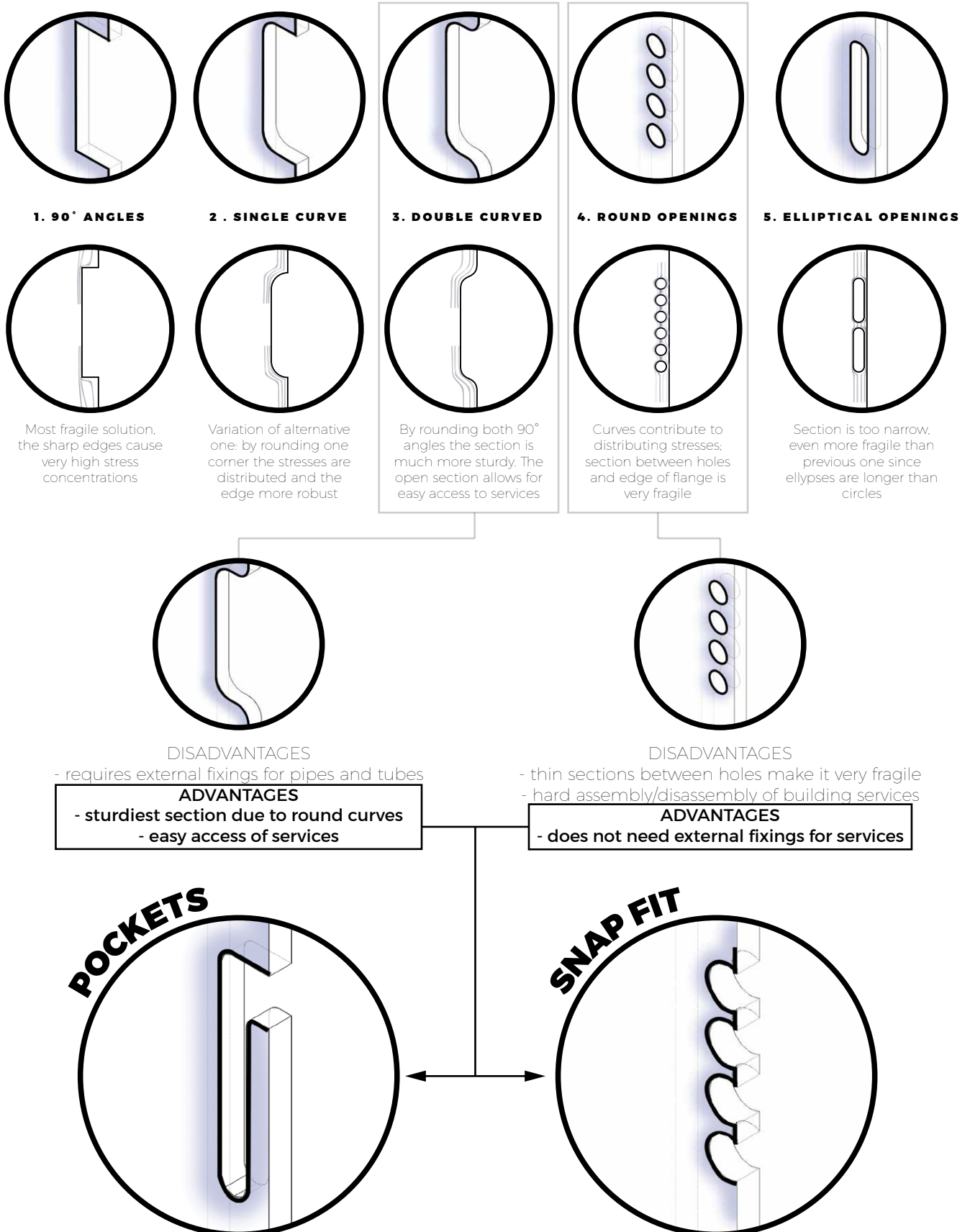
that those thin sections will be very easy to break during transportation, even more than alternative number 2 due to their longer thin section. This quick analysis was carried out to validate the choice of the geometry proposed for the openings.

6.7.2 SNAP-FITS AND POCKETS

Similarly to the idea that created the “embedded substructure” from merging the advantages of two distinct solutions, the most promising solutions for the shape of the openings in the flanges were also born by merging the pros of the 2 best performing shapes that have just been exposed, the round holes and the double-curved cut out.

The double-curve cut-out is structurally very resistant and the fact that it is open allows easy access to the services. On the other hand, the proposal of round holes does not need any external fixing connection for the services but it is also quite inconvenient for the installation and future disassembly of distribution lines of services.

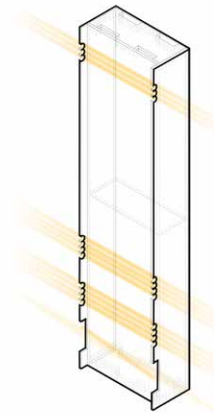
The snap fit and pocket solutions were created by exploiting only the advantages of round holes and double curved cut out; the image on the facing page explains the development of the concept



6.8.4 DESIGN ALTERNATIVES

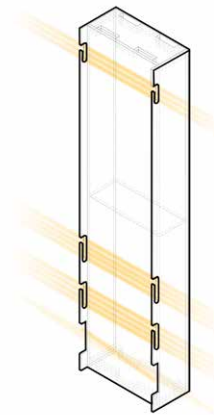
FLANGES WITH SNAP-FIT SLOTS

The first proposal is based on Snap Fit fittings, it is an idea based on merging the ease services' installation of having round holes and the flexibility of a simple cut-out. Snap-fit connections are theoretically very convenient for services' installation but each slot is only suitable for a single size; furthermore the sharp corners of the slots are quite fragile



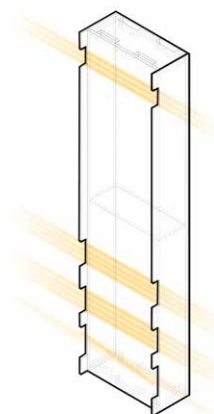
FLANGES WITH POCKETS

The idea of the pockets came again from merging two distinct proposals: the elliptical openings and the simple cut-out. Pockets can be very flexible, facilitate services' installation and disassembly as well as being suitable for more than one size of tube. Once again flexibility comes at a price: services would probably need to be further fixed to be kept perfectly in place; this design may also be quite fragile especially for its problematic stackability.



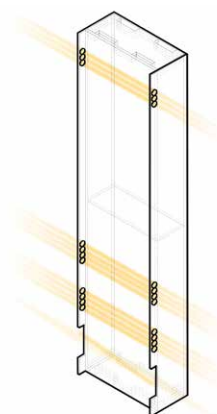
FLANGES WITH STRAIGHT CUT-OUTS

This very basic idea is as easy as it looks: horizontal flow of services is simply given by straight openings in the places where it is required. It is most definitely the solution that grants the most flexibility but the placing of services requires extensive use of traditional connections. It is also the proposal that requires the least struggle in the front end design.



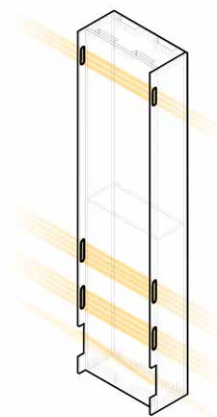
FLANGES WITH ROUND OPENINGS

Round openings give quite a tight connection for the building services and even though it generates a very thin section of the flanges it still performs very well in terms of resistance since the stress concentrators have been optimized by the round shape. Nevertheless, the installation of long rigid pipes would be very annoying and the disassembly as well since it seems very hard to slide a rigid pipe away from them.



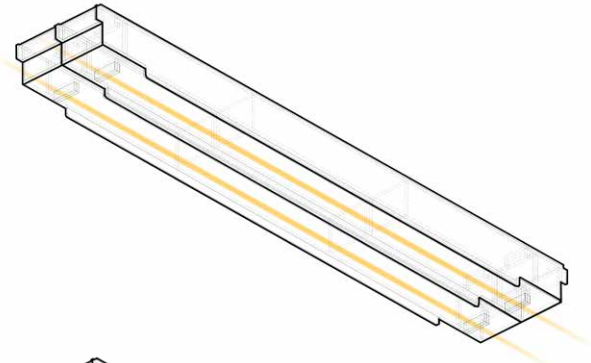
FLANGES WITH ELLIPTICAL OPENINGS

This alternative has the same flaws of the one previously exposed and it is even more fragile since its thin section is much longer and therefore much more subject to cracking; it is also problematic in terms of installation and disassembly of the services. The perks of it comprise the lack of need for external fittings.



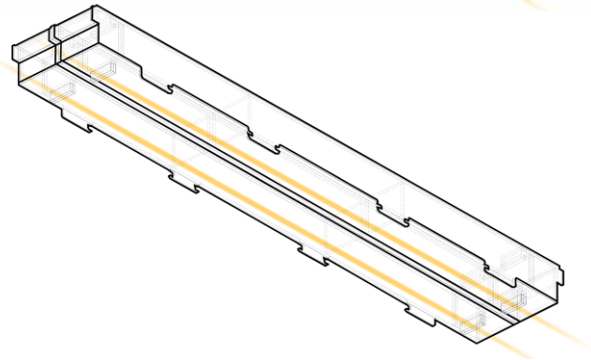
FLANGES AT BOTH SIDES

Each beam has a protruding flange for each side to allow the passage of services; the thickness created is 3cm and permits the parallel-to-component movement of services. The flanges are protruding so that the structural resistance of the beam is augmented as well as its overall height.



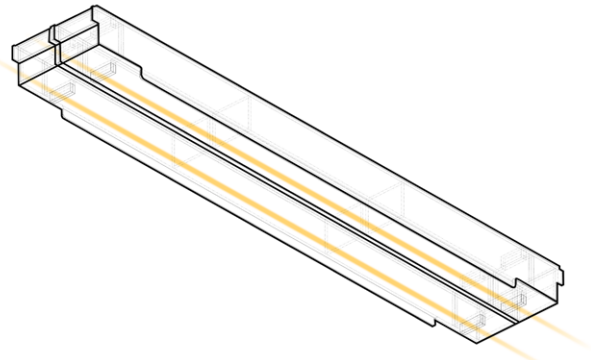
PROTRUDING NOTCHES

This proposal is also based on the idea of the flanges but some cut outs are applied. This way, if it was ever necessary, a free flow of services is allowed in the ceiling as well, the weight of the component is less than the one with normal flanges and the partial substructure could still support the finishing elements for the ceiling.



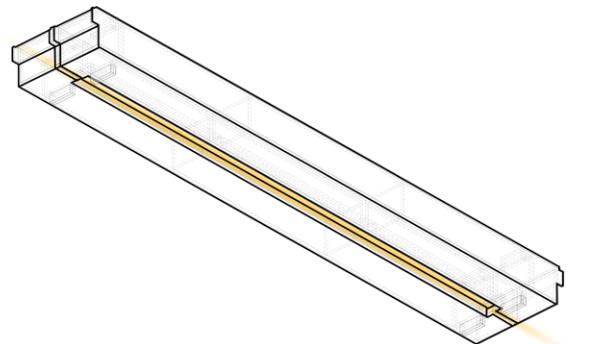
FLANGE ON ONE SIDE ONLY

This is exactly the same concept as the first one showed on this page, with the only exception that the presence of only one flange per beam makes it lighter but also asymmetric; during transportation the floor elements can be stackable by mirroring them, thereby saving a considerable amount of space and preventing the flange to get damaged.



CENTRAL RECESSED GAP

This component is the only one that doesn't add any thickness to the floor component and it is based on creating half a recess at the side of the component; when the component is mirrored the half recess becomes a full squared gap for the parallel flow of cables. The problem with this component is the assembly of its elements, specially in the recessed part, as very long, thin OSB elements are generally quite easy to break when handled.



6.8.5 COMPONENTS ASSESSMENT

The alternatives that have just been presented are thoroughly assessed through the methodology presented in appendix E. The roof components did not need an assessment since they have the same functional requirements of floor components. For this reason, the design principle applied for the floor components will be used for the roof components too. The table on the right presents the criteria and relative families through which each design alternative was assessed.

Simplified graphs of the methodology for walls and beams are presented in the following pages so that the overview is easier and more understandable. In the columns related to the families, the highest scoring alternative is highlighted in green whereas the lowest score is highlighted in red. If we take a look at each alternative we can see how the rows with many reds are the worst performing in those aspects and therefore less likely to be the final design whereas the ones with most green lights have once again the highest performance for that family. The reds and greens that are shared with at least 3 other alternatives are marked in yellow to underline the less importance of the highest/lowest score. On the right side of the graph a brief explanation is given so that the reasons for the low or high scores is easily understandable for each and every design.

DESIGN	●●●● FREEDOM OF DESIGN
	●●●● FLOW FLEXIBILITY
	●●○○ LENGTH OF DISTRIBUTION
	●●●● ADAPTABILITY TO FUNCTIONS
	●●○○ ADAPTABILITY TO APPLIANCES
	●●●● ADAPTABILITY TO FINISHES
	●●●● STRUCTURAL RELIABILITY
MACHINING	●●○○ NESTING
	●○○○ BATCH SIZE
	●●○○ MILLING TIME
COMPONENTS ASSEMBLY	●○○○ AMOUNT OF ELEMENTS
	●○○○ ELEMENTS VARIATION
	●●●● ASSEMBLY ERGONOMICS (C)
	●●●● ASSEMBLY TIME
	●●○○ ASSEMBLY COMPLEXITY
COMPONENTS TRANSPORTATION	●●●● VULNERABILITY
	●●○○ PILING EFFICIENCY
	●●○○ LIFTING ERGONOMICS
	●○○○ WEIGHT
BUILDING ASSEMBLY	●●●● ASSEMBLY ERGONOMICS (B)
	●○○○ COMPONENTS VARIATION
	●●●● BUILDING SPEED
SERVICES INSTALLATION	●●○○ EASE OF INSTALLATION (BS)
	●●●● SAFETY
	●●○○ POSSIBLE CLASHES
	●●○○ INSTALLATION TIME
FINISHES INSTALLATION	●○○○ EASE OF INSTALLATION (F)
	●●○○ FINISHES APPLICABLE
	●●○○ FINISH QUALITY
USE	●●●● ADAPTABILITY
	●●●● MAINTENANCE
	●●●● ACCESSIBILITY
	●●○○ AESTHETICS
END OF LIFE	●●●● LIFESPAN
	●●●● DISASSEMBLY
	●●●● RE-USE

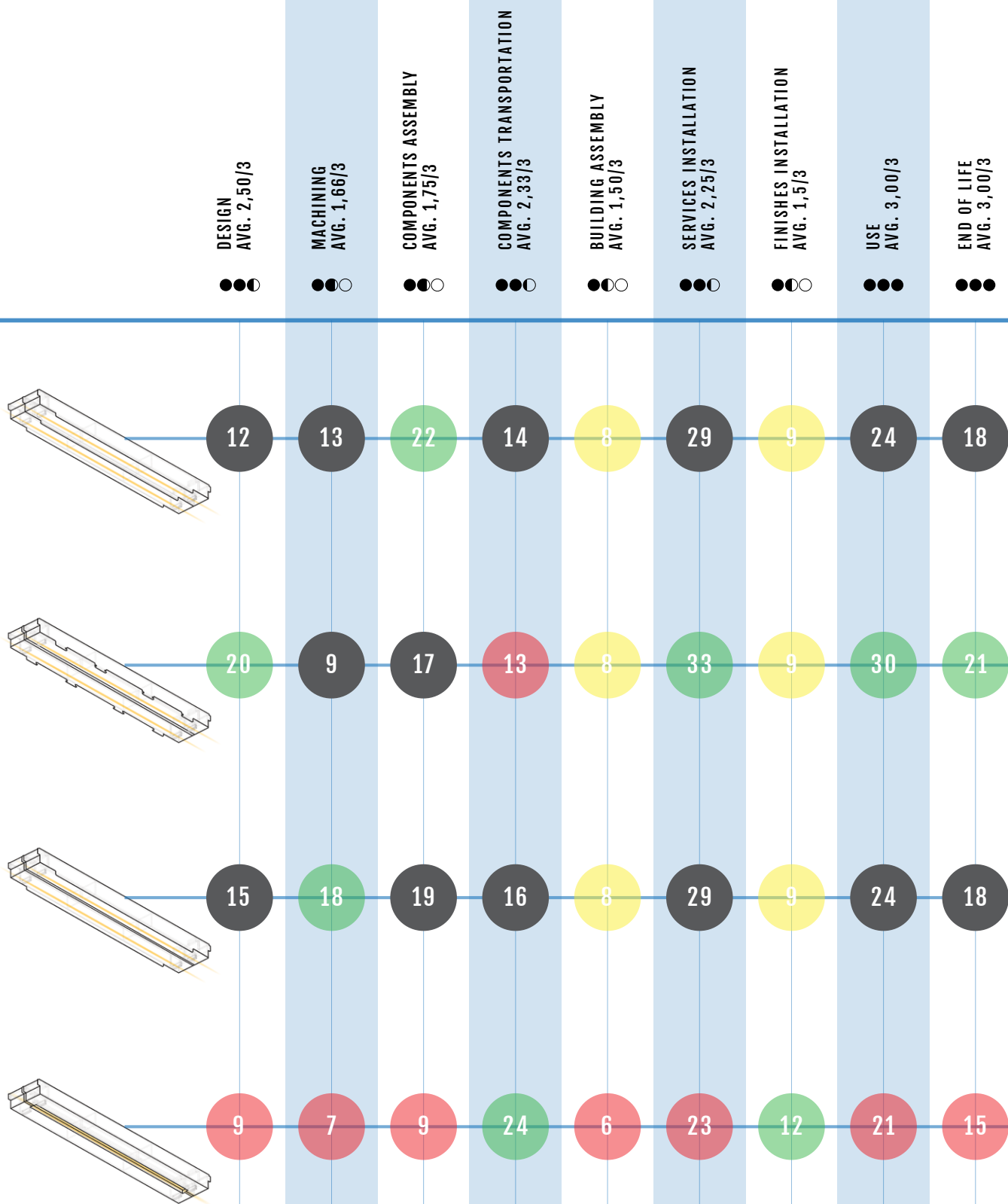
-
- Best for services installation for as the snap fit system is considered very fast and easy to use
 - Worst in transportation since it is both very fragile for its sharp edges and not ergonomic
 - Worst in finishes installation since the clipping creates an ulterior thickness over the flanges
 - The clipping system does not allow much flexibility and it's very fragile since wood is weaker than plastic, therefore it would be the first to brake if sightly forced

- Worst score in machining since the nesting would be quite a lot in this case
- Scores the best in services installation for its efficiency in the installation and flexibility
- Scores best in use, end of life and 4 other families
- The installation would be very convenient as well as future uses; scores best overall

- Best score for design as the large cutouts enable a great design freedom for every scenario
- Shortest milling time: the bit only has to change direction and keep on cutting the outline
- Scores very well in use for its great flexibility and ease of access for future maintenance
- Second best score; the only issue is that all services would require an external connection since the cutouts do not provide any kind of support for the latter

- Scores best in finishes installation because is the only one (along with the elliptical version) to provide a smooth, straight external section of the flanges
- Worst scores in 5 families mainly due to its fragility and lack of flexibility given by the holes
- Installation of services and disassembly of the latter would be very inconvenient in case the services consisted of rigid, not flexible pipes.

- Scores best in finishes installation because is the only one (along with the round holes version) to provide a smooth, straight external section of the flanges
- Worst scores in 5 families mainly due to its fragility and lack of flexibility given by the holes
- Worst score overall and the only one not to pass the structural soundness: the long and extremely thin section of the flanges are too fragile



- Best in components assembly as the two symmetric flanges keep the variation of elements very low, also building assembly scores high for the same reason: the component has a centric CG and there is no variation of components
- Low grade in finishes installation is shared with other alternatives, therefore not significant
- Good alternative but the main issue is the weight since two big flanges are added

- Best score in use and end of life is related to its much higher flexibility given by the possibility to allow services to flow in parallel but also perpendicularly between floor components
- Lowest score in transportation is given by the fragility of the notches and the asymmetric CG
- Lowest score in finishes installation is shared with other alternatives, therefore not significant

- Best score in machining is given by the fact that the only difference between this alternative and the original component is the presence of one flange
- The high score on assembly and low on finishes installation are marked as not significant due to the shared score with 2 other alternatives
- Second best overall score

- Worst scoring design overall
- Recess makes the batch size larger as well as the nesting and the difficulties in the components assembly, the asymmetric CG also creates difficulties in ergonomics and B. assembly
- Main perk of this design is the lack of protrusions which gives a great stackability and sturdiness of the component as well as the best score in finishes installation

6.8.6 FINAL COMPONENTS DESIGN

The outcome of the assessment is the final choice of the wall and floor components. The wall component design is based on the principle of the pockets which can accommodate multiple sizes of services at the same time without compromising too much the structural efficiency of the component. The main issue for this design is the fragility of the flanges where the pockets are, reason why the external section is as thick as possible to increase its stiffness. The fragility of the flanges comes out especially during transportation, when the components will presumably be stacked in a truck that will take them from factory to construction site. If instead of two protruding flanges only one was to be applied, the stacking of the elements wouldn't be problematic at all since the components could be mirrored on top of each other in such a way that the flange is always protected and never loaded by the component above; the main reason why this was not possible is that the design conclusion from thesis of Gunawan K. on the structural connection between wall components resulted in the necessity to connect wall components with bolts on the top and bottom part of the flanges, reason why there necessarily have to be two protruding flanges connecting two wall components next to each other. A solution to the problem could be to add a flexible mattress between wall components during transportation so as to shelter the flanges from excessive stresses. The pockets for electricity are 25mm in diameter and allow the tubes to be stacked on top of each other and later being clipped together with the typical plastic snap fit connections; water pipes are not placed on the same line to try to prevent hot water pipes from heating cold water pipes and also to allow vertical movements to rigid pipes without

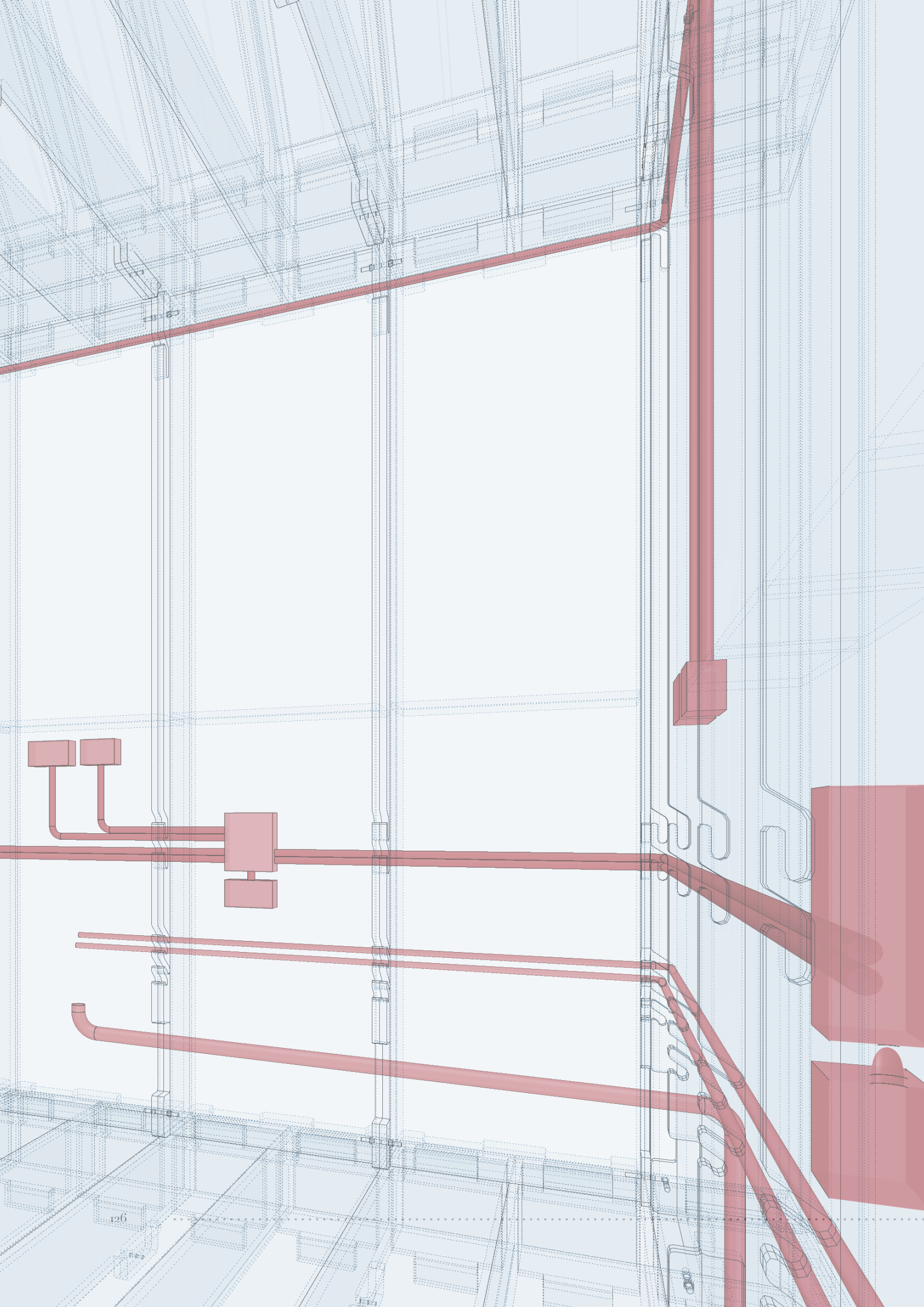
clashing to the one above. Furthermore, the upper and lower section of each flange is curved so as to prevent damage to it in case of tipping over from high wind loads. Overall, the new design doesn't add any thickness to the original component nor any additional weight, also 4 out of 5 original elements are leaving untouched, the flanges are the only elements to be redesigned. It needs to be pointed out that the overall system of distribution of building services only works when the same gaps applied on the main wall components is applied to the partition walls as well to allow a fully functional flow of services through any kind and arrangement of building. The floor component is maintaining the overall shape, nonetheless the notches are adding thickness to the original 25cm of height of the component which now became 30cm. In this case the flanges do not need to be symmetrical since the structural connection between neighboring floor components happens on the floor level through butterfly connections. This way the notches are less fragile when transported since they can be stacked in a more efficient way. The position of the notches will vary according to the overall length of the beam which can obviously change from case to case. This will be the typical beam component, which could also allow the passage of air ducts from floor to ceiling when required. This is backed up by the structural considerations made previously which proves that this is possible without compromising the overall resistance of the floor component. Later on, in the final chapter of the book, all components will be shown in detail along with some special components that were not assessed in the methodology.

CONCLUSIONS

The path that has been taken for the design of building components is strictly related to other aspects such as the previously designed distribution system, the desire to integrate dry finishing panels in the structure of the components and the struggle to foster the flexibility and ease of installation and future modifications for building services. The literature research showed different approaches for the integration of building services in buildings: the most traditional requires the services to be individually installed on site whereas a renewed approach is to assemble sections of services off-site which are only later put together with the adoption of plug&play systems. This approach shows multiple benefits: reduction of time spent on site, less risks and weather dependency as well as less inaccuracies of the final installation. Nevertheless, the already existing building system is based on relatively small building components that create difficulties in the integration of such approach in FabField; the approach of plug&play modules is definitely a better approach to be integrated in building systems which are also based on bigger plug&play sections, completely assembled on site with services and finishings and only later brought on site in a reduced number of sections to be connected.

The overall design process for the building components would have most definitely required more time dedicated to prototyping in order to learn the issues that only a hands-on approach can teach. The overall design is based on technical specifications of products from companies and digital drawings, the assessment of the components is related to criteria that were graded only based on my very little experience on the field. The real assessment for the building components design can only be valuable once the system is tested on site, gathering the issues that professionals might encounter with it.

To conclude, the concept works on paper but definitely needs more testing in real life scenarios in order to be able to give a final assessment. The further steps that need to be taken are the design iterations after each prototyping, thanks to which minor alterations could turn a promising idea into a real working solution for the FabField components.



FINISHINGS DESIGN

What are the possibilities for the interior finishing layers of the building?

The last chapter concerning the design is related to the finishing of the interiors of the building. As it was mentioned earlier the finishing layers are very closely related to the design of building components as well as building services. In fact, the concept of “embedded substructure” was also inspired from the research on finishings, which was restricted to dry, self finishes. In the next pages the methodology already applied for the main components will be applied to the aspects of the interior finishes. The aforementioned aspects were inspired by previous thesis by Jeroen van Veen, which only one year ago designed the exterior facade of the PD Lab. The aspects taken into account by him were obviously more complex since the exterior facade panels would also have to be water proof as well as resistant to wind loads.

There are some differences between the way the methodology was applied for building components and interior finishings:

Instead of assessing full design solutions this time design sub-solutions will be assessed in order to create a single design out of them. The finishing panels are bound to some characteristics such as their assembly, connection, transportation and so on. Thus the finish panels design can be created by analyzing different combinations of sub-solutions until the most favorable one is defined

The requirements for an exterior facade are mainly technical and objective whereas for interior finishings are mainly aesthetic and subjective (Fig.X). For this reason the methodology is used to create a library of possibilities rather than a final decision, so that each customer can have a final outcome according to his/her preferences.

Some restrictions need to be made once again to restrict the scope: The size and shape of the newly designed building components is seen as a restriction to which the finish panels will have to adapt. The materials taken into account will have to be light and processable by the CNC milling machine so as to stay in line with the overall concept of FabField

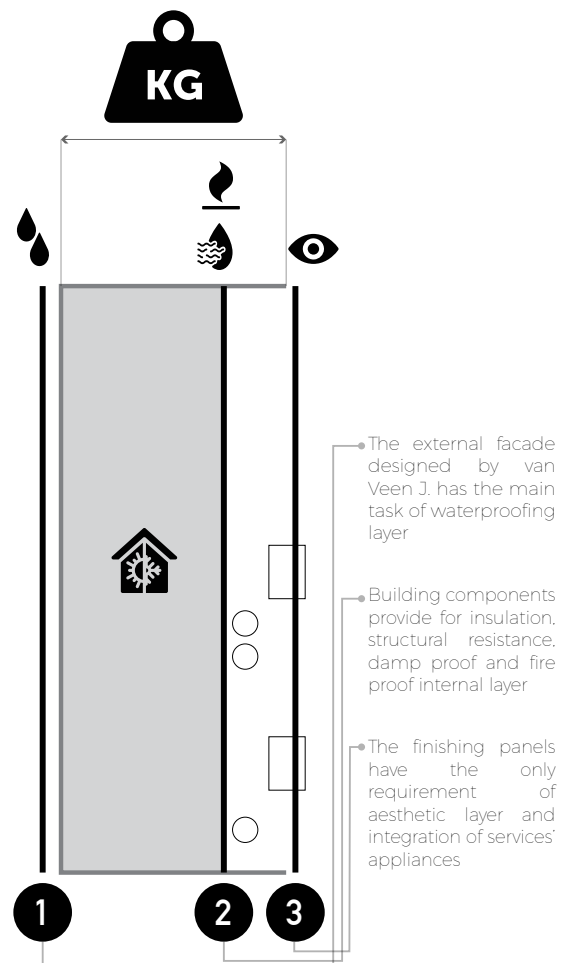
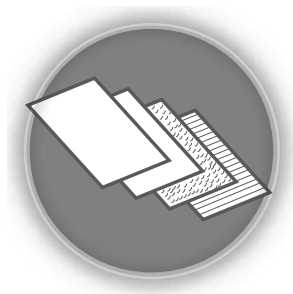


Fig.7.1_the requirements on the finishing layer are mainly aesthetic and the integration of appliances (own illustration).

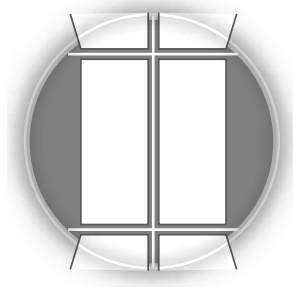
7.1 DESIGN ASPECTS



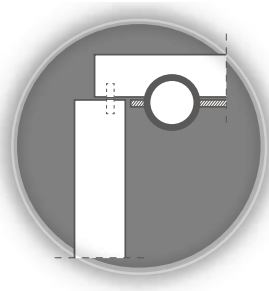
MATERIALS_ The first aspect is the decision of the most suitable material among the selected ones; the final material has to be structurally strong enough, light, aesthetically pleasant as well as processable in the CNC milling machine. Most materials are wood based: some of them are multi layered rather than solid, some have a smoother finish rather than rough, some others differ in weight.



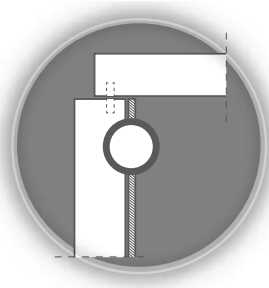
ASSEMBLY_ There are different ways to assemble a finish panel, all of them have an effect on the final result in terms of precision, stability and demountability; nevertheless the main aspect influenced by the assembly type is the ease of installation of the panel which in turn affects costs and risks related to the overall time spent on site.



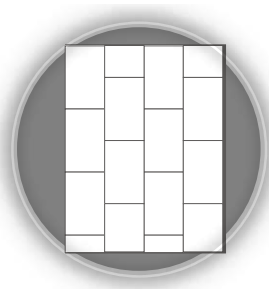
JOINTS_ In any kind of facade the joints between panels are fundamental for the overall performance of the facade as they effect it in terms of visuals and especially for water proof as well as preventing stagnation; in the case of interior finishing panels they simply need to provide a clean, smooth connection between panels with a proper tolerance for a convenient installation.



CONNECTION TO CEILING_ There is a myriad of possibilities to connect a panel to a backing surface. In this case the choice is limited by geometrical boundaries such as the distance between the flanges of the floor components as well as the thickness of the protruding notches. An important criteria for connection methods is the performance in demountability, therefore no wet connections are considered nor excessively destructive ones.



CONNECTION TO WALL_ Once again the library of possibilities is limited by the same factors mentioned above. The reason for the distinction between to-wall and to-ceiling connections is that they need to be attached to different substructures with different geometrical boundaries: the wall connections will need to be more solid as more subject to collisions whereas the ceiling could even be simply hanging.



CONFIGURATION_ The configuration of the panels in the interior has a strong aesthetic impact, which can differ for different users: one might prefer a narrow vertical pattern on the walls whereas someone else might prefer larger patterns. Nevertheless, this also has an impact on transportation, speed of installation, possibilities to integrate features in the finishing layers as well as an effect on tolerances.

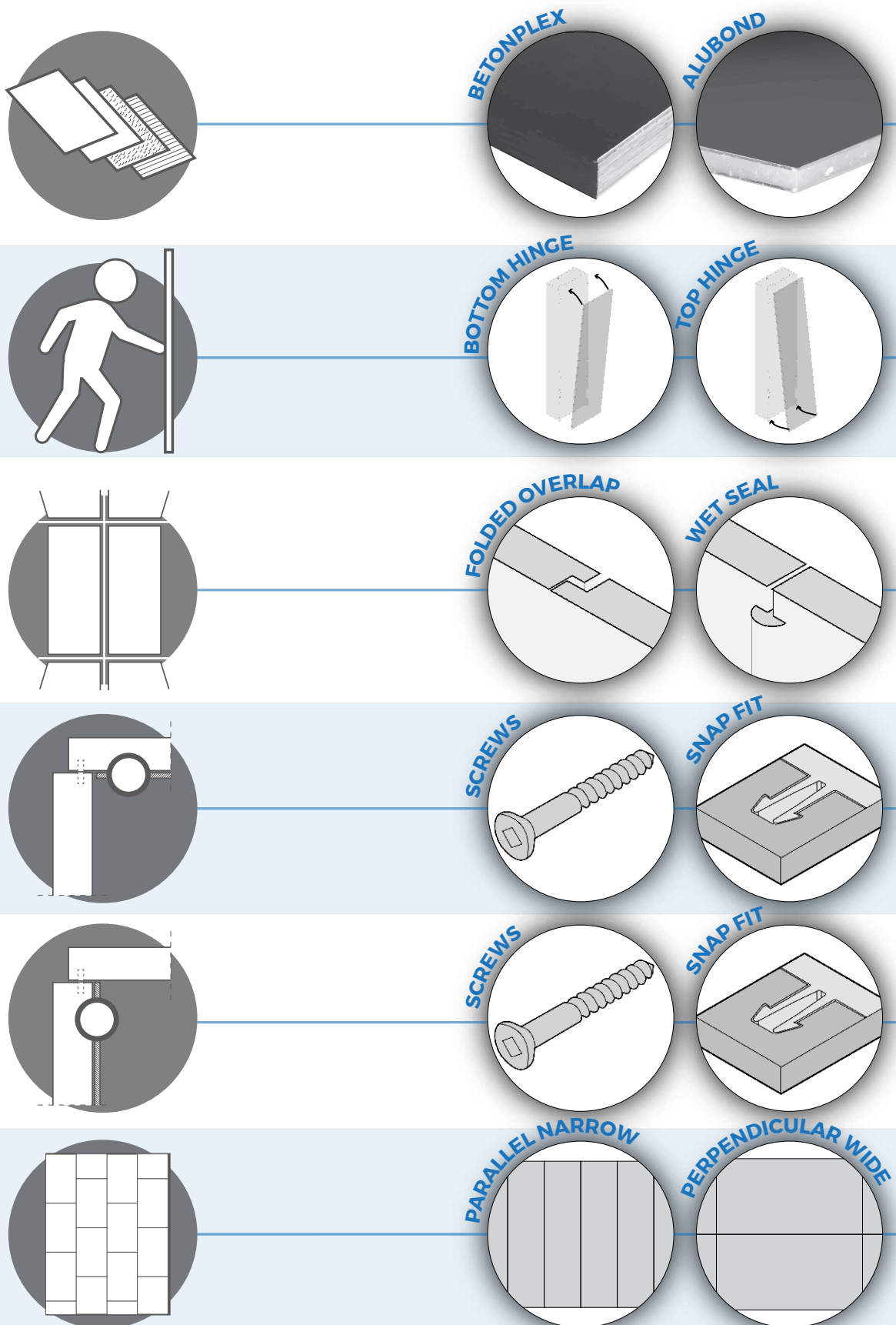
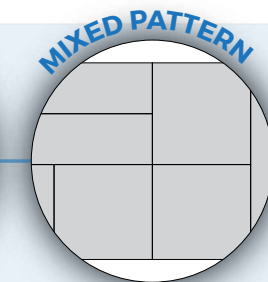
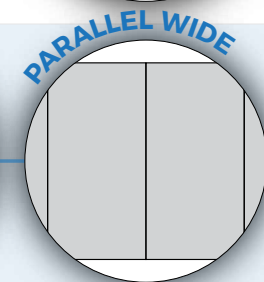
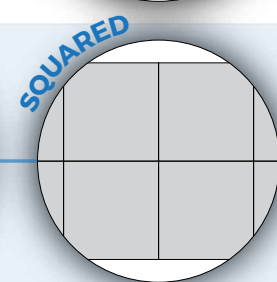
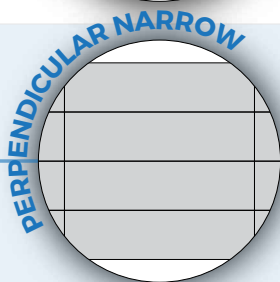
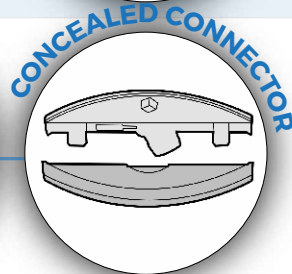
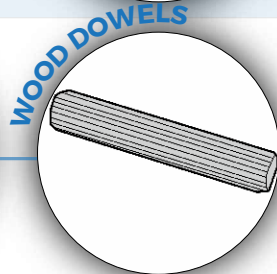
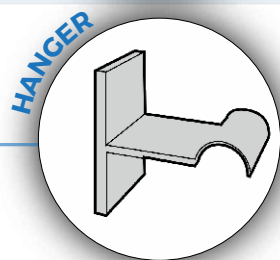
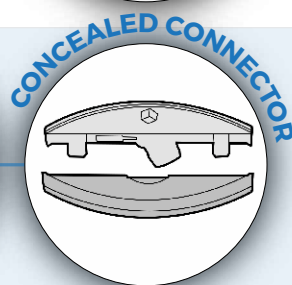
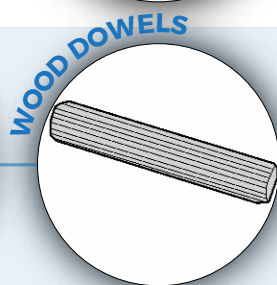
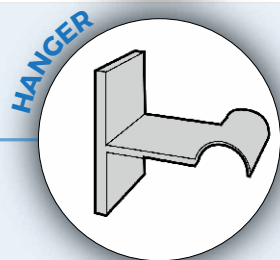
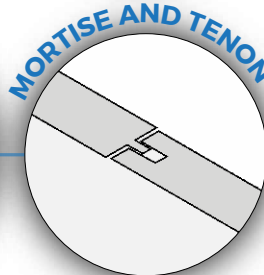
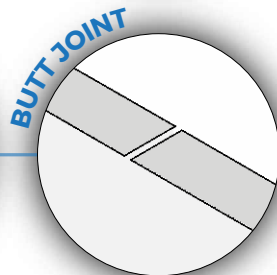
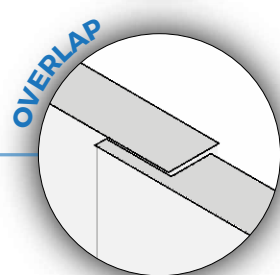
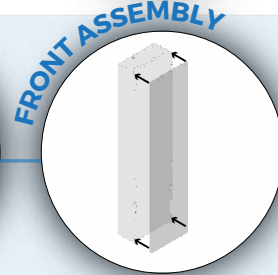
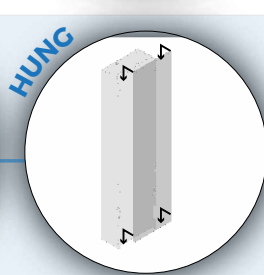
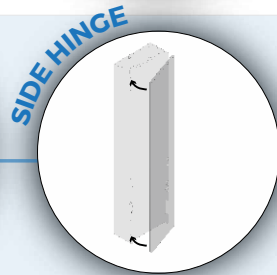
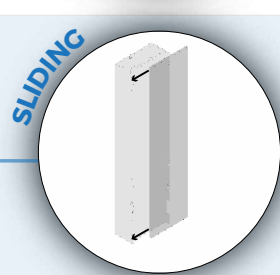
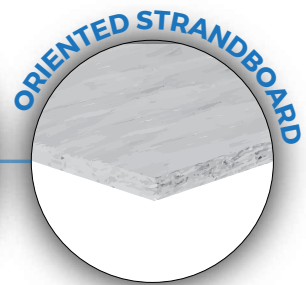
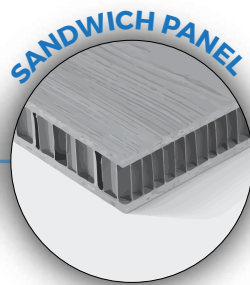
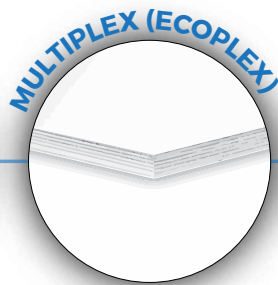
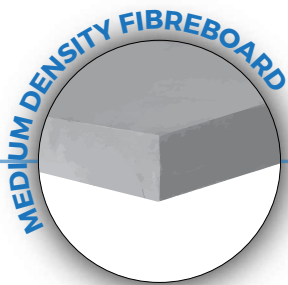


Fig.7.2_The different alternatives for each design sub-solution are hereby listed (own illustration).



	COST		ENVIRONMENTAL IMPACT	NESTING	MILLING TIME	ASSEMBLY TIME	AMOUNT OF ELEMENTS	STRUCTURAL VULNERABILITY	LOADING EFFICIENCY	AESTHETIC VULNERABILITY	SPEED	RISK OF ERRORS	AESTHETIC VULNERABILITY	TOLERANCE	ERGONOMICS	POSSIBLE CLASHES	ADAPTABILITY TO APPLIANCES	MAINTENANCE	COMFORT	ACCESSIBILITY	AESTHETICS	LIFESPAN	DISASSEMBLY	END OF LIFE ACTIVITY
	COST	ENVIRONMENTAL IMPACT	ENVIRONMENTAL IMPACT	NESTING	MILLING TIME	ASSEMBLY TIME	AMOUNT OF ELEMENTS	STRUCTURAL VULNERABILITY	LOADING EFFICIENCY	AESTHETIC VULNERABILITY	SPEED	RISK OF ERRORS	AESTHETIC VULNERABILITY	TOLERANCE	ERGONOMICS	POSSIBLE CLASHES	ADAPTABILITY TO APPLIANCES	MAINTENANCE	COMFORT	ACCESSIBILITY	AESTHETICS	LIFESPAN	DISASSEMBLY	END OF LIFE ACTIVITY
MATERIAL																								
PRODUCTION																								
TRANSPORTATION																								
ASSEMBLY																								
USE																								
END OF LIFE																								

7.2 WEIGHTLESS CRITERIA

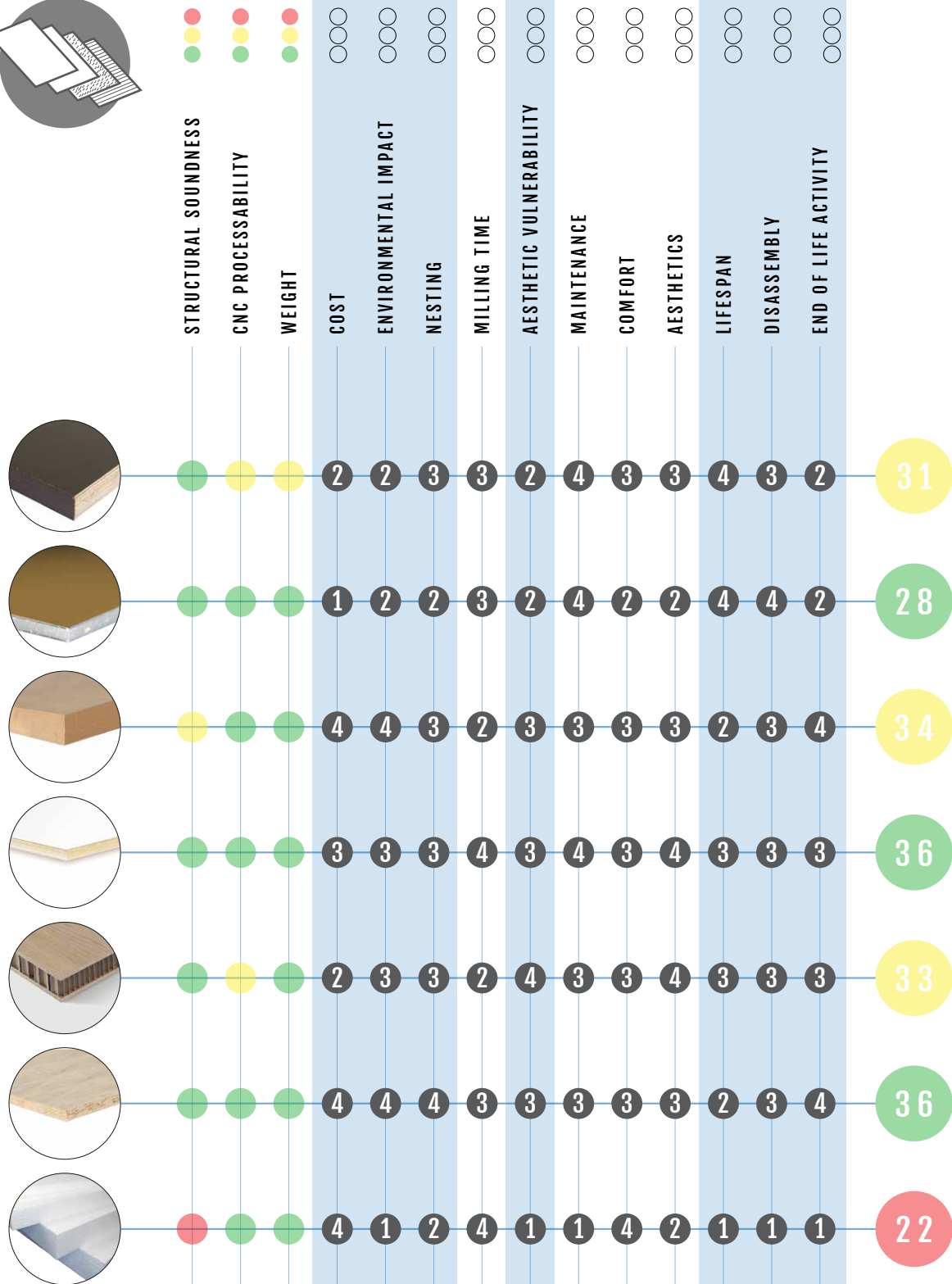
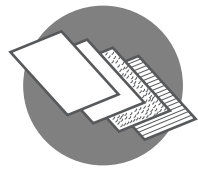
The image on the facing page represents the house of quality for weighing the new criteria to assess each design alternative. In this case some of the criteria used differ from the assessment previously carried out for the design of building components. This is an obvious consequence since the structural building components have different tasks to carry out throughout the building's life time, one of them being the accommodation of building services' distribution, whereas the finish panels are only supposed to accommodate the final appliances. Furthermore, the building components' aesthetics did not matter much for their final design, whereas in this case it is one of the most important aspects for the finishing layer of a building.

One fundamental step in the methodology was the weighting of criteria in the house of quality; the procedure is to assess all criteria against one another in order to give them a final score based on how many times one criteria was considered more important than another, scoring 1 point each time that happened. By the end of this extremely time-consuming process, each criteria had its own "weight" in form of a value from 1 to 3 that indicated his importance amongst all other criteria. This has always been important because in the final evaluation it helps valuing more the highest scores with high weight rather than the same score of a less weighted criteria. When it comes to product development, the weight is given by the designer so as to accentuate criteria that he/she values the most. In the components design my highest weighted criteria were structural reliability, safety during the installation of services, adaptability to functions and accessibility for easy maintenance.

Those were design aspects given by the important task that the components had to carry: they had to be strong so as to withstand the building, allow for a safe installation of services as well for easy inspection when required and I wanted them to be adaptable to different scenarios, sizes and kind of services.

In the case of internal finishings, in my opinion the flexibility should be kept even higher because the influence of the latter on the final choice of the client is enormous. Many customers do not even realize how many layers a building can hide, they might just judge it based on the visible one. For this reason, along with the low amount of technical requirement of the finish panels, I decide to keep the house of quality empty so that each customer (even yourself if you're curious of the outcome and patient enough) can fill it up himself and later assess the design alternatives by simply multiplying each weight to the related objective score that I provided to fill up in the following page. In the end each one can have the final score and best choice most suitable for him/her: one could like visible bolts, this will result in less weight for aesthetic related criteria and consequent lower score for smooth and neat connections and higher score for bolted connections.

The final finishings of a building are very personal and can vary in materials, colors, roughness, weight, joints and connections; the following pages show the objective score of each solution. As a result, the final outcome is a library of possibilities rather than a final design choice. This will be then followed by my personal preference in form of a design proposal.



7.3.1 SUB-SOLUTIONS: MATERIALS

BETONPLEX_ Betonplex is a chipboard panel with a water and moisture resistant layer applied on both sides. The strong cement based external layer increase the weight of the panels and create difficulties during the CNC process since bits are more vulnerable and get easily damaged

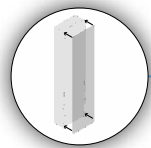
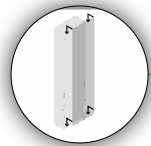
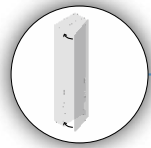
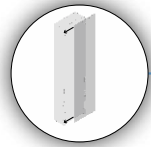
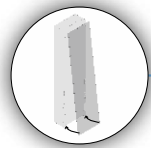
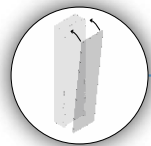
ALUBOND_ is an aluminum composite which had proven to work very well within the context of FabField: the exterior facade panels of the PD Lab are made of alubond. The material is extremely light and allows for engravings that enable to fold the panels into three dimensional systems without the need of further connections. Nevertheless the end of life of the material scores poorly, not to mention the “cold” surface of the material which might not be desirable in interior environments.

MDF_ medium density fiberboard with smooth coating layers is available and often used for interior paneling and furniture. The material is sustainable and widely used for interior purposes. Structural resistance for large sizes is achieved with large thicknesses, which would take away valuable interior floor area and dramatically increase the weight of the panels.

PLYWOOD_ Plywood is a sheet material manufactured from thin layers or “plies” of wood veneer that are glued together with adjacent layers having their wood grain rotated up to 90 degrees to one another. Plywood products with a water proof, smooth finish on both sides are available and widely used for interior purposes. It comes from the same family as MDF (processed wooden boards), nevertheless the same structural strength is achieved with much thinner and lighter sections.

SANDWICH PANEL_ Sandwich panels are very strong elements that achieve their strength thanks to the geometry of the interior layer; the outer layers are only carrying out the function of aesthetic layers. Nonetheless, the strength of the system is only achieved with large thicknesses which can be a problem for the CNC milling process that only allows panels up to a certain thickness.

OSB_ also known as flakeboard, is a type of engineered lumber similar to particle board, formed by adding adhesives and then compressing layers of wood strands (flakes) in specific orientations. All building components are made of OSB, which facilitates the production process thanks to the knowledge gathered through experience. It is sustainable and the cheapest of all wood-based products, which means it also performs poorly in some aspects, specially swelling to humidity



STRUCTURAL SOUNDNESS



SPEED

RISK OF ERRORS

AESTHETIC VULNERABILITY

TOLERANCE

ERGONOMICS

POSSIBLE CLASEHS

ADAPTABILITY TO APPLIANCES

ACCESSIBILITY

AESTHETICS

DISASSEMBLY

3

3

3

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4

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7.3.2 SUB-SOLUTIONS: ASSEMBLY

BOTTOM HINGE_ The bottom hinge allows for an ergonomic method of fixing a panel since a single person can fix the panel at the bottom while the panel itself is resting on the ground. The panel can then be simply pushed into place. An issue related to safety is that if the top part is not fixed properly the panel can rotate and fall down.

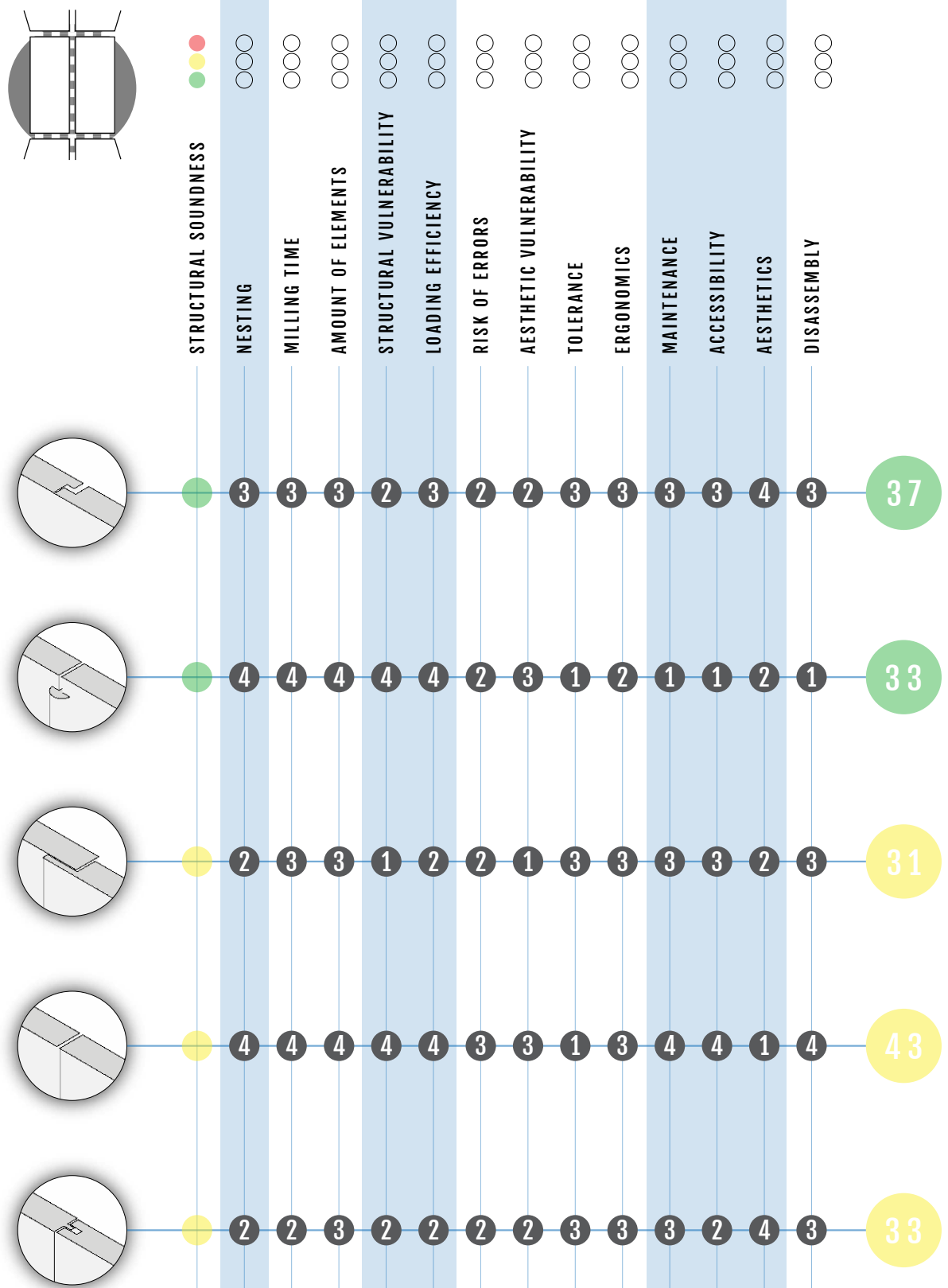
TOP HINGE_ This method resembles the one described above with the main difference being the increased difficulty in assembly since the panel can no longer be hinged at the top while resting on the ground. An additional person might be required during installation. Nevertheless, this approach might be safer: once the hinge is fixed the panel cannot rotate if the bottom part is not fixed yet.

SLIDING_ The concept of sliding the panels into a railing system has multiple benefits. The installation of the panels can be easily carried out by one person since the railing system would ideally be assembled separately. Nevertheless, the main disadvantage is that this approach requires a sequential assembly of the panels in which the last panel to be mounted is strictly affected by the architectural boundaries that it might encounter such as partition or external walls.

SIDE HINGE_ This approach is especially beneficial in terms of ergonomics and easy maintenance since the system can be imagined as a door hinged on one side. The disadvantage of this approach is that fixing the hinges on one side while the other one is still free to move might be difficult to do; also the vertical joints of the panels need to be carefully designed since they need to allow some tolerance for the rotation of the panel.

HUNG_ It is a common procedure for facade panels to be simply hung, which means that no external fasteners are required, gravity and friction would provide for the panel to be fixed in place. This method allows for a fast installation but creates some difficulties in the design of the panels as overlapping joints would probably be required.

FRONT ASSEMBLY_ Front assembly is extremely beneficial in terms of time spent on site: the panels can easily be installed without a specific sequence, allowing to assemble more than one section at the same time. The front assembly does not require complex details nor a complex production process of the panels, which nevertheless cannot be folded or overlapped, leaving the connections visible. Another problem is related to the assembly which might be difficult to carry out by a single person



7.3.3 SUB-SOLUTIONS: JOINTS

FOLDED OVERLAP_ This type of joint is often used in wall paneling and it allows to keep large tolerances with a smooth, almost seamless joint. The main defect of this option is that it does not allow every panel to be disassembled individually: the sequence of assembly must be respected during disassembly too. It also might get easily damaged during transportation or installment due to the thin sections of the overlap.

WET SEAL_ Silicon or any other kind of wet seal can save design and production time since the design of the panels can be simpler. Furthermore, tolerances and inaccuracies between panels can be easily disguised with the wet seal method. Nevertheless, maintenance and disassembly are basically impossible without destructive processes that might damage the panel itself. This produces a negative impact of the sustainability of the overall system as well.

OVERLAP_ Simple yet effective solution to increase design flexibility by maintaining a dry connection. Disassembly and reuse of the panels are positively affected with this method, which on the other hand does not perform well in terms of aesthetics since joints are always quite evident from the outside. Furthermore, the thin section at the edge of the panels is very fragile yet the most visible part once the panel is fixed into place, which leads to flaws in the finished product.

BUTT JOINT_ Panels produced with butt joints are fast to produce and hard to damage due to the lack of thin sections that are present in overlaps and other concealing systems. Transportation and stacking of panels are also positively affected with this method, which also gives a lot of design freedom. External, visible fixings are required and joints very evident, which impacts the aesthetic quality of the finishing. Assembly time depends on the method selected for fixing the panels but is most definitely longer and more convoluted than other more complex solutions.

MORTISE AND TENON_ Mortise and tenon is a technique often used for wooden joints. It allows for seamless results with a simple, dry technique. The main weakness is that the protrusion of the male panel is a weak spot during assembly and transportation as well as the fact that the panels cannot be individually taken away without respecting the sequence of assembly.

7.3.4 SUB-SOLUTIONS: CONNECTION TYPES

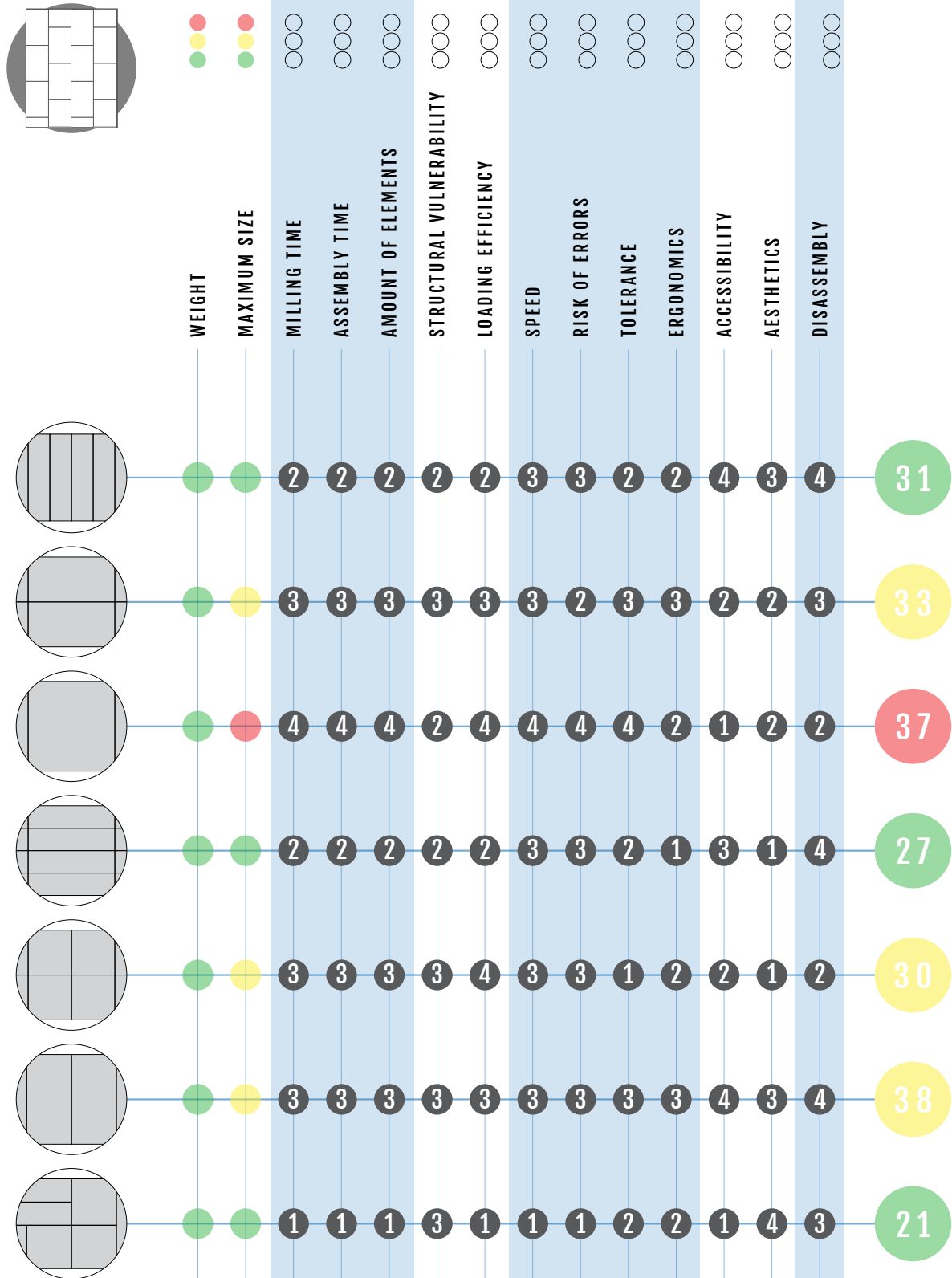
SCREWS_ The solution of using mechanical fasteners such as screws or bolts for fixing the finish panels gives a lot of flexibility to the system and allows for adjustments that wouldn't be possible with more integrated solutions. Nonetheless this solution is not integrated in the digital fabrication method at all and it follows the same principles from the traditional building industry that FabField is striving to get rid of with its renewed approach.

SNAP FIT_ Clicked connections need a male and female part in order to work; they do not allow great tolerances but on the other hand they allow the installation to be as easy as it gets. Disassembly might be hard to achieve without damaging the connection. The female connector needs always to be flexible yet elastic for the connection to work

HANGER_ Hanging connections are the simplest way to create hinges in fixing systems. There are tons of hanging connections but the principle is always the same: they are very easy to put in place and disassemble. In fact they are the highest scoring solution in the chart and score very high on almost every criteria. Nevertheless, the comfort provided by this solution is not high since the panels would be allowed for vertical movements, reason why this solution is not enough by itself for a comfortable, fixed system and should be integrated with another type of connection for the best system.

DOWELS_ are round wooden pieces that are very often used in furniture for seamless connections between elements. They are most definitely the best solution in terms of environmental impact and end of life activity, they are also perfectly integrable with digital fabrication techniques as the slots would be quickly provided by a cut through with the proper bit. On the other hand they are not easy to disassemble which also compromises the accessibility of the services' cavity; they also unfortunately allow for very small tolerances.

CONCEALED_ there are currently many solutions that allow to hide mechanical fasteners within the thickness of the panels and they are all based on a male and a female which can be connected either by clicking them or turning a hidden screw in the hidden side of the panel. They provide great structural stability, ease of disassembly and also a high quality aesthetic finish. Their disadvantages comprise the high costs and environmental impact of the plastic/metallic fasteners themselves. On the other hand, the panel can be reused as many times as desired and the connection shouldn't be subject to wear or damages over time.



7.3.5 SUB-SOLUTIONS: PANEL CONFIGURATIONS

PARALLEL, NARROW_ A mostly vertical pattern with slender panels covering one wall component in width and height and two floor components in width (length may vary). Easy assembly and disassembly is given by the small size of the panels which, on the other hand, create a lot of visible vertical joints and consequent lower tolerances. The large number of panels also negatively influences the milling time.

PERPENDICULAR, WIDE_ Large panels covering half the walls' height and 4 wall elements in width, creating both vertical and horizontal joints. The size is still manageable by the CNC milling machine and workers, accessibility and maintenance are high but tolerances and risks of errors are easy to make because of the large amount of seams.

PERPENDICULAR, NARROW_ Slender panels covering one quarter of the walls' height and 4 wall elements in width, creating both vertical and horizontal joints. This is subjectively not an aesthetically pleasant solution and the main configuration following the components in a transversal direction would cause the connection to require higher tolerances. The small size of the panels makes them easy to carry and increase accessibility and maintenance of the services within the cavity but the connection to the components would not be possible to carry out by a single person.

SQUARED_ Squared panels spanning half of the wall's height and two wall components in width. The square pattern is personally considered aesthetically unpleasant, on the other hand it allows easy assembly/disassembly as well as maintenance and the best loading efficiency during transportation.

PARALLEL, WIDE _ A mostly vertical pattern with panels covering two wall component in width and one in height and four floor components in width (length may vary). The joints created are only vertical, the size is still manageable by the CNC milling machine (2400x1200mm) and assembly/disassembly is made easy by the parallel to component configuration. Integration of appliances larger up to 1200mm wide in the finish panels is also made easy by this solution.

MIXED PATTERN_ The lowest scoring solution on the chart since it increases both production time and assembly. It also creates big problems in transportation for its low loading efficiency. It is objectively a very bad solution but it allows the customer to create his/her own personal pattern in the interior; reason why the aesthetic score is the highest on the list.

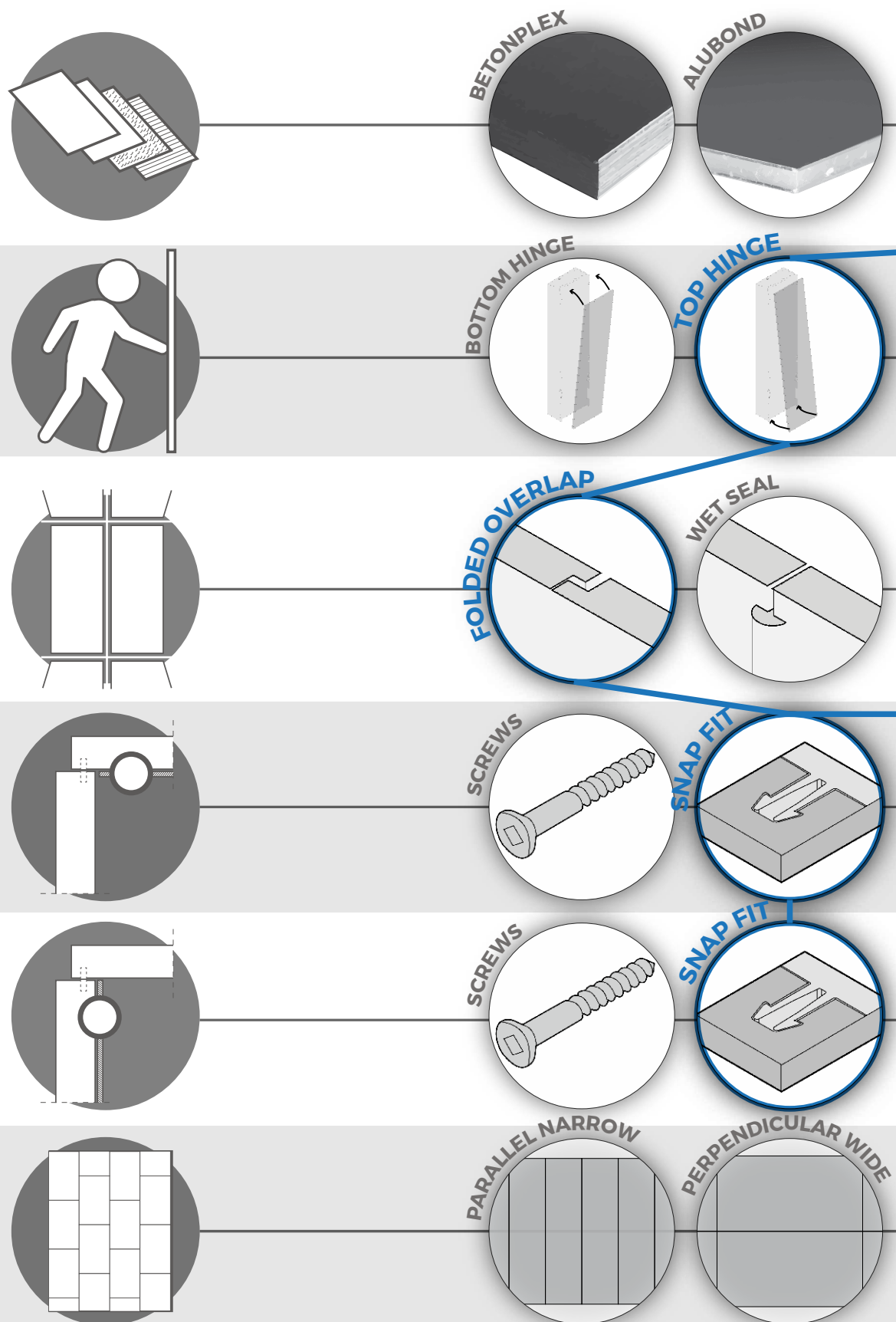
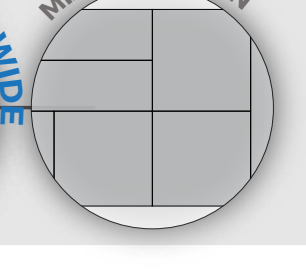
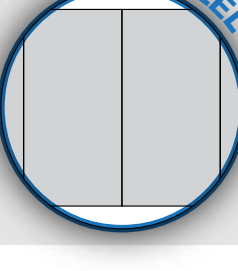
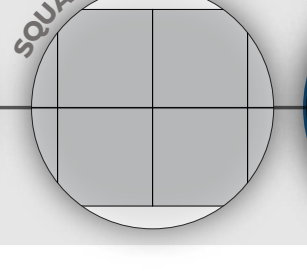
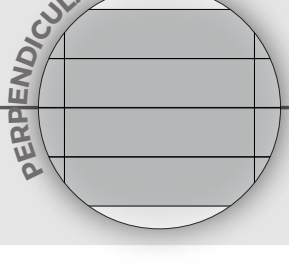
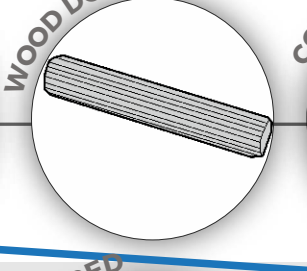
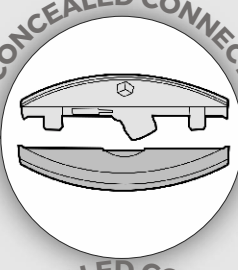
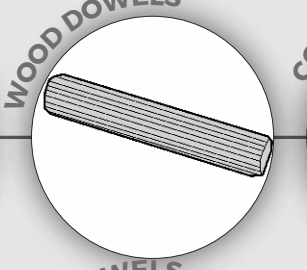
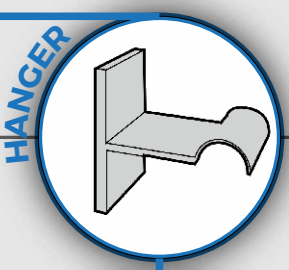
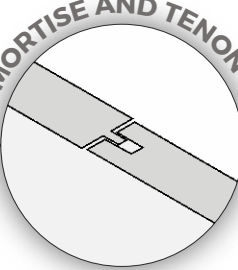
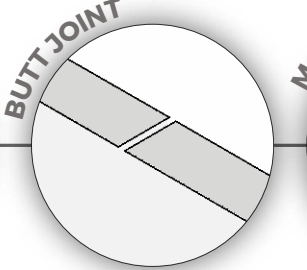
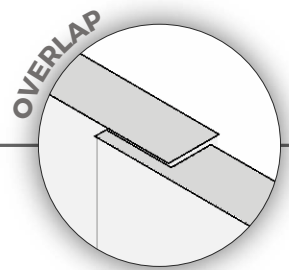
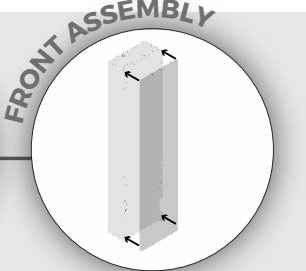
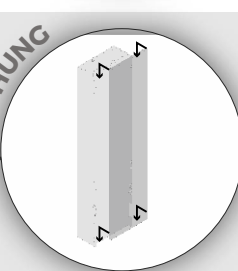
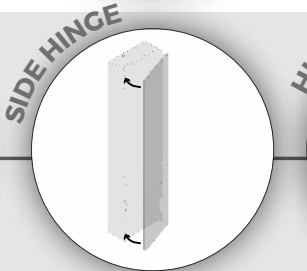
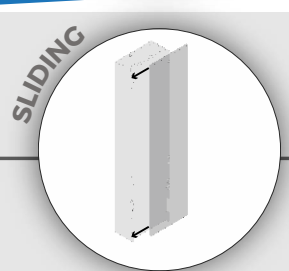
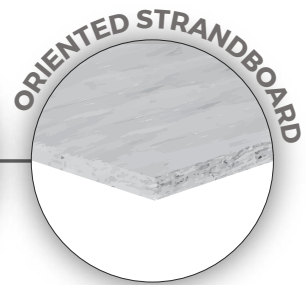
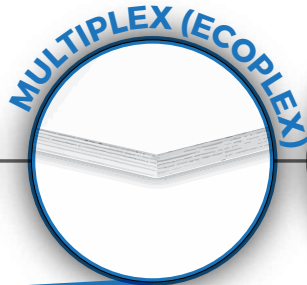


Fig.7.3 The methodology with weightless criteria gives objective scores that is meant to give indications on advantages and disadvantages of each alternative; nevertheless, a design proposal is selected for the final design (own illustration).



CONCLUSIONS

The finishings of a building are definitely a delicate part: their texture, joints and stability are actually what the customer will be in contact with and probably what influences the most his opinion along with the exterior looks of it. The methodology was used to give objective grades to the sub solutions without giving a final design solution, preferring to create an open library of different possibilities that could all be tested in order to accommodate the diverse requirements of the market. The reduced time spent on the creation of the library leaves it open to future introductions of other alternatives for each design sub solution.

The desire to enable customers to integrate all final appliances in the finishing panels has advantages and disadvantages. The advantages comprise the reduction of material wastes that are usually created during the installation of final appliances, less time spent on site for it, a smoother internal finish and a more integrated design process that necessarily requires to consider in advance the final details of the internal arrangement, comprising the exact position of flush boxes in the wall. On the other hand, future modifications in the internal arrangement of the house can lead to problems since the same panel can only be used in one spot if it integrates one or more final appliance. Furthermore, dry panels in housing functions, without any wet finish, can make simple actions like fixing a nail to hang a frame an issue for aesthetics. The possibility to finish the dry panels with detachable stripes of wall paper remains open to promote flexibility in internal arrangements. Nonetheless, the integration of appliances in the finishings is an interesting topic to explore, especially to test to what extent the integrated design can be pushed; nevertheless, the client still has the choice to adopt the traditional approach for the finishings, without any integration of final appliances.

To conclude, the design of finishings is the most experimental part of this graduation, yet the one to which the least time was dedicated. It definitely requires further research in the future to enlarge the library of possibilities and explore the advantages and disadvantages of each design solution.

APPLICATION

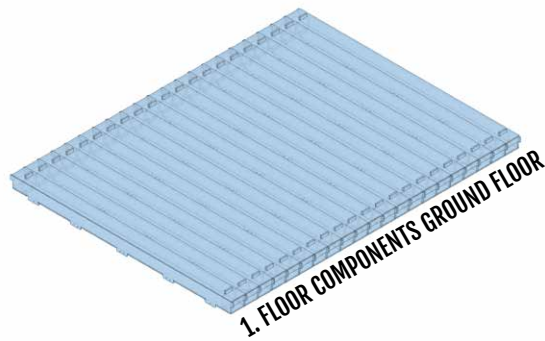
The last chapter is meant to show how the distribution design, components design and finishings design come together in a case study. The case study is based on the internal arrangement of one of the reference projects previously analyzed: Koda by Kudasema. The reason for this choice are mainly for the resemblance of the building in terms of size but also the strive for flexibility that Koda shows as well: the images on the side are renderings from the website of Kudasema, showing how the internal arrangement of the building can accommodate multiple functions at once.

In the following pages the same internal arrangement is shown in the FabField, starting from the assembly of the building components, followed by the services' sources, distribution and appliances, finishing layers and finally furniture. The sequence of assembly is then followed by the explanation of special components and some examples of integration of final appliances in the system. It was deemed fundamental for the final validation of all design stages to apply the latter in a real case study; the 3 subquestions have been answered separately in dedicated chapters, the main research question: *"How can building services be integrated in the FabField building system in such a way that the core values (digital fabrication, low-costs, high accuracy, light weight components, demountability; end of life strategies and short construction times) are perpetuated?"* is answered in this final chapter.

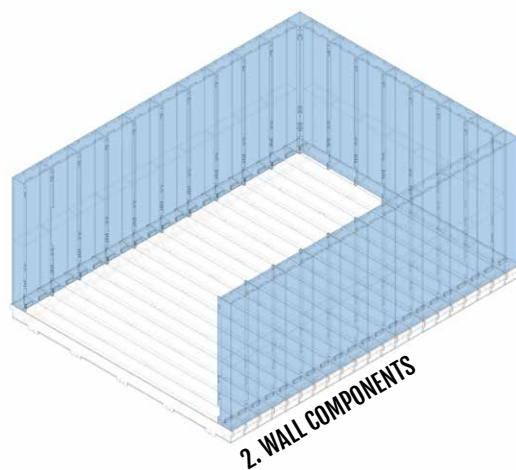
The finishing panels' assembly is based on the proposal of sub-solutions shown in the scheme from the previous page. It is important to point out that all other combinations are left open and this is not meant in any way to be a strict design choice.



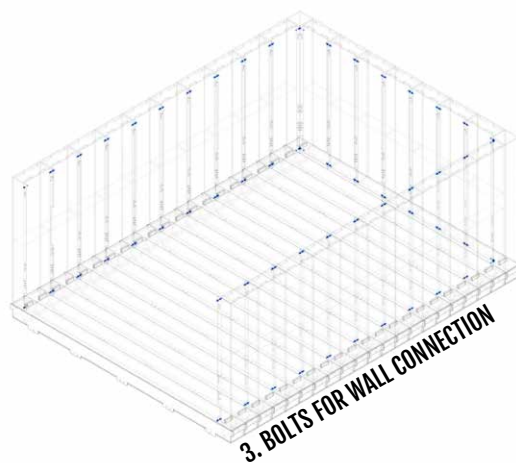
Fig.8.1 The images all show the same internal arrangement for different functions in Koda by Kudasema (www.kudasema.com).



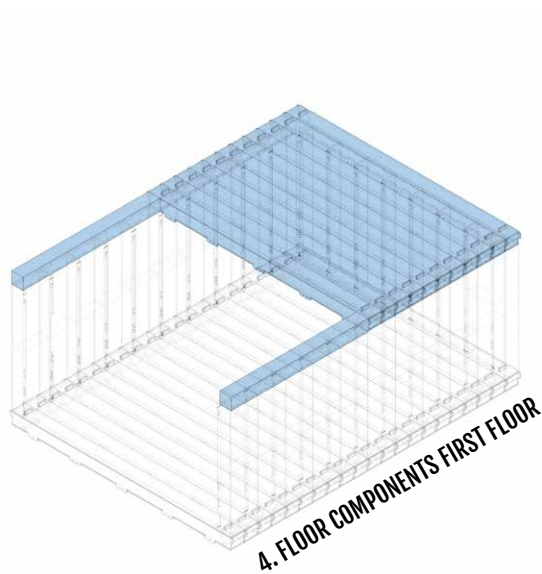
The first phase of the construction sequence consists in the arrival of the components on site; it is taken for granted that the base for the building (foundation or elevated scaffolding) has already been placed and the floor components can be correctly placed. The only connection between neighboring floor components is the 1200mm long transversal beam component joining 4 components. Thesis from Gunawan K. (2017) has concluded that also butterfly connections joining floor components are necessary. Each beam is carried by two people and accommodated on the beam components until the ground floor is completed.



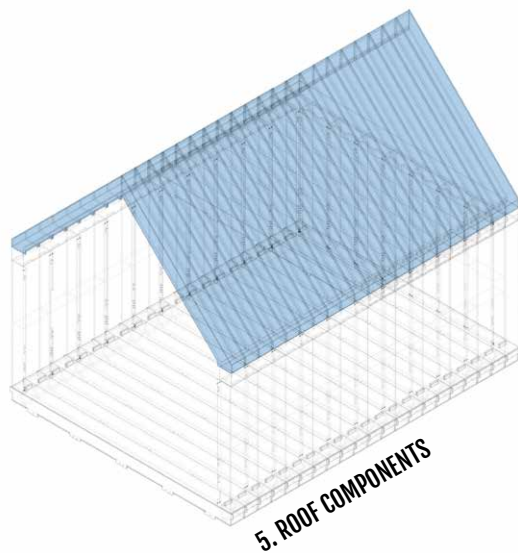
The wall components can now be brought on the required location and connected to the floor and beam components. The connection consists of allocating the protruding elements of floor and beam inside the wall components through a basic male-female straight connection. Each wall connects 2 neighboring floors, 2 walls are connected to a single beam component. Once again the assembly is supposed to be easily carried out by two people; nevertheless, the nature of the connection and the tendency of OSB to swell when humidity rises might create some difficulties at this point: some hammering might be required.



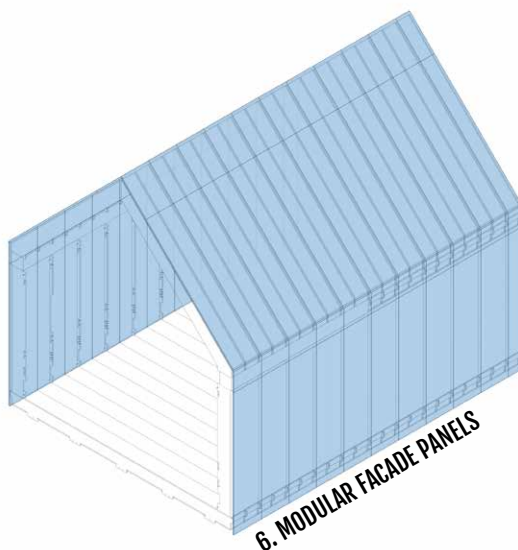
Thesis from Gunawan K. (2017) also concluded that there is a necessity for neighboring wall components to be connected by 2 Mio bolts at the top and the bottom of the component's flanges. The design conclusion from his thesis was inspiring for the final design of wall components: considering the structural requirement of protruding elements for the bolted connection, the idea of continuous flanges doesn't increase the fragility of the components, on the contrary it strengthens it. The design proposal is to replace the bolt components with longer threads having the same structural function but protruding 3-4cm on each side of the flange; this protrusion is used for the connection of the wall finish panels.



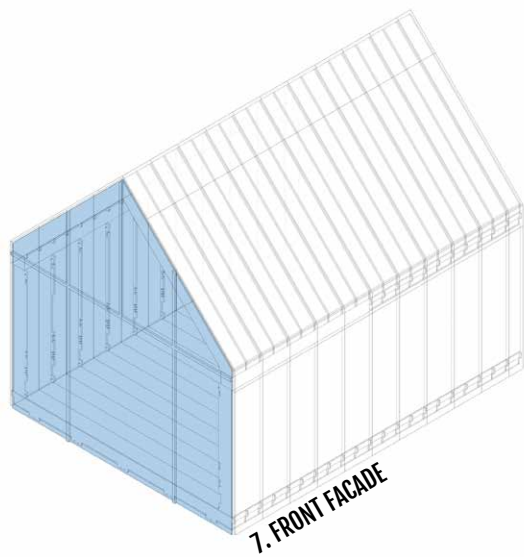
The first floor of the building is only partially covered by floor components; this because the reference building does so, but also because the original PD Lab built in the west entrance of BK proved that this is possible, letting higher ceiling heights with a subsequent increase of natural lighting. The first floor is used as bedroom of the living unit. Before the floor components can be placed the first level of beam components need to be inserted in the notches of the walls, creating once again the base on which the floor components will rest upon.



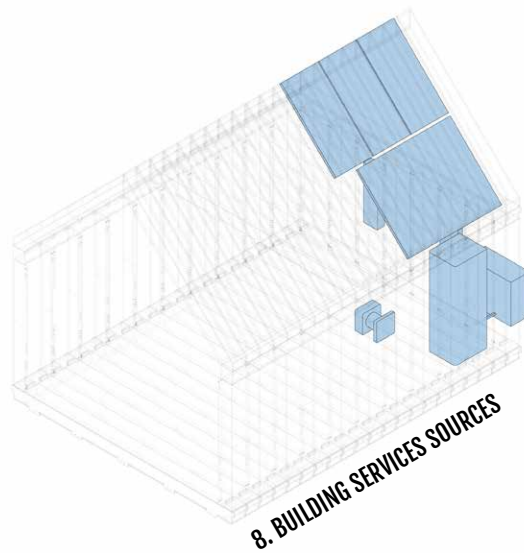
The roof components can now be put in place to complete the structure of the building. The dimension of the latter depends on the width of the design as well as the chosen slope for the roof: 30° , 45° and 60° are the possible slopes to choose from. Each roof components is connected to one beam and floor element, its width is in fact 300mm just like floor components. The assembly needs to proceed in a way that mirroring roof components need to be placed at the same time and connected at their tip so as to support each other at the top connection of the building. It is assumed that they also require a bolted connection just like walls.



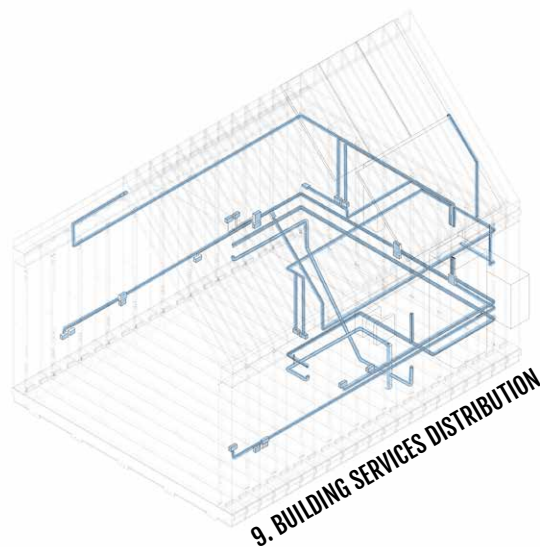
Once the structure of the building is completed the facade panels designed by van Veen J. (2016) can gradually clad two sides of the building; the system is only designed for the sloped sides, whereas the other two are clad in a different way. The assembly of the facade begins with screwing small brackets on the required locations on walls and roof elements; the brackets support the panels which are all 600mm wide and vary in height. The wall panel covers the whole wall length, the gutter panel upon it covers the beam length, the roof panel spans up until $3/4$ of the roof and finally the top panel covers the top of both sides of the slope so as to create a continuous, seamless ridge.



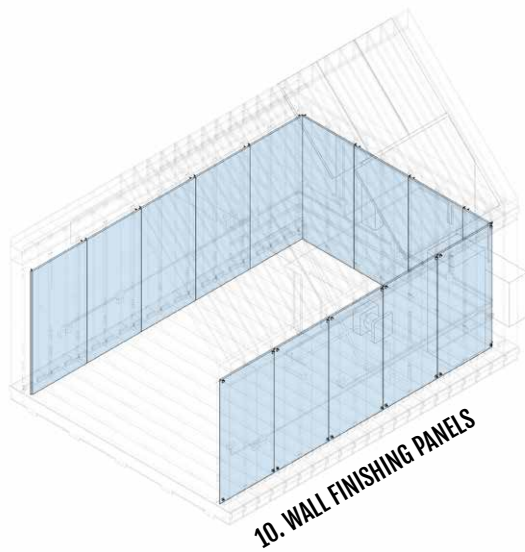
The design of the front and back facades can vary and has not been studied by van Veen. In the case of the PD Lab the back side is clad by a textile opaque facade whereas the entrance side is finished by a specially designed frame housing 7 glass frames. The reference building also has the same conditions, reason why also in this case study the same back and front facades of the PD Lab are adopted.



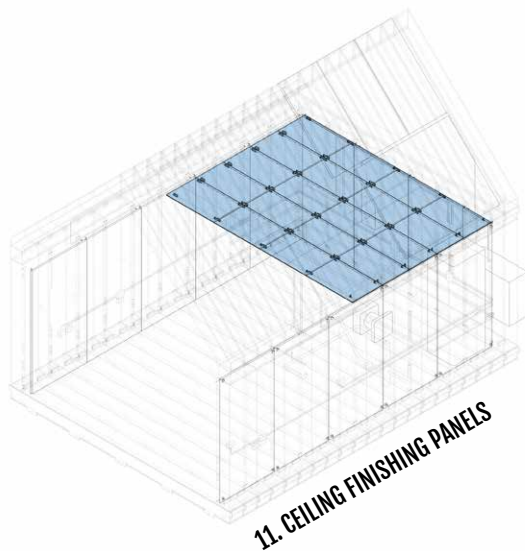
It is just deemed convenient in this example to consider that all services' "sources" are installed in this phase even though this is obviously not the case in reality. The building is supplied by water and electricity from the grid but also hosts a small PV array and a solar thermal panel on the roof. The technical room is placed in a corner of the building and accommodates the electric cabinet as well as a water boiler heated up by an air heat pump placed just outside the building. Ventilation in the case study is provided by two localized ventilation units, one for the bathroom and the other one for the rest of the house.



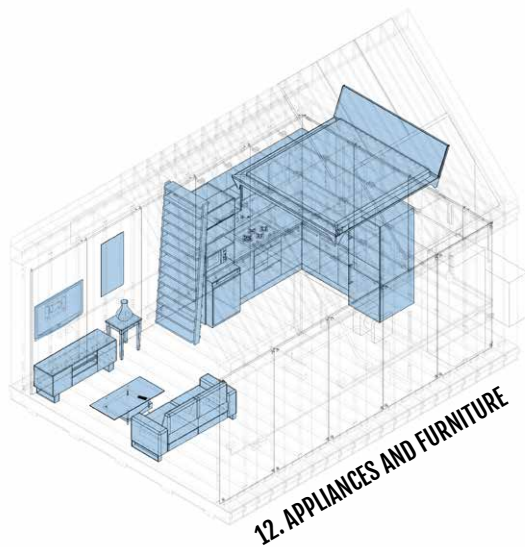
The distribution of building services snakes through the house from the technical room, where the electrical cabinet, main water inlet and boiler are. In this scenario no centralized ventilation system was used, therefore the two ventilating units are simply connected to electric sockets. Electricity is also supplied at the first floor, where the bedroom is, exploiting elements of furniture that cover the unusable spaces of the roof space. Heating is provided by wall heating elements that will later be shown in detail as well as the integration of other functions within the wall finishing layer.



After the distribution of services has been completely laid out the finishing panels can be gradually placed starting from the wall panels. The size of the panels is 1200x2400mm and the material taken into account in the case study is ecoplex 12mm thick. The panels can be simply hanged from the top thread connecting wall elements and later clicked through a snap-fit connection into the lower thread



Once the wall panels are placed it is time to finish the ceiling by covering the bottom part of floor and roof components. The connection works again the same way as the one for wall panels but instead of bolts simple 60mm wood dowels are inserted in slots in the protruding elements of the components. These dowels give a stable yet flexible support for the panels which are connected through a simple hanging connection at first and later fixed to the dowel through a snap-fit connection. The overlapping joint between neighboring panels prevent the latter to fall even if the snap-fit connection ever failed.



Floor finish has not been considered since the possibilities need to stay wide open. Moreover, no services are expected to flow in the floor thickness, which leaves the final decision on the floor design to the client. The building can now be furnished and the final services' appliances can be placed. In the next pages there will be details showing the integration of flush boxes, TV, ventilation units and heating elements in the thickness of the wall.

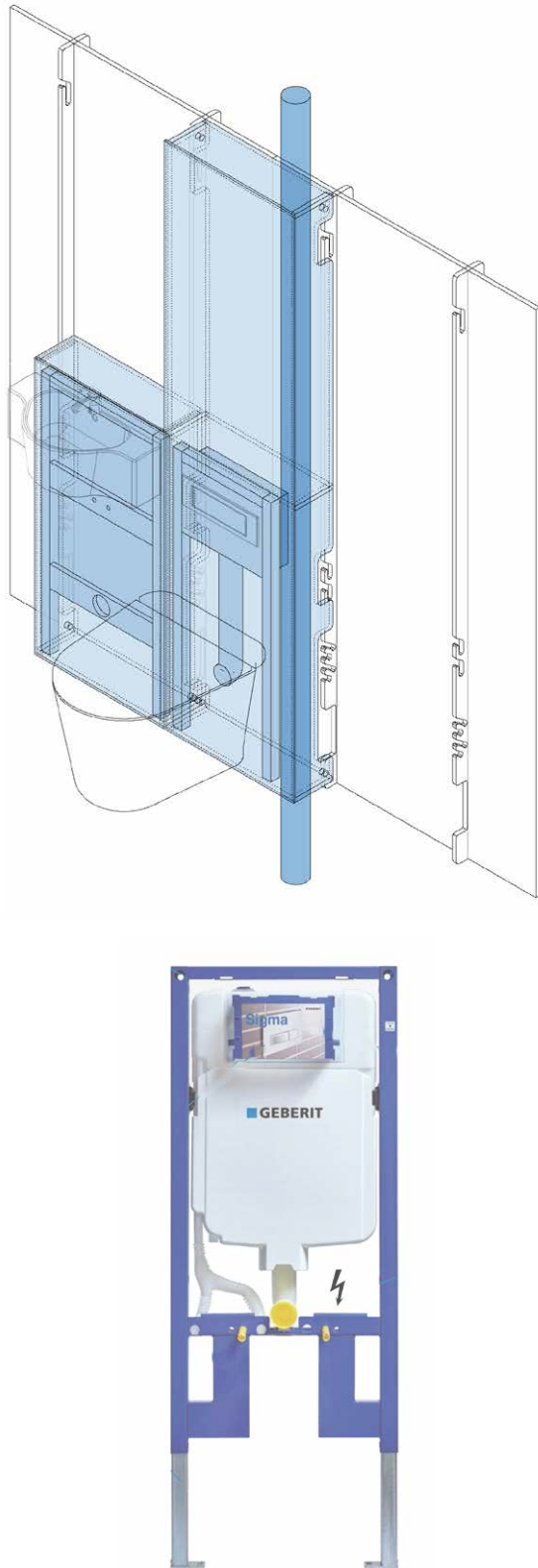


Fig.8.2 *The component that accommodates the main water disposal also integrates the flushing system Geberit Sigma for the toilet (www.geberit.com).*

8.1 MAIN WATER DISPOSAL COMPONENT

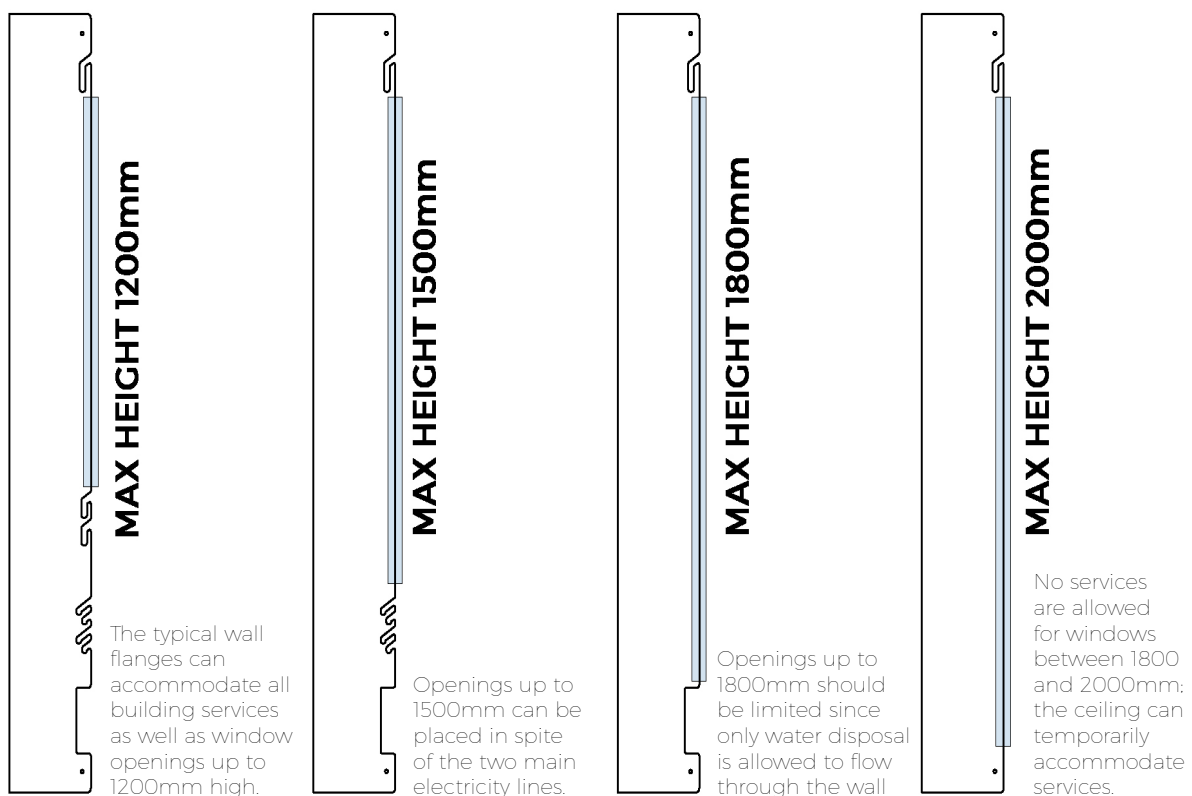
As already mentioned previously, the spatial requirements for the main water disposal pipe are not comparable to those of any other building service in small houses. First of all the direction of it needs to be vertical and snakes throughout the building, requiring an exhaust on the roof and a connection beneath the house to the water main. The thickness of the water disposal pipe cannot be less than 100mm and it is usually placed in bathrooms since also the toilet disposal demands the same thickness. The decision to integrate the water disposal in a special component was made to save space and increase flexibility of the system: the special component can in fact be attached to the flanges of the wall components or those of the partitions, without disrupting the flow of the other services thanks to the openings on the side elements. The flexibility of the component is given by the fact that it does not carry any structural function, it can be considered a special finish panel for the integration of the main disposal pipe. Furthermore, since it is better for the toilet to be as close as possible to the main disposal pipe, the component integrates also the flush for the latter: the example of its application is shown on the image: the product taken into account for this application is the Geberit sigma 8 system for dry wall systems. Thanks to its compact size (450mm) this can be integrated in a component 600mm wide, allowing at the same time the water disposal pipe (100mm) to fit as well.

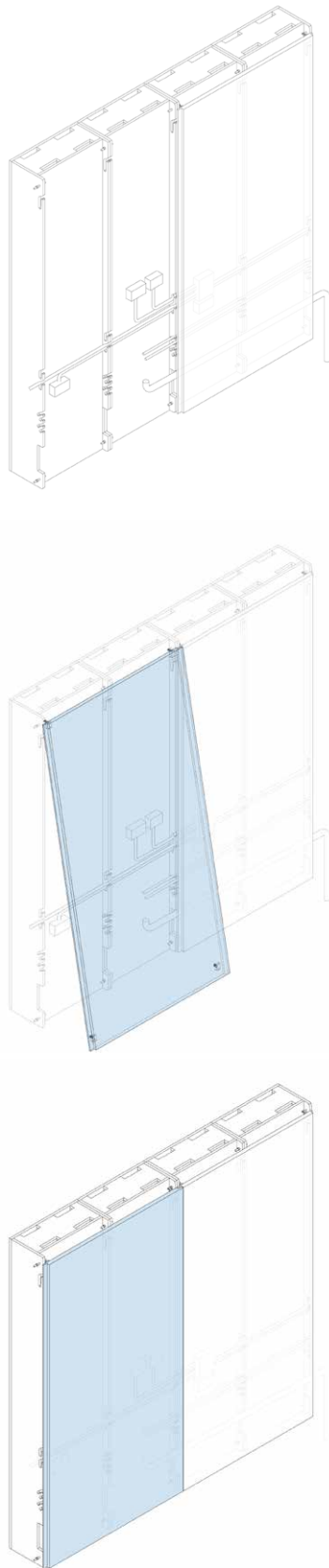
The suggestion for a further development of the product is that the water pipe should be tightly fixed to avoid vibrations during flushing; also a layer of sound insulation might be advisable if not yet integrated in the pipe itself.

8.2 WALL COMPONENTS FOR LARGE OPENINGS

The new design for the wall components was carried out in such a way that window openings could be allowed at any time without disrupting the flow of building services. The optimal size of window that can always be allowed in the wall components is 1200mm; this should not be a fixed limitation of the system, the possibility of having larger openings has been considered too. Nevertheless, bigger openings have consequences on the services since the flanges cannot accommodate services anymore after a certain window size. The image shows the variation of wall flanges to accommodate bigger windows: on the left we can see the current flange that allows 1200mm high windows and can accommodate water disposal, supply and 3 power lines. Next to that, the first variation is a wall component that allows for windows up to 1500mm high, although the two main power lines cannot be accommodated anymore; nevertheless, the upper power line can temporarily host all electricity tubes until right after the window. Bigger openings (1800mm and 2000mm) can be applied but only when services do not need to flow after it.

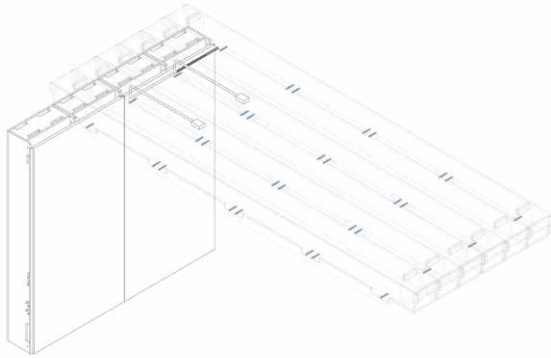
This is one of the main drawbacks of the distribution system: doors and big windows bring major limitations to the free flow of services on walls, therefore their application should be limited to the strict necessary. Nevertheless, the free flow allowed on ceilings can accommodate services when big openings are applied.





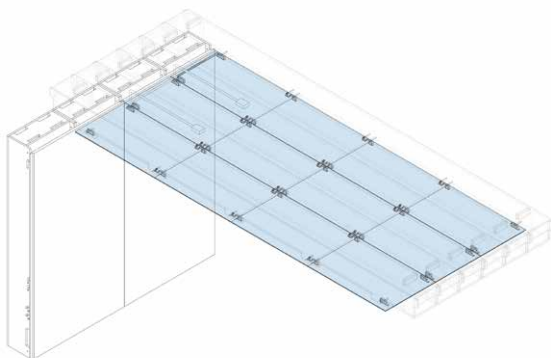
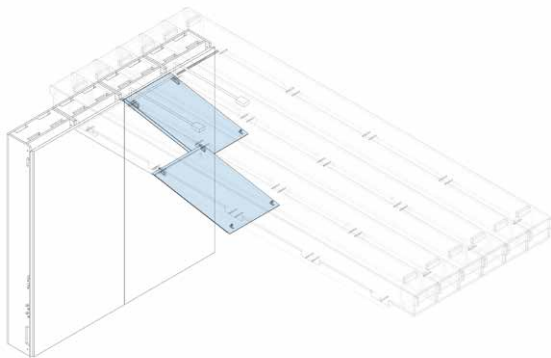
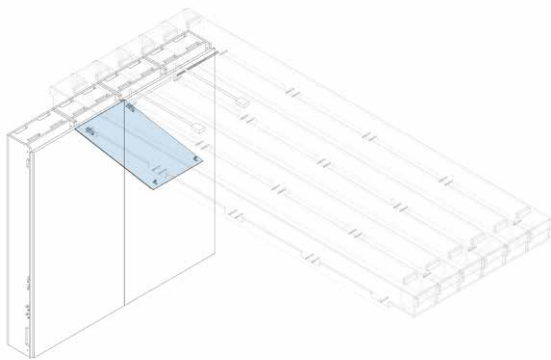
8.3 WALL FINISH PANELS

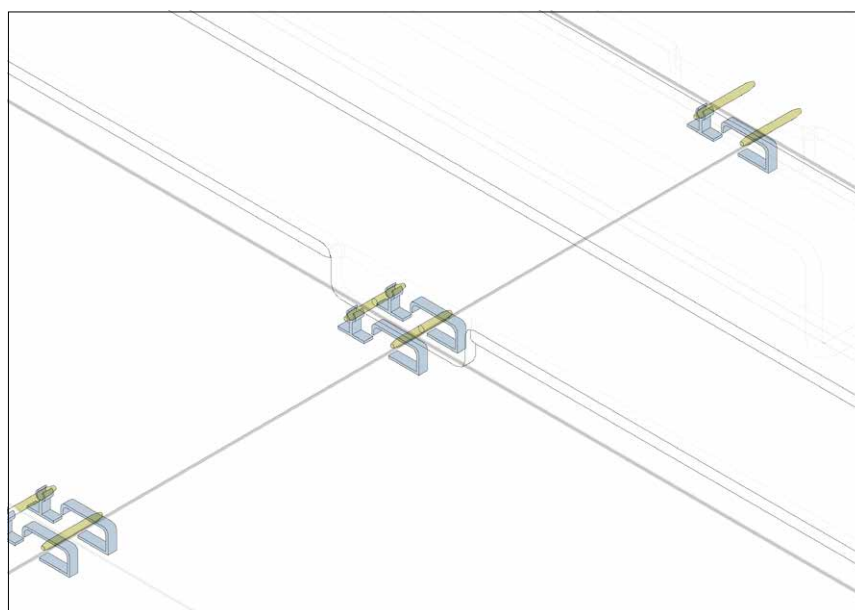
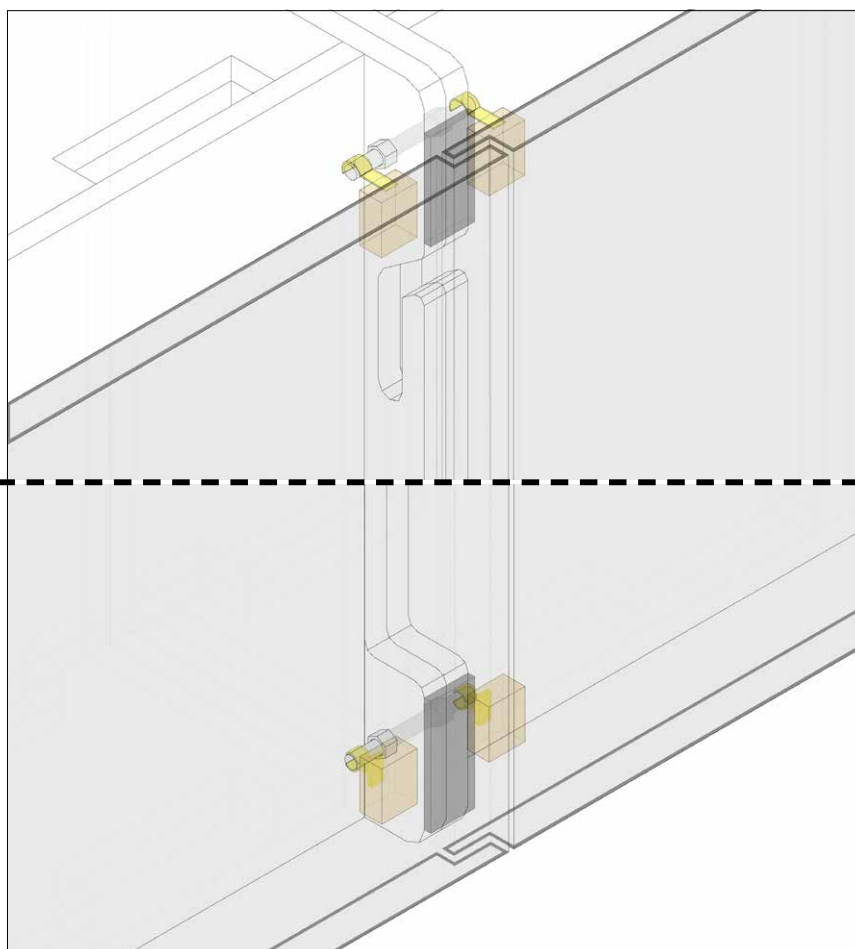
The design proposal for the wall finish panels makes use of a hanging connection on top acting as a hinge and a snap fit connection at the bottom acting as a fixed connection. The material used for the panels is a 15mm thick Ecoplex board which is just multiplex with a finishing layer of white, smooth waterproof layer. The panel is processed in the CNC milling machine which processes the folded overlapping joints between two panels for an almost seamless joint between elements. The bit also engraves the exact position on which the connections should be later attached in the assembly of the panel, still carried out in the factory. The bit might also operate other openings for integrations such as electric flush boxes, ventilation units, heating elements and so on (the library of integrations is limitless and up to the designer to define and enlarge). The size of each wall panel is 1200x2400mm, covering the whole height of a wall and the width of two walls. The installation of the panels is easy and might be carried out by one person thanks to the light weight of the element. The sequence on the left shows how a panel is fixed in place: first the distribution services are placed, secondly the panel is connected to the bolt thread connecting two wall components, lastly the wall is pushed to fit in the snap fit connection at the bottom which is again constituted of the bolt thread connecting two neighboring wall components. The folded overlapping joints allow for the disassembly of single panels in half of the cases when required, in the other half of the cases if the panel to be disassembled is a negative, then the two neighboring elements should be taken off too in order for the latter to be too. Images on the right show the detail of the top and bottom connection as well as the joints between panels.

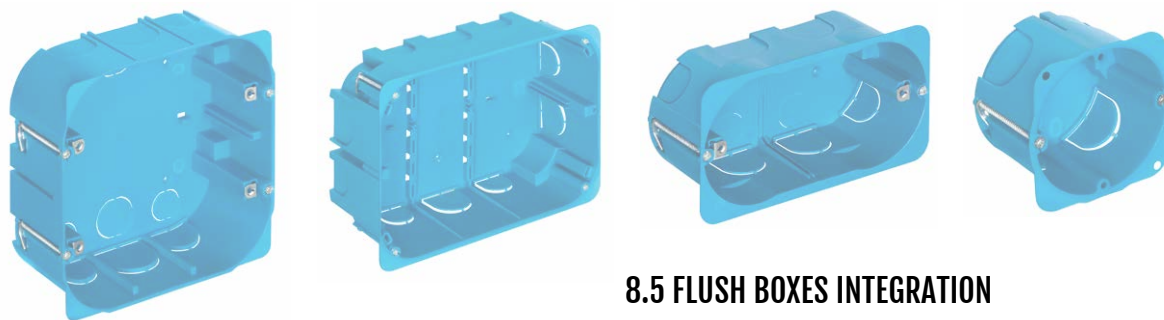


8.4 CEILING FINISH PANELS

The ceiling panels are also made of 15mm thin ecoplex boards with a water proof smooth finish on the visible side. The production of the panel is similar to the one for the wall: the panels are CNC processed to create the folded overlapping joints, the engravings for the connections to be fixed on and any other opening required for integrations such as lights, air vents or any other electrical appliance. Once again the overlapping joints allow for single panels to be taken off in some cases, in some others the neighboring elements should be taken off first in order to allow the internal joint to be released. The proposal for the connections is again based on a hanging connection that acts as a hinge on one side of the panel, the other side is simply pushed to fit in the snap fit connection of the other side. The protruding elements of the floor components are perforated during production so as to allow wooden dowels to be placed and acting as the support for the finish panels. If the snap fit connection ever failed, the joint between panels would prevent it from falling down. It is important to point out that for both wall and ceiling panels, some kind of spongy layer should be attached to the flanges of the components prior the installation of the finish panels; this is suggested in order to prevent any kind of vibration of the panels. The sequence on the left shows the sequence of installation of the panels; image on facing page show the detail of the connections of the panels to the wooden dowels of the floor components.







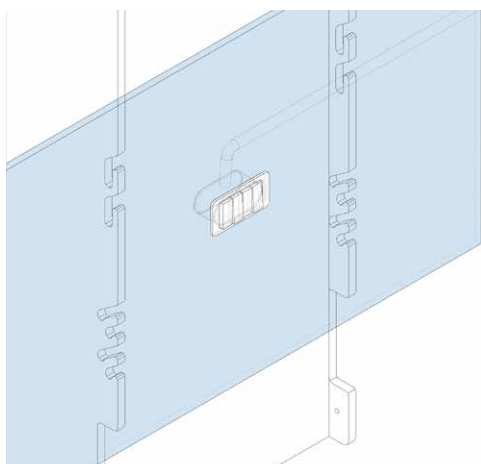
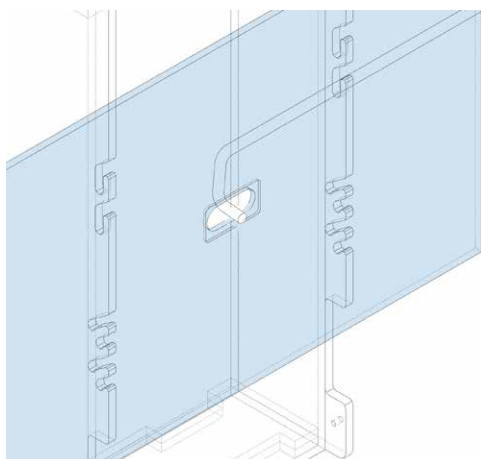
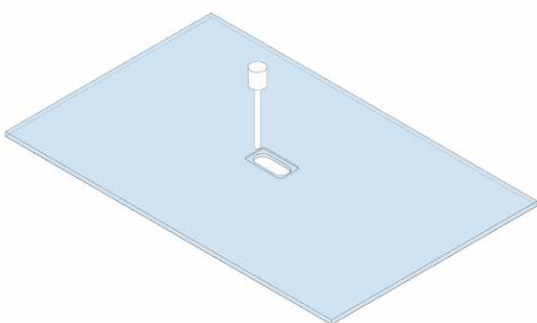
8.5 FLUSH BOXES INTEGRATION

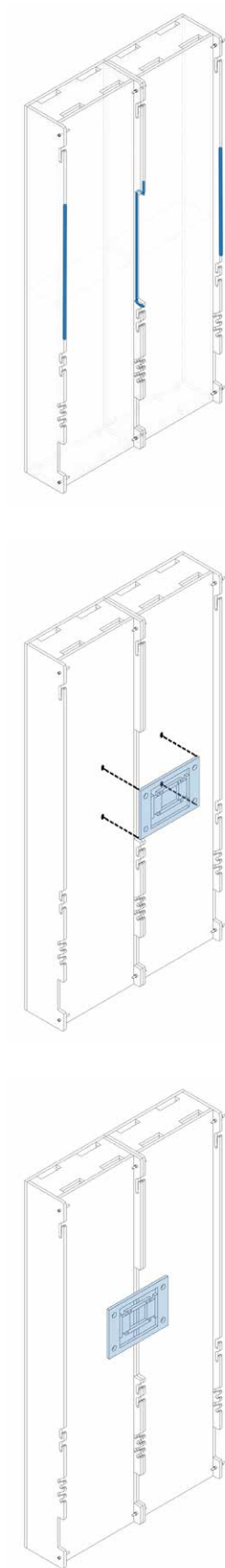
The integration of flush boxes in finish panels is very simple and straight forward and allows for a considerable reduction of time spent on site and an increase in the accuracy of the operation. Flush boxes are the final interface of most electrical appliances and their integration was fundamental in the contribution to a successful overall result. The ease of the operation is given by exploiting digital fabrication methods and it would never be possible without an extensive consideration of all building services' aspects in the early design phase.

The integration begins from the early production of the panel:

- The CNC bit operates a first cut through the elements for the flush box to be accommodated
- The bit now engraves the surroundings so that the sides of the flush boxes (shown on the images on the right) can easily fit within the thickness of the wall.
- The wall panel is placed and the hole provides the worker an opening to reach for the required cables, which he pulls out.
- The cable is accommodated in the flush box which is only at this point placed in the CNC milled predisposed slot.
- In the final operation the worker installs the frame with all the required plugs/switches.

The operation is much easier than the traditional one and the final result is already smoothly finished, whereas in traditional operations this would require further finishing. The method allows for all thicknesses up to 60mm to be installed; if a thicker flush box is required, the finish panel should be slightly thicker as well.





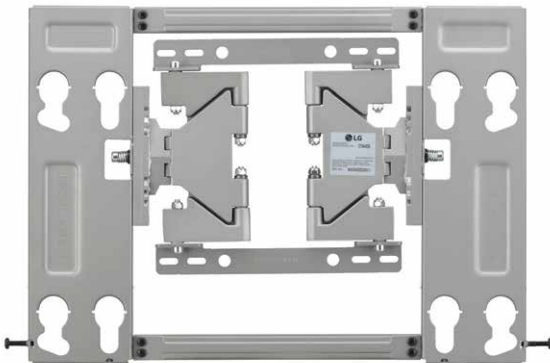
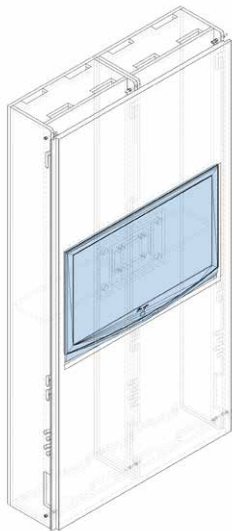
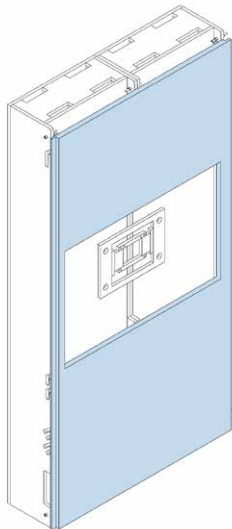
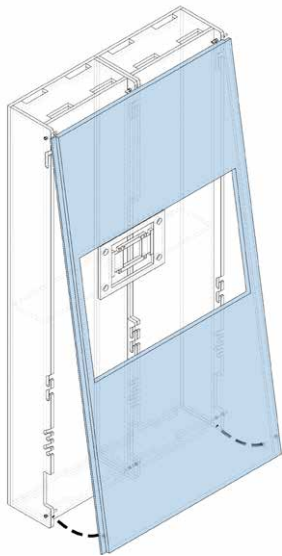
8.6 TV EMBEDDED IN FINISH PANELS

The possible integrations can also comprise everyday appliances such as a TV. The integration of such device has to be made according to the exact shape, size and specifications of the device itself; every TV has different thicknesses, whereas the size of the screens has been standardized and restricted to just a bunch of possibilities. In the case study displayed here the model of the TV is a 55" SJ810V from LG; the Dutch company also provides a flexible tilting bracket which is compatible with most LG TVs.

This here is the perfect example of how digital fabrication techniques along with a design phase that takes into account everything, from structure to services up until the final model of TV and its location, can really lead to a building in which every single element is perfectly integrated in the overall product. The sequence hereafter shown can be applied to any other kind of TV and bracket simply by tweaking some values and keeping the principle untouched.

- The two wall components accommodating the TV have two cuts in the flanges which are directly processed in the production of the components
- The bracket is fixed in the slot through simple screws
- The finish panel is placed
- The extendable bracket is pulled out to allow the TV installation
- The TV is installed in the bracket and can now be pushed within the thickness of the wall

The next step would be to provide for a finishing frame closing the gap to prevent dirt and dust to enter the cavity.

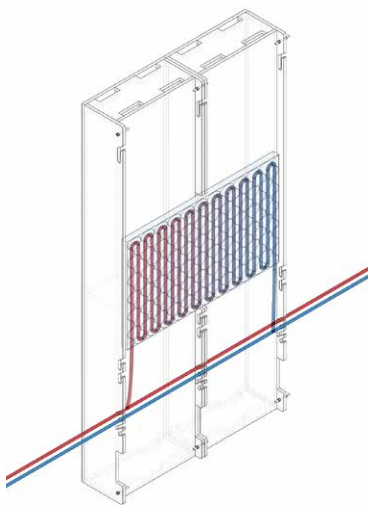
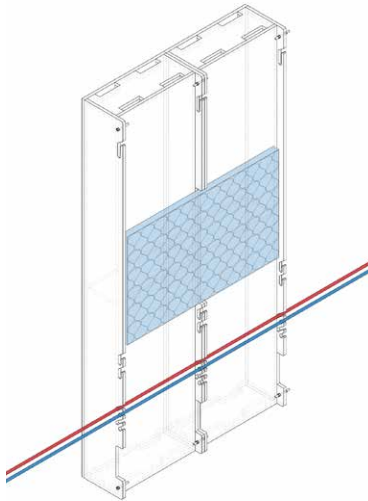
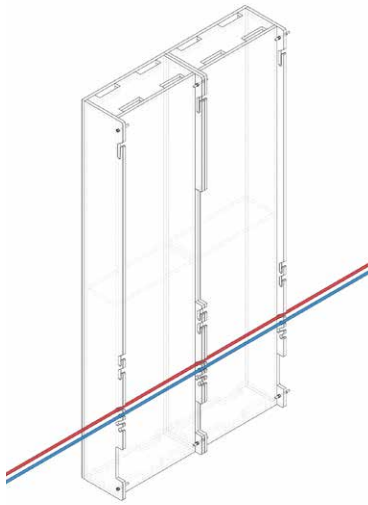


EZ SLIM WALL MOUNT

Mounting your stunning OLED TV or Premium UHD LED TV on the wall with the LG OTW420B EZ Slim Wall Mount. Developed specifically for 2016 OLED and Premium UHD LED TV's, this wall mount will help highlight the surprisingly slim design.

If you can fit it in: EZ Slim Wall Mount for 2016 OLED and Premium UHD LED TV's.
If you can't: 2016 EZ Slim Wall Mount

SPECIFICATIONS	
Dimensions with Bracket Removed (WxHxD)	17.5" x 12.6" x 0.7"
Weight with Bracket Removed	6.0 lbs
Max Tensile Load with Bracket Removed	70.5 lbs
Dimensions with Bracket Attached (WxHxD)	18.1" x 12.6" x 0.9"
Weight with Bracket Attached	9.5 lbs
Max Tensile Load with Bracket Attached	70.5 lbs
Shipping Dimensions (WxHxD)	19.7" x 14.7" x 1.8"
Shipping weight	12.1 lbs
VESA measurements	400x200, 300x200
WARRANTY / UPC	
Limited Warranty	1 Year Limited Replacement
UPC	719192605824

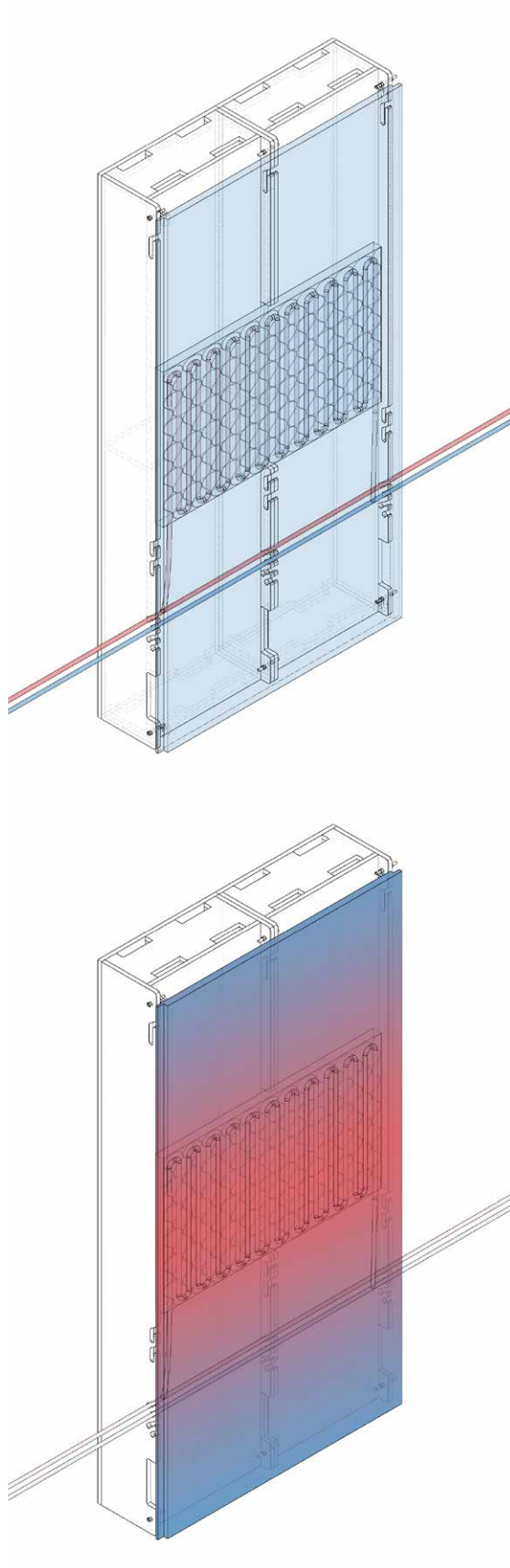


8.7 WALL HEATING

The wall heating is another integration that might be revolutionary for the industry: why would anyone need a radiator anymore when the heating could be embedded in your wall element without compromising the accessibility of it? This can lead to a great amount of money saved for the radiator itself as well as an indisputable better looking internal finishing.

The process of installation is as follows:

- The building components are once again produced according to the space needed by the serpentine coil, a cut in the flanges allows the flow of the serpentine between neighboring wall components.
- An insulation panel is placed on the interior side of the wall component to prevent any kind of heat loss to the exterior.
- The coil (which can be made of several materials, thicknesses and brands) is allocated on the insulation panel and connected to the supply and return heating water system with all the necessary valves and fittings.
- The wall finish panel can at this point be simply installed normally, thus creating a heating wall component.



CONCLUSIONS

COMPLEXITY

The task of the integration of building services in the FabField building system is not an easy one and carries a complexity that is hard to thoroughly explore in a single graduation project. Building services by itself is enough of a convoluted field that the authors of the many books that have been referenced throughout this thesis did not succeed to fully explore in single manuals. Moreover it is an ever evolving discipline that grows by the day: the theory behind it is more or less stable at this point (with the exception of some occasional new discoveries); on the other hand, the more “practical” side never stops to grow, pushed by the market which in turn never ceases to raise its expectations in new, game changing products and systems. Furthermore, the complexity is raised by the driving concepts of the FabField building system, which have been respected in all phases: sustainable material production and transportation, digital fabrication methods, prefabrication, end of life strategies, flexibility, reduced times and risks on-site are all criteria that needed to be satisfied in every aspect of the design.

SURVIVAL OF THE FITTEST

The current state of the building industry is flawed and stuck with the same traditional methods that it has been based on for the past decades, even centuries for some aspects. The current, traditional approach produces tons of waste materials in both the building phase and demolition, the whole building process makes use of antiquated methods and materials that make it rigid in its function and

obsolete in its realization and disposal. Nonetheless some exceptions are leading the way towards a renewed building industry based on the reduction of waste materials, pollution and flexibility for future uses. All the references encountered and gathered from the research make an extensive use of industrialized processes for the production phase and product development approaches which have been adopted by other industries for decades. The path that these innovative buildings are outlining had already been followed in the past by important figures (i.e. Gropius and Le Corbusier) without success, people had been relating prefabrication and standardization as low-quality houses due to the past extensive use of prefabrication for emergencies and military use. It has to be stressed out that in those times the technology used for prefab houses was not as effective and accurate as today, often leading to actual uncomfortable interior environments with condensation and high heat losses as well as sloppy finishes. Interestingly enough the most humble approaches are also the ones that had the most success (i.e. balloon frame system).

The state of today’s technology is mature enough to enable a growing number of small companies to follow the same path, this time successfully, giving life to higher quality products than traditional buildings. The main issue is that these companies to look up to (The New Makers being one of them) are still a minority largely outnumbered by traditional ones that still lead the way in terms of quantity, surely not quality. Larger industries and material suppliers offer better deals to those who purchase greater amounts, which causes the minority to always be the minority. Actions at the highest legislative levels, in both national and global scale, still need to keep

on narrowing the numbers related to pollution and material wastes so that the natural survival of the fittest will cause the disappearance of industries not willing to adapt.

THE DRIVE TO EVOLVE

On the other hand, the building services industry seems to be on the right path, being driven mainly by the market's demand which is directed towards reduced energy consumptions and sustainable, clean energy sources. Reassuringly, the largest producing companies are all focused on the above mentioned key-points. People are increasingly aware of sustainability issues which brings the demand of sustainable products to rise; moreover, the adoption of green energy sources produced directly on site comes along with money savings, which is and always will be a crucial factor in the free market. Likewise, building services' installing companies are following the off-site approach, with the main incentives being the increase of accuracy and reduction of time that comes with the installation of larger assemblies in optimized factory conditions. Notwithstanding the buildings supplied by off-site assembled building services are still a minority, just like the ones following industrialization approaches in the building industry. The blame is once again on traditional construction processes that hardly allow any other approach: the extensive collaboration between architectural, engineering and building services engineering is only adopted for the largest, most complex buildings like big hospitals or other public constructions where there simply would be no other way to do it. To put it in metaphor, a good student should not just go to lectures because

attendance is mandatory, on the contrary one should attend for sheer curiosity and the drive to learn more. Likewise, the industry should not promote extensive use of collaboration only when it would be impossible to do otherwise but it should endorse it in order to learn advantages and disadvantages in smaller, less convoluted buildings.

AN ORDERED SHELF

The methodical approach used for the design assessment of building components and finishing panels was originally borrowed by the QFD (quality function deployment) ideated by Toyota in the 70's to improve their understanding of customers and incorporate it in their product development process. Previous theses by van Veen J. and van der Knaap N. (2016) have analyzed the method and implemented it for the assessment of design aspects in the front-end phase of the design. The main perks of a methodical approach is that the designer is forced to take into account many criteria that influence the design in different ways and influence each other as well. Every designer, no matter what the final result is, develops a design process that often remains unspoken and belonging to the designer itself only; the possibilities that each designer has to succeed in his/her career is obviously related to knowledge and creativity but also very much dependent on the efficiency of the personal design process that each one develops by experience. This is also the reason behind the success of many designers that had equally successful mentors: not because they transmitted their creativity but rather because they were able to transfer an efficient design process to their students. A methodical

approach in the creative design is a tool that directs our individual design processes into a mainstream, efficient process that forces to take into account many different aspects at the same time. In the beginning of the methodology one might think that the latter drastically disrupts the flow that each designer builds in years of practice; once the tool has been used and understood it becomes obvious that its only function is to manage the design into an ordered shelf rather than on a messy office desk. The perks of it are rather clear: better understanding of the overall process and correlations between design criteria with a subsequent increase of rationality in design choices.

However, there is no denying that some of the best inventions and designs were created out of irrational, sometimes foolish choices that only proved their brilliance at a later stage. The risk of an excessively methodical approach is to kill creativity and genius in favor of rationality and efficiency. The user of the methodology should constantly be aware of this.

CONTRIBUTION TO THE WIDER SOCIAL CONTEXT AND FUTURE RECOMMENDATIONS

The final outcome of *FabField: a new approach to building services design* is successful in many aspects; nevertheless, its limitations mustn't be overlooked and a critical review is essential for future studies.

The design of the distribution system is based on the function of family housing only; the maximum height and width of the building are limited by the digital fabrication process. The commercial products upon which the design is based are the ones with

the smallest sections on the market, which is the reason why the whole distribution concept only applies to small family housing scenarios.

Parts of the study on distribution were carried overlooking the characteristics of the FabField building system, taking into account only general characteristics of modular, standardised building systems based on a grid. For this reason, the outcome of this study might be considered valuable for future studies on distribution of building services in modular building systems. Nevertheless, the final distribution design is strongly based on the physical characteristics of the components of FabField and the varying difficulties in allowing certain movements of services for the already existing components; the outcome is an adaptation of already existing components to accommodate a new function. If the building system was to be designed taking into account services since the beginning the design of the latter would be very different. Since the conclusions of the distribution design are the starting assumptions of the components' design, it would be interesting to try in the future different outcomes from the distribution design to test also the different outcomes for the building components' design.

The final design of the components is based on the idea of the so-called "embedded substructure" in which the perks of two different approaches in building services distribution are merged into one. I believe the approach is a successful one, being the perfect example of how an extensive front-end design can benefit the final outcome. Nevertheless, the concept still carries with it the need for building

services to be installed on site. The literature research and reference projects have proven that off-site approaches for building services can be very successful too, bringing the same advantages of prefabrication of buildings. Notwithstanding the plug&play approach was deemed unsuitable for FabField. The reason for this choice is that such approach has been applied mostly on plug&play based buildings, where the amount of connections between sections of services is reduced; in the case of FabField, the services would need to be connected in multiple locations making the concept inconvenient.

As a critic to the approach adopted, the design process for building components would have required more time for prototyping in order to learn the issues that only a hands-on approach can teach. The overall design is based on technical specifications of products from companies and digital drawings, the assessment of the components is related to criteria that were graded only based on my very little experience on the field. The real assessment for the building components design can only be valuable once the system is tested on site, gathering the issues that professionals might encounter with it. The further steps that ideally would need to be taken are the design iterations after each prototyping, thanks to which minor alterations could turn a promising idea into a real working solution for the FabField components.

To conclude, the last remarks are directed to the finishings' design; the desire to enable customers to integrate all final appliances in the finishing panels has advantages and disadvantages. The advantages

comprise the reduction of material wastes that are usually created during the installation of final appliances, less time spent on site for it, a smoother internal finish and a more integrated design process that necessarily requires to consider final details of the internal arrangement in advance, comprising the exact position of flush boxes in the wall. On the other hand, future modifications in the internal arrangement of the house can lead to problems: the same panel can only be used in one spot if it integrates one or more final appliances. Furthermore, dry panels in housing functions, without any wet finish, can make simple actions like fixing a nail to hang a frame an issue for aesthetics. The possibility to finish the dry panels with detachable stripes of wall paper remains open to promote flexibility in internal arrangements. Nonetheless, the integration of appliances in the finishings is an interesting topic to explore, especially to test to what extent the integrated design can be pushed. Nevertheless, the client still has the choice to adopt the traditional approach for the finishings. Design of finishings in FabField definitely requires further research in the future to enlarge the library of possibilities and explore the advantages and disadvantages of each design solution.

The final system does not cause major changes to the traditional approach for the installation of building services but it carries improvements in every aspect of it: less time spent on site, less risks and faster installation, reduced material wastes, design of assemblies into sub-assemblies and so on. Furthermore, FabFac can maintain the current workflow with only minor changes in the design of the already tested building system.

REFLECTION

The choice for the subject on which one will end his career as a university student is not a task to be taken lightly. In my personal motivational letter that I had submitted before being admitted to TU Delft I answered the question “what would you like your graduation project to be about?” with the wish to graduate on the design of a small zero energy building which gathered all the latest technologies in terms of thermal efficiency and sustainability. I must say that in the end the final result is not far from what I had expected. Nevertheless, when I had to choose between the many subjects that the Building Technology track had to offer I was awfully indecisive. I remember thinking about the difficulties that I would have to go through for each subject, focusing on the negative aspects instead of the positive things that I could have learned from each. The approach was wrong, we should all let our curiosity be the main driver of our choices instead of letting fear stop us from achieving great results. Nevertheless, in the path to my quest I found the graduation thesis of a student that had just graduated focusing on the development of a facade system for the “PD Lab”. The student is Jeroen van Veen and his graduation thesis had a huge role in my final decision.

Another factor that influenced my final choice was the sheer curiosity to know more about a subject that always fascinated me but I never got to know properly: building services. My initial goals were much higher than one could achieve in a year but I think that holding the bar high pushes us to give more than what would normally be expected.

The first reflection goes to methodology, a subject that I held dear since the very beginning. The already existing methodology developed by Jeroen van Veen and Nick van der Knaap fascinated me and I spent a considerable amount of time to understand it and improve it. Looking back at it, I would definitely try to focus more on other subjects that I did not find the time to explore in the end.

The first period was entirely focused on research, mainly about the theoretical background of climate design and building services but also about methodology; I wanted to improve the already existing one ideated by van Veen and van der Knaap on their previous theses and this took me a lot of energy and time, which looking back at it now, could have been dedicated to some other aspects that I did not have enough time to explore.

The proposal for the final distribution system, as already mentioned before, was found almost by accident, during a time consuming process of trial and error that ultimately gave the hoped result. It was a subject very hard to fit in a methodology because of the necessity of a previous extended knowledge and more detailed design proposals to truly understand the consequences of a different distribution system during that phase. In the end, the final distribution system works well with the case study and the restrictions previously defined. Nevertheless, it is likely that other distribution systems could also succeed through a proper design of the building components. Ultimately, the research carried out can be seen as a base on which future distribution of services in any kind of modular construction can be evaluated in terms of space and

material saving solutions.

The re-design of building components was the most representative part of this project in my opinion. In terms of time and effort, the research by design and the services' distribution study carried out beforehand was extremely beneficial and eventually led to a mostly smooth, effortless design of the final components. I consider the concept of "embedded substructure" as the future of building services, thanks to which huge time and effort on site can be saved in favor of systems that might differ in flexibility and final target-function but all follow the same principle of considering the flow of services already in the front end design phase of building components. I am satisfied of the final result and strongly believe in this concept, even though I still regret not giving more time to a hands-on approach which in my opinion could have been extremely beneficial to this project, adding an extra layer of evaluation that is currently the missing piece of the puzzle

As for the design of finishing panels, the final goal was to create a library of what the possibilities are rather than a final design choice; this because the technical requirements of the finishing layer are quite open. On the other hand the subjective criteria at play are many, leading to the conclusion that each customer should have the possibility to choose the finish that suits them most in terms of aesthetics. This is a subject that would require the full focus of an entire graduation project, and therefore was not fully explored in this book.

To conclude, *FabField: a new approach to building services design* is not the final and only solution to building services design, and quite frankly it is not the final solution for FabField either. The method used to approach the problem has always been very cautious by my side. The subject was completely new and my lack of initial knowledge resulted in an extremely prudent approach: every single aspect had to be discovered and studied before attempting any design integration. On the other hand TU Delft promotes a hands-on approach for students to learn through their own mistakes and failed attempts, which I probably haven't exploited to the fullest for the afore mentioned reasons.

Nevertheless, my final goal was to design a simple system that could work immediately, allowing FabField to keep the original design of the components without major changes and at the same time saving money and time on site; I do realize that the final outcome does not revolutionize the traditional approach but I also consider it as the first step that already brings multiple benefits from the initial, non-existent integration of services in FabField.

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Kasita: <https://kasita.com>

Woody's housing: <http://woodyshousing.com>

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Floor water heating: <http://www.rihoclimatesystems.nl/voor-thuis/klimaatssystemen-thuis/vloerverwarming-en-koeling-thuis/>

Floor heating: <https://www.flexelinternational.com/products-underfloor-heating>

Radiators: <http://www.zehndergroup.com/en/products-and-solutions/business-segments-and-product-lines>

Boilers, solar heating panels: https://www.viessmann.com/com/en/residential_buildings.html

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Pipes: <http://www.valsir.it/en/sistemi-di-scarico/prodotti/sistemi-di-scarico/sistemi-di-scarico-rev>

Pipes: <https://www.geberit.it/prodotti/sscarico/sistemi/geberit-silent-pro/>

Pipes: <http://www.johnguest.com/speedfit/push-fit->

[plumbing-heating/plumbing-and-heating/](#)

VENTILATION RELATED PRODUCTS

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Solatube: <http://www.solatube.com/residential/>

[daylighting/technology](#)

Wiring: <http://www.bticino.com/products-catalogue/>

Home automation: <https://www.vimar.com/en/int>

Wiring: <https://www.woertz.ch/en/products/routing-systems/>

Wiring: <http://www.pipelife.com/com/#>

APPENDIX A

APH BY ABATON

Reference buildings taken as examples for different reasons: method of prefabrication, internal arrangement, sustainable building services and prefabrication of services

This project, designed by Spanish firm Abatòn, is an interesting reference to look up to in general for its flexibility and manufacturing. It is easily transported by road as a fully finished dwelling, comprising interior furniture and fixtures, this thanks to special joints that allow movements while the house is transported and lifted. The height of the building is exactly 3.5mt to comply with Spanish road transport regulations, two hooks are then fixed to the gabled roof so that the house can be lifted by crane and positioned on the predisposed foundations. The structure of the house is made of a CNC milled solid timber frame; the interiors are then clad with fir panels dyed white, the outside walls with gray cement wood boards, an organic material which also contributes to increasing the buildings' thermal inertia. APH is not only a building, it is modular system with different arrangements and sizes, the smallest (APH40) consists of just a bedroom and a bathroom in 4.5x3mt for 21.900€, the biggest (APH80) comprises a double bedroom, bathroom and living/kitchen area in just 9x3mt for 42.800€. In between there are many other modules like two bedrooms (APH58), living room and kitchen (APH66), two bedrooms and one bathroom (APH70) and a big living room and bedroom (APH80s). All these modules can be imagined also as a customizable cluster of buildings that can fit any desire and functional requirement. The manufacturing time varies from 6 to 8 weeks depending on the model, the time from the end of manufacturing to the building ready to be entered is just one day and it only comprises the transportation and its placement on site. Of course the foundations need to be taken care of previously so that no time is wasted once the building reaches the site. The concept behind this building is that the client does not need to stress about permits, architectural design and all the practical aspects and costs that are normally involved in traditional buildings; the house is like a piece of furniture which the client orders and is shipped on site. For all this reasons this is an approach that really focuses on seeing the house as a product, revolutionizing the building process.



Fig.1.19 APH by Abatòn is transported by truck and lifted by a crane directly on site. (www.abaton.es)

KASITA BY JEFF WILSON

Kasita is a project by Harvard educated professor Jeff Wilson, whose idea is to reform the housing industry so that it becomes more flexible and available to everyone. It is very valuable since it strives to tackle the social conditions which were described earlier on these pages. The design is very compact and designed for one, max.2 persons with its 30m². The mobile structure is a rectilinear pod clad in metal and glass, with one side featuring a cantilevered glazed box for maximum light. The glass used is electrochromic so that the user can adapt its transparency according to his/her privacy requirements and sun exposure. It is intended to slot horizontally into an engineered steel frame, or "rack", which can include many units stacked high and wide. The idea is that Kasita can be bought as an individual unit which can be placed on a previously acquired plot, alternatively it can be bought and stacked into one of the racks that the company would provide in different plots and cities. Owners with mobile lifestyles could contact the company to have the home transported to a new location, using a crane and flatbed truck.

Once in place, the home would tie into city utilities via a special docking technology. "The utilities are distributed throughout the rack to each individual Kasita," the company said. Designed to be assembled in under a week, each Kasita would be able to swap between different racks

The design involved product designers more than architects because the available space needed to be exploited as efficiently as possible. The plug for utilities, for example, was inspired by iPhone, which integrates power and data plugs into a single compact entrance. Sewer, electric, water and sprinklers are therefore connected into a compact space of just 30x20 cm on the lower right side of Kasita.

Production of Kasitas is carried out with industrial processes which guarantees rapid and precise assembly in only a couple of weeks, the installation of the building itself takes only one day upon delivery.

This system comes also fully finished and furnished with the latest smart technologies like built-in speakers, washing/drying machine, ventilation fans, thermostats and electrochromic glazing, making it a very smart integrated solution.



Fig.1.20 *Kasita is a fully prefab one-person studio that strives to tackle the modern "nomad" lifestyle. (www.kasita.com)*

VIPP SHELTER BY VIPP

VIPP is a product design company based in Copenhagen, Denmark, widely known for some of its iconic designs, like their famous pedal bin from the 1930's. The firm has recently decided to design an object like no others in their past, a product that reflects the image of their company and contains a set of all their most representative objects and designs, the VIPP shelter. This product is fully prefabricated in a steel plant in Frederiksværk, Denmark and then shipped just about anywhere in the world. The company specifies that it can be really placed everywhere, the only requirements comprise the fact that the trucks have to be able to reach the place and the plot should allow the small crane to be placed during the lifting procedure. Since it is a product design company, their final goal was to produce a product rather than an object; "the objective was not to make a house or a mobile home," said Morten Bo Jensen, chief designer in Vipp. "Vipp is rooted in the manufacture of industrial objects, so the term shelter is a typology that allows us to define this hybrid as a spacious, functionally generic, livable object." The production process takes approximately 5-6 months and the final result are 3 individual transportable modules already fully furnished by VIPP. The overall size of the shelter is 5.2x11.5x5mt, the transportation is carried out by three separate trucks and the final assembly of the three modules is done on site in just 3-5 days by crane. It is a very interesting approach from a company that has decades of experience in the manufacturing industry as well as in product design; the final result is an extremely high quality, almost luxurious product. This time, opposed to the first two references, the product is not fully finished but follows the "plug&play modules" approach which allows the shelter to be much more spacious and directed to customers with high quality and space expectations. The company specifies that it's only a shelter, not a real house, for the client to escape from the city and dive in nature; nevertheless, if we consider that the final price is 580.000€ excluding permits, crane rental and transportation, we can really understand who this product is intended to. Thus the choice of splitting it into three big modules, making operations on site more complex but ensuring an object which is not spatially restricted by road dimensions. One would assume that such advanced manufacturing process and level of prefabrication would lower the overall price of the house but no, 580.000€ excluding permits, delivery and crane rental is simply too much. Furthermore, Jensen calls the shelter a "plug & play getaway" without taking into account that the plugs aren't just about anywhere, the client ideally has to provide that too at its own expenses whereas nowadays one would expect such a high quality product, which claims to work just about anywhere, to at least try to be self sufficient in terms of energy.



Fig.1.21 *VIPP shelter is transported and assembled with "plug&play" modules; it is an extremely sleek, expensive and minimal house. (www.vipp.com)*

HONOMOBO

Honomobo follows the trendy concept of creating living spaces out of shipping containers, which has now become widely adopted all over the world. Shipping containers are modular and structurally sound, easy to transport and spacious enough to create a tiny studio out of a single container. Nevertheless, Honomobo offers much more than that: 8 different designs of varying sizes but all based on stacking and/or connecting shipping container modules to form a bigger unit or even multi family housing buildings. Containers were originally created with modularity and durability in mind, they withstand all kinds of abuse as they journey through the world's harshest climates, from salt water to freezing temperatures, a shipping container is meant to handle the worst of the worst while protecting some of the world's most precious cargo. The opportunity lies within the fact that there are currently more containers being imported than exported in North America, where Honomobo is based. Shipping containers can be imagined as life-size lego blocks with which one can build a single level or multi-storey building and can place it in his/her backyard and later move it somewhere new. When it comes to construction methods and building materials there are few alternatives that are as durable, portable and sustainable. This company is even proud of their aspect and does not hide it: "At Honomobo we have set out to leverage the modularity and durability of the shipping container while not apologizing for what they are. We don't hide our boxes, but we have embraced the essence of the shipping container" (www.honomobo.com). While the finished product is produced in factory under controlled conditions, the client only has to provide foundations and services as well as a building permit; once the building arrives on site the company itself will provide the installation of the latter and within a week the client can already move in. Once one of the 8 designs mentioned earlier does not even require a foundation and is publicized as an alternative workspace or even a man-cave where one can find his own privacy. The interior finishes, as shown on the facing page, are not basic but actually quite luxurious, in contrast to what one might expect when thinking about prefabricated, modular houses built in shipping containers. In fact the final price is not very accessible after all, putting this product in a high-end market along with the VIPP shelter, constituting more of a luxurious item rather than a cheap housing solution. Prices range from 24.000€ for the smallest unit (10m²), up to 335.000€ for the largest, two-stories 142m² unit.



Fig.1.22 *There are several models of Honomobo, all of them use containers as main structure. (www.honomobo.com)*

WOODY BY WOODYS HOUSING

Sustainability, health, community, innovation and affordability are the key values of Woodys housing, a dutch company currently hosted also by the green village in the campus at the TU. The "Woody" is the building created and based on a healthy, sustainable, adaptable, flexible, stackable cozy studio affordable for everyone. On the company's website many rendered views are available and focus mainly on the possibility to create entire communities just by stacking and repeating the same "woody" module over and over. The building is fully prefabricated and comes with kitchen and bathroom units; since it is currently exposed at the green village, I was lucky enough to see one live for the first time while they were still applying the finishing layers and services, which I could see the flow and distribution of. Interestingly enough, the services did not seem to be integrated in an innovative way like one would expect from such modular building system. Instead, they were being installed by a normal operator with traditional cutting tools and screws and such; this is in my opinion a contradiction with the way the rest of the building is produced and the concept of Woodys housing itself. There are different sizes of Woodys, the smallest unit offers a surface of 3,6x7,2m and a height of 3,1m. Woodys Housing offers also quite some flexibility in the interior design, furniture and equipment and a key point of the design is also the flexibility for future uses and transformations. The company's website states: "from student to starter to family to elderly.... it's possible with Woodyshousing! Growing in your housing career can mean extensions in space. For starters or small families another Woody® can be the solution. Different sizes and configurations are possible: from one-person apartment, starters flat or family houses up to buildings of up to 12 levels high. Woodys are flexible and can easily be connected next to or above each other: plug & play". Therefore Woodyshousing offers a broad scale of customization and personalization for both the building itself and the apartments. Furthermore, by using the WOODYZAPP design plug-in a home owner or architect can design and configure many different buildings and different exteriors within a couple of hours.



Fig.1.25 *It is hard to find real images of woodys, none have been actually acquired; one is exposed at the green village. (www.woodyshousing.com)*

PRET A LOGER BY TU DELFT

Pret a Loger is a design by TU Delft for the Solar Decathlon Europe 2014, in which it won the first prize for sustainability, communication and social awareness and the second prize in energy efficiency. It was used as a reference mainly for the sustainable technologies and building services used in it. The case study was chosen in the city of Honselersdijk, typical Dutch urban settlement, the typology was set to be a "Doorzonwoning", most widespread type of residential building in the Netherlands (42% of the building stock). The house is completely insulated, the glazings are replaced with HR++ glass, a central solartube provides for light access, a ground duct for ventilation cools or heats the air, PCM materials are also used as well as a heat exchanger. Other technologies comprise a Heat pump, collection of rain water and a translucent PV panels array. The house makes use of multiple sensors to detect motion, temperature and humidity in every room and sends feedback to the domotic system that adjusts accordingly turning on and off lights, radiators and ventilation. 3 solar tubes gather light from the roof and reflect it to the living room in the ground floor; thanks to a special reflective material with an efficiency of 99.6% (mirror would be 99%) a lot of light is spread in the living room from these solar tubes. The main technical room comprises the domotic system, an inverter for the PV array that gives information regarding the energy produced daily, monthly and yearly, a special air heat pump that absorbs heat from the roof, inside the greenhouse, it is not very common, nor very efficient. Heat pumps are usually set to 35° but since the heating system uses the old radiators, this one is set to 55° which makes it even less efficient. When I visited, the temperature in the greenhouse was -2°C and the water heated from the heat pump reached merely 24°C.

There's also a water collection system: water from the roof is gathered through the gutters and collected in the greenhouse, where a small tank is positioned. Water for watering the plants can be directly taken from a tap in that storage, no pumps are required, it uses pressure from height difference. When that storage is full, excessive water is redirected to the main big storage which then uses a pump to send water for toilets and plants. The technical room also has a backup water access for toilets and plants in the case water collected from rain is not enough.



Fig.1.26 *The Pret a Loger is currently exposed at the Green Village in the campus; the visit gave a lot of insights on many sustainable services.*

BOKLOK BY IKEA

Boklok is used as a reference because considered probably the most successful modern prefabricated system in Europe so far, showing that not all attempts were failures and some actually succeeded. The reason for the success of BoKlok is the well established power of Ikea that allows for lower prices in production as well as a great immediate visibility in the market: people already know and trust the swedish brand, they know what to expect from it. In 1996, when IKEA's founder Ingvar Kamprad met Skanska's chairman of the board Melker Schörling at a housing fair, all new homes that were built were expensive and luxurious. Ikea and Skanska decided then to team up in a joint venture called BoKlok. In the beginning the main target were single parents with low incomes, young people leaving home, and seniors longing for easy and convenient living. Nevertheless, the idea was just as appreciated by families in other living situations as well, and the development of terraced houses began. It is interesting to point out that Ikea is a global brand that manages to produce affordable furniture for the whole world, this thanks to its huge size which enables it to produce immense quantities at low prices. Yet when it comes to houses, not even Ikea managed to unite Europe; in fact, most of the Boklok's houses were sold in Scandinavian countries whereas other nations still seem not to be as interested, even though Ikea stands for affordability and yet acceptable quality and good design. Ikea currently offers Boklok in different configurations, from blocks of flats to terraced houses, satisfying all requests at prices starting from 65.00 euros furniture comprised. BoKlok homes don't come in flatpacks, but they're not far off. The timber-framed buildings are almost entirely prefabricated. They are usually brought to the site on the back of trucks as pre-assembled units, like Portakabins, with the interiors already fitted out. Each apartment is made up of two of these units, which are simply moved into position by crane. Put on the roof and exterior wall cladding, plumb and wire it in, and it's ready to live in.



Fig.1.28 *BoKlok was born in 1996 from Swedish companies Ikea and Skanska to tackle the rising prices of houses in the country.*

APPENDIX B

Market survey for building services; sources, distribution and final appliances were gathered to analyze their characteristics, installation and space requirements. Links for all products are listed in the URL list

The following pages are a display of the solutions that have been considered for a possible integration in the FabField system.

Once these first restrictions are made, the integration of building services in the system necessarily needs a research phase into commercially available products; the technologies that we now know have potential in the integration need to be analyzed in their technical features such as size, weight, efficiency, optimal location to be placed and so on.

The market research was based on the amount of technical data available for each product, the reliability and fame of the companies and the material and indications gathered from technical construction fairs such as Bouwbeurs in Utrecht and Klimahouse in Bozen, Italy.

The products hereby displayed are not the only ones that have been analyzed but a restriction had to be made in order to have a clear selection of possibilities to choose from. The selection has been done favoring low prices, high efficiencies, small dimensions and thicknesses, low weight, demountability, sustainability, possible integration with other products and flexibility. The order they are displayed is somewhat related to the way energy is first produced by the sources, then distributed and supplied through the final interfaces.

BIOMASS BOILERS

Considered as sources, they can be fed by either pellet wood or wood chip; pellet wood will be the only one considered as it is more dense, therefore easier to store and transport. A big issue of this products is in fact the space for storage, which in case of wood chips is just too large for any application in the FabField system. Dimensions range from small boilers for residential units to huge ones for industries. Compact boilers range from 7 to 50 KW. Hot water produced from biomass boilers can be used for both DHW and heating water; it can therefore serve radiators, tubs, taps, showers, washing machines, floor heating etc. Sizes can vary widely, the smallest model that is going to be considered measures 1000x500x1000mm, weighting 250Kg.

Advantages comprise the fact that it's an all-in-one solution with very fast production of hot water and it's suitable for all heating systems, low and high temperature. The main disadvantage with this product is related to the way it's fed, which needs to be done manually every day. Automatic feeding is available but requires very large storage spaces which are not considered suitable nor convenient for the FabField.

Biomass pellet boilers have to be coupled with a layered buffer tank, which is more expensive but allows two different intakes for hot water at different temperatures. It can be coupled with solar thermal so that water that enters the tank is pre-heated, therefore saving on the boiler's energy demand.

The models considered come from 3 different companies:

- ETA PU 7-15 KW
- Froling P4 Pellet 15-20-25 KW
- Viessmann Vitoligno 300C

To conclude, it is a good choice especially for the cases in which a larger space is available both inside the house but also outside as an external storage can allow for the automatically fed version. Just like heat pumps, the pellet boilers considered here modulate the power according to one's needs, which represents a big energy saving advantage.

HEAT PUMPS

A heat pump is a device that transfers heat energy from a source of heat to a destination called a “heat sink”. Heat pumps are designed to move thermal energy in the opposite direction of spontaneous heat transfer by absorbing heat from a cold space and releasing it to a warmer one. It uses a small amount of external power to accomplish the work of transferring energy from the heat source to the heat sink. (Bundschuh J., Chen G.; 2014)

Heat pumps, according to models, can exploit heat from the air, from water or from the ground. In this case, only air and the zeolite variant will be considered. The heat produced can heat water from both heating and DHW; it is still advisable to couple it with low temperature heating systems for maximum efficiency.

Sizes again depend on the energy demand but are generally much more compact than biomass boilers. A distinction needs to be made between external air unit (975x1100x463mm; 126Kg) and internal zeolite unit (1665x772x718mm; 160Kg).

Advantages comprise sustainability given by the fact that it runs on electricity at extremely low consumption levels. It has low operation costs and it's very flexible as it only requires a reduced space outside the house for the compressor to run. Last but not least it can provide for both heating and cooling if required.

The main disadvantage is its temperature dependence as well as the fact that it can only produce hot water that reaches limited temperatures.

It is a very flexible solution and can be coupled with many other products such as solar thermal systems, PV array and power storage. It can also provide for ventilation if integrated with mechanical ventilation unit. The products hereby listed are the one that have been considered for the study:

- Vaillant Arotherm (AHP) + Unitower 190l buffer tank
- Vaillant Zeotherm VAS 106/4 (AHP) + Aurostor VIH300l buffer tank
- Viessmann Vitocal series for both indoor and outdoor units

To sum up, the zeolite product is interesting in terms of efficiency (it works with wider temperature range and provides higher temperatures). Overall, air heat pumps are trending and offer probably the most compact, flexible and sustainable solution nowadays, which make it a perfect choice for FabField on paper.

PHOTOVOLTAIC PANELS (PV)

Photovoltaic is a technology widely used for turning solar energy into electricity. PV solar cells are the single elements that constitute a PV module; multiple PV modules, or panels, form a PV array, or system. Photovoltaic panels produce DC outputs (direct current) typically ranging from 100 to 365 Watts, their efficiency ranges from 10%, for the most commonly used, cheap panels, to 22% recently reached by Elon Musk's SolarCity, almost reaching the theoretical limit of the technology. Typical PV installations comprise multiple modules and a DC-AC inverter, optional features include energy storage, interconnection wiring and even solar tracking mechanisms. The amount of energy collected is obviously proportional to the space available (either on the roof or on the facade) the related number of panels installed and their energy output. The distribution comprises single cables, approximately 4mm², that connect each module to the inverter. An interesting solution offered recently by Tesla is the PowerWall II, an energy storage unit which integrates the inverter. Size of the panels is incredibly flexible according to one's needs, every company offers many different sizes.

The main advantage of this technology is that it produces free, clean energy that can generally quickly pay back the initial investment, often granted by the government or local authorities in the struggle to reach European standards in time for 2020. The ideal case in the future is the addition of an energy storage, although the technology is still very young and not financially convenient. The main disadvantage is the high investment required in the initial phase and the relatively long pay back time, ranging from 7 to 15 years.

Nevertheless, most PV modules come with a warranty of 25 to even 35 years.

The commercial modules that will be considered belong to the Viessmann Vitovolt series.

SOLAR THERMAL SYSTEMS

Solar thermal systems consist of modules that usually comprise a collector, a heat transfer medium, transport equipment and a heat storage facility. This technology converts sunlight into heat for water heating. Mainly 4 different kinds are currently available on the market, differing in technology, cost and efficiency: Open absorbers, flat plate collectors, air collectors and evacuated tube collectors.

The versions commonly used in residential applications are mainly evacuated tubes or flat panels. They are usually placed on rooftops and therefore require space, which would ideally be shared with PV panels so that both electricity and hot water can be produced on site from clean sources. The system also requires a solar station, which is the pump that regulates the flow of water through the panels; another requirement is a boiler, dedicated or integrated with the main one. Some products integrate the boiler on top of the panel directly.

The water heated up by solar panels is usually used for DHW only, there are also applications in which it is also used for heating. The final interface of solar panels can be considered to be the boiler in most cases, an exception is represented by panels that integrate the boiler on top. Size and weight are extremely variable, depending on requirements and type of panels.

Solar panels can be paired with pellet boilers as well as heat pumps of any kind, this makes them quite a flexible integration for sustainable hot water back up. Integration with tank-in-tank or puffer boilers would even allow the production of heating water.

The commercial products comprise:

- Vaillant Aurotherm VTK/VFK
- Vaillant Solar Aurostep pro
- Viessman Vitosol line

Further technical informations can be found in appendix x.

Nowadays solar panels appear to be an obvious choice when the necessary space is available and climate conditions are favorable. They are tested products which allow a fairly quick break even point. The possibility to produce both DHW and heating water is very interesting but requires additional costs for special boilers.

CENTRAL MECHANICAL VENTILATION

Central mechanical ventilation systems can be provided with a control mechanism, a filter and even heat recovery units. Mechanical ventilation systems can generally be differentiated in central systems and local systems. The former ones require ductwork to distribute and exhaust air from the building, which makes them quite costly and complex when compared to localized units. They require electricity to work and draw fresh air from outside through an air intake; usually these intakes are placed on rooftops in form of ducts of 100-200mm. A central

unit provides for the suction of air and it usually features a heat exchanger so that heat from stale, outgoing air can be recovered to pre heat fresh air to the required temperature. Some ventilation concepts use mechanical units exclusively for exhausting, while fresh air can be drawn in by other means, such as natural ventilation or window integrated fans and grills. The distribution is usually very space demanding and it represents the main downside of mechanical ventilation systems; ducts should usually be carefully dimensioned according to the ventilation rates required by internal environments. The sizes considered are the most compact that the market currently offers: flat ducts H50mm.

Small units can be as compact as 50x50x20cm whereas bigger units with heat exchanger widely vary in size according to the ventilation rate they supply. The weight of the smallest units can be as low as 20Kg which makes them transportable by a single individual; bigger units, still within sizes that make sense for FabField, are always below 50Kg. Main advantages are energy savings and healthy environments, the main disadvantage is the consumption of electricity and the large space required by the air ducts.

The products chosen for the FabField are

- Ducobox (exhaust only)
- Zehnder comfoair Q
- Brink Renovent Sky 150-200-300

Central mechanical ventilation can also be paired with humidity and CO₂ sensors which can make the whole system very responsive and automatic. Integration with heat pumps allows for fresh air to be pre heated.

LOCAL MECHANICAL VENTILATION

Local mechanical ventilation systems do not require any kind of ductwork, which makes them extremely suitable for the Fabfield system for their flexibility and ease of integration in any modular system. They consist of a heat exchanger and a small fan which is integrated into the exterior wall. The functioning principle is based on cross ventilation: half of the units draw fresh air in while the other half removes exhaust air in intervals of one minute; each wall opening is approximately 0150-250mm depending on the maximum air flow rate.

Size of the units varies, the two products taken into account measure respectively 40x40cm + any needed depth and 110x30x16cm.

The smallest unit is extremely light and can easily be installed by a single operator; the bigger unit still weighs under 20Kg, which makes it transportable even by a single person, it is however suggested that the installation is carried out by two persons.

Main advantage is the complete lack of distribution, no ducts, no dust, no fungi, low and easy maintenance and an easy and fast installation. The main disadvantage is that it offers less control over each room, integrated heat exchangers are less efficient due to their compact size.

The products considered are hereby listed:

- Vaventis Fresh-r (bigger unit)
- Brink Air-70 (smaller unit)

These are extremely flexible products that only require a plug in the proximity.

FLOOR HEATING

Underfloor heating is a form of central heating and cooling which achieves indoor climate control for thermal comfort using conduction, radiation and convection. It is often referred to as radiant floor even though this definition is technically correct only when radiation is responsible for 50% or more of the overall heat exchange between floor and surrounding environment.

The “source” of underfloor heating systems is warm water coming from any kind of source really. In our case, considering that a selection of suitable source services has already been carried out, the warm water would come from either a biomass boiler or a heat pump; as already stated before, solar thermal systems could also provide heating water but would require special tank-in-tank or puffer boilers for it. The distribution requires a serpentine laid down in such a way that the warmest water flows closer to the colder spots of each room, i.e. next to windows or doors. The pipes of the serpentine can be made of copper or different kinds of plastics, their diameter is always approximately 16mm; a manifold to connect all pipes running through a floor must be present at every level, it usually is a simple box embedded in the wall. The manifold requires at least 110mm in the wall thickness. An alternative source can also be electricity, in this case we’d be talking about underfloor electric heating. It covers room’s surfaces in form of thin foils with an embedded electric resistance, the distribution simply requires a thermostat and a 01,4mm cable connected to 230V AC. The thickness that this solution requires can be as little as 1 cm. A small flaw with this product is that, contrary to water underfloor heating, it can only heat and not cool as well.

Advantages of these products are fast reaction times, high comfort levels thanks to the conductive nature of heat exchange between feet and floor. The low temperatures are allowed by the large surface covered, which means energy savings and low convective air flows that are usually responsible for comfort problems. Electric floor heating only allows for dry finishes, which makes the product completely demountable, easy to install and fully reusable; furthermore, electric floor heating is space saving in terms of thickness required as well as the futility of boilers of any kind. A disadvantage is that this system does not allow any other service to run underfloor, leaving only floors and ceilings for the remaining services. The products taken into account are:

- Flexel Ecofilm set (electric)
- Karbonik (electric)
- Jupiter Ideal Eco (water)

CEILING HEATING

Ceiling heating follows the same principles as floor heating but it's located above the user instead of below, this causes some major differences given by the fact that warm air tends to flow upwards; it is therefore a less comfortable heating solution compared to the previous one, but it is a better cooling solution. The main source is again water pre heated by any of the selected sources, the low temperature system enables to exploit renewable energy sources like heat pumps and solar thermal systems.

Size of these products widely varies in length whereas the width is kept constantly at 600mm,

which makes the product suitable to the grid of FabField. The relative weight obviously depends on the length of the selected panel, it ranges between 5 to 21 Kg; assembly should always be made by 2 operators due to the high position of the panels.

Advantages comprise very fast reaction times, full demountability and flexibility for all other building services since, in contrast to water floor heating, this panels do not forbid the presence of other systems within the ceiling thickness. Just like underfloor systems, it can provide for both heating and cooling and it saves energy thanks to the low water temperatures required.

The main disadvantage is the already mentioned aspect that heat naturally flows upwards, so this system implies that upper parts of environments need first to be heated up for the heat to reach lower levels.

The selected products are:

- Zehnder Carboline grid version
- Zehnder Carboline sail version

To sum up, it is a sustainable, low-energy, fully demountable solution which can provide for other tasks like sound absorber, cooling panel and finish layer. It is very suitable to the integration of services for all these reasons and especially for the fact that it still allows other installations to run through the ceiling. In terms of comfort, floor heating is still preferred for residential environments, whereas all other functions like offices, schools or shops can efficiently and sustainably be served by ceiling heating panels.

POWER STORAGE

The concept of using power storing batteries to accumulate energy and use it later to run lights and home appliances is very appealing but the technology is still not mature enough to be economically attractive. However, in the multitude of products currently offered by the market there is one which stands out for its incredible competitiveness in terms of both price and storing capacity; it's the Powerwall by Tesla, an innovative enterprise that is currently investing more than any other company in the world in renewable energies with great success. The battery packs they offer are an ideal pairing for solar panel systems, especially in the case of off-grid projects where homeowners need or want to become fully independent of their utility. A solar storage solution like the Tesla Powerwall allows you to maintain a sustained power supply during the day or night. Nevertheless, it is still not very realistic for a house to be off-grid simply being backed-up by a single Powerwall as the latter only provides energy for a couple of hours.

In just over a year Tesla is offering the new Powerwall for the same price but with two times the amount of capacity, from 7 to 14KWh, and a built-in Tesla inverter. Tesla Powerwall II obviously makes sense only when coupled with a PV array. The exact size of the product is 1150x755x155mm for 122Kg, it can be mounted on walls or floor, indoor or even outdoor. Theoretically the house could really be independent from any kind of externally produced electricity. The main drawback is that it is a very fast developing technology, which means that a high investment made now could prove to be inconvenient in a matter of months. It provides 14KWh of energy, a power of 5KW with a peak of 7KW, operating temperatures that range from -20°C to 50°C.

HOME AUTOMATION SYSTEMS

Home automation can include the scheduling and automatic operation of water sprinkling, heating and air conditioning, window coverings, security systems, lighting, and food preparation appliances. Home automation may also allow vital home functions to be controlled remotely from anywhere in the world using a computer connected to the Internet, using the trending principle of the IoT (Internet of Things). It requires only a low amount of energy necessary for the communication and data sharing between services, appliances, switches and monitors. The distribution is based on BUS wires which connect each sensor to the corresponding service and central home automation system, the "brain" of the whole system. Some sensors can also share data and information wireless through radio frequencies (RF sensors), saving space and installation time otherwise required for laying wires.

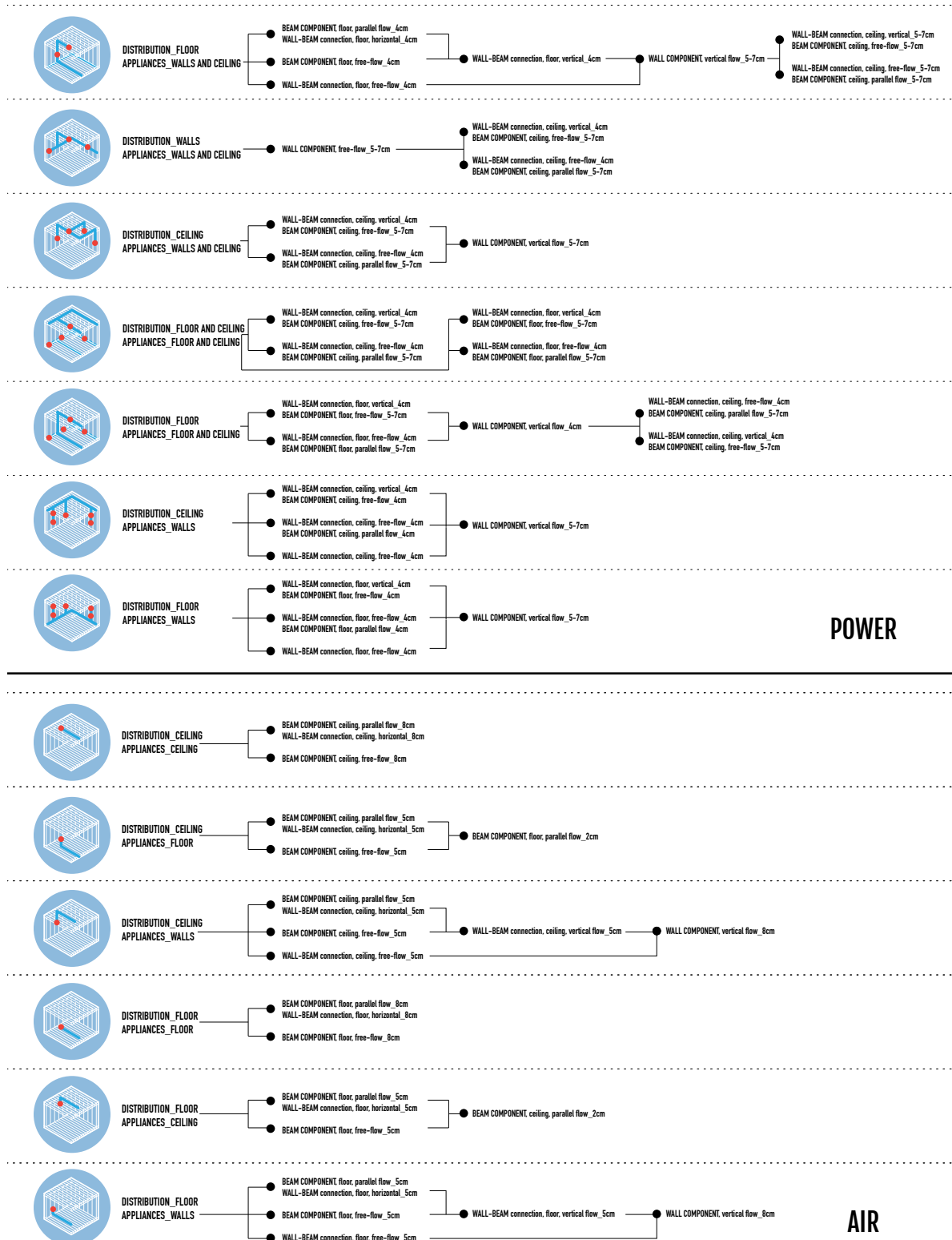
The main upside of this products is that all installations can communicate with each other and make the house an integrated system where every service shares data and info with all others. It can improve control, security, comfort and energy savings. Nevertheless, security can be breached by hackers since the whole house is remotely controllable.

The product lines selected for the system are:

- Vimar By-Me home automation
- Be-Next home automation add-ons (wireless)

APPENDIX C

Space requirements and complexity of building components for different distribution systems





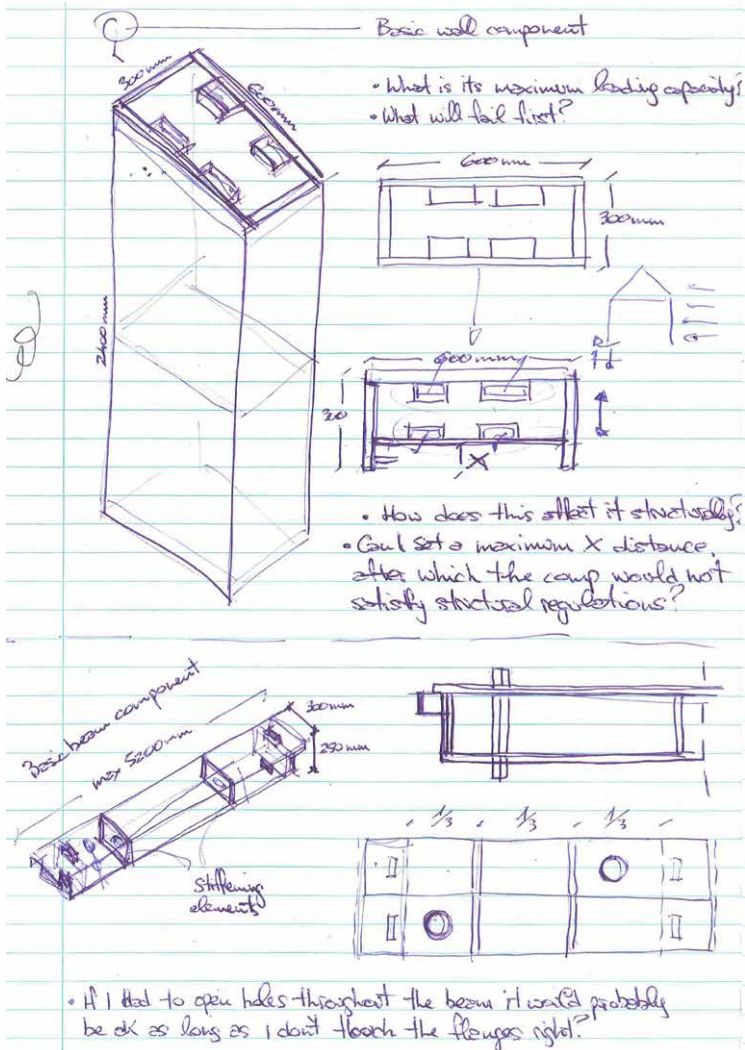
WATER



WATER DISPOSAL

APPENDIX D

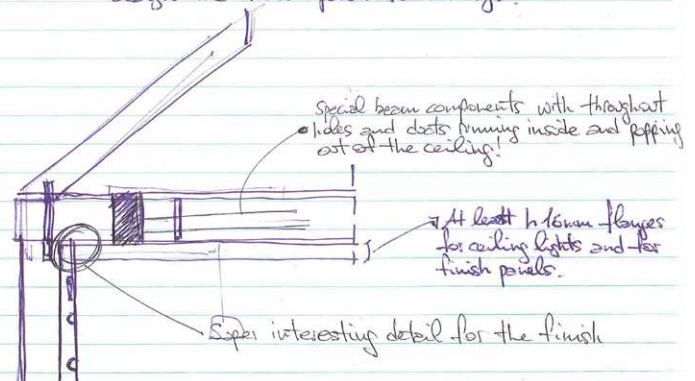
Structural considerations and calculations have been carried out to test the design concept's feasibility



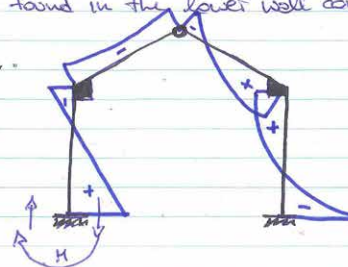
beam components -

- no water for sure
- cables only in ceiling (or 16)
- Air ducts (150mm) probably better if flow "inside" the beams and then pop out from the ceiling. This means special beam components, ~~only~~ only when necessary.

Sum up - Floor free of anything
Throughout holes for Air ducts
Ceiling with flanges for cables!
Design the finish panels for ceilings.



1. The flowing structure of the Fabfield system can be simplified with all fixed connections. The FEM shows that the Max bending moment can be found in the lower wall connections

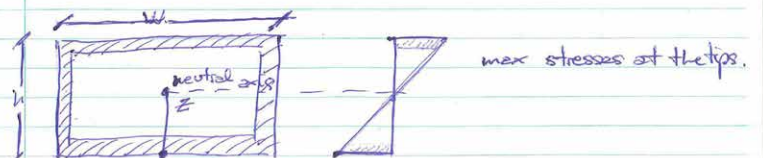


The reduction of the section of the wall component affects the wall-floor connection, which is the one that has to withstand the most stress (b.m.)

Bending moment is generated by Force times distance. In this case the distance is between the wedges.



By reducing the distance d by x , the force applied to the connections increases, which requires x to be kept as low as possible

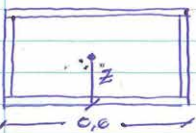


We know that OSB 3 has a max bending strength of 18 N/mm^2
We also know that $\sigma = \frac{M \cdot z}{I}$

Let's check how this specific section behaves. —>

$$\bar{\sigma}_{max} \sigma_{B3} = 18 \frac{N}{mm^2} \rightarrow 18000000 \frac{N}{m^2}$$

$$M_{max} = 4,6 \frac{KJ}{m} \rightarrow 4600 N \cdot m$$



$$z = 0,15 m$$

$$I = \frac{0,6 \cdot 0,3^3}{12} - \frac{0,58 \cdot 0,28^3}{12} = 185212032 mm^4$$

$$I = 0,00135 - 0,00106 = 0,000289 m^4$$

$$\bar{\sigma} = \frac{M \cdot z}{I}$$

$$\frac{4600 N \cdot m \cdot 0,15 m}{0,000289 m^4} = 2381515 \frac{N}{m^2}$$

$$1,42 \frac{N}{mm^2} < 18 \frac{N}{mm^2} \text{ VERIFIED... how much can we reduce } I?$$

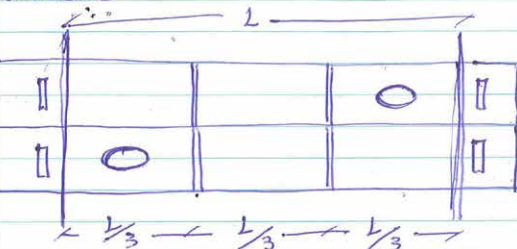
$$18 \frac{N}{mm^2} = \frac{4600000 N \cdot mm \cdot 150 mm}{I}$$

$$I_{min} = \frac{4600000 N \cdot mm \cdot 150 mm}{18 \frac{N}{mm^2}} = 38333333 mm^4 \text{ (current is } 289000000 mm^4)$$

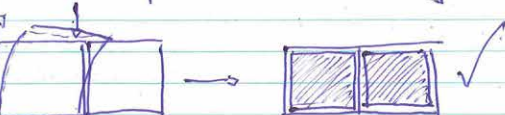
$$40000000 = \frac{600 \cdot x^3}{12} - \frac{582 \cdot (x-18)^3}{12}$$

- Some beams will need services to pass inside them. It requires special design!

Structurally, it is important that the flanges stay untouched



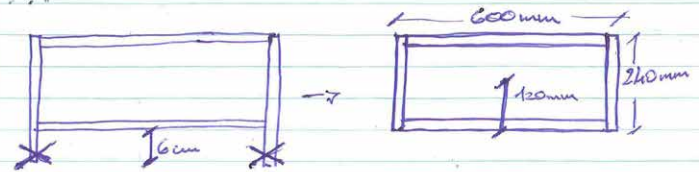
Stiffening elements are roughly located at span to prevent torsion of the component. They can be perforated to allow air ducts to pass but their continuity must persist.



- Holes throughout the components must be placed in the center of the $\frac{1}{3}$, not too close to the connections nor to the middle.

The calculation proves we have a lot of redundancy. We already know that the max thickness needed would be 60 mm for a comfortable installation of water disposal pipes.

- Check



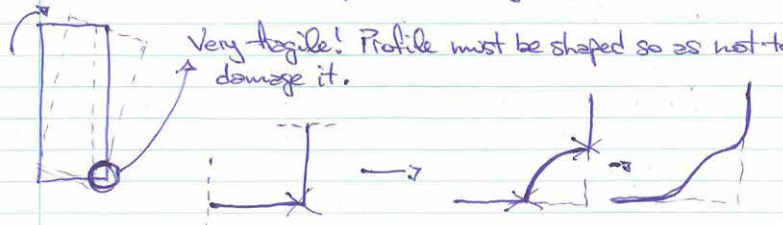
$$I = \frac{600 \cdot 240^3}{12} - \frac{584 \cdot 204^3}{12} =$$

$$691200000 - 391014308 = 292185792 mm^4$$

$$\bar{\sigma} = \frac{4600000 N \cdot mm \cdot 120 mm}{292185792 mm^4} = 1,889 \frac{N}{mm^2} < 18 \frac{N}{mm^2}$$

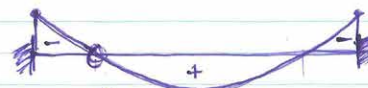
STILL LARGELY VERIFIED SECTION

- Wind loads tend to flip the components, concentrating a lot of stress on the tip of the flanges.



New shape on top and bottom can provide additional space for services.

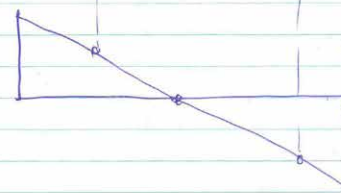
If we consider the beam as fixed at both ends then



Bending moment is 0 at approx $\frac{1}{5}$ from the edges

Nevertheless...

shear forces are still quite high in those point. $\frac{1}{3}$ is a good compromise,



even though shear stress is mainly absorbed by flanges



Conclusion... beams can be tweaked to accommodate services but parallel flow only is strongly suggested since the flanges absorb most of Bending moment and shear stresses.

APPENDIX E

House of quality and criteria; detailed assessment according to criteria and final scores of wall and beam components

		FREEDOM OF DESIGN																																		
		FLOW FLEXIBILITY																																		
		LENGTH OF DISTRIBUTION																																		
		ADAPTABILITY TO FUNCTIONS																																		
		ADAPTABILITY TO APPLIANCES																																		
		ADAPTABILITY TO FINISHES																																		
		STRUCTURAL RELIABILITY																																		
		NESTING																																		
		BATCH SIZE																																		
		MILLING TIME																																		
		AMOUNT OF ELEMENTS																																		
		ELEMENTS VARIATION																																		
		ASSEMBLY ERGONOMICS (C)																																		
		ASSEMBLY TIME																																		
		ASSEMBLY COMPLEXITY																																		
		VULNERABILITY																																		
		PIILING EFFICIENCY																																		
		LIFTING ERGONOMICS																																		
		WEIGHT																																		
		ASSEMBLY ERGONOMICS (B)																																		
		COMPONENTS VARIATION																																		
		BUILDING SPEED																																		
		EASE OF INSTALLATION (Bs)																																		
		SAFETY																																		
		POSSIBLE CLASHES																																		
		INSTALLATION TIME																																		
		EASE OF INSTALLATION (F)																																		
		FINISHES APPLICABLE																																		
		FINISH QUALITY																																		
		ADAPTABILITY																																		
		MAINTENANCE																																		
		ACCESSIBILITY																																		
		AESTHETICS																																		
		LIFESPAN																																		
		DISASSEMBLY																																		
		RE-USE																																		
DESIGN	FREEDOM OF DESIGN	1	1	1	1	1	0	1	1	1	1	1	0	1	1	0	1	1	1	1	1	1	0	1	0	1	1	1	0	1	1	1	1	1	1	
	FLOW FLEXIBILITY	0	1	1	1	1	0	1	1	1	1	1	0	0	0	0	0	0	1	1	1	1	0	1	0	1	1	1	1	1	1	1	1	1	1	
	LENGTH OF DISTRIBUTION	0	0	0	0	0	0	1	1	0	1	1	0	0	0	0	0	1	0	1	0	1	0	0	0	0	0	1	1	1	1	0	0	0	0	
	ADAPTABILITY TO FUNCTIONS	0	0	1	1	1	0	1	1	1	1	1	1	0	1	0	1	1	1	1	1	0	1	1	0	1	1	0	1	1	1	1	0	0	0	1
	ADAPTABILITY TO APPLIANCES	0	0	1	0	0	0	1	1	1	1	1	1	0	0	1	0	1	0	1	1	1	1	1	1	1	0	0	0	0	0	0	1	1	0	0
	ADAPTABILITY TO FINISHES	0	0	1	0	1	0	0	1	1	1	1	1	1	0	1	1	1	1	1	1	0	1	1	1	1	1	0	0	0	0	0	1	1	0	0
STRUCTURAL RELIABILITY	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1		
MACHINING	NESTING	0	0	0	0	1	0	1	0	1	1	0	0	1	0	1	0	1	1	1	0	0	1	0	1	0	1	0	1	0	0	0	0	0	1	0
	BATCH SIZE	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	
	MILLING TIME	0	0	1	0	0	0	1	1	1	1	1	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	1	0	0	0	0	0	0	0
COMPONENTS ASSEMBLY	AMOUNT OF ELEMENTS	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	1	0	1	0	0	0	0	0	0	1	1	0	0	0	0	0	0	
	ELEMENTS VARIATION	0	0	0	0	0	0	0	0	1	0	1	0	0	1	0	1	0	1	0	1	0	0	0	0	0	0	1	1	0	0	0	0	0	0	
	ASSEMBLY ERGONOMICS (C)	1	1	1	0	1	0	0	1	1	0	1	1	0	1	1	0	0	0	1	0	1	1	1	1	0	1	1	1	0	1	0	1	0	0	
	ASSEMBLY TIME	0	1	1	1	1	0	1	1	1	1	1	0	0	1	0	0	0	1	0	0	1	0	1	0	1	0	0	0	0	1	1	0	0	0	
	ASSEMBLY COMPLEXITY	0	1	1	0	0	0	0	1	1	0	0	0	0	0	0	0	0	1	1	0	1	0	1	0	0	0	1	0	1	1	0	0	0	1	
COMPONENTS TRANSPORTATION	VULNERABILITY	1	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	0	0	0	1	1	0	0	
	PIILING EFFICIENCY	0	1	0	0	1	0	0	1	1	0	0	1	1	0	0	0	0	0	0	0	1	0	1	0	0	0	1	0	1	1	0	0	0	1	
	LIFTING ERGONOMICS	0	0	1	0	0	0	0	1	1	1	1	1	1	0	0	1	0	1	0	1	0	1	0	0	0	1	0	1	1	1	0	0	1	0	
	WEIGHT	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
BUILDING ASSEMBLY	ASSEMBLY ERGONOMICS (B)	0	0	1	1	0	1	0	1	1	1	1	1	1	1	0	1	1	1	1	1	0	1	0	0	0	0	1	0	1	0	1	0	1	0	
	COMPONENTS VARIATION	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	
	BUILDING SPEED	1	1	1	0	0	0	1	1	1	1	1	1	0	1	1	0	1	1	1	1	0	1	0	1	0	1	1	1	1	1	0	0	0	1	0
SERVICES INSTALLATION	EASE OF INSTALLATION (BS)	0	0	1	1	1	0	0	1	1	1	1	0	0	1	0	1	1	1	1	1	1	1	0	0	0	1	0	1	1	1	0	0	0	1	0
	SAFETY	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
	POSSIBLE CLASHES	0	0	1	0	0	0	1	1	0	0	0	1	1	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0
	INSTALLATION TIME	0	0	0	0	0	0	0	1	1	0	0	0	0	1	1	1	1	1	0	1	1	0	1	0	1	0	1	0	0	0	1	0	0	0	0
FINISHES INSTALLATION	EASE OF INSTALLATION (F)	0	0	0	0	1	0	0	0	1	1	1	0	1	0	0	0	0	0	0	1	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0
	FINISHES APPLICABLE	1	0	0	0	0	0	1	0	0	1	1	0	0	1	1	0	0	0	0	1	1	0	0	0	0	0	1	1	0	0	0	0	1	0	0
	FINISH QUALITY	0	0	0	0	1	1	0	1	1	0	1	1	1	0	0	1	0	0	0	1	0	1	0	1	0	1	0	1	1	1	0	0	0	1	0
USE	ADAPTABILITY	0	0	1	1	1	0	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	
	MAINTENANCE	1	1	1	1	1	1	0	1	1	1	1	1	0	1	1	0	1	1	1	1	1	0	1	1	1	0	1	1	1	1	0	1	1	0	1
	ACCESSIBILITY	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	0	
	AESTHETICS	0	0	0	1	0	0	0	1	1	0	1	1	0	1	1	0	0	0	0	1	0	1	1	0	0	1	1	1	0	0	0	0	0	0	0
END OF LIFE	LIFESPAN	0	0	1	1	0	0	1	1	1	1	1	1	0	1	1	1	1	1	1	1	0	0	1	0	0	0	1	1	0	0	0	1	1	0	0
	DISASSEMBLY	0	0	1	1	1	0	0	1	1	1	1	1	0	1	1	1	1	1	1	1	1	0	1	0	1	1	1	1	1	1	1	1	0	0	1
	RE-USE	0	0	1	0	1	1	0	1	1	1	1	1	1	0	1	0	0	1	1	1	1	1	1	1	1	0	1	1	1	1	1	0	1	1	0

CRITERIA DEFINITION AND RELATED WEIGHT

On the facing page a version of the house of quality is displayed; it works as a matrix, listing the criteria on the left and top of it and systematically comparing them in order to finally give them a “weight” that gives insights on their overall importance. Starting from the first row, “freedom of design”, belonging to the “design” family is compared to each of the ones on top (except freedom of design itself). The question asked each time, for each row until the end is: do I consider criteria X more important than criteria Y? scoring 1 when it is considered more important and 0 when not. When the last row is filled each criteria gets a final score based on the sum of all the “wins” it got, the final score is finally converted in a number between 1 and 4 that defines its weight amongst all other criteria.

In the next page, a graph showing the first level of the assessment is displayed: on the left side of the graph the design alternatives and on the top row the criteria defined for the assessment. For each criteria the weight needs to be applied to get the final score of each design; every grade shown in the round shapes is multiplied by the weight of the corresponding criteria, the final sum gives the overall score of the design option. The first four criteria do not have any weight as they are actually not proper criteria but rather strict requirements in which every design alternative can either have a green light, meaning it satisfies the latter, a yellow light, meaning it barely satisfies it, or a red light, meaning that it is insufficient in that aspect. If a design alternative is assigned a red light it automatically fails the assessment as one of the strict requirements is not satisfied. Weight limitation for instance is a requirement that restricts the overall

weight of a component to maximum 50Kg, which means that if a design alternative weighs more than that it simply cannot be taken into account.

In the right side of the graph the overall weighted score of each alternative is shown and surrounded by a colored bubble that refers to the requirements. If an alternative scores very high but is surrounded by a red bubble this means that it has a high potential but if the aforementioned requirement is not satisfiable with some tweak to its design then it cannot be taken into account.

The score of each design gives some insights on its potential; obviously higher scores are more likely to be the final design but it is important to stress out that the overall assessment is not a scientific tool that gives as an outcome the objective best design. It is rather a tool that helps the designer to assess design options in a systematic way so that every single aspect is taken into account and nothing is left out. For this reason, the criteria should not only be seen as a single value but also as a family, reason why they were divided into groups in the first place.



