Source: AI SpaceFactory. (n.d.-a). AI SpaceFactory (@aispacefactory) | Instagram. Retrieved January 20, 2020, from https://www.instagram.com/aispacefactory/?hl=en, Edited by Thijs Koeleman

Student: Thijs Koeleman
Design Tutor: Henriëtte Bier
Research Tutor: Arwin Hidding
Building Technology Tutor: Ferry Adema

The construction industry of tomorrow implemented today

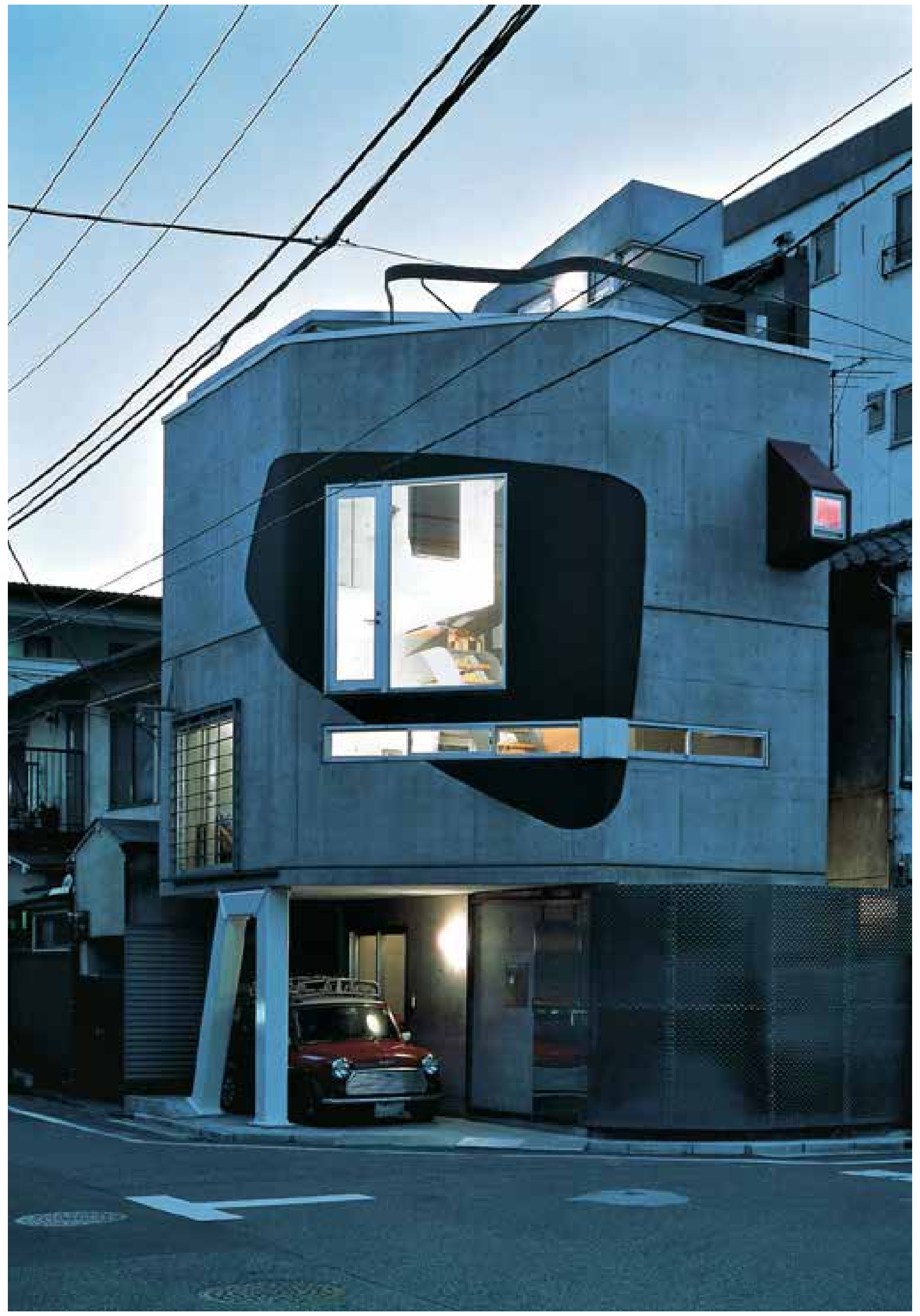
Research

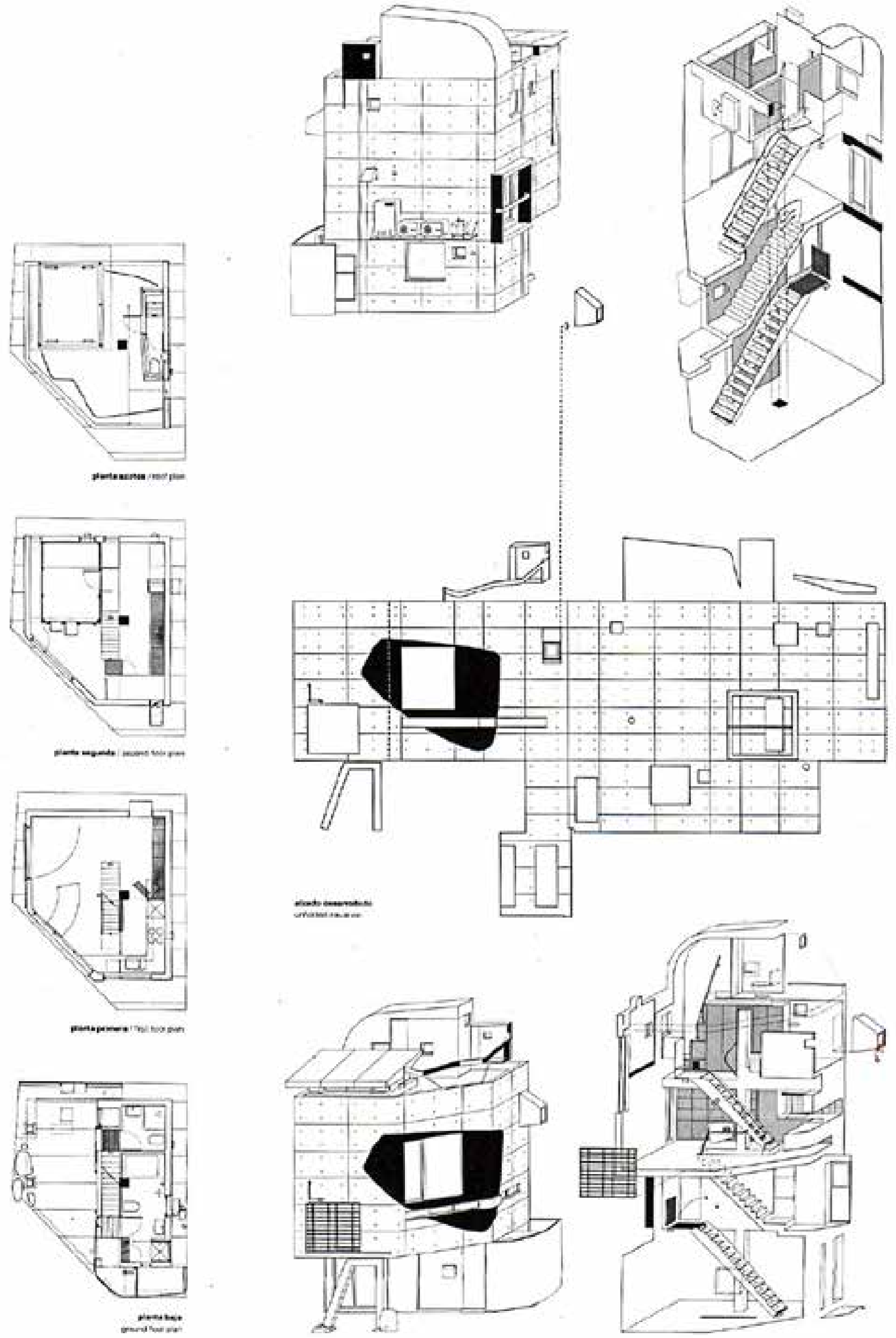
Content

Tiny/Parasitic House References

Suzuki House:

The Suzuki House is a project that shows both exterior and interior integration of functions to make a high quality tiny house. Several architectural elements determine the quality of the indoor space and the relation of this indoor space with the facade. Firstly the great height makes the space feel larger than it actually is. This height is not seen as wasted space because the bedroom is hanging in this space, providing a physical connection between the living room and the bedroom. Beside the great height, different types and sizes of windows make up for a lot of the facade. The Suzuki house is positioned on a corner and gets daylight from multiple facades, which enhances the overall light infall and the occupants' experience of a larger space. One last remark is about the interior furniture. There are three different types of stairs which are all related to their daily use. The main stairs are made like a normal stair, but stairs which are not used as often are designed totally differently to save space. For example the stairs to the toilet/roof terrace is very steep and is actually also a closet. The aspects of height, daylight and the integration of furniture are all very relevant aspects for the graduation project.





Source: Miyamoto, R., & Bolles + Wilson. (2019, February 2). Suzuki House / Bolles + Wilson [Illustration]. Retrieved from https://archeyes.com/suzuki-house-bolles-wilson/

Sou Fujimoto Architects/NA House

The NA House is made of different platforms with varying height that is in accordance with its function. This allows the building to include more functionality in the same amount of volume. Beside the fact that these platforms save space in the vertical direction, their connection and open character adds to the experience of this house, because every space seems bigger than it actually is. The platform concept is an important design principle that is used in the graduation project throughout the entire building. These platforms are also the way to move vertically through the building, because they are all connected via small and moveable steps.

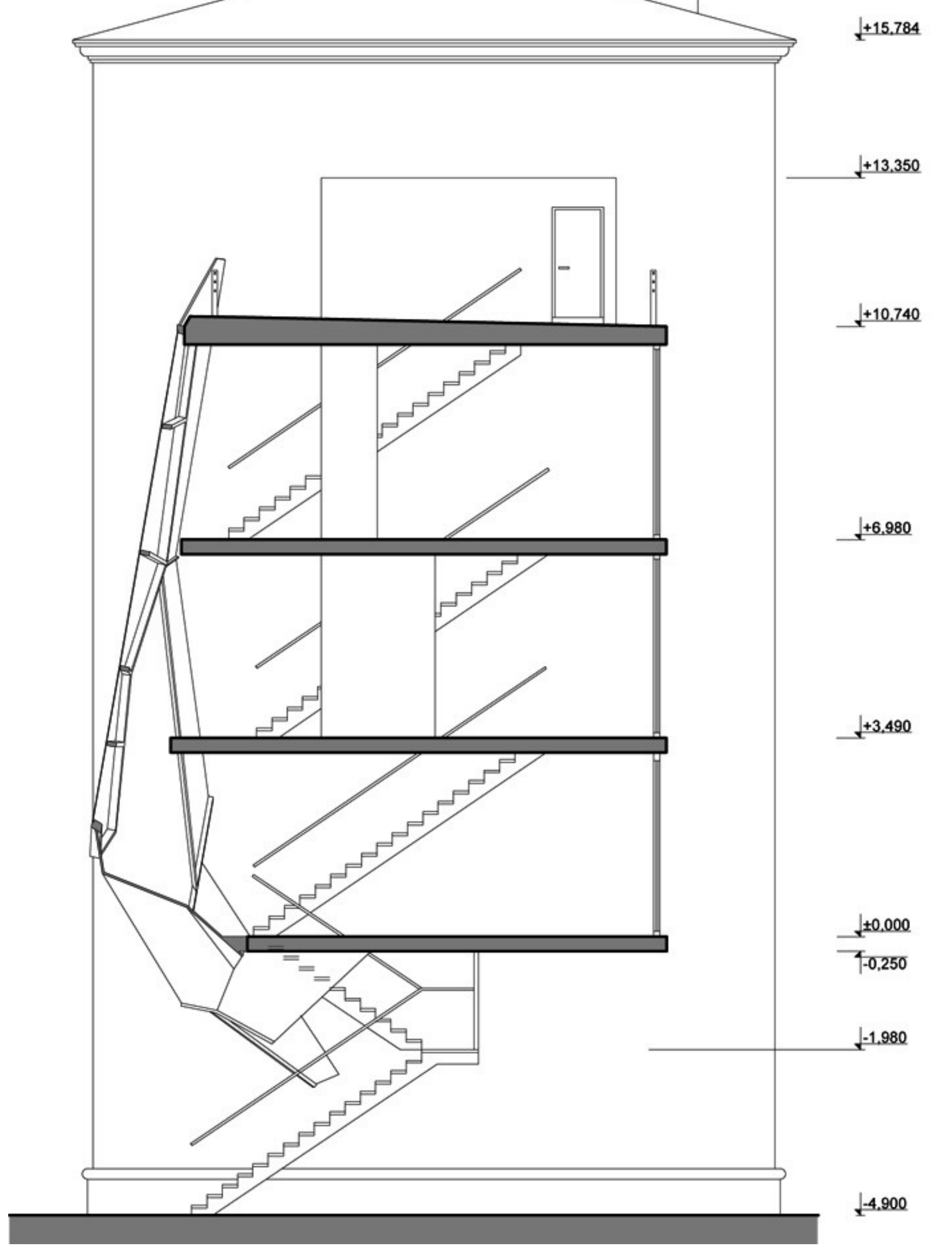


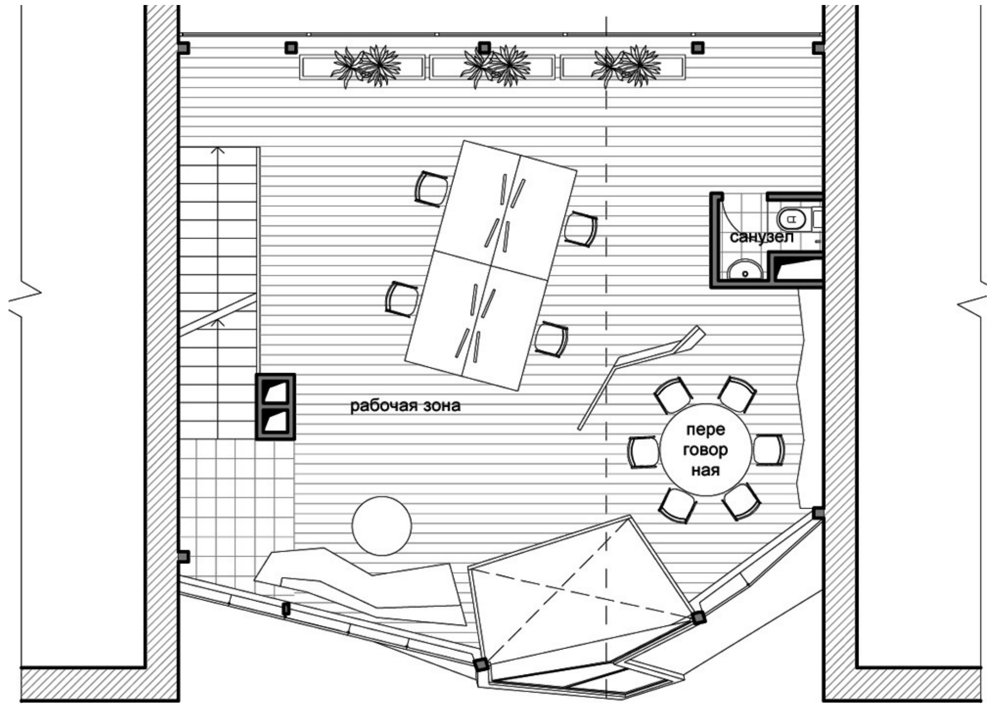


Source: Baan, I., & Sou Fujimoto Architects. (2012). House NA / Sou Fujimoto Architects [Photograph]. Retrieved from https://www.archdaily.com/230533/house-na-sou-fujimoto-architects

Parasitic Office

The parasitic office is a great example of how parasitic architecture can be implemented in the city and also contributes to the city with its appearance. Gaps in the city structure can be fixed with unconventional building volumes that make use of the location’s potential. In the case of the parasitic office the that means the dead facades on either side of the existing buildings serve as a basis to attach the building to. How this building is attached to the existing structure is something that should be considered. Does it use the existing structure and merge that one with the new one or is it placed against the dead walls with its own structure. Beside the fact this building finishes the city structure, it also functions as a building sized lantern post to provide a more safer way to cross from the open street space towards the inner courtyard. Design principles should emerge from the perspective of using existing buildings as an advantage as well as keeping those buildings in mind when designing.





Source:Zaytsev , P., & Za Bor Architects. (2011). Parasite Office / za bor architects [Photograph]. Retrieved from https://www.archdaily.com/138151/parasite-office-za-bor-architects

Locations

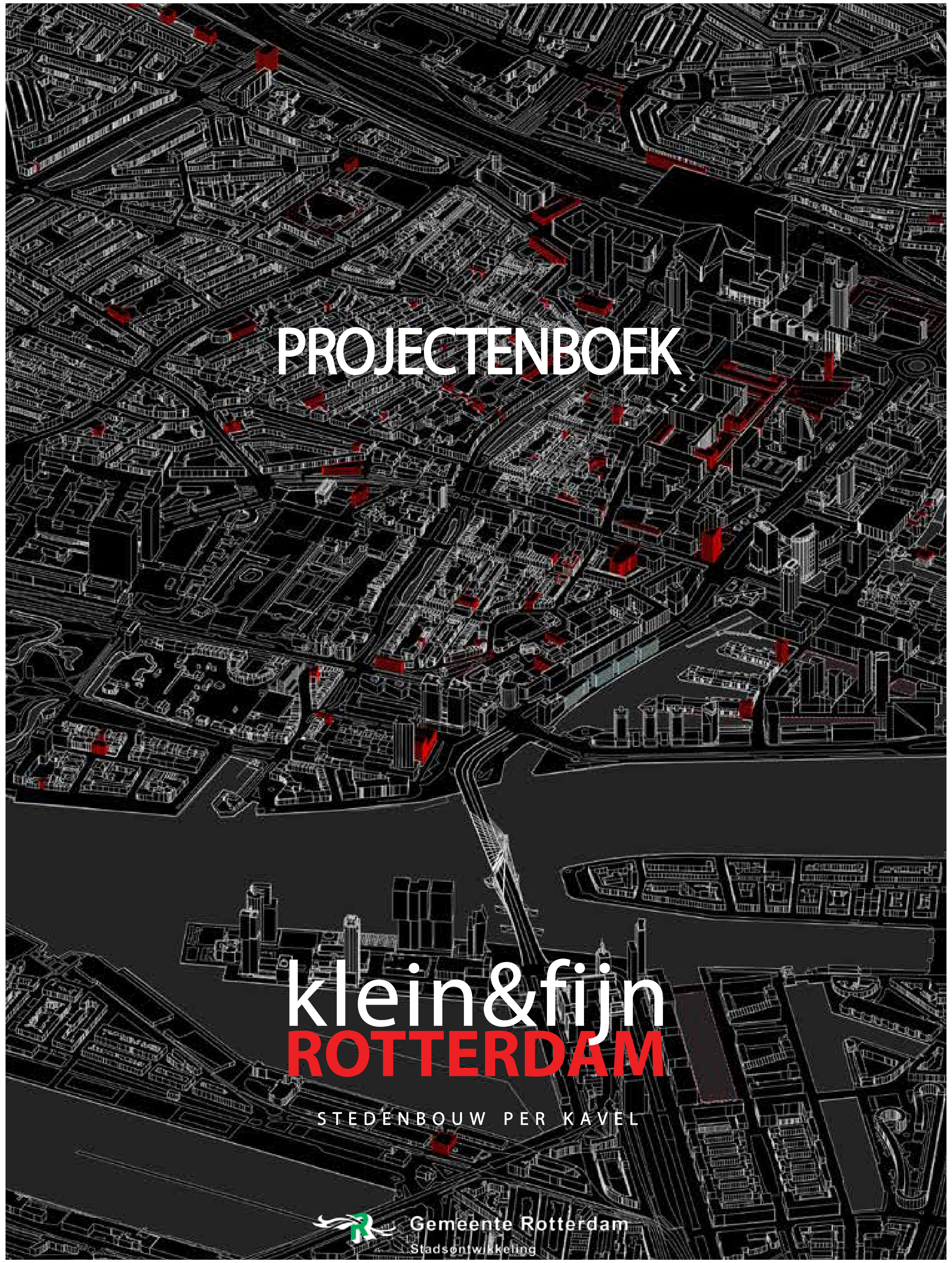
Locations Rotterdam

Introduction

When determining the most suitable location for the implementation of the graduation plan concept several large cities were investigated, namely Amsterdam, Rotterdam and The Hague. Rotterdam was chosen because of a report made by the municipality in collaboration with studio Hartzema, named Klein&Fijn, but also the innovative character of Rotterdam and its buildings is mostly suited for this graduation project.

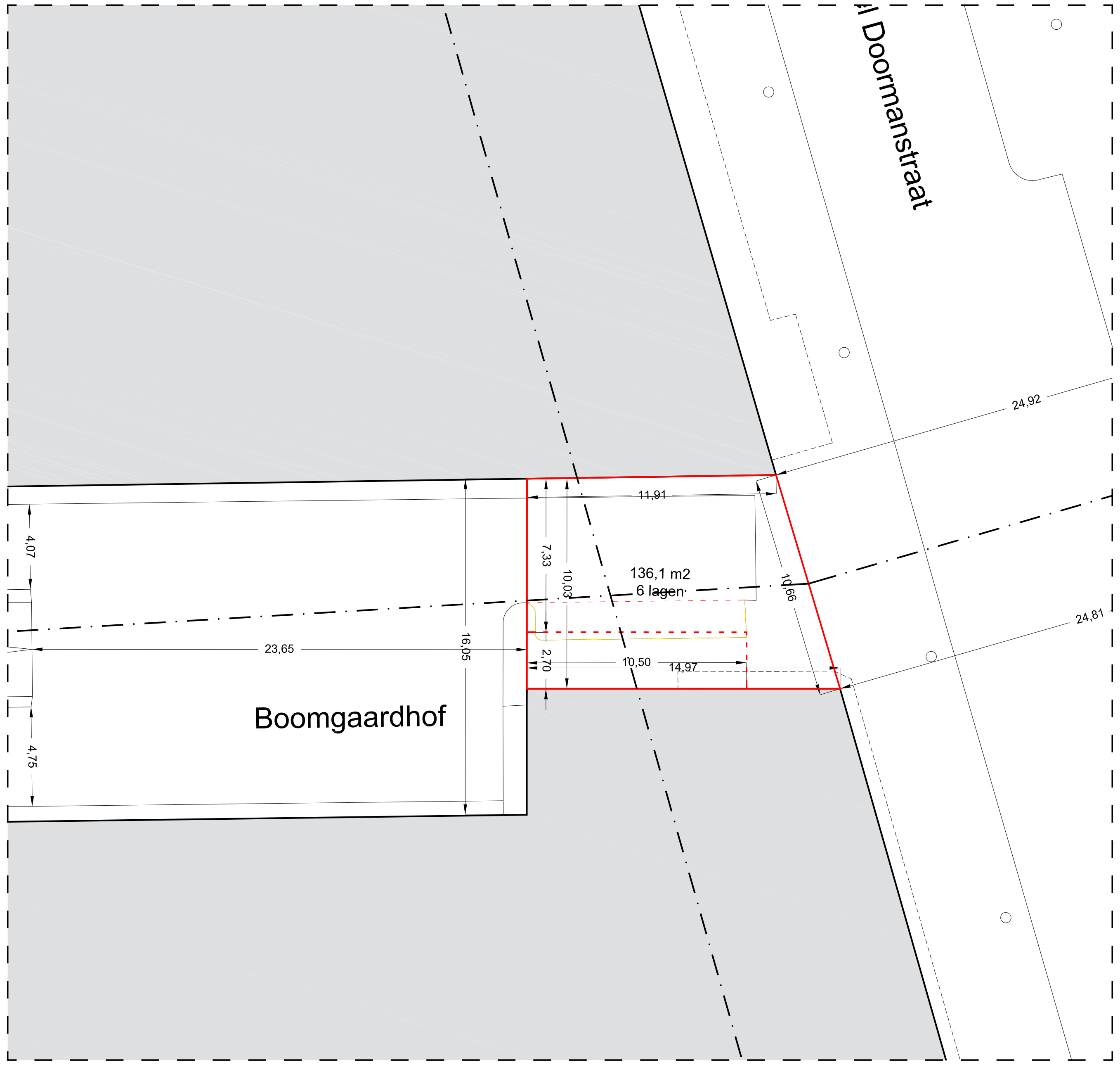
This report shows all possible (small) locations in the city center of Rotterdam where new building volumes would be beneficial for the city structure. From those locations four of them were chosen based on a number of requirements. One of the most important aspects of these locations is that they should be both near to a public transport station as well as contribute to the existing city structure. Another feature was the smaller plot size, because in the case of a smaller plot size the 3D printer can unfold its true potential in creating a specific solution for each location.

One of the goals of the graduation project is to design a building for these small plots that can be parametrically made. This way a lot of locations in the city can be densified using the same algorithm, while still maintaining design freedom due to the fact of many different parameters, and of course the uniqueness of each single location. These small architectural interventions will not only contribute to the city of Rotterdam, but also can densify cities at a fast rate to reach 1 million homes in 2030.

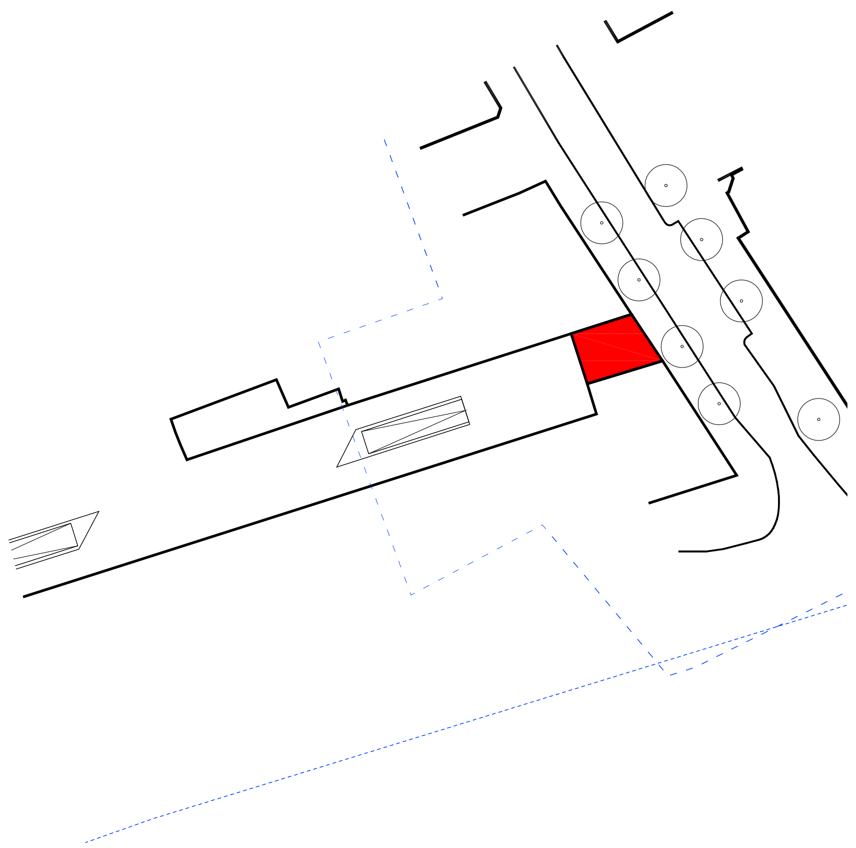


Source: Studio Hartzema BV, & Stadsontwikkeling Rotterdam. (2012). Rotterdam Klein & Fijn - Stedebouw per kavel. Retrieved from https://www.studiohartzema.com/werken/rotterdam-home-town/

Karel Doormanstraat



LOCATIE
schaal 1:200



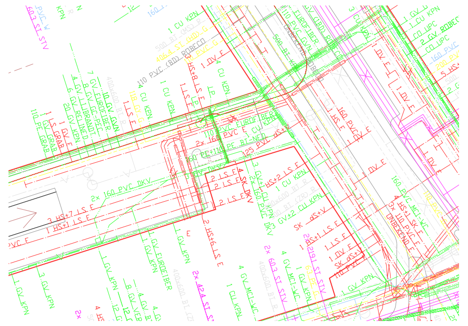
HORIZONTALE DOORSNEDE
schaal 1:1000

Karel Doorman-straat — A10

footprint: 136m2
hoogte: 18m
fsi: 6
grootte: 816m2 BVO

situatie: Opening in straatwand
mogelijkheid: Straatwand sluiten
kans: Versterken straatbeeld Karel Doormanstraat
risico: Het aangrenzende pand aan de noordkant bevat ramen, bovendien is het aangrenzende pand aan de zuidzijde momenteel in ontwikkeling
kabels en leidingen: Ja

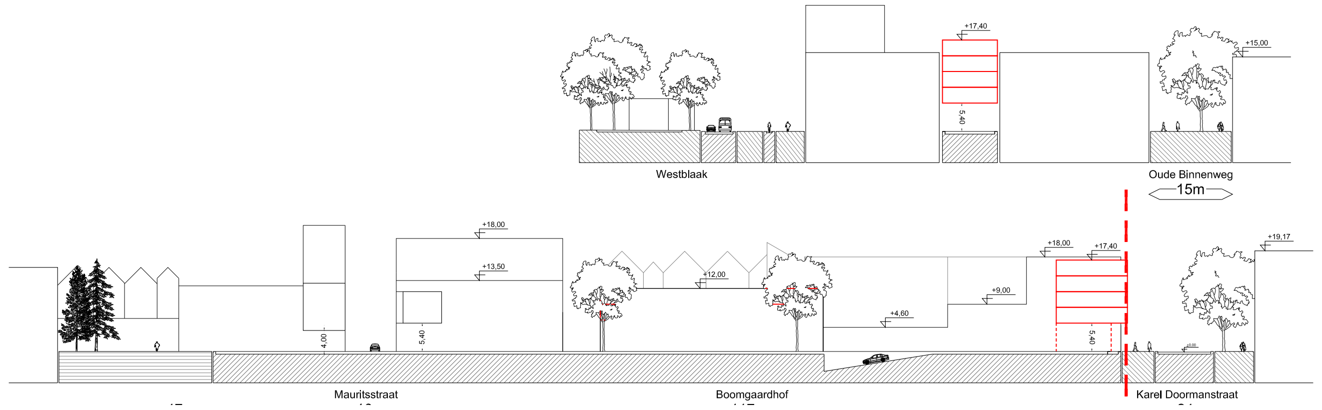
Doordat de Karel Doormanstraat iets gedraaid ligt t.o.v de Westblaak, kijkt men bij het binnenkomen van de Karel Doormanstraat in de Boomgaardhof en tegen de blinde gevel van de La Place. Het dichtzetten van deze grote opening zorgt voor een aangesloten straatwand en een betere introductie van de het Lijnbaankwartier. De onderdoorgang voor expeditieverkeer en de toerit tot de parkeervoorzieningindeBoomgaardhofdienen gehandhaafd te blijven. Daar boven is ruimte voor een aantal lagen woningen met een entree in de onderdoorgang. De architectuur van de panden aan weerszijden van het bestaande gat lijkt niet de voor de hand liggende drager van een eventueel bruggebouw. Het is daarom wenselijk te onderzoeken of de invulling op de grond komt te staan met inbegrip van de eerder genoemde onderdoorgang.



KABELS EN LEIDINGEN

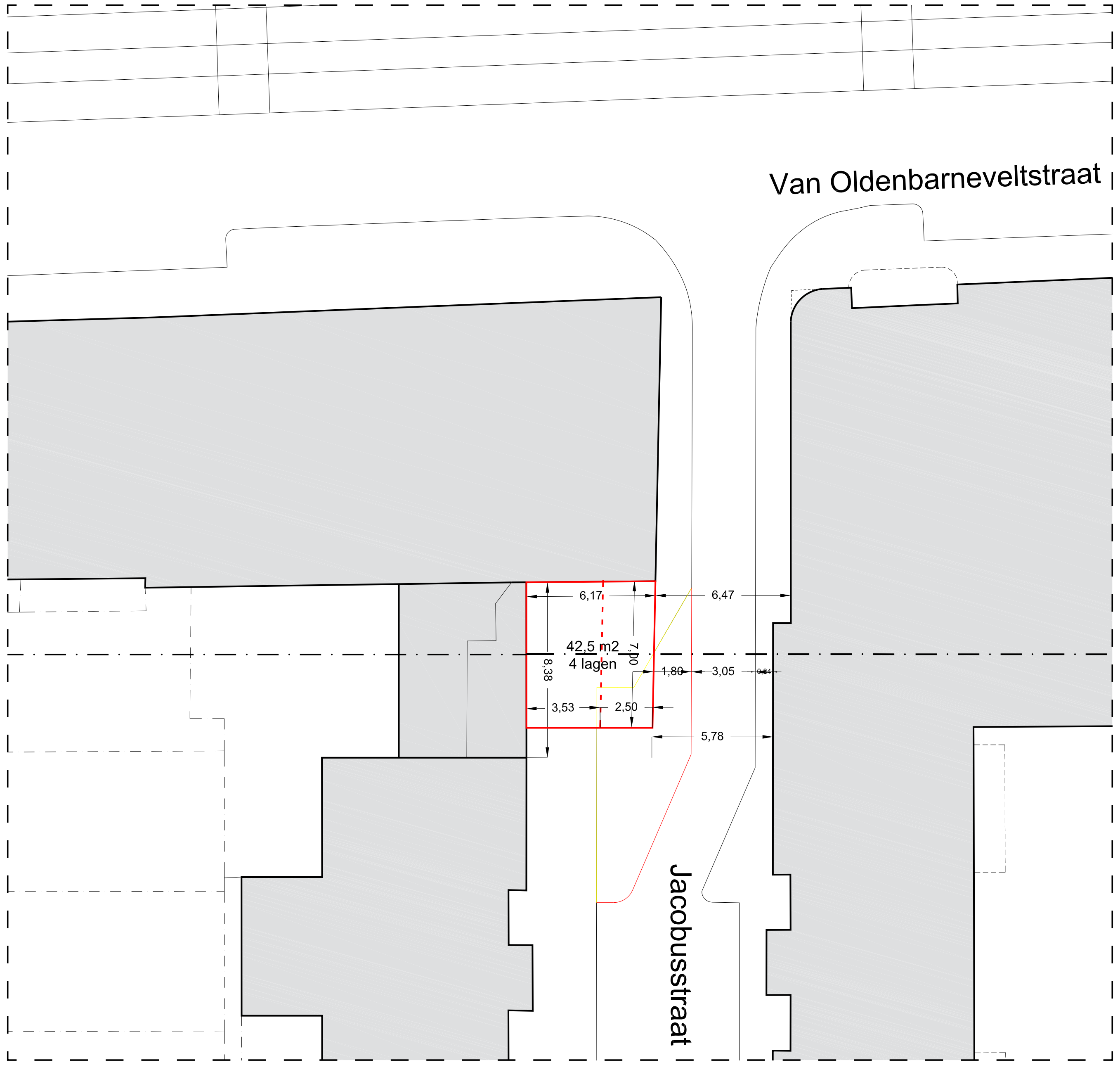
EIGENDOMSSITUATIE

LUCHTFOTO SITUATIE

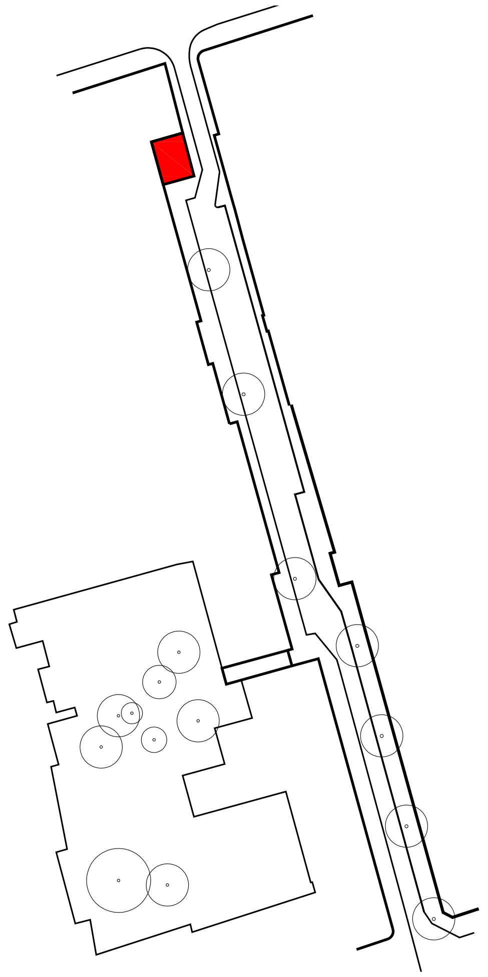


Source: Studio Hartzema BV, & Stadsontwikkeling Rotterdam. (2012). Rotterdam Klein & Fijn - Stedebouw per kavel. Retrieved from https://www.studiohartzema.com/werken/rotterdam-home-town/

Jacobusstraat A



LOCATIE
schaal 1:200



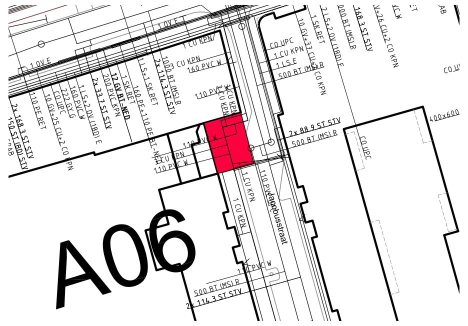
HORIZONTALE DOORSNEDE
schaal 1:1000

Jacobusstraat	A06

footprint: 42m2
hoogte: 12m
fsi: 4
grootte: 170m2 BVO

situatie: Achterzijde pand Oldebarneveldstraat
kans: 1 grondgebonden woning, de straat afmaken en verlevendigen
risico: Naastgelegen bloemenwinkel
kabels en leidingen: Ja

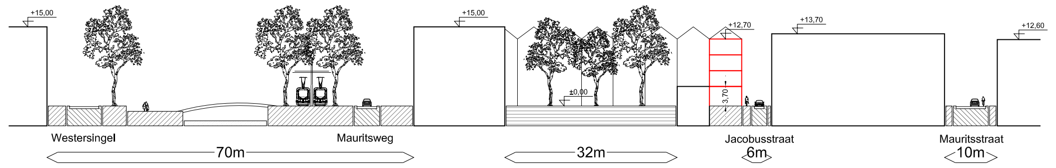
Aan het einde van de Jacobusstraat vernauwt de vooroorlogse bebouwing van de Van Oldenbarneveltstraat de straatruimte. De oorspronkelijke Jacobusstraat was maar 6,50m breed. Een invulproject uit de jaren '80 ligt 6 meter terug waardoor de nieuwe straatbreedte 12 meter is geworden. Deze extra breedte komt weer overeen met de pandbreedte aan de Van Oldenbarneveltstraat. Hierdoor staat het hoekpand volledig vrij en met een dichte kopgevel 'in' de straat. De lage uitbouw tussen het buurpand en de bebouwing in de Jacobusstraat is onlangs door bloemisterij Zomers in gebruik genomen als achteringang. Ter plaatse van de sprong in rooilijn zou een klein volume kunnen worden gerealiseerd dat de straat in kijkt. Wellicht een kleine woning en/of studio die alle randvoorwaarden van de plek in zich opneemt.



KABELS EN LEIDINGEN

EIGENDOMSSITUATIE

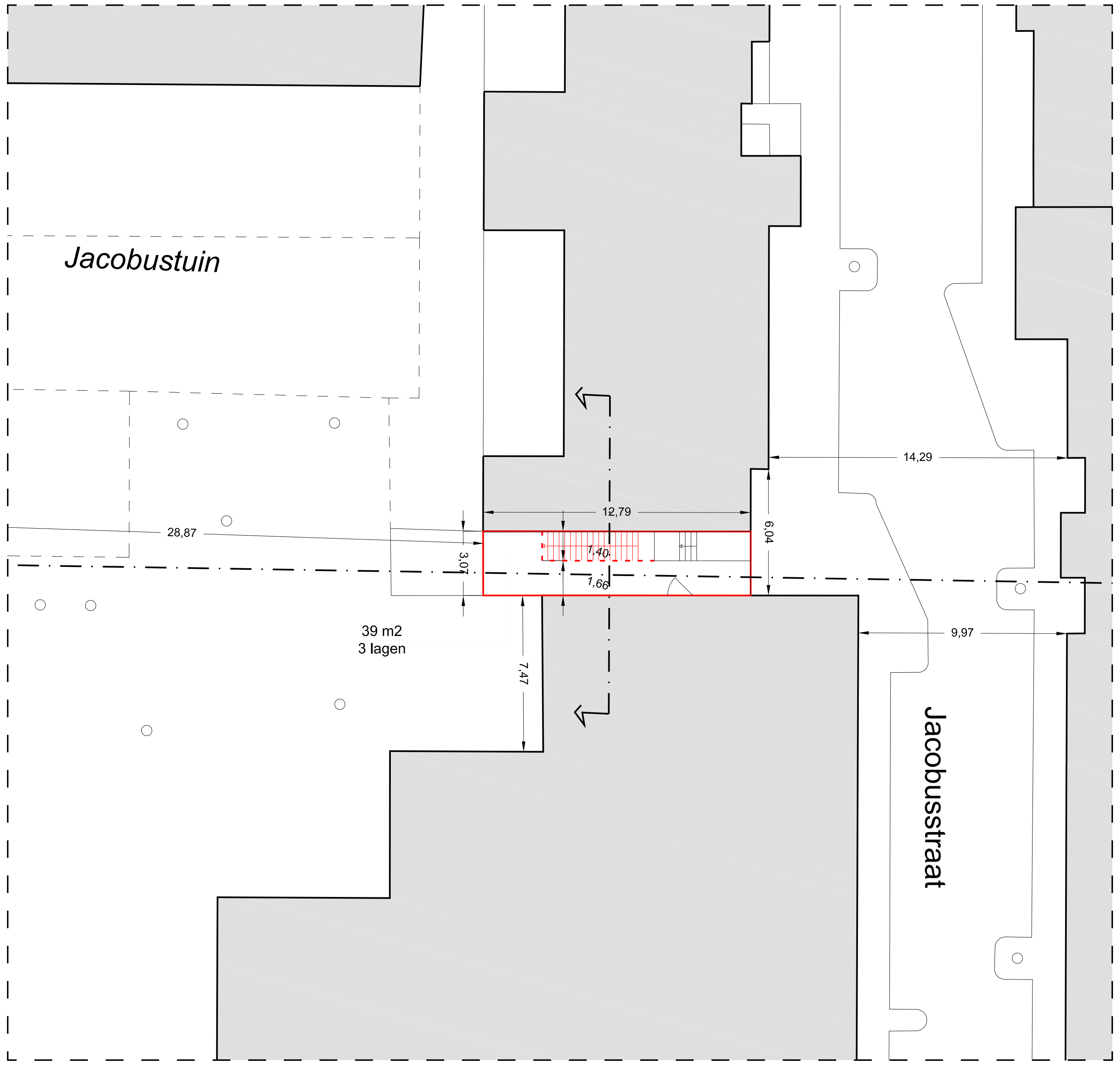
LUCHTFOTO SITUATIE



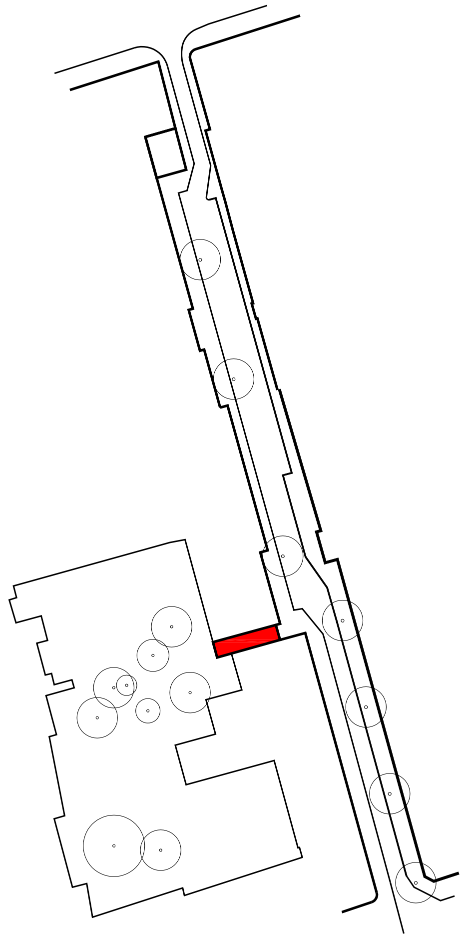
VERTICALE DOORSNEDE
schaal 1:1000

Source: Studio Hartzema BV, & Stadsontwikkeling Rotterdam. (2012). Rotterdam Klein & Fijn - Stedebouw per kavel. Retrieved from https://www.studiohartzema.com/werken/rotterdam-home-town/

Jacobusstraat B



LOCATIE
schaal 1:200



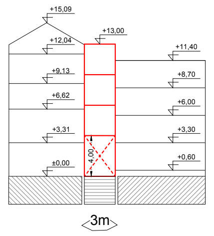
HORIZONTALE DOORSNEDE
schaal 1:1000

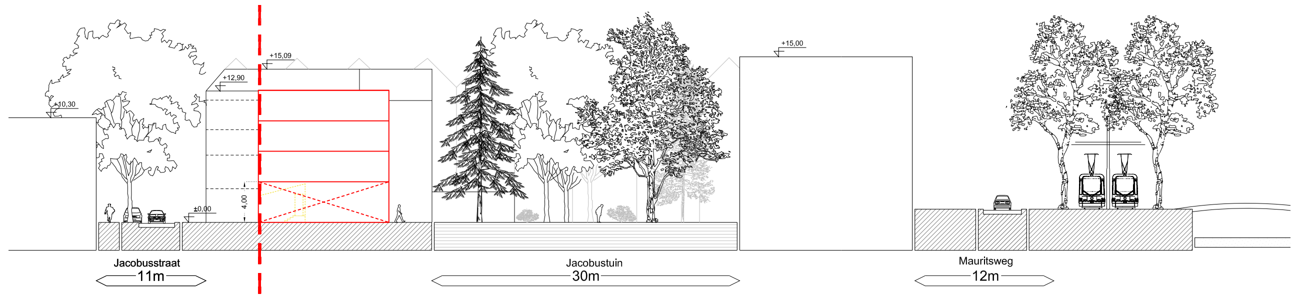
FOTO SITUATIE

EIGENDOMSSITUATIE

- vol eigendom
- gedeeltelijk eigendom
- vol eigendom
- erfpacht verkregen
- recht van opstal verleend
- recht van opstal verkregen
- overige zakelijke rechten verleend
- overige zakelijke rechten verkregen
- derden, niet zijnde gemeente
- onbekend

LUCHTFOTO SITUATIE





VERTICALE DOORSNEDE
schaal 1:500

Jacobusstraat — A14

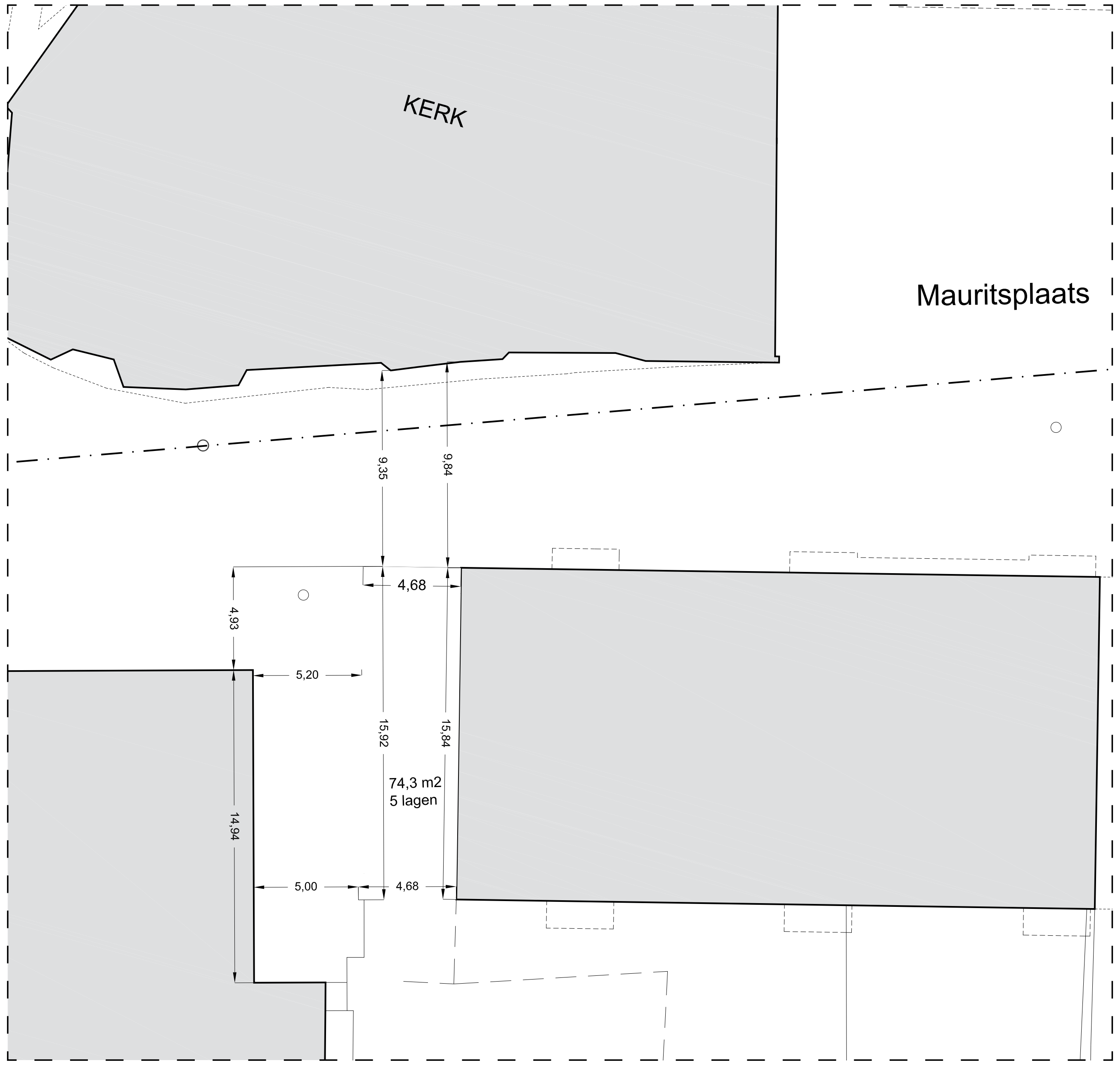
footprint: 39m2
hoogte: 13m
fsi: 3
grootte: 117m2 BVO

situatie: Smalle gang tussen twee gebouwen mogelijkheid: Entree van binnentuin overbouwen
kans: Naad tussen oud- en nieuwbouw repareren
risico: Integratie van de entrees van de naastgelegen appartementen
kabels en leidingen: Nee

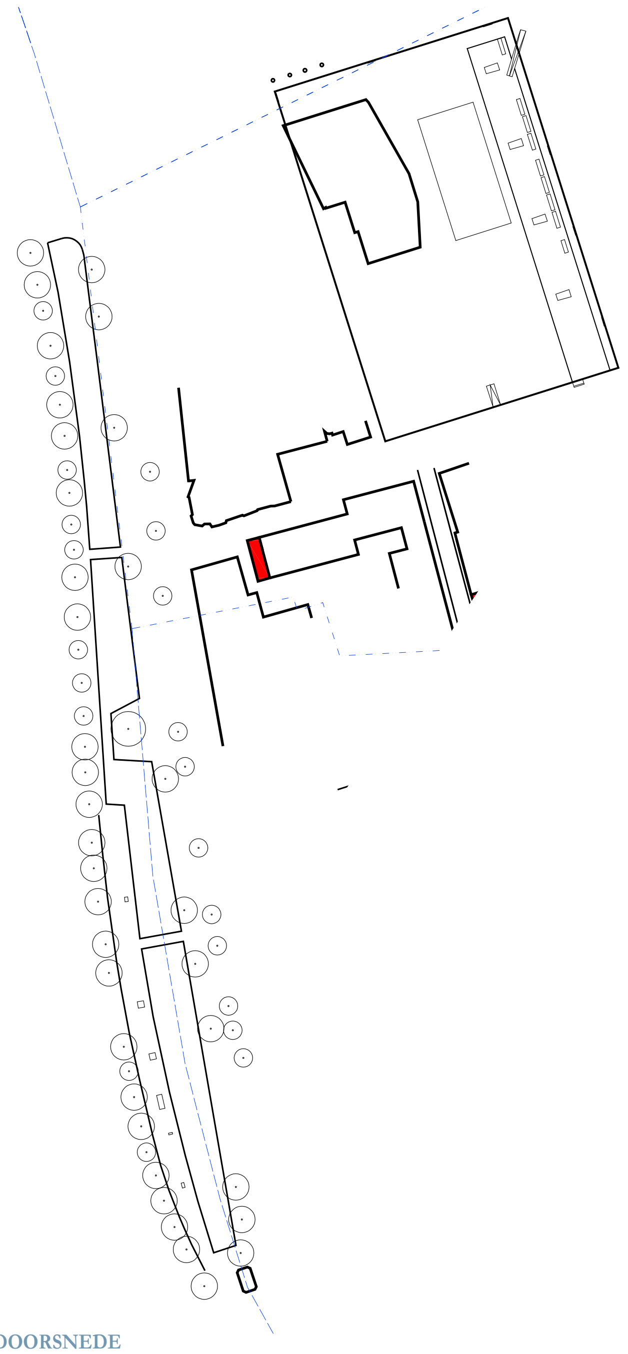
De Jacobustuin is een bijzondere groene plek in de binnenstad. Verscholen in een bouwblok ligt de tuin als een groene oase in de luwte van de binnenstedelijke dynamiek. Een waardevolle stilteplek in de binnenstad. De toegang van de tuin, een donkere steeg, is onopvallend en oogt weinig aantrekkelijk. Het invoegen van een woning in deze steeg kan de entree op bijzondere wijze accentueren en van meer kwaliteit voorzien. Bovendien is het een unieke woonlocatie. In de Jacobusstraat is de aanwezigheid van de brandgrens sterk voelbaar. Aan de zuidzijde staat bebouwing die de WOII heeft overleefd. Ten noorden hiervan zijn in de jaren '70 de straatwanden opnieuw gemaakt. Deze bebouwing volgt een onregelmatig belijning waardoor de breuk van de brandgrens meer dan een stijlbreuk is geworden. Op één plaats sluit de bebouwing ook niet op elkaar aan. Hier is een doorgang ontstaan naar de schitterende Jacobustuin. Deze doorgang is smal (3 meter) maar in potentie een uitgelezen plek voor een opgetilde woning. Deze interventie zou een aantal zaken tegelijk moeten oplossen. Namelijk het maken van een koppeling van de bouwblokken aan weerszijden, het upgraden van de portiek van het jaren '70 complex en als laatste de verbeterde toegang tot de Jacobustuin. De charme van de woning is gelegen in de bijzonderheid van plek in combinatie met een uitzonderlijk smalle plattegrond.

Source: Studio Hartzema BV, & Stadsontwikkeling Rotterdam. (2012). Rotterdam Klein & Fijn - Stedebouw per kavel. Retrieved from https://www.studiohartzema.com/werken/rotterdam-home-town/

Mauritsplaats



LOCATIE
schaal 1:200



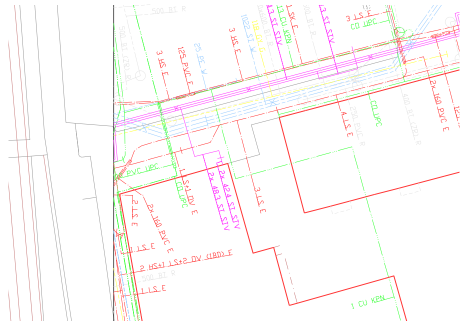
HORIZONTALE DOORSNEDE
schaal 1:2000

Mauritsplaats **A15**

footprint: 74m2
hoogte: 15m
fsi: 5
grootte: 370m2 BVO

situatie: Open plek langs lange lijn Meent, Aert van Nesstraat, Schouwburgplein en Mauritsplaats
mogelijkheid: Inpassing klein bouwvolume
kans: Verbeteren leesbaarheid en levendigheid van de straat
risico: Huidig gebruik (achter hekwerk)
kabels en leidingen: Nee

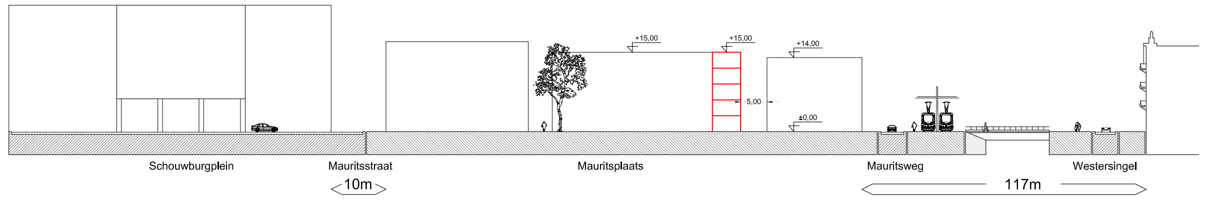
De locatie betreft een open plek langs een van de lange lijnen die door het centrum loopt. Een fragment van deze lijn, de Mauritsplaats, verbindt twee belangrijke stedelijke ruimtes; de Westersingel en het Schouwburgplein. De rooilijn is op dit fragment behoorlijk inconsistent en verspringt regelmatig. Dit creëert open, onbenutte plekken langs de lijn waardoor kansen voor een klein bouwvolume ontstaan. De locatie profiteert van de middag en avondzon. Het heelt de nu onbeduidende begrenzing van de straat en geeft de straat een gezicht of duidelijke voorkant. Op de begane grond liggen kansen voor een publiek programma dat bijdraagt aan de stedelijke dynamiek langs deze straat. De zorgvuldigheid van de ingreep houdt verband met tegenstrijdigheid van de krappe maatvoering van de locatie enerzijds en de wens tot een extraverte uitstraling anderzijds. De toegang van de Westersingel tot het Lijnbaankwartier krijgt een gezicht.



KABELS EN LEIDINGEN

EIGENDOMSSITUATIE

LUCHTFOTO SITUATIE



VERTICALE DOORSNEDE
schaal 1:1000

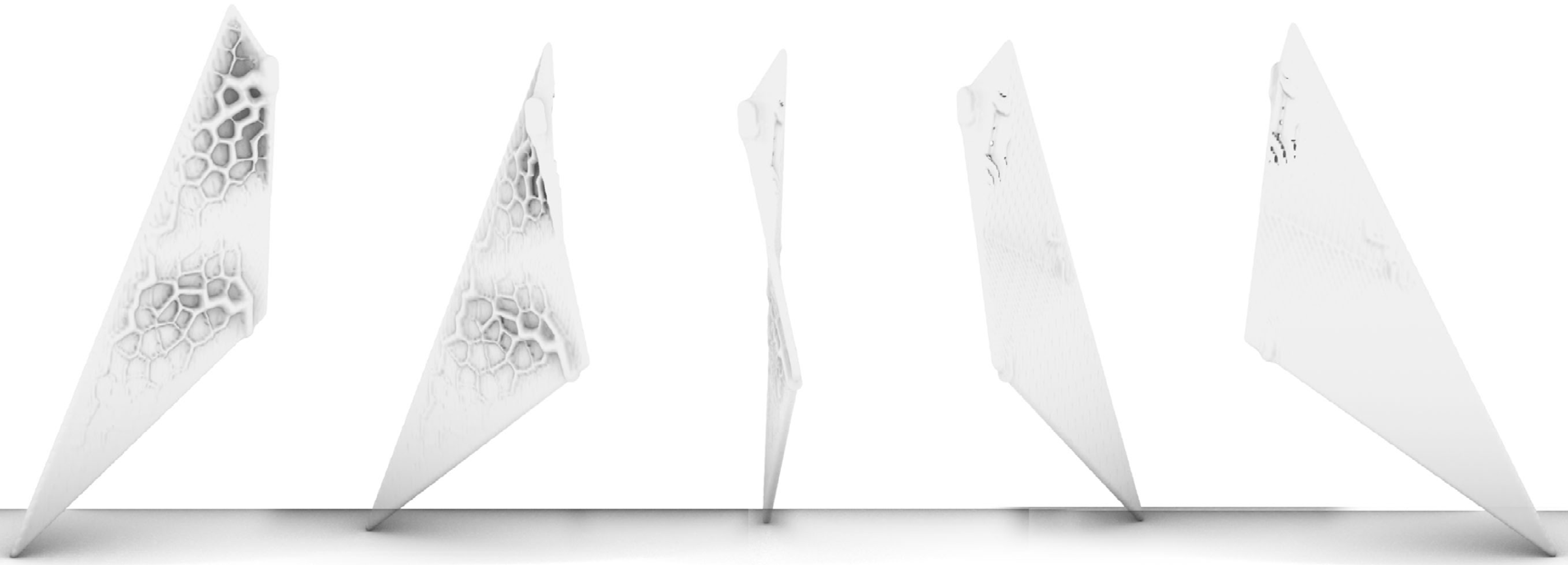
Source: Studio Hartzema BV, & Stadsontwikkeling Rotterdam. (2012). Rotterdam Klein & Fijn - Stedebouw per kavel. Retrieved from https://www.studiohartzema.com/werken/rotterdam-home-town/

Research Workshop

Graduation Studio
Architectural Engineering
Robotic Building

Student: Thijs Koeleman
Design Tutor: Henriëtte Bier
Research Tutor: Arwin Hidding

RESEARCH REPORT
workshop 01



Workshop introduction

During the first semester of 2019/2020 one workshop has been conducted that introduced the design to robotic production process. In this workshop we were encouraged to develop a design that informs our own thesis design.

The starting point of this workshop were the random beams as seen in figure on the right. These beams could be seen as the main structure of a building whereas the challenge was to make certain add-ons to these beams to make it a complete 'building'. The main objective was to design a panel for a building envelope that has multiple functions integrated. The main driver behind the concept of integrating different functions into one envelope is that it will become possible to use less materials and is overall a smarter skin compared to the facades that are built right now. To see the implications of integrating different functions we started with only two aspects. These aspects were chosen out of personal preference and are respectively acoustics and structure.

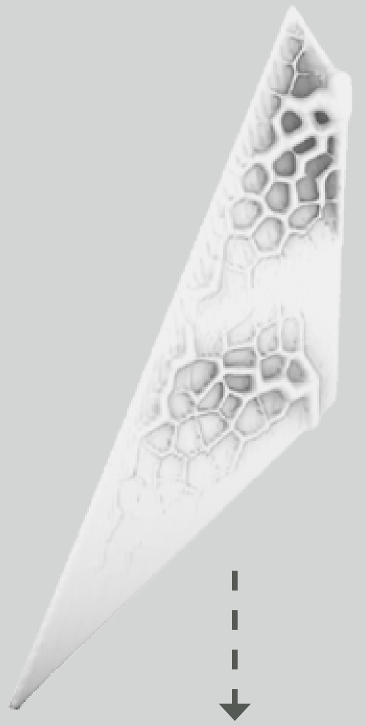
This research report consists of three parts:
A. Relation with thesis
B. D2RP process + discussion
C. Reflection
Whereas this introduction and part B. is co-authored with Thomas Geraedts

Relation with Thesis

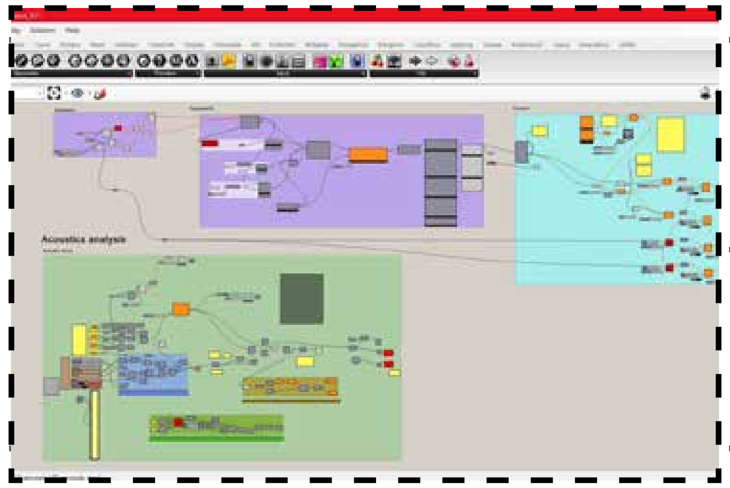
A

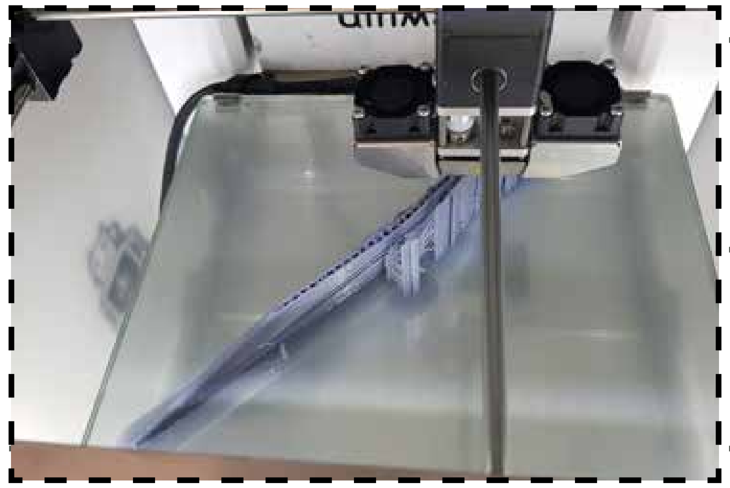
Workshop

Generative virtual model



3D printed prototype





How to integrate different functions into a mono material envelope that uses the potential of the 3D printing technique?

- Computational knowledge about generative design in grasshopper
- Integrating different functions, but also systems in envelope
- Until what level should functions be integrated?
- 3D printing technique for on site printing (layered, lattice, etc.)?
- Mono-material printing for different types of functions
- Porosity of structure tiny house?

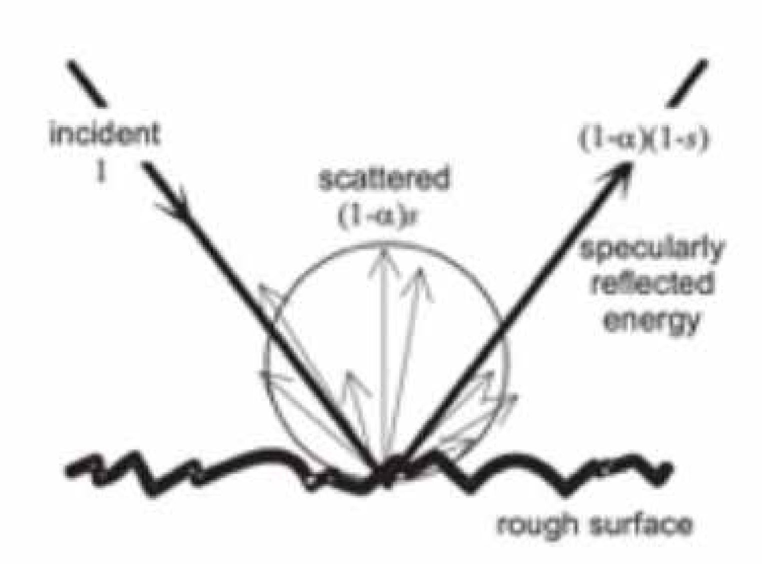
Thesis

Acoustic Research

Sound quality or acoustics can be divided into direct and indirect sound coming from a sound source. The combination of direct, first order and second order reflections of sound determine the overall quality of acoustics. The sound source produces energy, which is traveling towards a surface, then transmitted, reflected or absorbed. The energy which hits the surface is distributed into one of the three mentioned [...], the extent is dependent on the material's acoustic properties. Relating this to architectural terms, large flat surfaces generate strong specular reflection, which refers to second order delayed sound waves hitting the receiver (Cox & d'Antonio, 2016). This is unwanted and can be optimized through morphology. Diffused or scattered sound waves are pleasant in combination with the necessary absorption in a room. Hence, creating dispersed sound waves is the aim, which loses energy in the process of scattering and transform into background noise.

In architecture the term acoustics refers to the performance of sound based on reflection, absorption and diffusion in a room. To increase interior comfort it is eminent to decrease direct reflection and thus, create a scattering geometry in order to transform noise sources into ambient background sound (figure 1, Cox & d'Antonio, 2016). Furniture (e.g. sofa, carpet, curtains, etc.) is capable of absorbing a part of the emitted sound waves, because of its porous material properties these waves keep 'bouncing' and thus losing significant energy. Hence, researching diffusion as integrated functionality is interesting in order to determine the effects of different surfaces in architectural scope in order to increase the acoustics while having optimized structural features.

Figure 2 (Cox & d'Antonio, 2016)



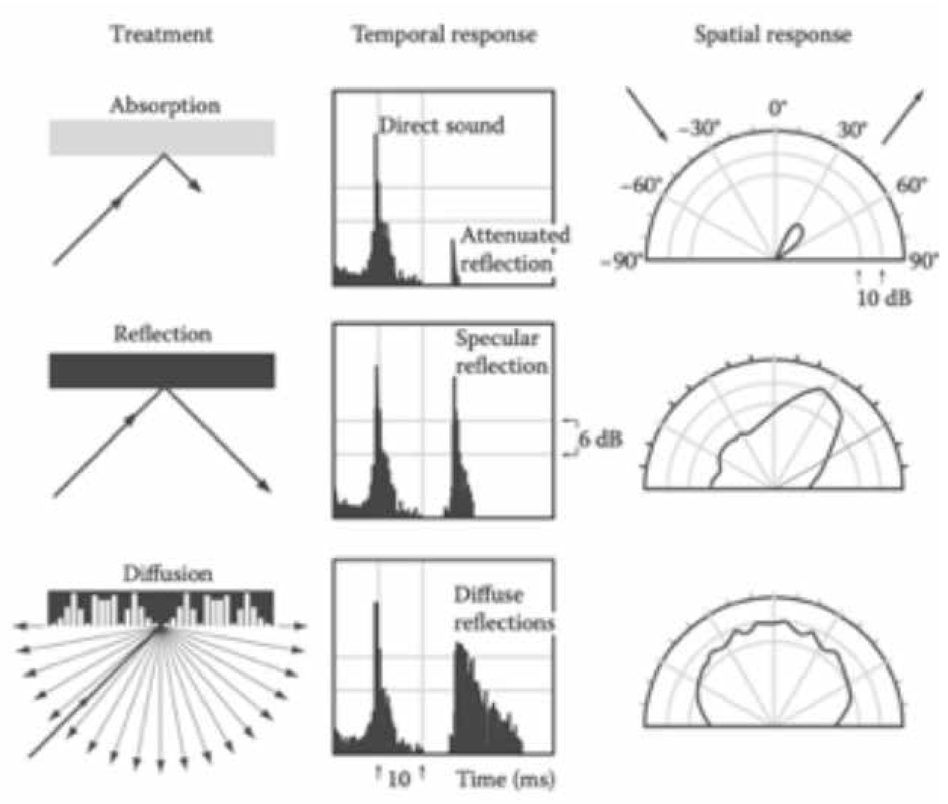


Figure 1 (Cox & d'Antonio, 2016)

Cox, T., & d'Antonio, P. (2016). Acoustic absorbers and diffusers: theory, design and application. Crc Press.

Structure Research

The difference between structural optimization with conventional methods and new, additive techniques is the level of complexity and the different amount of possible solutions. Current practices rely primarily on the use of concrete, steel and wood. These are manufactured in predetermined sizes and dimensions. The 3D printer changes this approach completely because it can print almost any form on demand. In doing so, it places only precious material on places where needed without losing performance. This structural optimization is only possible with additive manufacturing technologies. To know how much material is needed in what place, an analysis of the possible forces should be conducted. The manner in which these forces are transported from the panel to the main structure defines the local thickness the panel needs.

Figure 3: Optimization of structure in nodes (Galjaard et al., 2015)

Galjaard, S., Hofman, S., Perry, N., & Ren, S. (2015). Optimizing Structural Building Elements in Metal by using Additive Manufacturing. Presented at the International Association for Shell and Spatial Structures (IASS), Amsterdam, The Netherlands. Retrieved from https://www.arup.com/projects/additive-manufacturing

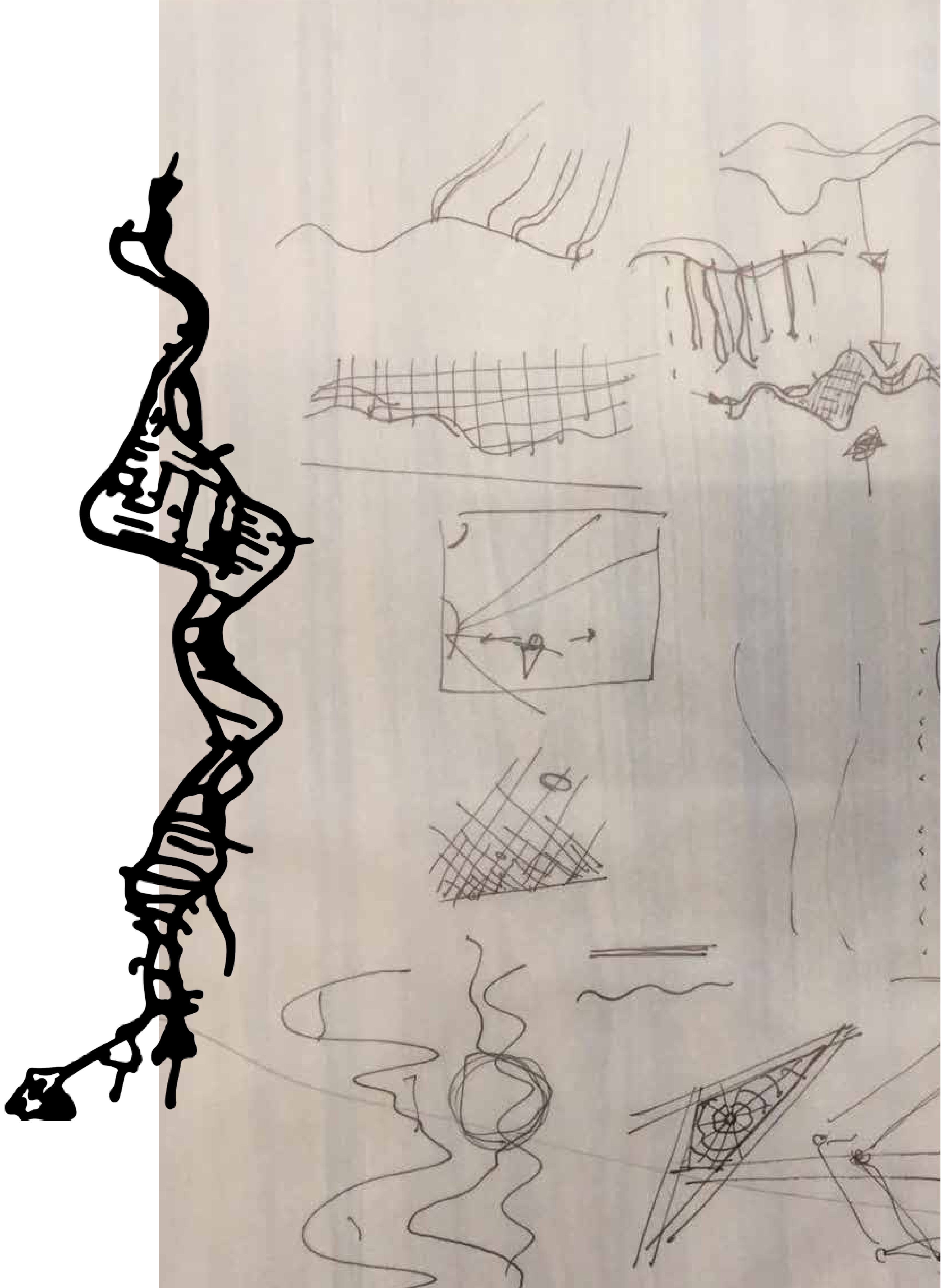
Workshop 01

Considering the research about both structural and acoustic design as our starting point we developed some design principles. Firstly these functions should be integrated by using only one material, because that material is the leading factor in our thesis design, namely plastic. This is a hard material, so in order to design an acoustic panel the surface should be rippled. A rippled surface means for the structural design that it should have many different small sized beams that form the structure of the panel. This way the concept would have both used the requirements of the acoustic research, as well as the possibilities and potentials of the structural research. We started sketching these principles into a lot of different variants.

Eventually after sketching for a while we discussed them based on the level of integration, complexity and the feasibility. The concept should be simple and straightforward to communicate and to develop further into a prototype. We chose the concept as seen in the drawing. This drawing has the highest potential of integrating the two functions into a single panel element because it relies primarily on an irregular surface that is created by thickened stress lines of possible forces.

Conceptual Design

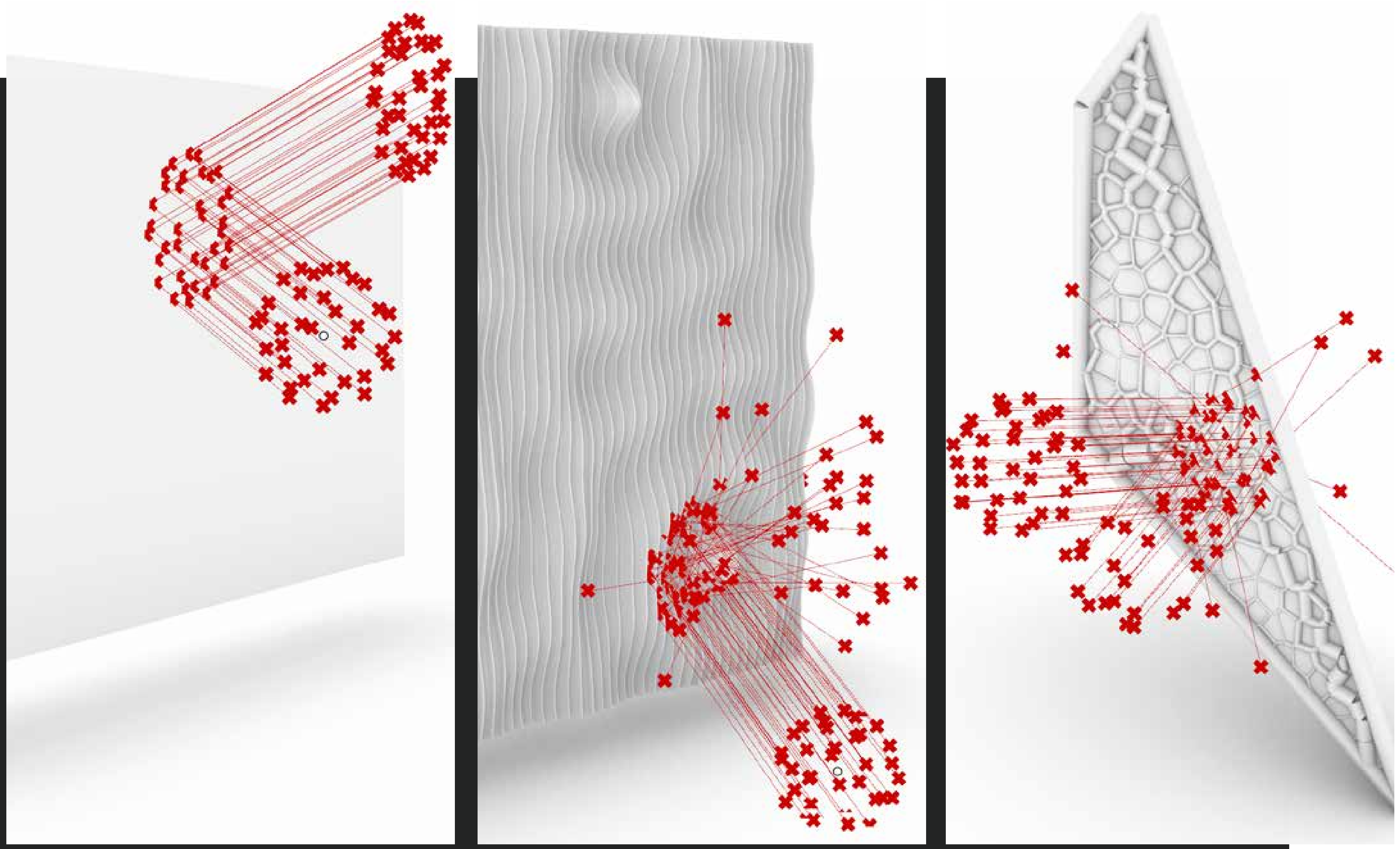
Section integrated panel



Workshop 01

B

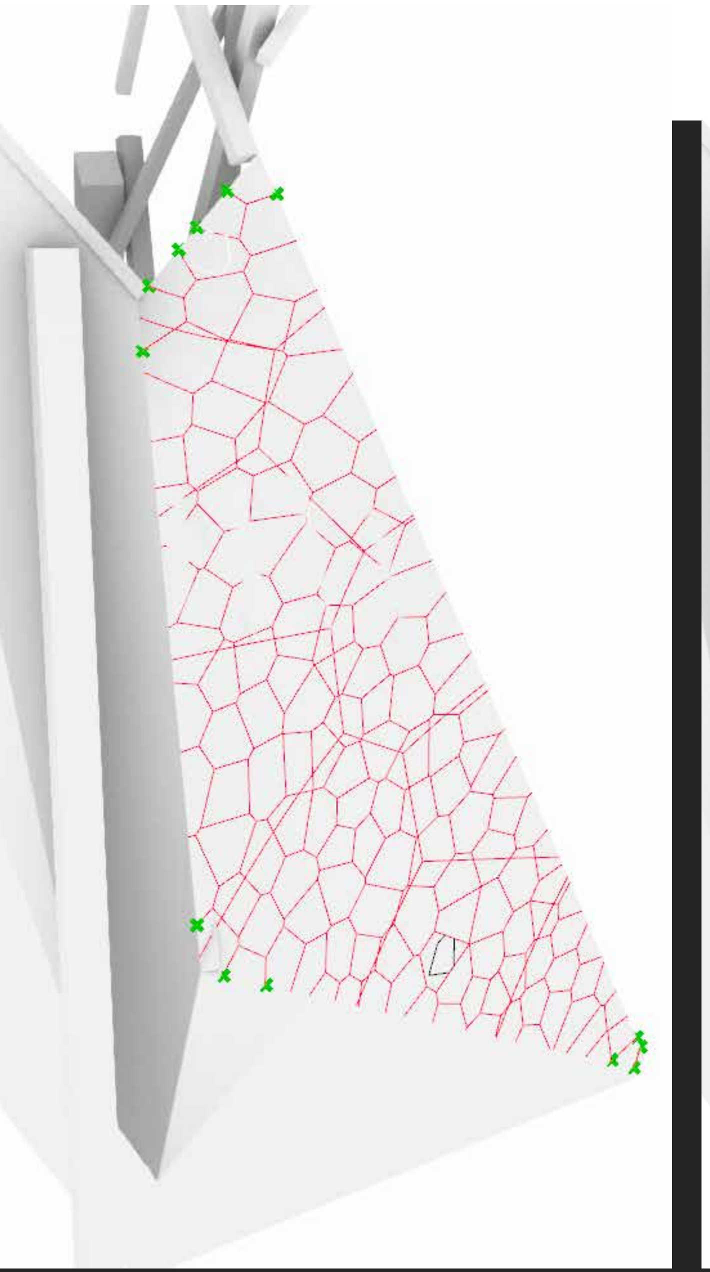
The research on acoustics explained theories on acoustics state the importance of creating scattered sound waves. Parametrically modeled surfaces will analyze the scattering rays of sound in three simulations. Research through design, based on analysis by the forward ray tracing component in Ladybug, can project the scattering potential of a surface. The more dispersed pattern in reflection is wanted, in contrast to the direct reflection by a flat surface like the left figure. The geometry acquainted from the structural optimization model is the basis for creating random scattering (see right figure). The ray tracing component shows the results in crosses, which start at a point based source, hitting the irregular surface, scattering in high degree of randomness and are smaller because of the decrease in energy (see figure in the middle).

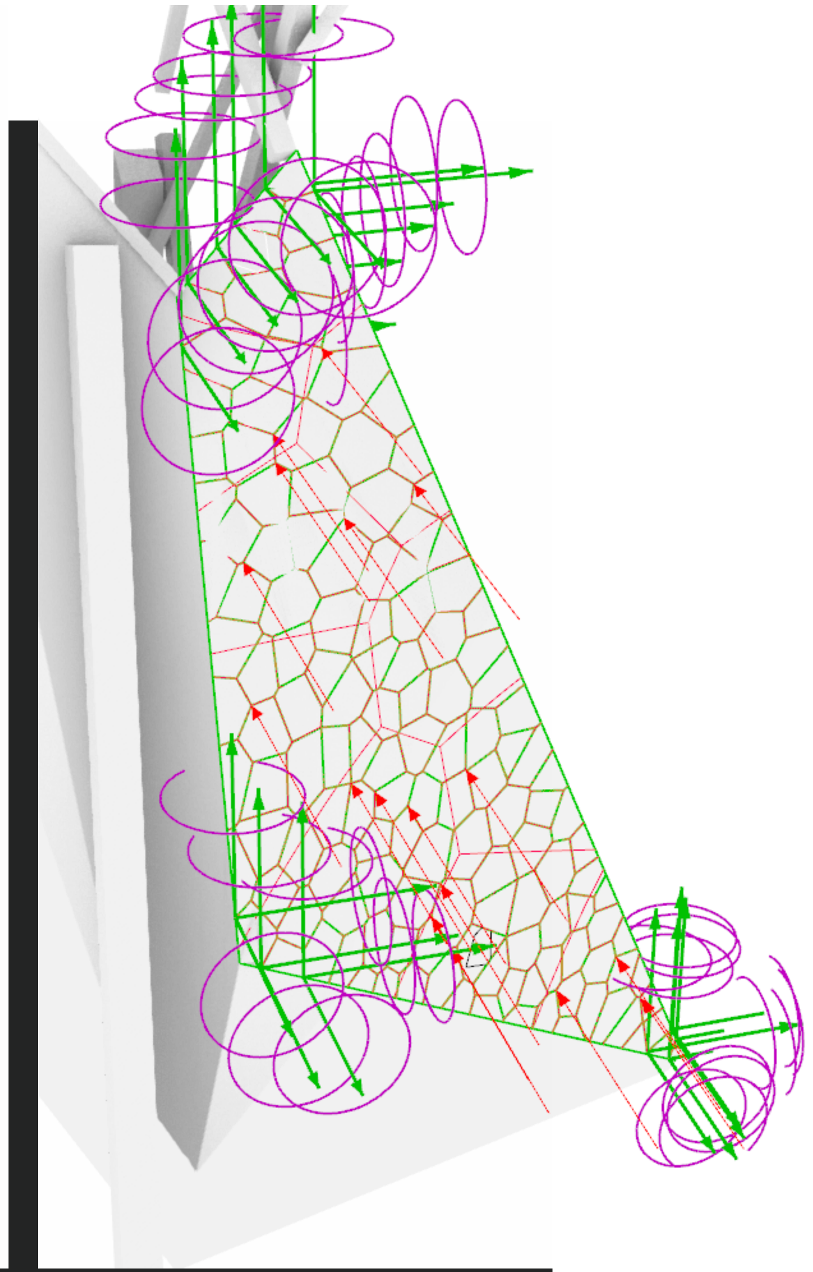


Computational Design: Acoustics

Workshop 01

To transform the preliminary sketched concept to a fully working prototype grasshopper is used to parametrically design the panel. A parametrically adjustable voronoi pattern is used to divide the surface into smaller sub segments. These voronoi lines are used as stress lines in the solver script of Karamba to get their supposed thickness. The panels are attached to the main structure on the corner points and they correspond with the overlaying voronoi pattern. A gravity load and a wind force are applied on this particular panel.
The integration with acoustics comes forward when looking at the voronoi lines. The higher the level of stress lines, the applied forces can be more evenly distributed to its determined support points. That means that there will be more different types of irregular surfaces that can scatter the sound.



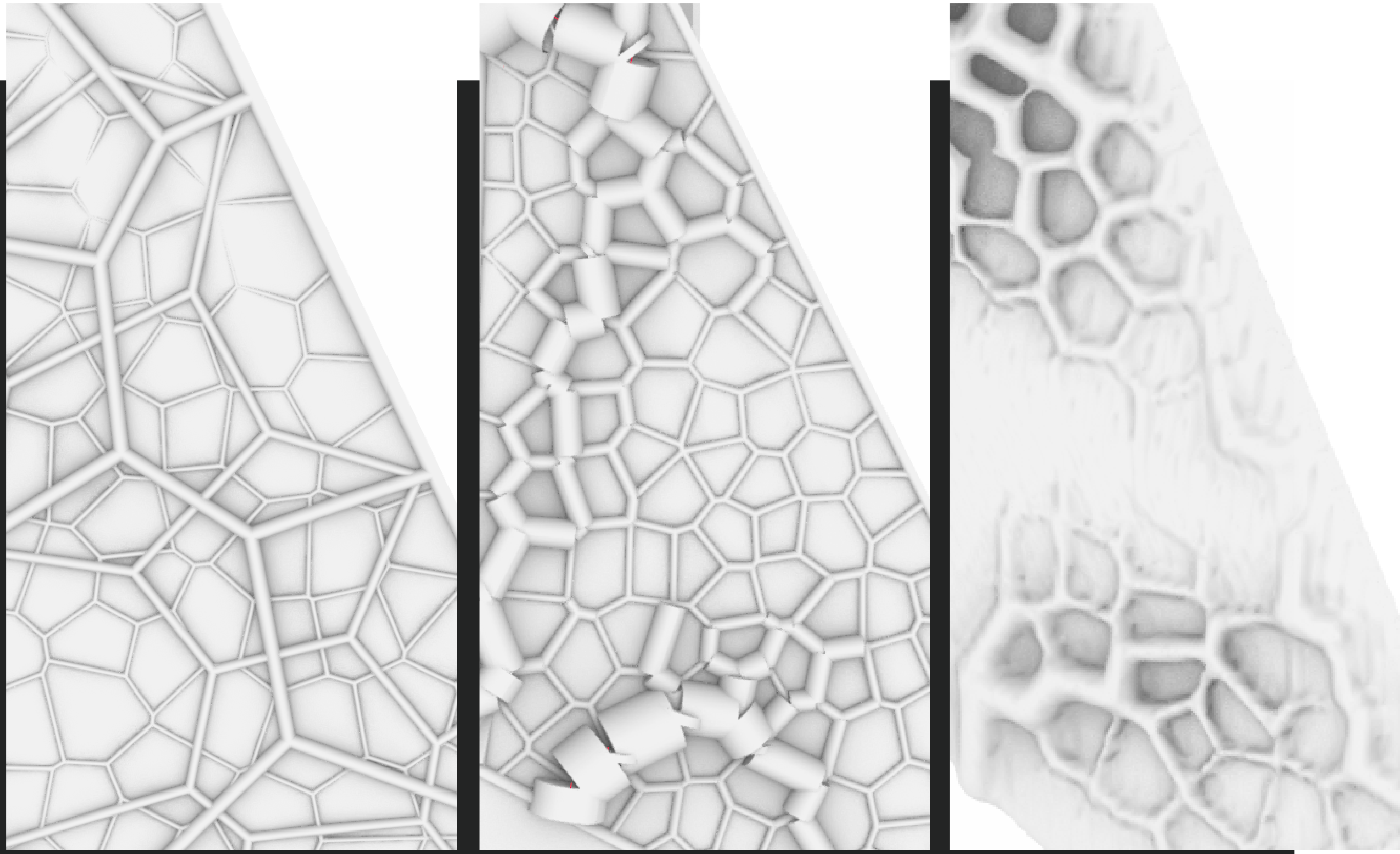


Computational Design: Structure

Workshop 01

B

The idea of using multiple heights according to both stress lines and the best acoustic scattering can be seen in the figure on the left. This figure shows the main concept virtualized without any optimization. The second one shows the optimization of the stress lines according to the applied different forces gravity and wind. The last image shows the integration between the optimized forces of the second image and the implementation of the acoustical requirements, like rippled and irregular surfaces, as described before. This procedure is done with a marching cubes algorithm plugin for Grasshopper named cocoon.



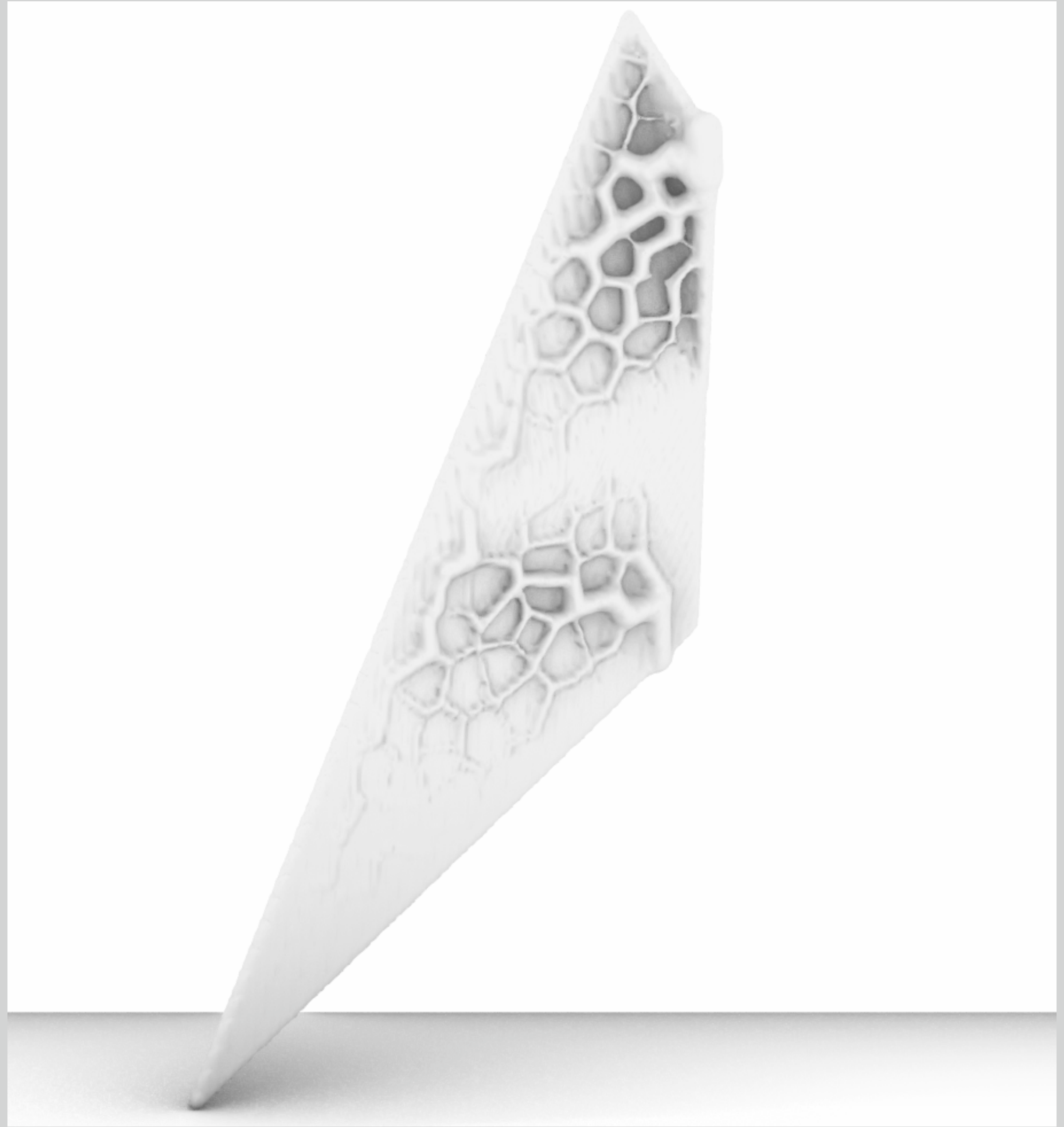
Computational Design: Integrating Functions

Workshop 01

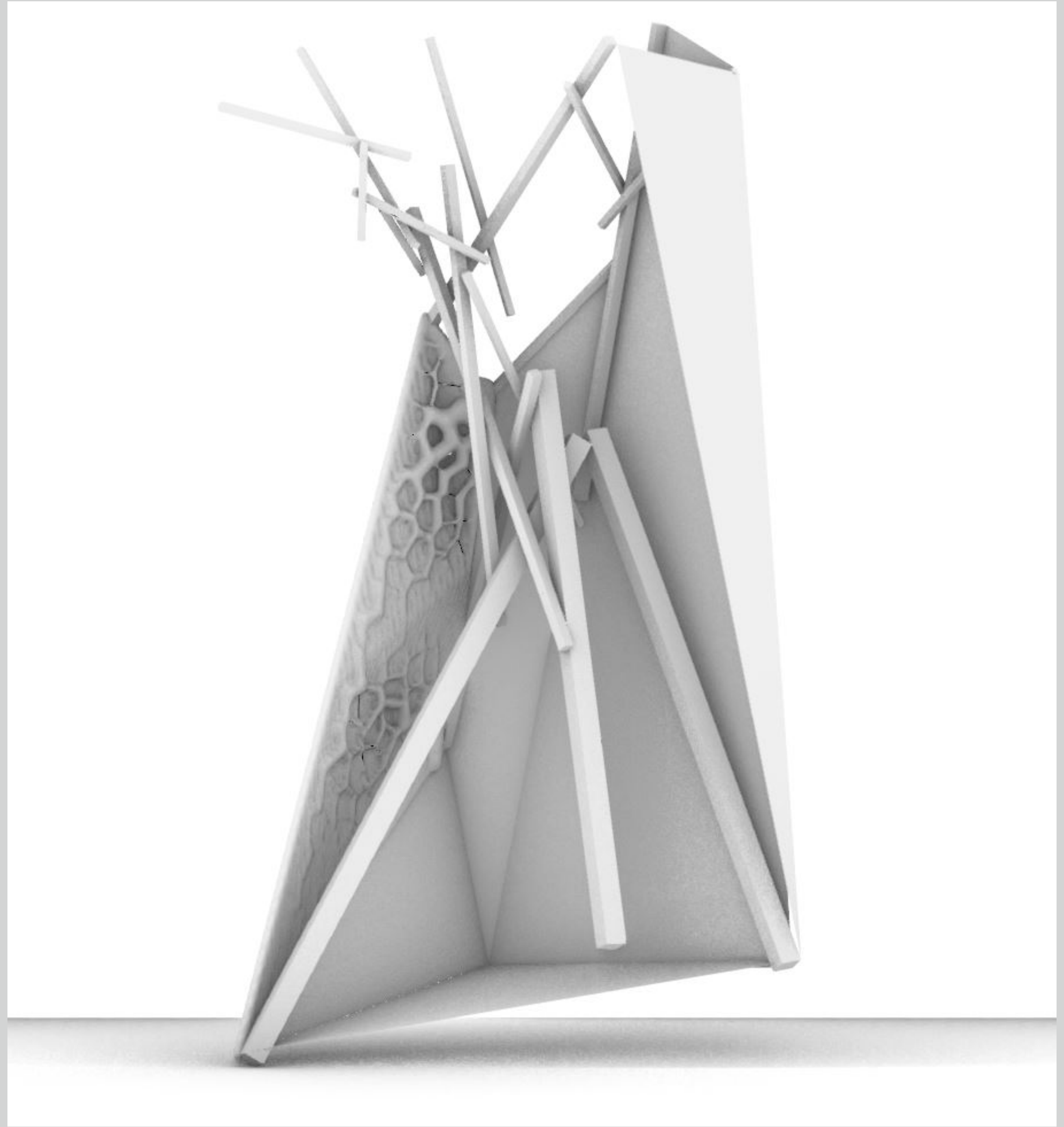
B

Final Design Panel

Optimized acoustical and structural panel



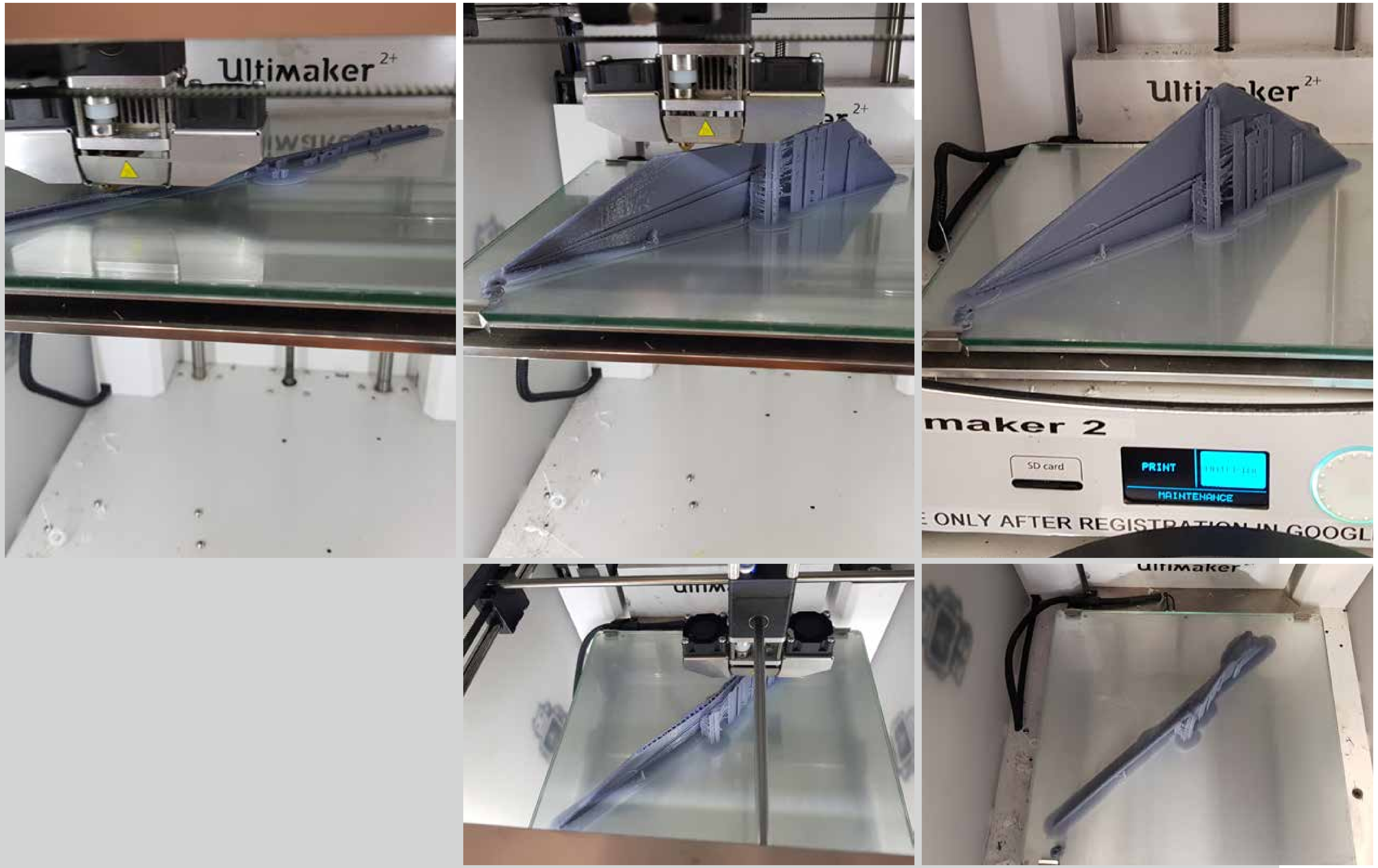
Without any context



Attached to main structure

Workshop 01

B



Overview D2RP

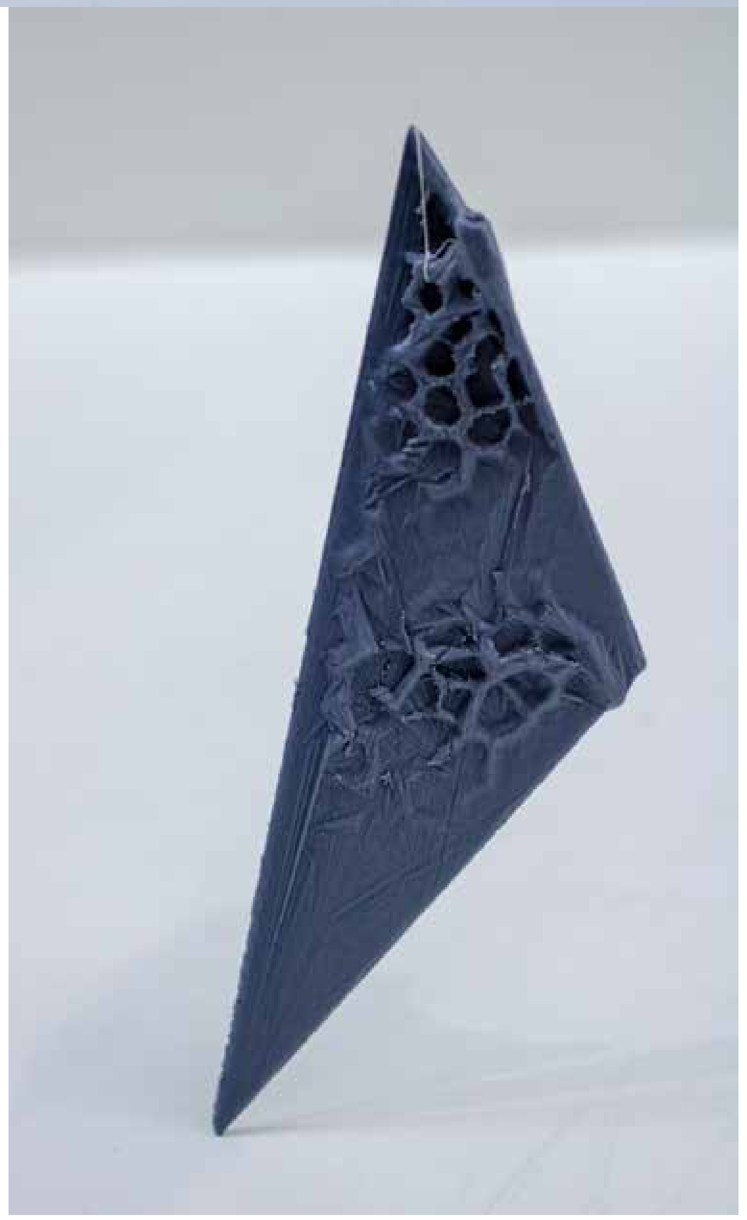
3D Printing Process

The prototype is printed with a layer height of 0.25mm and is a scaled version of the original virtual model. However this prototype certainly shows the proof of concept of the design, even when the print is not at high quality. The printing result is not everywhere as good as one would hope for, but this can have multiple causes, like the orientation of the print, print speed, layer height and the used material. It should be stated that the prototype panel is still too flat on certain places, while in the virtual model there is almost no flat surface. Scale can play an important role in this aspect because there is a ruled surface on the prototype, but it is not that visible. Probably when printing a 1:1 prototype this problem will be resolved.

Workshop 01

Physical Prototype

B

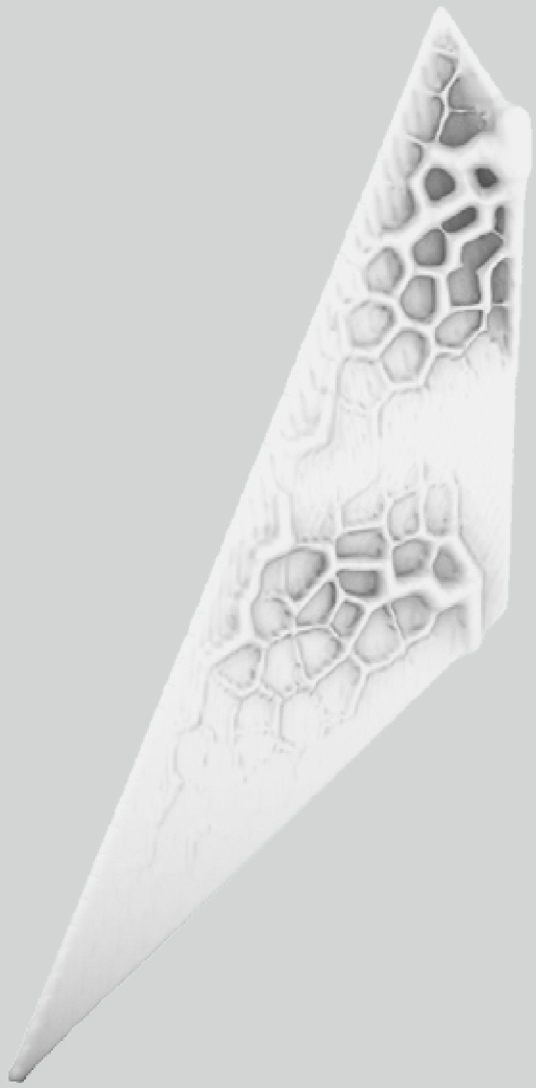


Workshop 01

B

Overview D2RP

From concept to prototype



Conceptual (sketched) idea/design

Design Principles:
- Mono material
- Integration of functions
- Stress lines as acoustic panel

Virtual prototype

Design Execution:
- Dense voronoi
- Irregular surface
- Tree structure

Physical Prototype

Proof of concept:
- Plastic material
- Conventional 3DP
- Structure = Acoustic panel

Reflection workshop/thesis

During this workshop I gained a lot of knowledge to support, evaluate and improve my thesis design. During the design process I gained a lot of computational knowledge about the possibilities of grasshopper to generate a lot of design proposals. But also the process of actually printing the virtual model to a physical prototype raised a lot of questions that I did not consider in the first place regarding my thesis design. The layer height, printing speed, printing technique and the porosity of the prototype made me wonder about these aspects in my thesis design, how they can be used in a positive manner to proof that future building can be 3D printed.

Other insights appeared to me when the workshop and the integration process took place. It should be possible to also add sensor actuators in the designed panel to enhance the functions one panel could have. This insight is roughly translated in the thesis design, whereas there is a strong preference for innovation in the current building systems. The workshop shows that integrating different functions is possible, but that these interventions can be very hard. However integrating several functions does lead to a more innovative design that can be aimed towards a sustainable constructed building.

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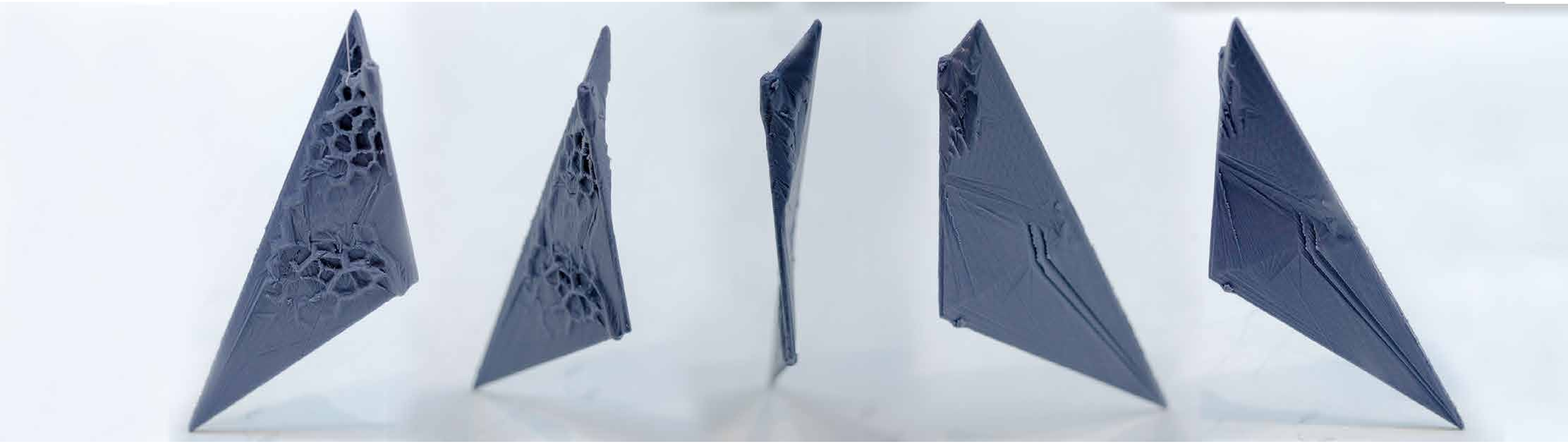


3D Printing In-Situ

State of the art references

Introduction

One of the main reasons to implement in-situ construction in the graduation project is to make use of the 3D printers' full potential of creating something without the need of any additional framework. This means that there is less transportation from the factory to the construction site, while also reducing the amount of transport of raw materials to those factories (Helm et al., 2012). These aspects can all be replaced by a 3D printer, because it can transform raw materials into objects on demand. The use of raw materials can also drastically reduce the construction costs by optimizing different building elements, while giving the architect the ability to create more unique forms compared to traditional techniques (Keating et al., 2017; Craveiro et al., 2019). However the traditional construction industry is rather slow in the implementation of innovative robotically operated construction techniques (Helm et al., 2012). When looking at this trend in a broader perspective, like the need to build one million homes while also building those homes in a more sustainable way, the current construction industry is not suitable at all. When using a 3D printer the material is only placed where needed and, when a more sustainable material is used, the materials that are used when 3D printing can be reused finite times (Sobotka & Pacewicz, 2016).

But there are also some disadvantages when this method of construction is compared to prefabricated objects, which are made in a protected environment. Mainly the elements possess a great threat for the implementation of the 3D printer on the construction site. Sobotka & Pacewicz (2016) have conducted an entire SWOT analysis for the introduction of the 3D printer on the construction site which can be seen in figure 01.

Beside the aspects listed in the SWOT analysis Giftthaler et al. (2017) mention yet another advantage for the use of robotics. These robotic printers can plan the entire construction process and also simulate it, reducing unforeseen problems and reducing them to a minimum.

To see in which projects a 3D printer is already used, some state of the art companies are investigated and compared. This way the graduation project has a framework on which certain choices can be built upon. The companies that will be discussed are ICON Build, AI Spacefactory, Apis Cor and DUS Architects.

	STRENGTHS	WEAKNESSES
INTERNAL FACTORS	• Reduced density of roads - works held only in the designated area, where machine works. Other roads are used for the transportation of raw materials and as the escape routes. • Lack of large landfills on site. Printing machine consumes a certain amount of material and conducts constant monitoring of material consumption. You can schedule the exact delivery of the material. Waste materials on site practically do not exist. Easier logistics service construction. • Printing machine can work 24x7. It should provide a source of energy. Fewer special equipment is needed on site, which results in lower power consumption [10] • A limited amount of heavy equipment for construction. Heavy equipment is required only excavation. Other devices such as eg. Crane, printing machine replaces. • Reduced demand for staff workers increases while for skilled. Increases safety on the site. Limited is the human factor, increases safety on the site through its automation. • No need for formwork. Printing machine does not need formwork, all components can be printed and installed on site. • Shorter duration of construction. The precise time of the machine work. Lower technology costs.	• The high cost of construction equipment. Due to the fact that this is a new technology, you will need to plan device service or obtain a construction site in the second printing machine. • Increased quality requirements and testing, conducting continuous monitoring of the printing of a building. Due to the possibility of a fault or defect feedstock. Careful planning of supply material in order to obtain continuity of the production. • The need for additional / complementary work, for example. Installation of windows and doors by teams of workers. • The need to develop the production of raw materials for printing products and buildings. • Poor recognition of properties of the materials of construction of printing technologies objects
	OPPORTUNITIES	**THREATS**
EXTERNAL FACTORS	• High-tech equipment and manufacturing equipment. Increased automation of processes on site. Increased safety on the construction site, fewer workers working physically, increased control over the working machine by qualified personnel. • The use of recycled materials for the printing of new construction. The reduced amount of waste occurring during the construction process. • The ability to print buildings on the land after the disaster, construction, natural, areas that were covered by the war, in the areas of third world countries and developing countries. • In the future, the ability to build solid objects on other planets, without the people participation. • You can lower the implementation cost than traditional methods. • Low costs of building the massive scale of construction in 3D.	• Lack of a wide range of building materials market for print design object difficulties with the supply of construction materials to the right. The need to create your own nodes of production. • Smaller worker's employment on construction sites (reduction of jobs) • Difficulties / lack of supervision of the construction. The possibility of illegal construction. • Lack of data on weather conditions. They can make delays on the construction site and in the worst case damage to the structures and machines. • Production of print materials, buildings may require the most advanced technological processes.

Figure 01: SWOT analysis of implementation 3D printer on construction site (Sobotka & Pacewicz, 2016)

ICON Build: Project 01

ICON Build is a company that tries to bring affordable 3D printed houses to the people who lack any form of quality housing. To achieve this goal they created a printer that can print entire villages, going at a speed of a building per day. The projects that are shown here are their first project of the 3D printed house (350 square foot = 33 square meters) in a day, and their current project of 3D printing an entire community in Mexico. This company is particularly interesting for the graduation project because it shows how implemented and quick 3D printing has become in the past years and could be in the future.

Housing unit printed in 24 hours

Source: Badalge, K. (2018, November 13). In World's First 3-D Printed Home Community, Houses will be Built in a Day for $4000. Retrieved January 20, 2020, from https://www.archdaily.com/891065/in-worlds-first-3d-printed-community-houses-cost-4000-dollars-and-are-built-in-24-hours

ICON Build: Visuals

Source: ICON. (2019b, December 11). New Story + ICON + Échale | "3D Printed Housing for Those Who Need It Most." Retrieved January 22, 2020, from https://www.youtube.com/watch?v=PbgCu0aUobE&feature=emb_logob_logo

ICON Build: Project 02

Printing an entire community in Mexico




Source: Grace, K. (2019, December 21). World's First 3D Printed Community Minimises Homelessness in Mexico. Retrieved January 20, 2020, from https://www.archdaily.com/930556/worlds-first-3d-printed-community-minimises-homelessness-in-mexico

ICON Build: Visuals

Source: Tech Insider. (2018, March 24). 3D-Printed Home Can Be Constructed For Under $4,000. Retrieved January 22, 2020, from https://www.youtube.com/watch?v=wCzS2FZoB-I&feature=emb_logo

ICON Build: In-Situ Construction

The company uses a temporary constructed tent to protect the 3D printer from the elements. However the elements for this 3D printer have still a minimal impact so only the roof has sheets, the sides of this tent are open. This allows for easy access because the printer needs to be operated by a crew of 4-6 people.

Source: ICON. (2019a, March 11). Frequently Asked Questions | ICON. Retrieved April 2, 2020, from https://www.iconbuild.com/about/faq

ICON Build: In-Situ Construction

ICON usually prints in environments where the sun is abundantly present throughout the day. Therefore they mostly need protection from the sun to protect the 3D printer from all sunlight exposure and to protect the newly printed layers. The influence from the elements for this specific printer/material combination are rather small, which will hopefully be the case for many 3D printers in the future.

Sources: ICON. (n.d.). ICON (@icon3dtech) | Instagram. Retrieved April 02, 2020, from https://www.instagram.com/icon3dtech/?hl=en
https://www.instagram.com/p/B5772mXHovv/

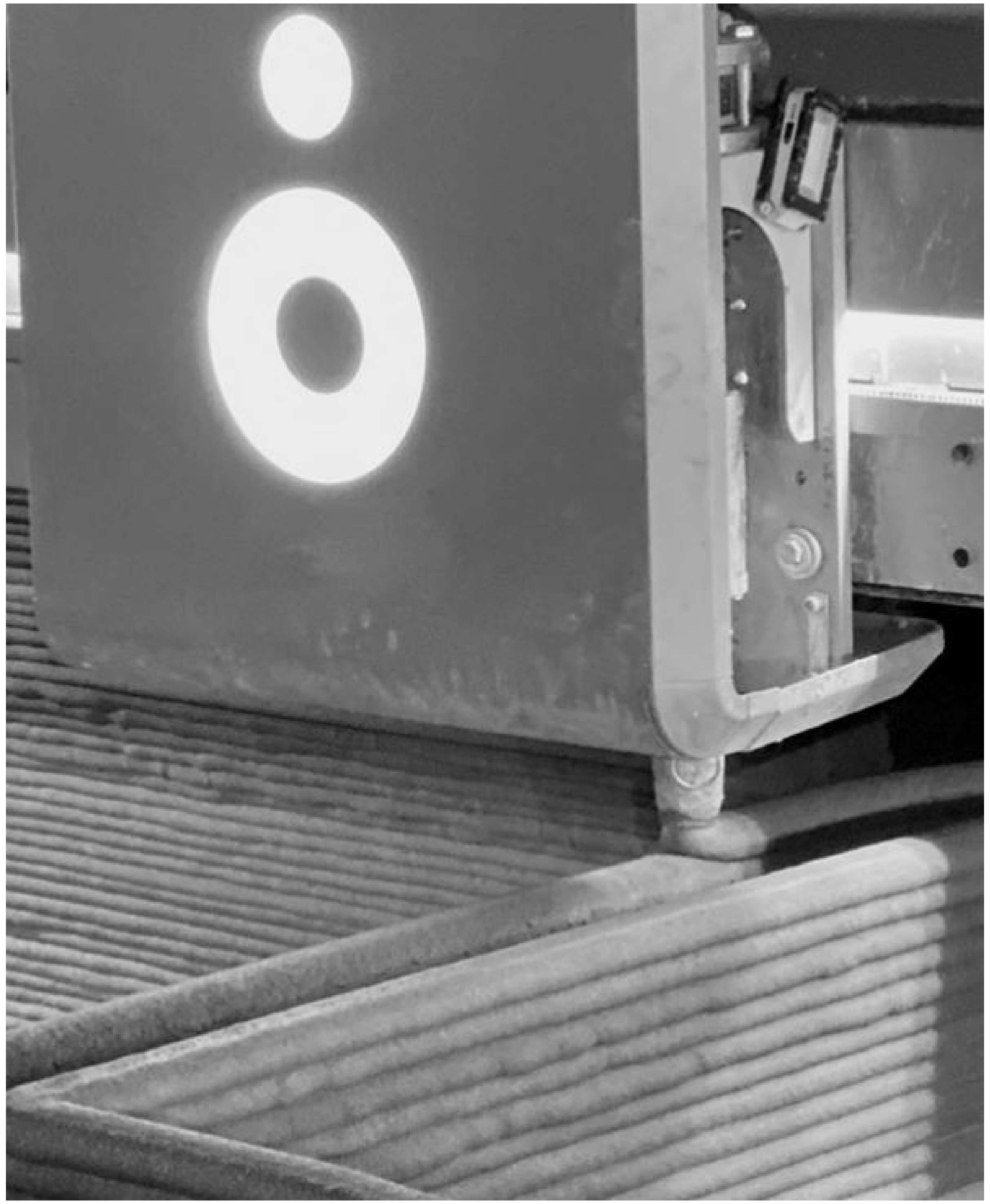
ICON Build: In-Situ Construction

ICON uses a custom made concrete especially for 3D printing named lavacrete. Specific characteristics of this material are not shared but this type of concrete is better printable than standard concrete due to the fact it stays more in place when extruded. The aesthetic look of this product is gray with visible printing lines that determine the reliëf of a skin component.

Source: Badalge, K. (2018, November 13). In World's First 3-D Printed Home Community, Houses will be Built in a Day for $4000. Retrieved January 20, 2020, from https://www.archdaily.com/891065/in-worlds-first-3d-printed-community-houses-cost-4000-dollars-and-are-built-in-24-hours

ICON Build: 3D Printer

This 3 axis robotic 3D printer called Vulcan is transported in the back of a lorry, so it is a rather large printer overall. However it is made to fit exactly in the back and is easy to pack and unpack. Minimal adjustments have to be made when installing this printer on the construction site, other than calibrating the printing head. To install this printer on the construction site one should place linear tracks where the printer can move on in the Y direction. The rest of the printer is made of a gantry system that can move in 2 directions, namely X and Z. This means the printer is limited in the X and Z direction while having an infinite print length in the Y direction. The Vulcan can reach printing speeds up to 150mm/s, which together with a layer height of 2.5cm (width 5cm) relates directly to the achievement of printing a small house in under 24 hours.



Source: ICON. (n.d.). ICON (@icon3dtech) | Instagram. Retrieved April 02, 2020, from https://www.instagram.com/icon3dtech/?hl=en

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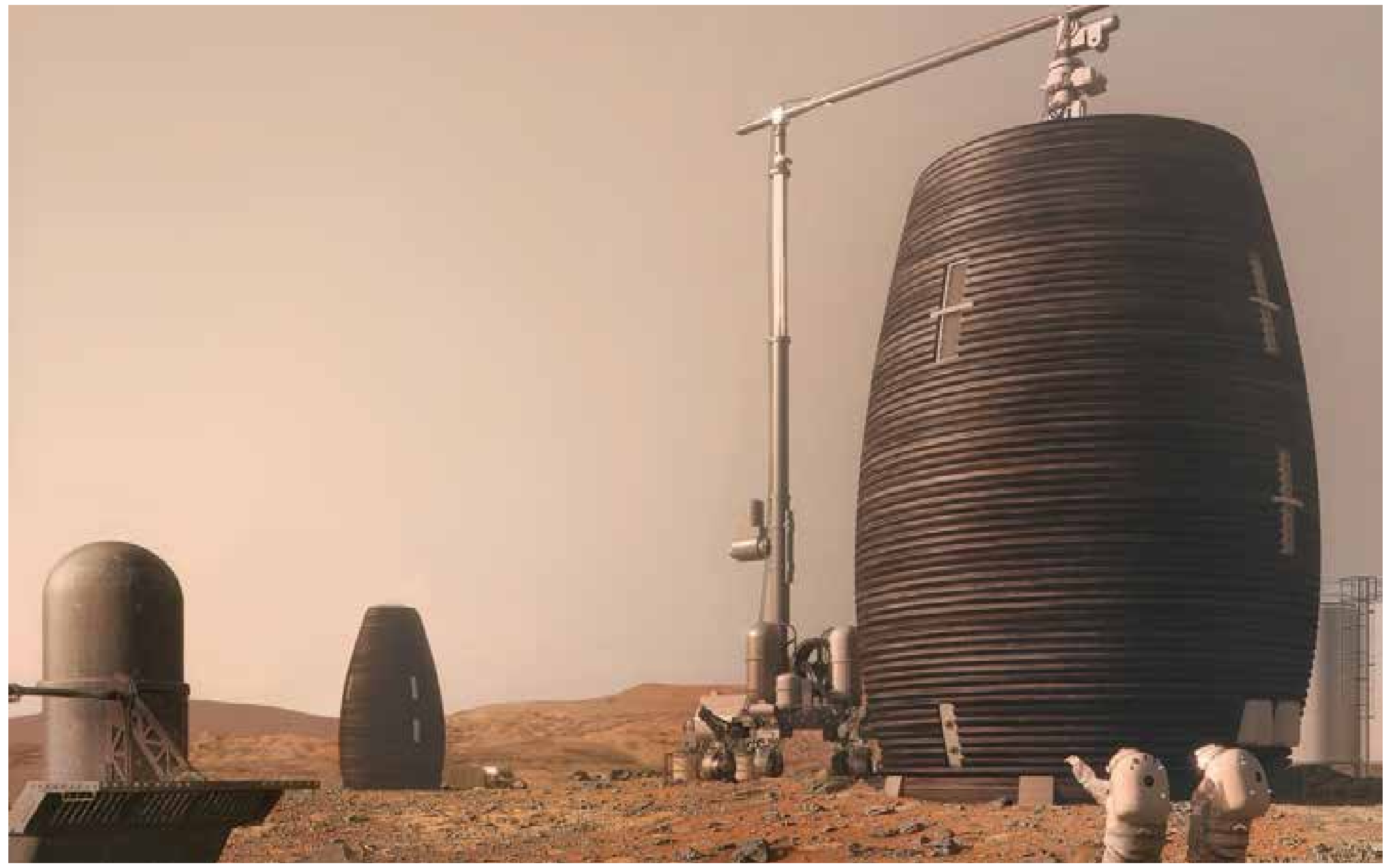
Source: ICON. (n.d.). ICON (@icon3dtech) | Instagram. Retrieved April 02, 2020, from https://www.instagram.com/icon3dtech/?hl=en

AI Spacefactory: Project 01

AI Spacefactory is known for its participation in the NASA challenge to print a building on mars. They introduced a design that specifically makes use of the availability of materials on mars, namely basalt. This material mixed with renewable sources can be 3D printed on mars without the need of bringing much materials from earth into space.



Source:
AI Spacefactory. (2019a). AI SpaceFactory Builds 3D Printed Mars Prototype for NASA [Illustration]. Retrieved from https://www.archdaily.com/910764/ai-spacefactory-builds-3d-printed-mars-prototype-for-nasa

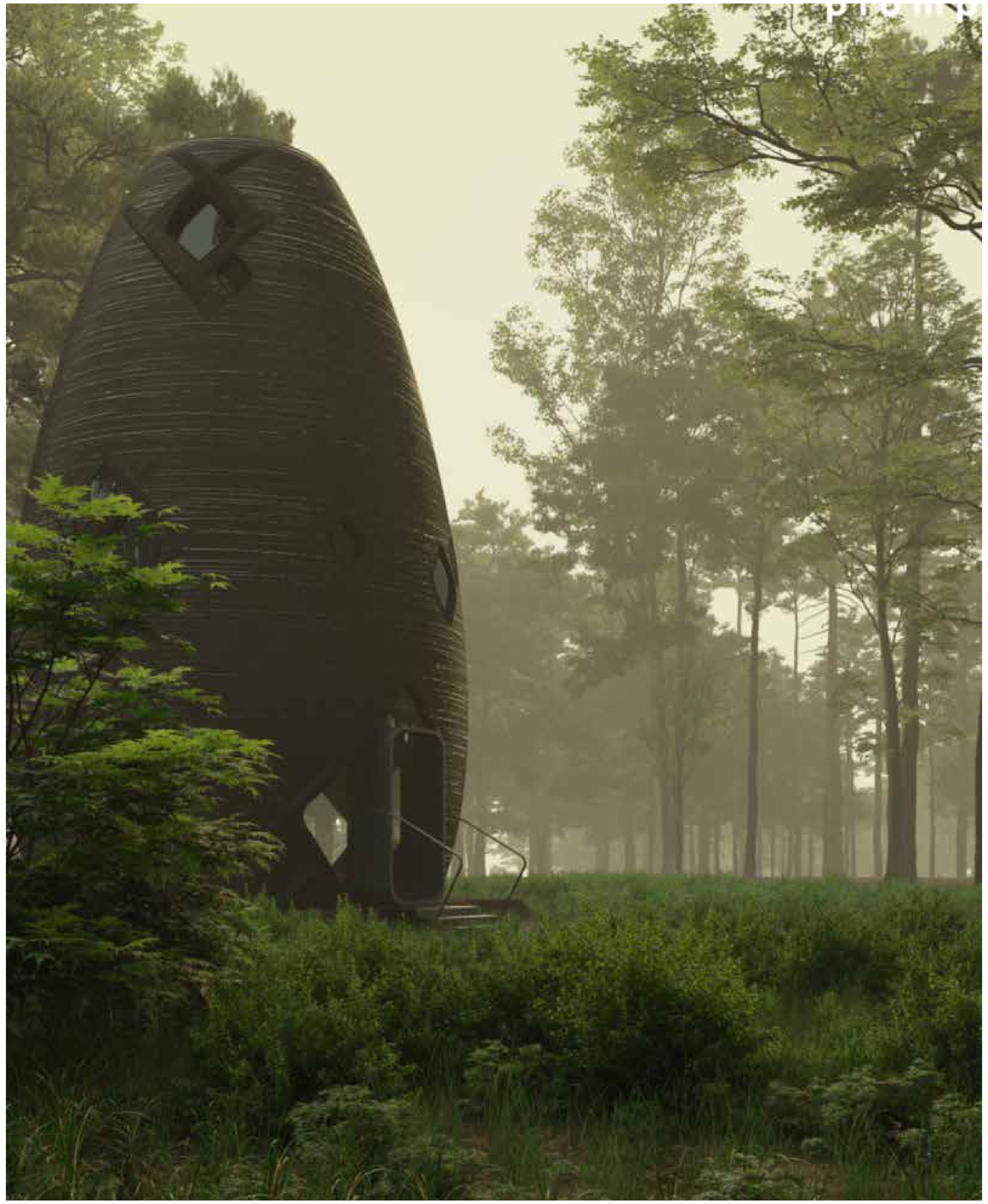
AI Spacefactory. (2019b). AI SpaceFactory Wins NASA's 3D-Printed Mars Habitat Challenge [Illustration]. Retrieved from https://www.archdaily.com/916888/ai-spacefactory-wins-nasas-3d-printed-mars-habitat-challenge

AI Spacefactory: Visuals

Source: AI SpaceFactory. (2018, July 23). Our Vertical Martian Future - Part One. Retrieved January 20, 2020, from https://www.youtube.com/watch?v=XnrVV0w2jrE&feature=emb_logo

AI Spacefactory: Project 02

Tera is the concept of Marsha but not on the planet mars, but on earth. This building is also constructed with basalt, because also on earth it is available. Mixed with PLA they want to make a 3D printed building that is made from organic and renewable sources. The graduation project uses this reference therefore a lot.

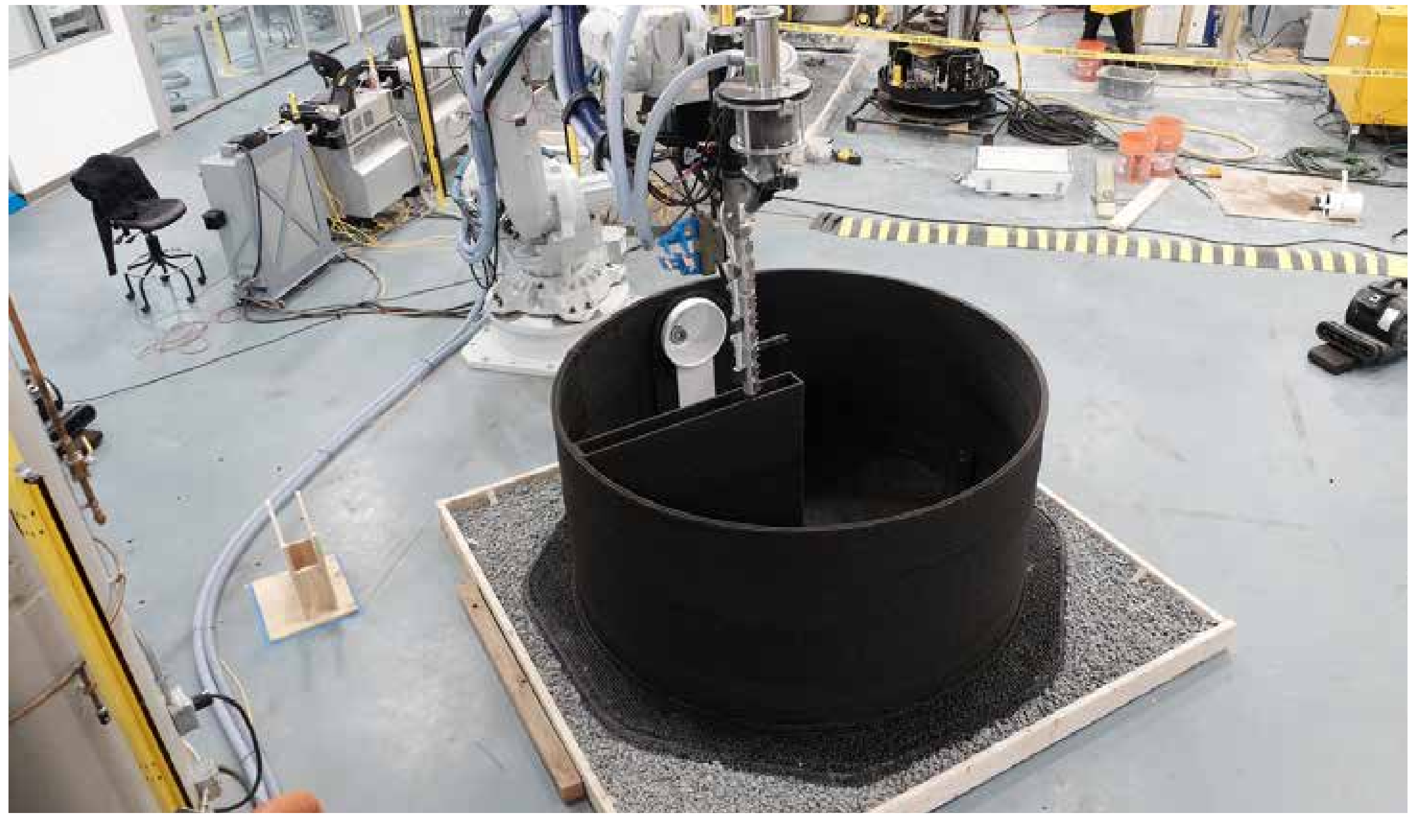


Source:
AI SpaceFactory. (n.d.-b). AI SpaceFactory (@ AISpaceFactory) | Twitter. Retrieved April 02, 2020, from https://twitter.com/AISpaceFactory

AI Spacefactory. (2019b). AI SpaceFactory Wins NASA's 3D-Printed Mars Habitat Challenge [Illustration]. Retrieved from https://www.archdaily.com/916888/ ai-spacefactory-wins-nasas-3d-printed-mars-habitat-challenge

AI Spacefactory: Project 03

This basin is printed to see how different elements can be robotically placed with the same 3D printing machine. It shows that the 6 axis robotic arm is very versatile and can do both operations. The material secures the additional elements (pipe and inlet) of this water basin and makes sure they don't move. The elements placed provide a new underground to print onto. This concept is also used in the NASA challenge to insert the windows.



Source: AI Spacefactory. (2019a). AI SpaceFactory Builds 3D Printed Mars Prototype for NASA [Illustration]. Retrieved from https://www.archdaily.com/910764/ai-spacefactory-builds-3d-printed-mars-prototype-for-nasa

AI Spacefactory: Project 04

Marsha was originally made for the NASA competition to make a 3D printed building on mars. During this competition AI Spacefactory reached the finale where they had to 3D print a scale 1:3 prototype of their design. This prototype was printed in 30 hours and has been proven 50% stronger than their concrete competitors. After the competition the prototype was demolished and is now being reused as material for the new building named Tera.

Source:

AI SpaceFactory. (n.d.-b). AI SpaceFactory (@ AISpaceFactory) | Twitter. Retrieved April 02, 2020, from https://twitter.com/AISpaceFactory

AI Spacefactory. (2019b). AI SpaceFactory Wins NASA's 3D-Printed Mars Habitat Challenge [Illustration]. Retrieved from https://www.archdaily.com/916888/ai-spacefactory-wins-nasas-3d-printed-mars-habitat-challenge

AI Spacefactory: In-Situ Construction

AI Spacefactory does not use any protection from exterior elements like rain, sun, wind and temperature. They try to print in open air with several successes and several unsuccessful results. Currently they are still experimenting with printing in open air.

Source: AI SpaceFactory. (n.d.-b). AI SpaceFactory (@ AISpaceFactory) | Twitter. Retrieved April 02, 2020, from https://twitter.com/AISpaceFactory

AI SpaceFactory. (n.d.-a). AI SpaceFactory (@ aispacefactory) | Instagram. Retrieved January 20, 2020, from https://www.instagram.com/aispacefactory/?hl=en

AI Spacefactory: In-Situ Construction

When printing in open air without any protection from the elements they had some setback with the layers adhering due to temperature fluctuations as they printed in winter with snow. Therefore a heat reflective protection is placed around the 3D print to cope with that problem. Results of this adjustment are not shared (yet).

Source: AI SpaceFactory. (n.d.-b). AI SpaceFactory (@ AISpaceFactory) | Twitter. Retrieved April 02, 2020, from https://twitter.com/AISpaceFactory

AI Spacefactory: 3D Printer

This specific 3D printing robot unit will approximately reach printing speeds of 65mm/s. That value is determined by timing the print speed over a certain length compared to the time it took for that. This information is obtained from a video from AI Spacefactory's participation in a NASA competition to print a scaled model of their Marha proposal.

The size of this 3D printer is determined by two components: the forklift and the 6 axis robotic arm. These components together also define the reachability of the 3D printer.

Sources:
AI SpaceFactory. (n.d.-b). AI SpaceFactory (@AISpaceFactory) | Twitter. Retrieved April 02, 2020, from https://twitter.com/AISpaceFactory

ICON. (n.d.). ICON (@icon3dtech) | Instagram. Retrieved April 02, 2020, from https://www.instagram.com/icon3dtech/?hl=en

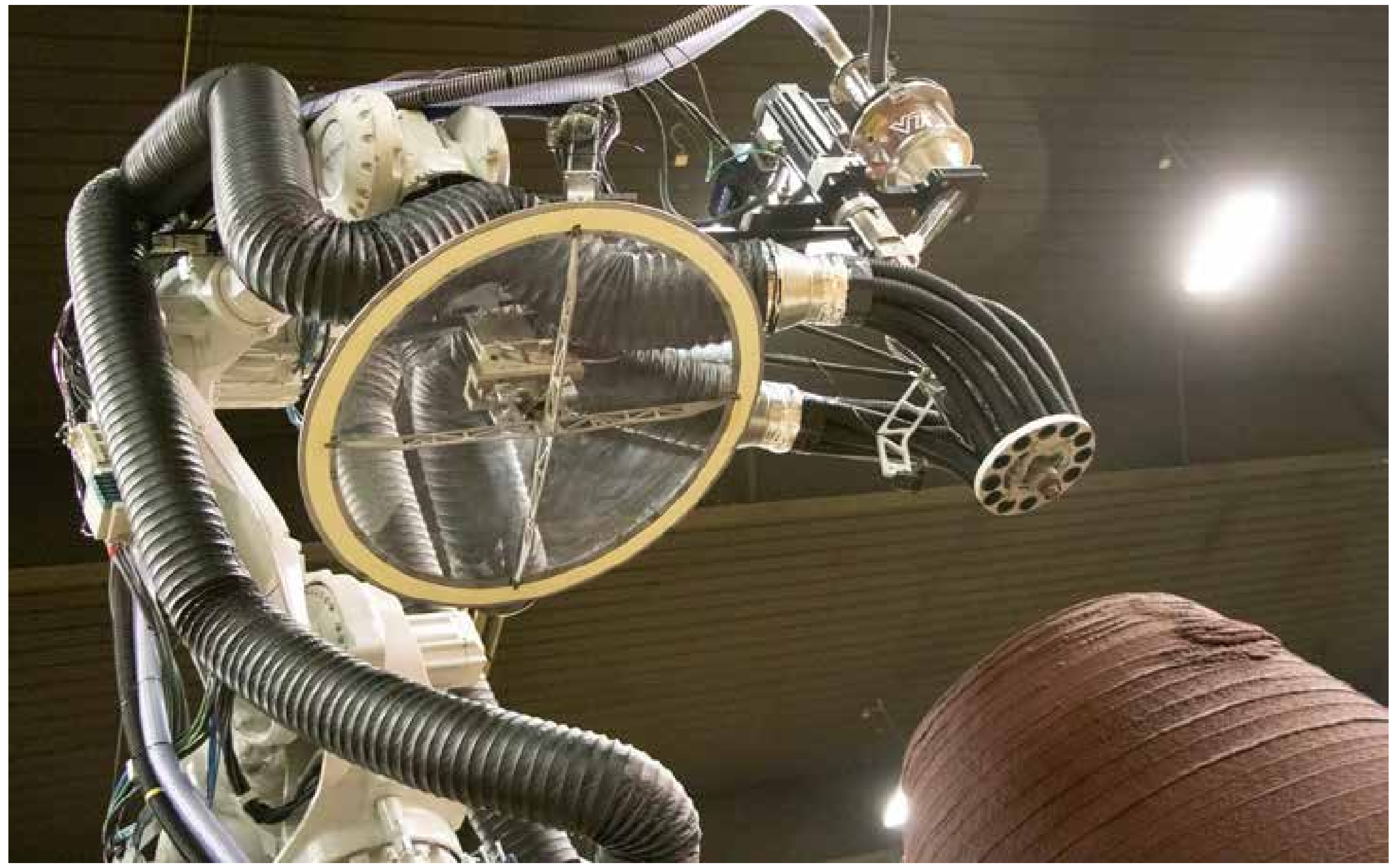
AI Spacefactory: 3D Printer

The 6 axis robotic arm 3D printer is attached to a forklift and called Mobi. Transporting to the construction site will take place with a large truck. The printer can manoeuvre freely on the construction site and position itself on the most fitting location.

Sources:
AI SpaceFactory. (n.d.-b). AI SpaceFactory (@ AISpaceFactory) | Twitter. Retrieved April 02, 2020, from https://twitter.com/AISpaceFactory

AI Spacefactory: 3D Printer

The tolerance of this 3D printing machine is very marginal when used in a factory. The 6 axis robot arm is accurate to the millimeter. If the machine is properly installed on the construction site and is calibrated, it should have similar properties. To what extent the calibration is possible will eventually determine the tolerance of the 3D printer.



Source: AI Spacefactory. (2019b). AI SpaceFactory Wins NASA's 3D-Printed Mars Habitat Challenge [Illustration]. Retrieved from https://www.archdaily.com/916888/ai-spacefactory-wins-nasas-3d-printed-mars-habitat-challenge

AI Spacefactory: 3D Printer

A closeup of a part of the prototype from AI Spacefactory shows that the layer height/thickness is way larger than conventional 3D printers. It is also based on a double layer envelope to increase the overall strenght.

Source: Jung-Harada, C. (2019b, September 18). AI Space Factory visit at ICC Hong Kong. Retrieved January 20, 2020, from https://cesarjungharada.com/notes/tag/Art

AI Spacefactory: Visuals

Source: Jung-Harada, C. (2019a, September 16). David Malott gives a tour of AI SpaceFactory at HK ICC. Retrieved January 21, 2020, from https://www.youtube.com/watch?v=1U4Jg-obJ78

AI Spacefactory: Material

The company uses the material Basalt Fiber reinforced PLA, which is also the main material of the graduation project. The material has originally a grey color, but for the sake of the Marsha Prototype they added a different color in the mixture. More information about this material can be found in the dedicated chapter.

Sources:
AI SpaceFactory. (n.d.-b). AI SpaceFactory (@AISpaceFactory) | Twitter. Retrieved April 02, 2020, from https://twitter.com/AISpaceFactory

AI Spacefactory. (2019b). AI SpaceFactory Wins NASA's 3D-Printed Mars Habitat Challenge [Illustration]. Retrieved from https://www.archdaily.com/916888/ai-spacefactory-wins-nasas-3d-printed-mars-habitat-challenge

Apis Cor: Project 01

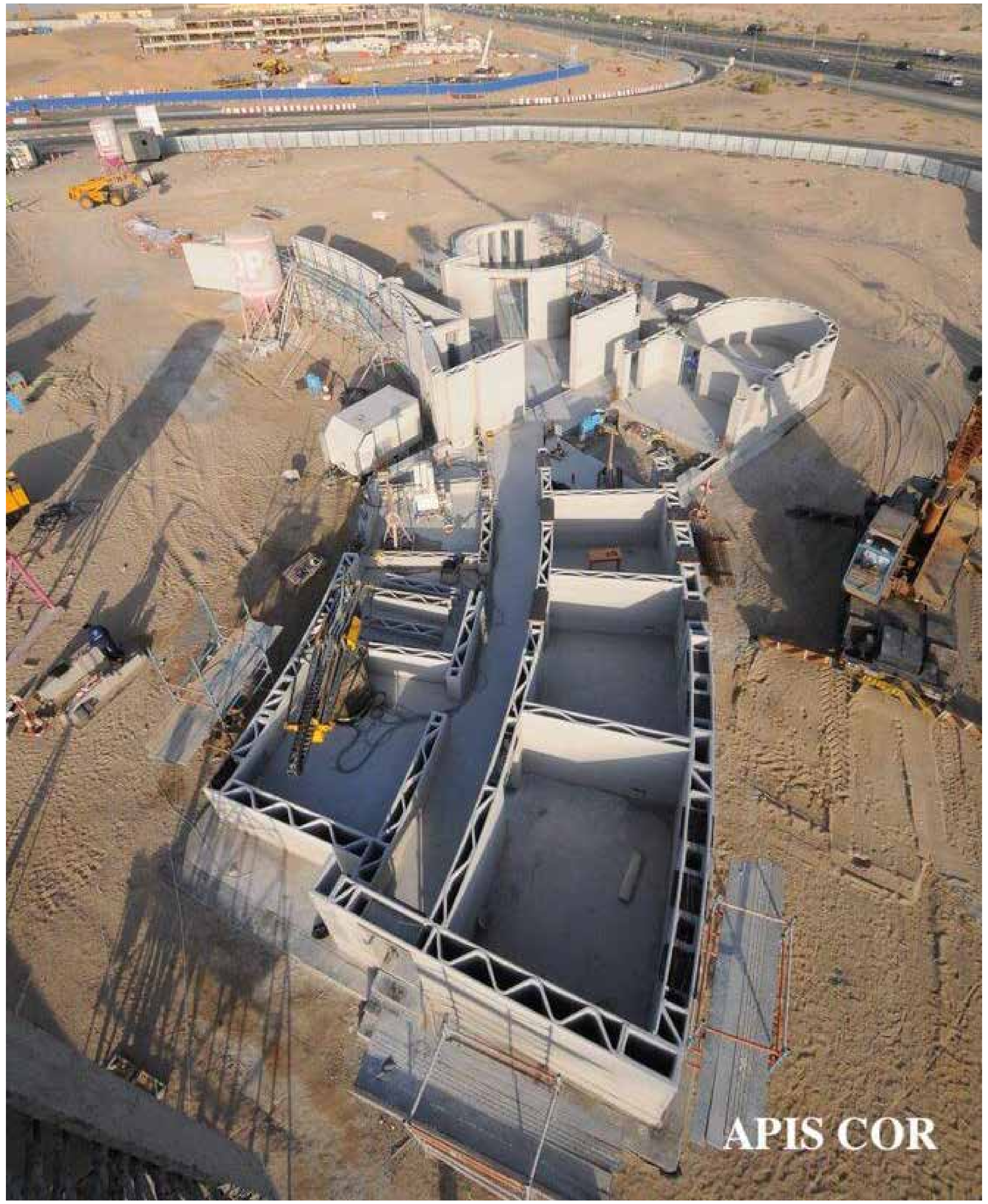
This building is located in Dubai and is one of the larger buildings that has been 3D printed entirely on-site.

3D print Dubai

Source: Harrouk, C. (2019, December 24). Dubai Municipality to Become the World's Largest 3D-Printed Building. Retrieved January 22, 2020, from https://www.archdaily.com/930857/dubai-municipality-to-become-the-worlds-largest-3d-printed-building?ad_source=search&ad_medium=search_result_all

Apis Cor: In-Situ Construction

This building is printed with a single 3D printer that is moved from place to place, together with 3 construction workers. In the harsh environment of Dubai they managed to print a 640 square meter building consisting of two stories with concrete. (Only walls/columns were printed)



Source: Harrouk, C. (2019, December 24). Dubai Municipality to Become the World's Largest 3D-Printed Building. Retrieved January 22, 2020, from https://www.archdaily.com/930857/dubai-municipality-to-become-the-worlds-largest-3d-printed-building?ad_source=search&ad_medium=search_result_all

Apis Cor: 3D Printer

The printer printed in open air without any protective cover against wind, sun or heat. Apis Cor created the material in such a way it did not have any influence from the local weather.

Source: Harrouk, C. (2019, December 24). Dubai Municipality to Become the World's Largest 3D-Printed Building. Retrieved January 22, 2020, from https://www.archdaily.com/930857/dubai-municipality-to-become-the-worlds-largest-3d-printed-building?ad_source=search&ad_medium=search_result_all

Apis Cor: Visuals

Source: Apis Cor. (2019, October 23). Apis Cor: The biggest building ever 3d printed. Retrieved January 22, 2020, from https://www.youtube.com/watch?time_continue=43&v=TtcGH1iLM1w&feature=emb_logo

Apis Cor: Project 02

This house was 3D printed in Russia to prove the potential of the new application in the construction industry.

3D printed building in Russian freezing temperatures

Source: Bari, O. (2017, March 13). Build Your Own 3D Printed House, All in One Day. Retrieved January 22, 2020, from https://www.archdaily.com/806742/build-your-own-3d-printed-house-all-in-one-day

Apis Cor: In-Situ Construction

The house was printed in the winter of Russia with temperatures of -35 degrees celsius. To overcome this cold weather the team build a temporary construction tent over the 3D printer with a heater to regulate the interior climate for an optimal printing result.

Source: Bari, O. (2017, March 13). Build Your Own 3D Printed House, All in One Day. Retrieved January 22, 2020, from https://www.archdaily.com/806742/build-your-own-3d-printed-house-all-in-one-day

Apis Cor: Visuals

Source: Apis Cor. (2017, February 22). Apis Cor: first residential house has been printed! Retrieved January 20, 2020, from https://www.youtube.com/watch?time_continue=256&v=xktwDfasPGQ&feature=emb_logo

DUS Architects: Projects

DUS Architects' goal is to entirely print an Amsterdam canal house. They want to do this on the construction site by introducing a printer in a sea container.

3D print proposal for canel house in Amsterdam

Source: DUS Architects. (2016). 3DPRINTCANALHOUSE by DUS Architects. Retrieved January 22, 2020, from https://3dprintcanalhouse.com/

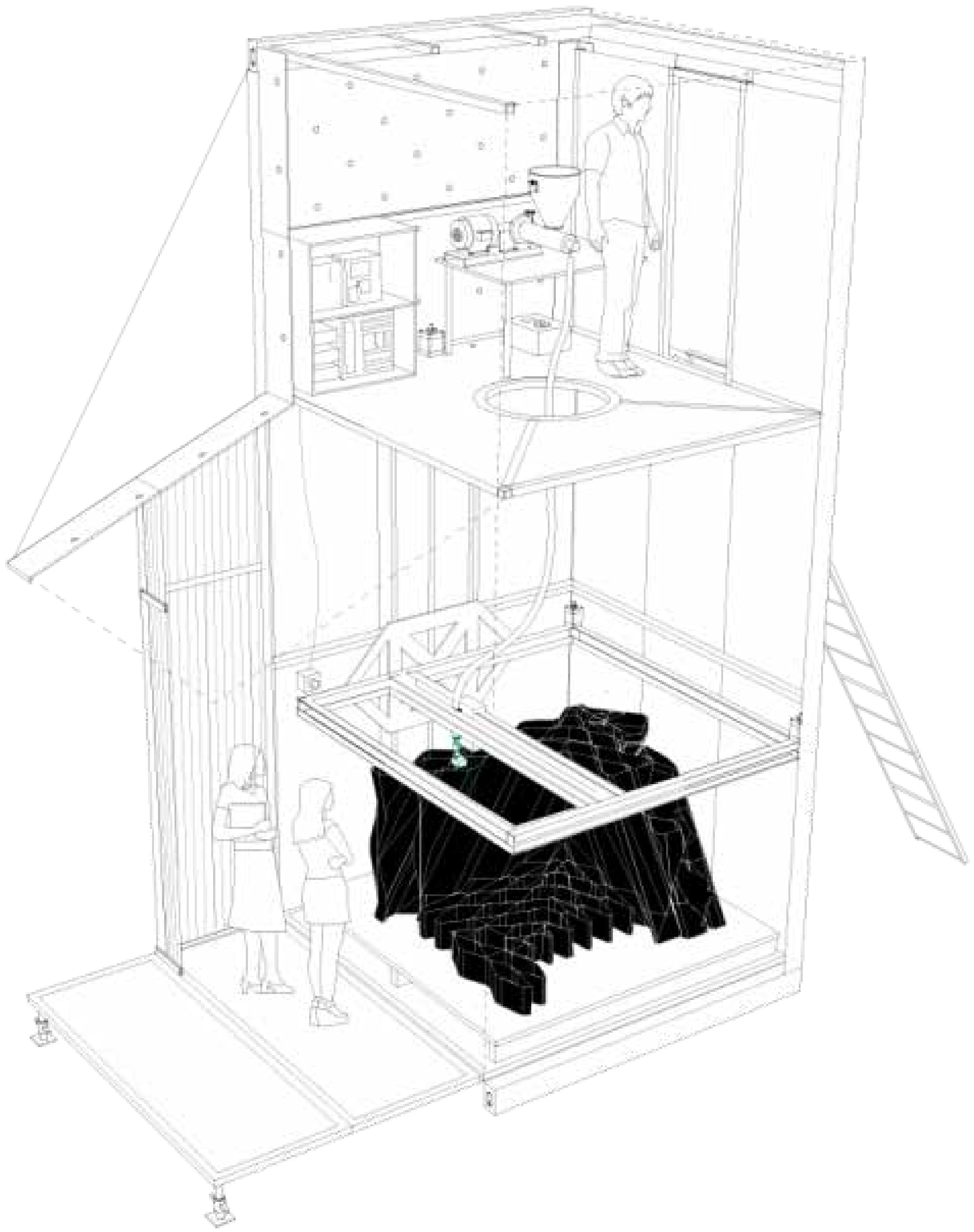
DUS Architects: In-Situ Construction

The 3D printer, called the Kamermaker (Room Creator), is situated in a closed sea container that is transported to the construction site and put vertically to increase the print height of the objects. The printer is protected from local weather and can maintain a steady temperature.

Source: Designboom. (2013, March 19). DUS architects: kamermaker 3D printer pavilion. Retrieved January 22, 2020, from https://www.designboom.com/architecture/dus-architects-kamermaker-3d-printer-pavilion/

DUS Architects: 3D Printer

The location of this project is The Netherlands which means a lot of rain, wind and colder temperatures than desired to 3D print. The solution according to DUS is to print the house in parts and connecting them with concrete.

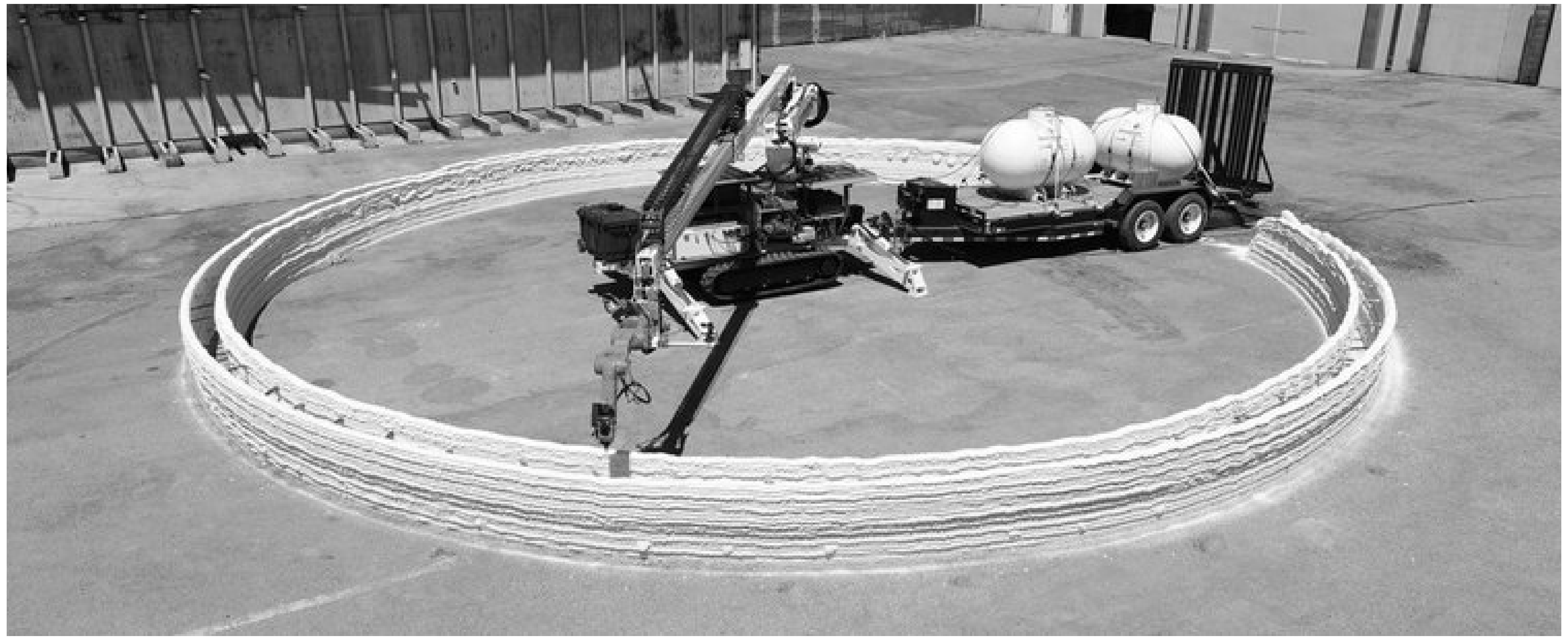


Source: DUS Architects. (2011). XL 3D Printer – DUS Architects. Retrieved January 22, 2020, from https://houseofdus.com/project/kamermaker/

3D Printing Robots

General Intro

In order to make a 3D printed building that is constructed in-situ a new type of 3D printing machine should be made. Conventional 3D printers are too small and if they can be scaled up, in most cases they would be too static. A 3D printer that operates on the construction site would not be suited because the construction site is not something static, on the contrary, it is very dynamic with a lot of things happening. The 3D printer would be a nice addition to the construction site as described in the general introduction of this chapter. To research the possibilities of 3D printing on the construction site three concepts are made. These concepts tend to keep a few things in mind, namely transport, printing construction type (parts of monolith structure), operational control, setup time, obstacle avoidance and other general advantages.

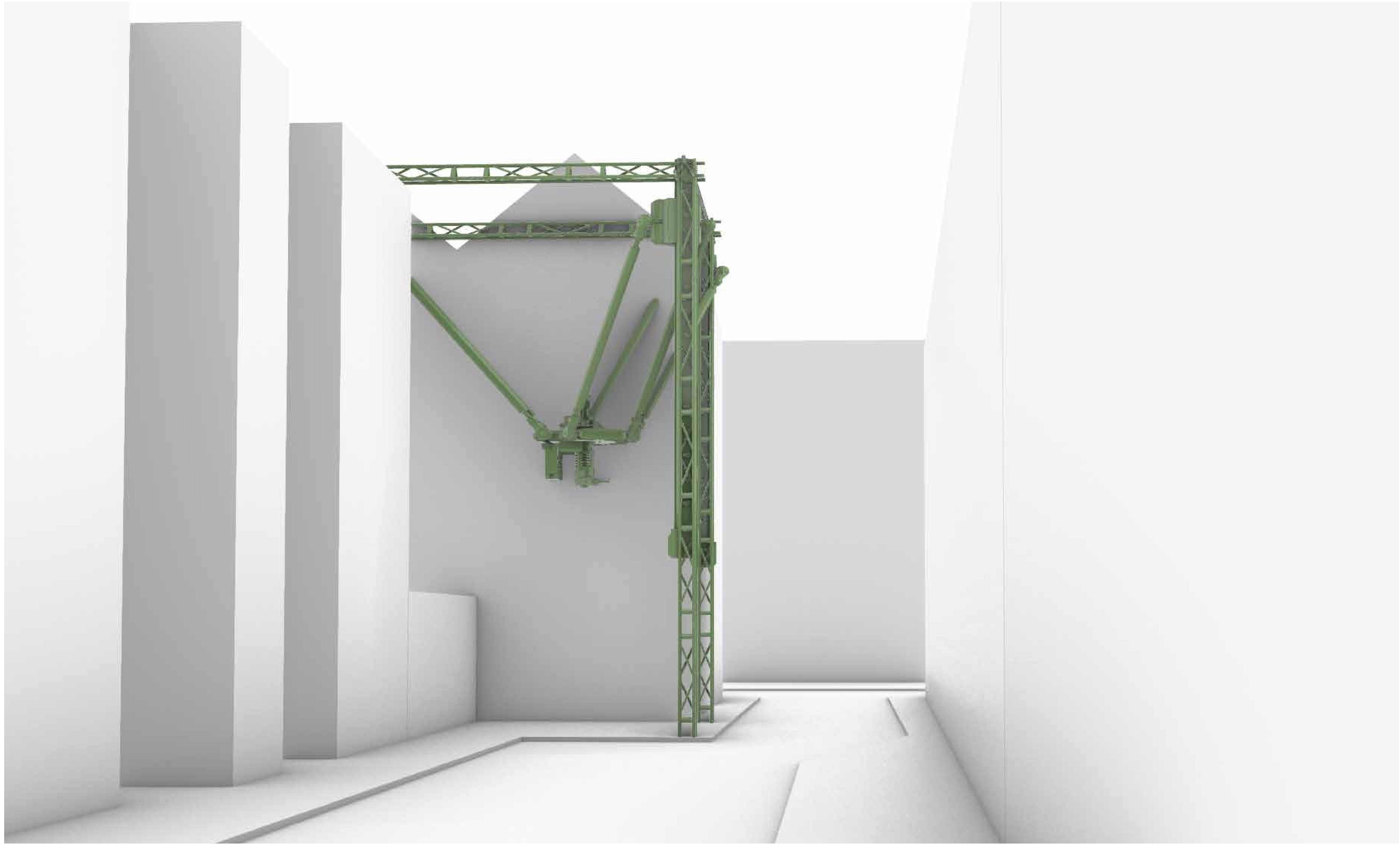


3DP Robot: Upgrade Existing Hardware

From a sustainability perspective the idea of making an entirely new machine to 3D print on the construction site is not viable. Therefore the existing stock of construction hardware (excavator, forklift, etc.) should be upgraded with 6 axis robotic arms to improve the precision and flexibility at the extruder head. This machine is easy to transport (as far as the existing machine could transport itself) as well as good to place on-site. Aside from the machine that can 3D print, the existing hardware could still fulfill specific tasks before it was transformed into a 3D printer. For a lifting machine this means it can also place prefab floors. The construction form of this machine would be a hybrid, meaning it can print the walls and separately print the floors and place those on the walls. This means that humans and the 3D printer should work together to complete a building. The fact that this machine is easy to transport and the fact it can function as multiple equipment machines makes this printer the excellent choice for this graduation project. Protection of the 3D printer should be covered in the next chapter.

3DP Robot: Gantry System

A gantry based system would be a desktop 3D printer resized to the extreme to print everywhere it is built. This printer would have to be built on each single construction site from single beam elements to form a system that covers the entire site. Transporting this printer to the site is doable, but the assembly of the 3D printer would be very labour intensive. Besides, the dimensions and possibility of placing supports of each location change drastically so it would be very hard to make a one size fits all solution. This type of 3D printer can best be used for projects that are newly built in an open space, rather than in a dense city. It is therefore not suited for the graduation project.



3DP Robot: Sea container

A printer in a sea container would also be based on a gantry system, but instead of placing this gantry on the construction site, it is made in a sea container (like DUS Architects). This entire sea container is transported with a lorry to the construction site where it can start printing the moment it is placed. By using a sea container the 3D printer is immediately protected from the elements while it can also easily maintain a steady temperature. However there are also some disadvantages with this approach of 3D printing in-situ. Because the 3D printer is placed inside a sea container the volume of the 3D printer is exactly the size of this container. This means not an entire building can be printed in-situ, but parts have to be printed and have to be connected by labour. The placement of these parts requires heavy duty equipment to lift the parts. This does not seem to be a problem at first, but because the locations in the graduation project are rather small and available in tight spaces, there is no space for large equipment. This is also a problem for the transportation of the sea container to the construction site, because it is hard or cannot be reached with a lorry. Therefore this option for a 3D printer on the construction site is not suitable for the concept of the graduation project.

Protection Construction Site

General Intro

3D printing is a process that requires a material to be heated and melted before it can print the material. When this material is printed it needs time to cool down in order to fully harden. During this process new layers are added which will adhere better to the previous layer if this layer is still hot. When using a printer in an interior and controlled environment this task is manageable, but in this particular case where the 3D printer is brought to the exterior some measurements have to be made in order to control the printing process. External influences like rain, wind and sun could all have a negative impact on the final 3D print. The construction site should be protected from the elements, but it is also important to keep an eye on the surrounding temperature of the 3D printer. Outdoor temperature varies a lot and could possibly be fatal for the 3D printing process. When layers cool down too soon due to cold weather or cool down too slow due to hot weather the adhesive bond between the layers can get worse. These are all reasons why the construction site should be protected. Therefore three proposals are made to protect the construction site. These concepts tend to keep a few things in mind, namely ease of use, elemental protection, temperature control, transport and setup time.

Elements

Wind *Rain* *Temperature* *Sun* *Snow*

Protection Construction Site: Gantry Cover

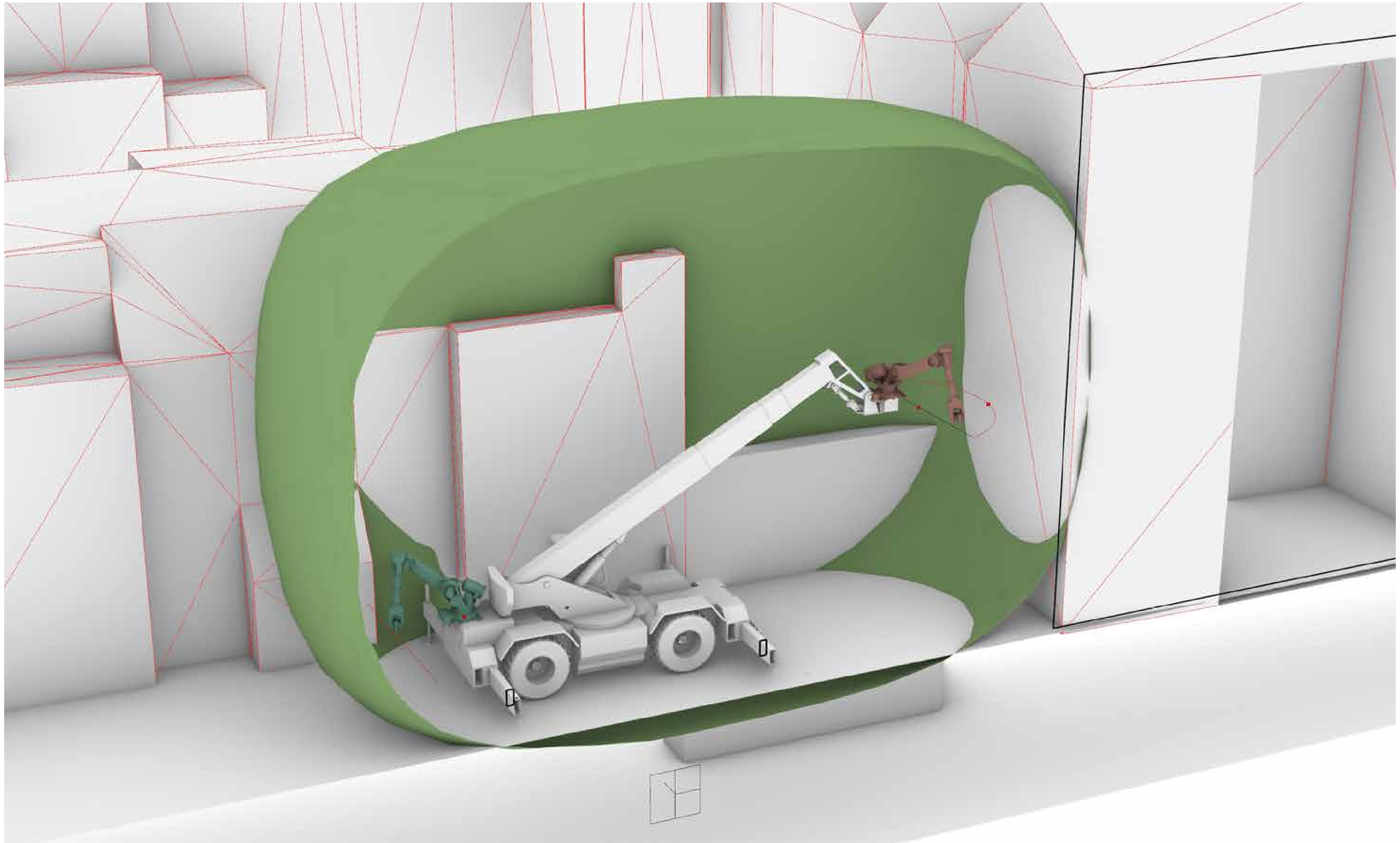
Gantry Cover

This concept relies on the use of a 3D printer in-situ that is made from scaffolds. These scaffolds can be connected with multiple canvases to provide a fully enclosed shelter for the 3D printer and the 3D print. This protection is easy to apply on the existing structure and keeps the elements away from the print. It is also beneficial for temperature control and is easy to transport (the protection at least). This 3D printer setup would be a combination of DUS Architects sea container printer and the protection from the Apis Core printer. While this option seems the best to use, the disadvantages of the installation of the actual 3D printer are very high and very specific for each new location.

Protection Construction Site: Inflatable

Inflatable Bubble

The concept of an inflatable bubble origines from the idea of easily transporting a small transporting system that can quickly be transformed to a very large volume without the need of any support elements. The shelter would be fully enclosed to keep the elements out and keep the temperature at a steady level by controlling the temperature of the air that comes in. Even changing locations are no problem for this type of protection, because surrounding buildings can just collide with the soft exterior of the inflatable. However, the main problem of this inflatable is that the entrance is hard to regulate as well as the impossibility to print on the foundation due to the fact the exterior of the bubble is present. That is the main reason this option is not suitable



Protection Construction Site: Canvas

Canvas cover

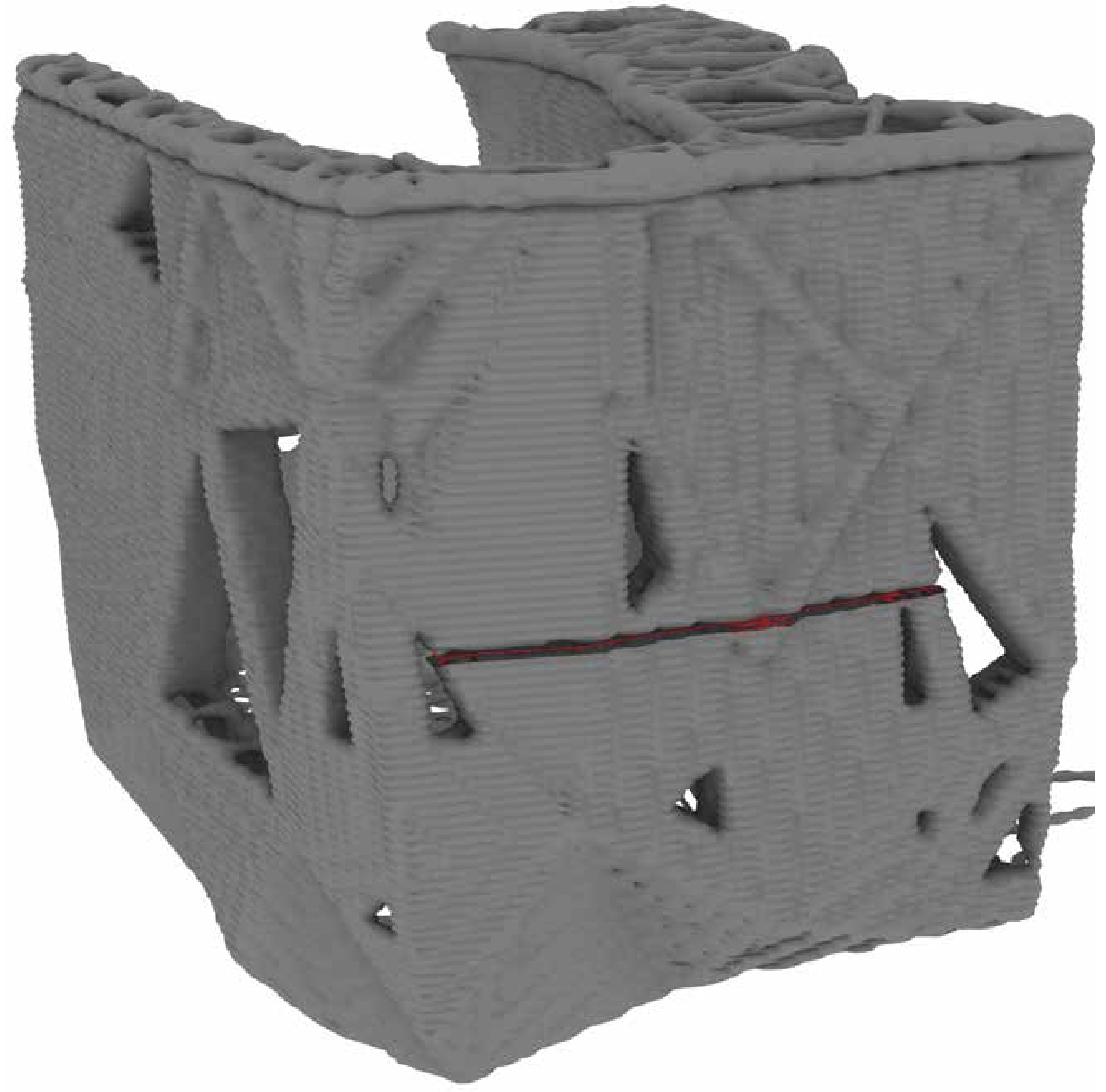
The sheet cover concept uses the surrounding buildings in a beneficial way by attaching the protection to these buildings. This way no extra support is required to install or transport, meaning it will be an excellent way of lightweight construction site protection. The construction site is protected from external elements by means of the buildings and the provided sheets. Temperature control remains the most weak factor in this concept, however this can be overcome with completely covering the location by using a modified mobile printer. When used in combination with a mobile 3D printer, several attachment points can also be introduced to the 3D printer to fully cover the construction site while also reducing the amount of disturbance surrounding buildings.

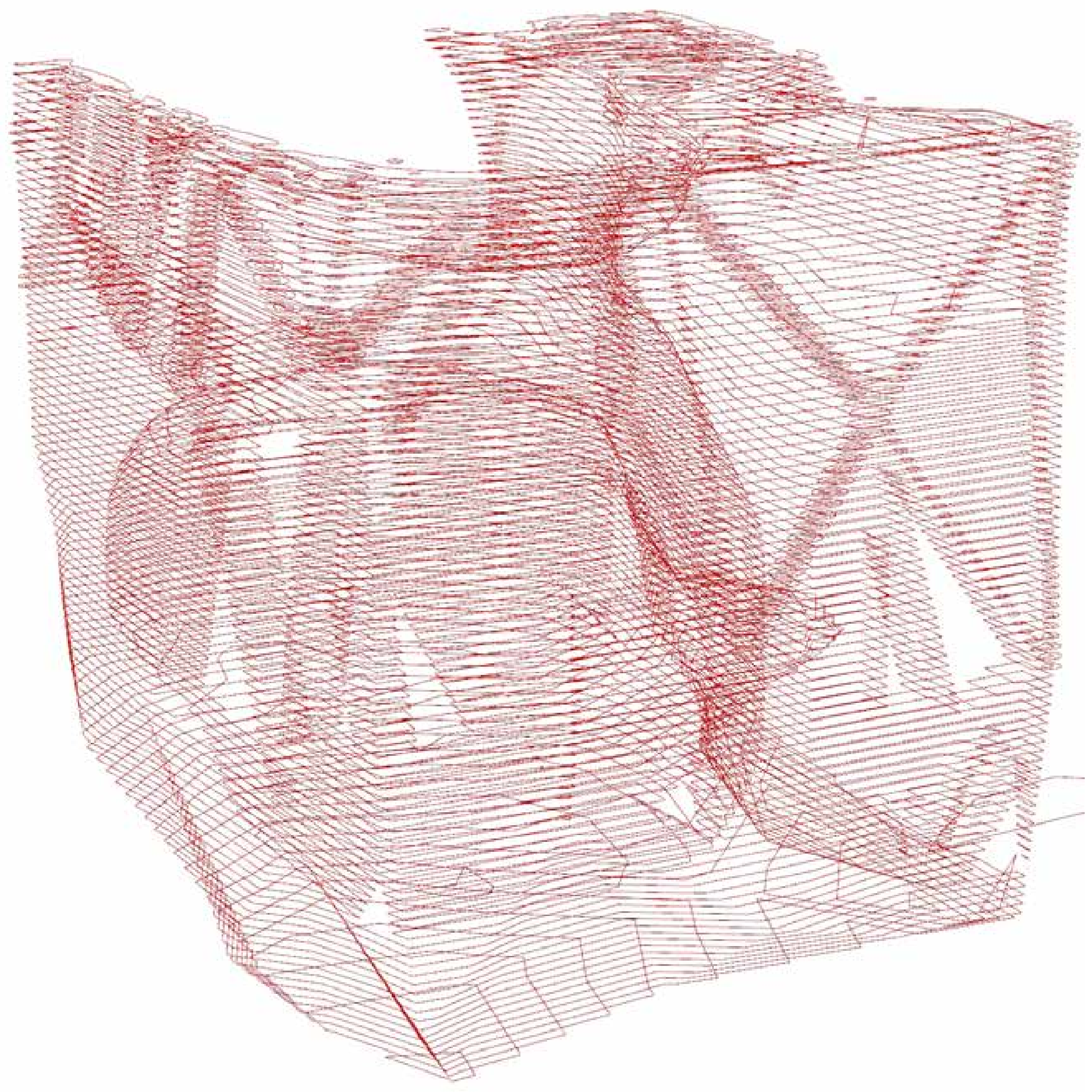
Printing Time Calculation

Using an older version of the fragment the rough printing time of the entire building is calculated. The printing path is generated in grasshopper with a layer heigt of 50mm. This calculation was based on an older detail concept that relied on a wall of two printed layers. This results in a printing length of 2280 meter. These calculations will serve as basis for the final design calculation.

Option A: Printing Speed ICON Build (150mm/s)
Print length of this fragment: 2280 meter
15cm/s = 900cm/min = 9m/min
2280/9 = 253 minutes = 4 hours
Fragment is 1/8 of the entire building so the print would take about 32 hours

Option B: Printing Speed AI Spacefactory (65mm/s)
Print length of this fragment: 2280 meter
7cm/s = 420cm/min = 4.2m/min
2280/4.2 = 542 minutes = 9 hours
Fragment is 1/8 of the entire building so the print would take about 72 hours





Basalt Fiber reinforced Poly-lactid acid

Why BFRPLA?

The material basalt fiber reinforced polylactic acid is specifically chosen for several reasons. The most important reason was that one of the goals of the graduation project was to incorporate materials from renewable sources that could also be 3D printed. PLA was chosen fairly soon in the design process because it had both aforementioned abilities. However there are some big downsides when choosing PLA, mostly regarding its low heat resistance and being brittle. To cope with these main problems, the investigation was for a material that is fire resistant and can make the PLA thermoplastic stronger, so the sustainable image of PLA could be held intact. The choice was made for basalt fiber because it is a natural material that has a high fire resistance and can strengthen PLA. This composite is also chosen because of the available references towards 3D printing this material for a building. Because there are few publications for this material available, PLA and basalt are researched separately and their conclusions will be combined in the last paragraph together with the addition of state of the art references and scientific papers about reinforcing thermoplastics (whether this is PLA or something similar) with basalt fibers.

A piece of 3D printed BFRPLA

AI Spacefactory. (2019b). AI SpaceFactory Wins NASA's 3D-Printed Mars Habitat Challenge [Illustration]. Retrieved from https://www.archdaily.com/916888/ai-spacefactory-wins-nasas-3d-printed-mars-habitat-challenge

Polylactic Acid

PLA: Production

Polylactic acid or PLA can be produced from a variety of agricultural crops that contain high levels of sugar, like maize, sugarcane, potato and sugar beet. These crops are transformed into PLA via several steps as can be seen in the figure on the right. Through fermentation and polymerization PLA can be derived. PLA is a bioplastic that is also biodegradable if it is not combined with other plastics that are made from fossil fuels (van Wijk & van Wijk, 2015). This material is specifically interesting because the combination of the product being made of renewable sources as well as the biodegradability of the material make this a very sustainable bioplastic (Castro-Aguirre et al., 2016). However there are some shortcomings when one starts constructing with this material for applications that are to last. In the coming paragraphs these things will be discussed.

CROPS TO BIO-BASED PLASTICS

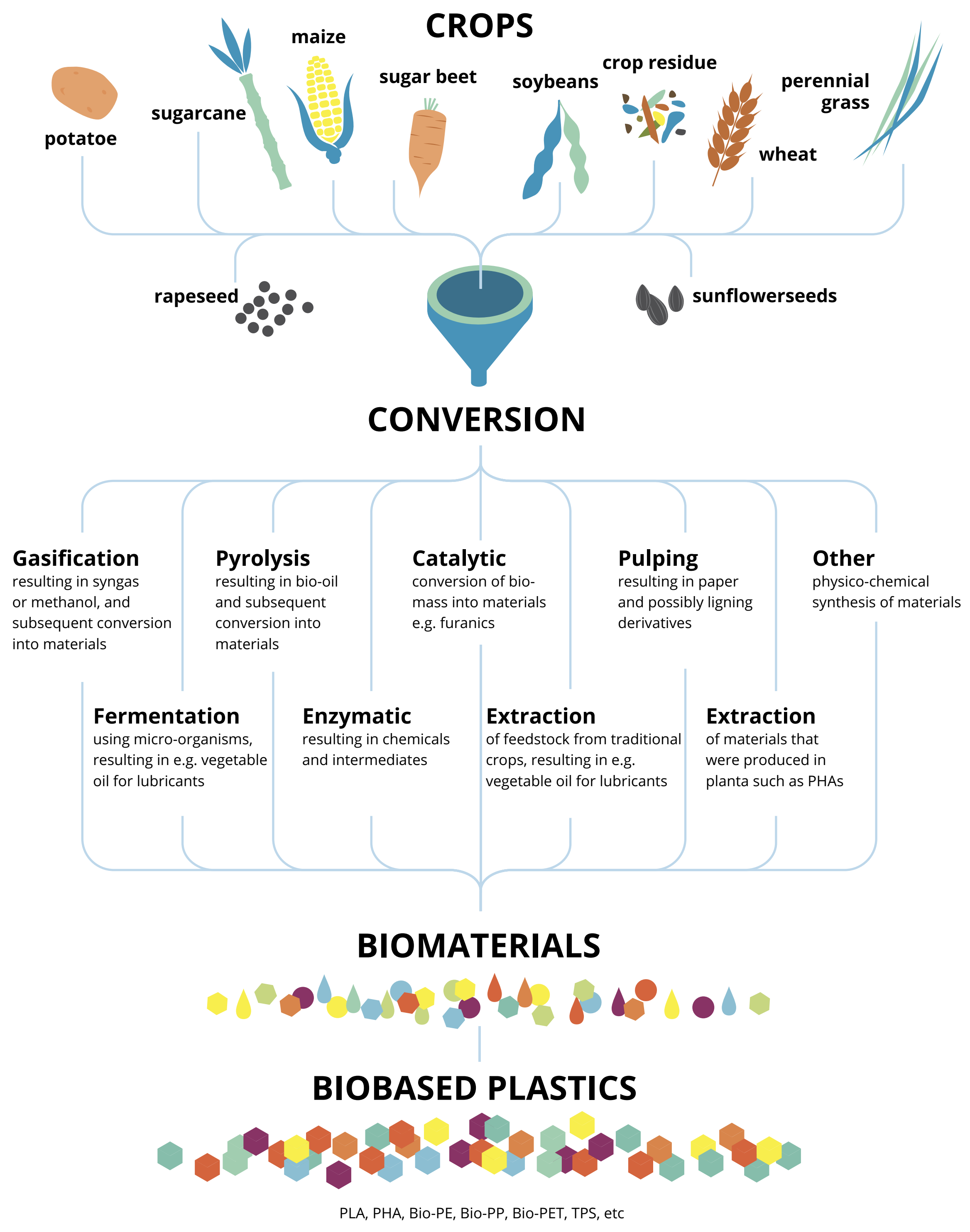


Figure 2: Agricultural crops to PLA (van Wijk & van Wijk 2015)

PLA PRODUCTION PROCESS

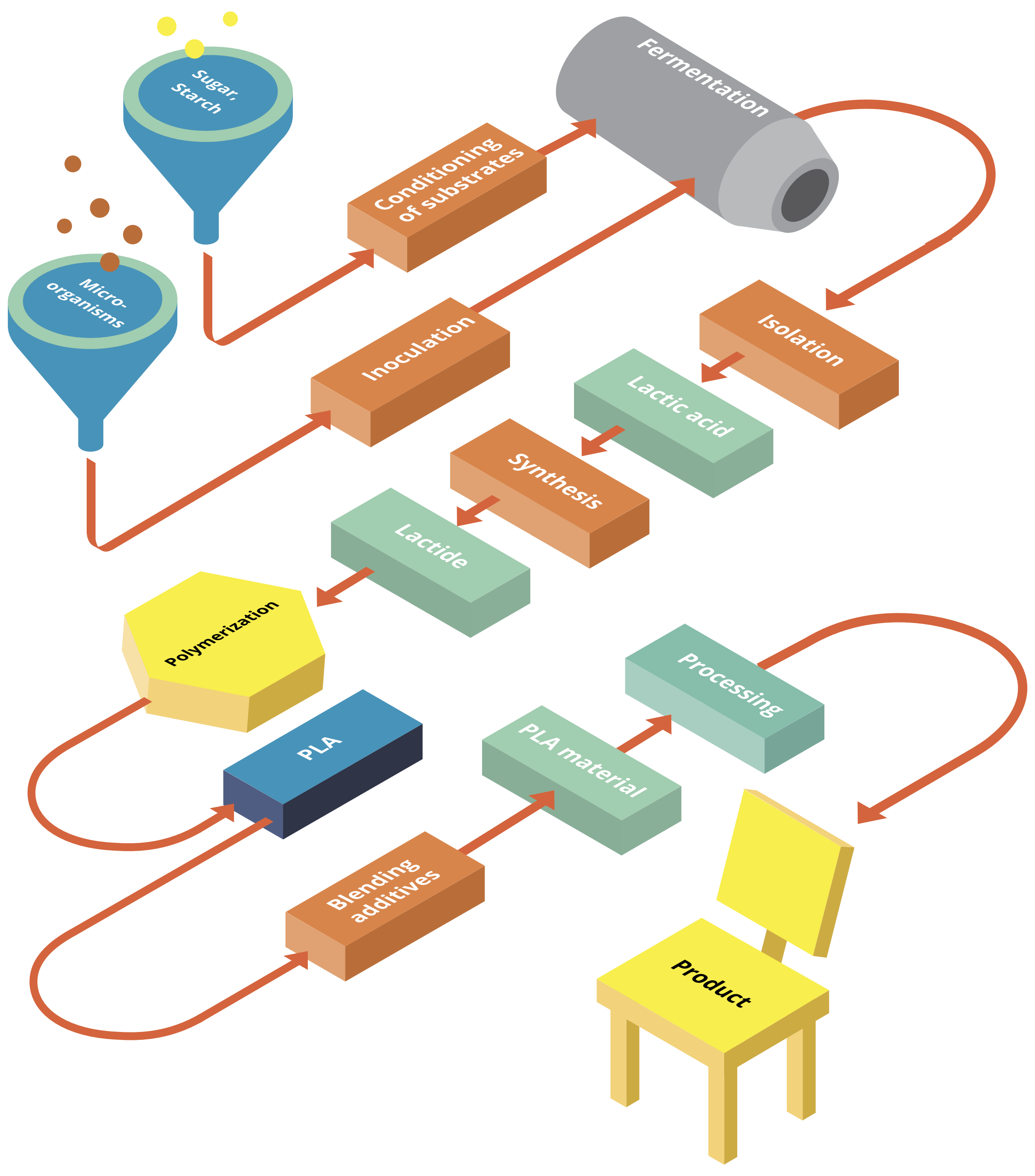


Figure 3: Sugar to PLA (van Wijk & van Wijk 2015)

PLA: Local Sources

PLA can be derived from different crops that are also grown in the Netherlands. That would mean it is a very local product that not only can be made in the Netherlands, but everywhere in the world where the suitable crops grow. Although PLA can be made from several agricultural crops, for the sake of this graduation project sugar beet is used to research production rates, availability and those amounts are used for a calculation based on multiple sources. On the images on the right it is evident that sugar beet production in the Netherlands compared to other countries in Europe is quite high. When zooming in, the closest farms to Rotterdam (graduation project location and to reduce transportation) that also produce a large quantity of sugar beets can be found around Rotterdam itself and Zeeland. This is great because the material can get produced very locally.

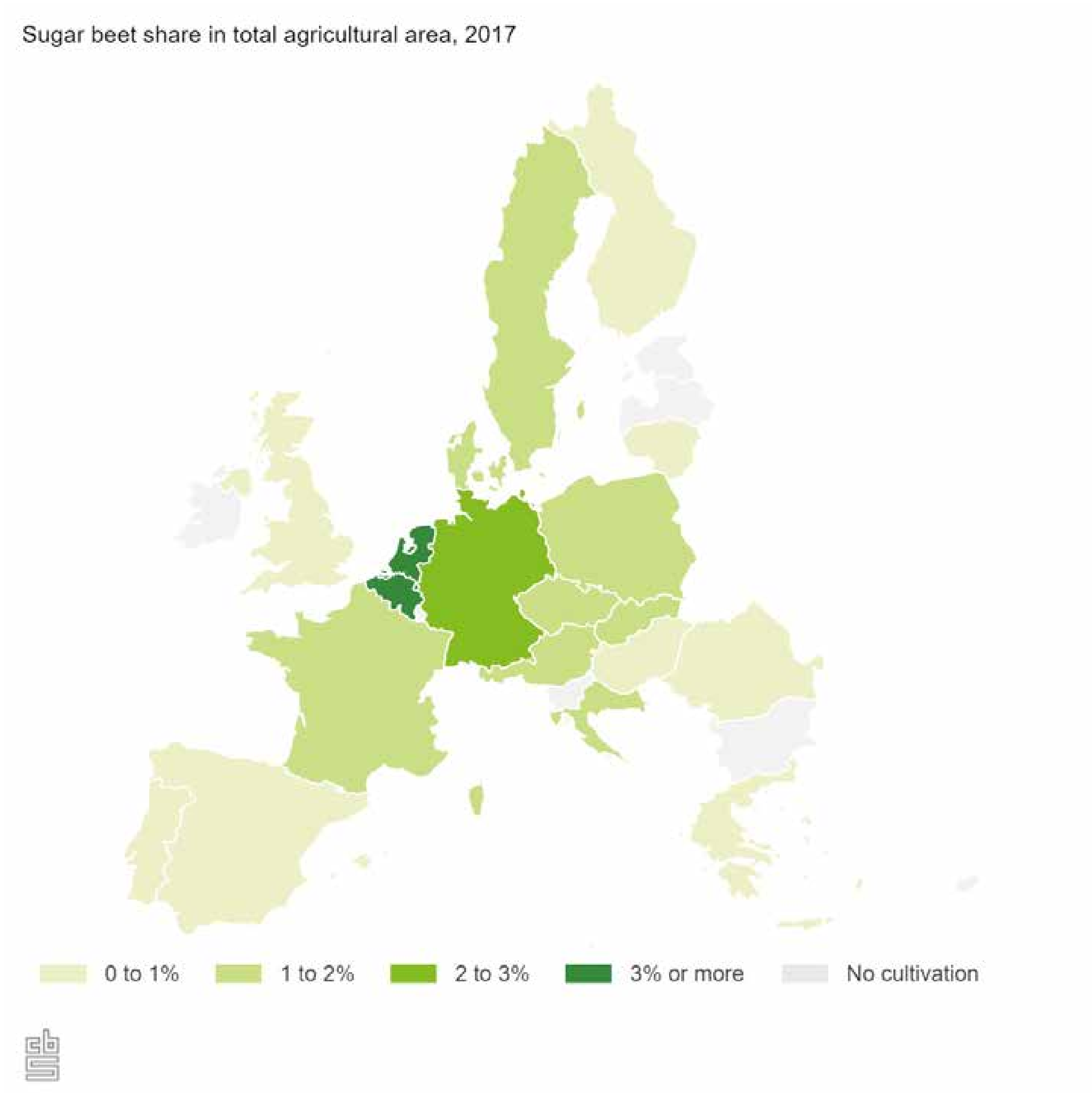


Figure 4: Sugar beet share Europe, agricultural area (CBS, 2019)

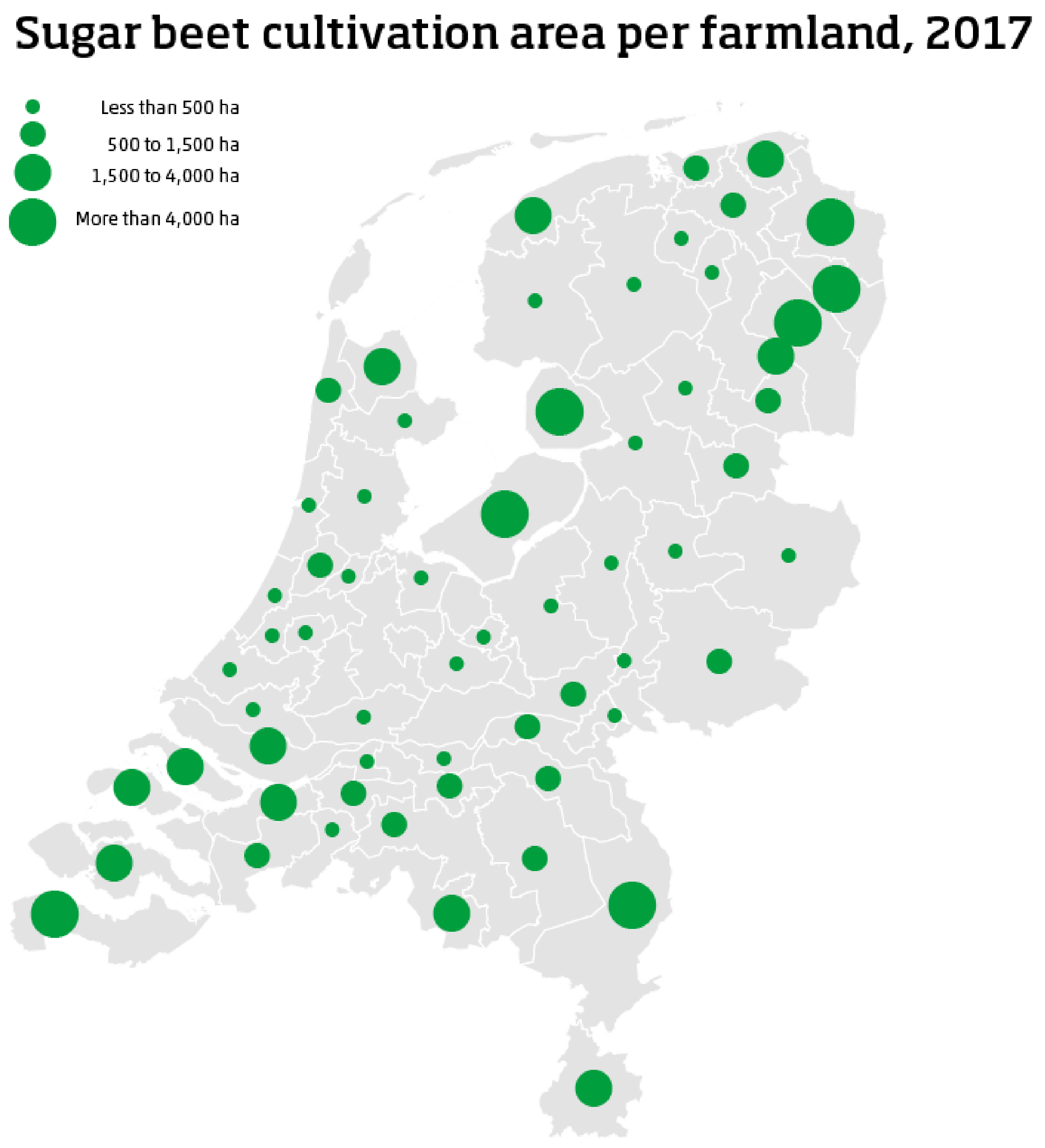


Figure 5: Sugar beet cultivation are per farmland (CBS, 2019)

PLA: Local Sources

The Netherlands has a very high sugar beet cultivation area compared to other countries as can be seen in the figures on the right. This would imply that the country can be self-sufficient in the production of construction materials made from not only renewable, but also very local resources.

These graphs will later be used to calculate the amount of sugar beets needed for the construction of a small house, which can be find at the end of this chapter.

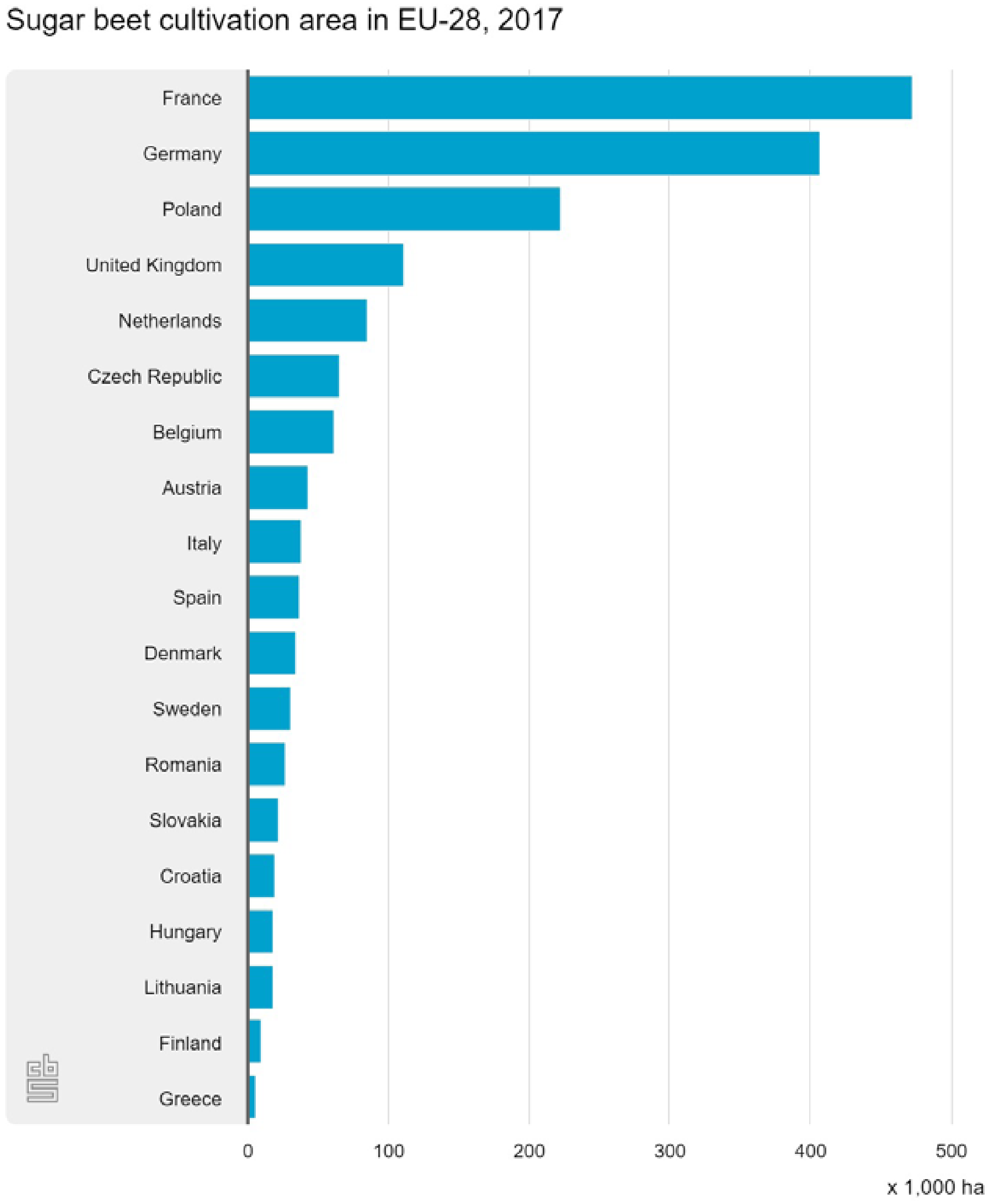


Figure 6: Sugar beet cultivation area (CBS, 2018)

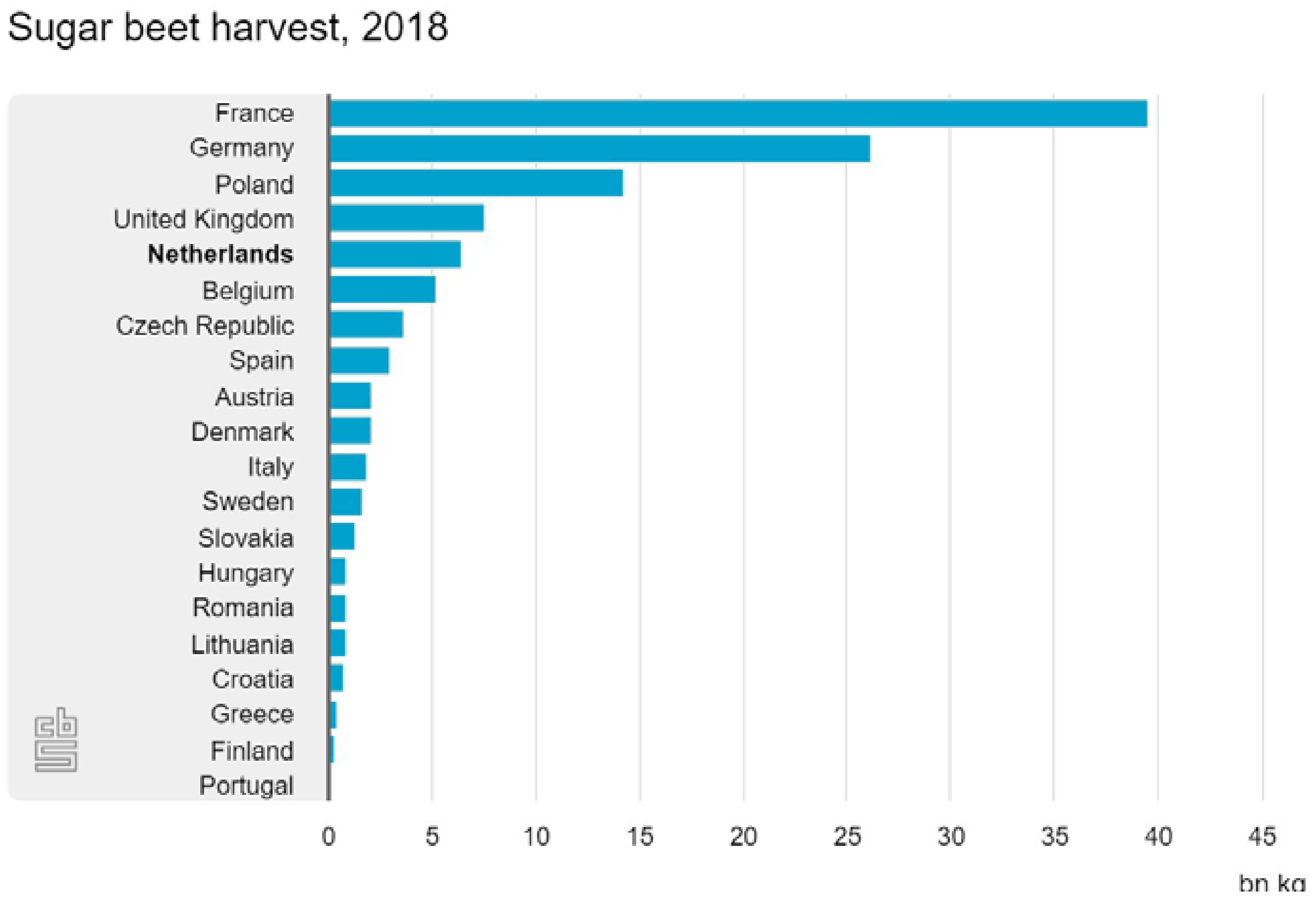


Figure 7: Sugar beet harvest (CBS, 2019)

PLA: General Properties

Structural

PLA is a biodegradable material, which means it can be broken down by naturally occurring circumstances. However, in order to break down PLA it should be placed in a controlled composting industry plant where conditions like temperature and humidity are optimal for PLA to disintegrate (Castro-Aguirre et al., 2016). When placed in regular soil, or in a regular composting heaps, PLA will show no or very minimal signs of disintegration. Karamanlioglu et al. (2017) state that when PLA film was buried in regular soil for 120 days no degradation was observed.

This means PLA will show no signs of disintegration in regular day use, whereas these conditions vary all the time, but it does mean that there should be thought about how PLA can be collected and transported to these plants so no accumulation and pollution will eventually form (Karamanlioglu, Preziosi & Robson, 2017).

Disintegration in environment

PLA has good mechanical properties, like high strength and stiffness. But it is also a very brittle polymer which breaks quite fast and does not allow very much impact strength (Tábi et al., 2014). This would immediately be a problem if the material is used as a structural component in a building. This is one of the reasons to introduce basalt fiber as a strengthening material. The structural results of this composite can be found in the BFRPLA chapter.

Insulation

PLA has one of the lowest conductivity values known among plastics. It is therefore not a very good heat distributor and has an insulation value of 0.110 W/mK (SpecialChem SA (n.d)). This is also the reason other companies started to make insulation foam based on the low conductivity of PLA. Synbra Technology BV (n.d.) is such a company that makes a product called Biofoam as seen in the images below. It has very good insulation properties, with a thermal conductivity value of 0.034 W/mK (Synbra Technology BV (n.d.)). This product is also made carbon neutral and does only disintegrate in a controlled industrial composting plant (like raw PLA).

Figure 8: Biofoam insulation boards (SpecialChem SA (n.d)

PLA: Heat Properties

PLA is very susceptible to heat. The glass transition temperature of pure PLA is about 60 degrees celsius, which is above room temperature, but when used in a facade where the sun is exposed all day long it would be just fitting. It would be better to increase this glass transition temperature, hopefully with the addition of fibers. Another great threat PLA is susceptible to is fire. PLA melts at around 180 degrees which makes it 3D printable, but also very flammable. When PLA is exposed to a fire, it will melt, bend and deform as can be seen in the image on the right. Beside these very unwanted aspects a building could pose, dripping of hot PLA is also something that occurs in case of a fire. Kolibaba et al. (2019) developed a more fire resistant and even self extinguishing PLA that still could be 3D printed, by adding other components like polyvinylamine and poly(sodium phosphate) (Kolibaba et al., 2019). Also Castro-Aguirre et al. (2016) developed a PLA alloy with high heat resistance and flame retardant. While these solutions already show good developments in making PLA more heat resistant, they still use many additives and are complex to make. They can be used but in this graduation project a more integrated approach is desired in order to keep the sustainable aspect of PLA.

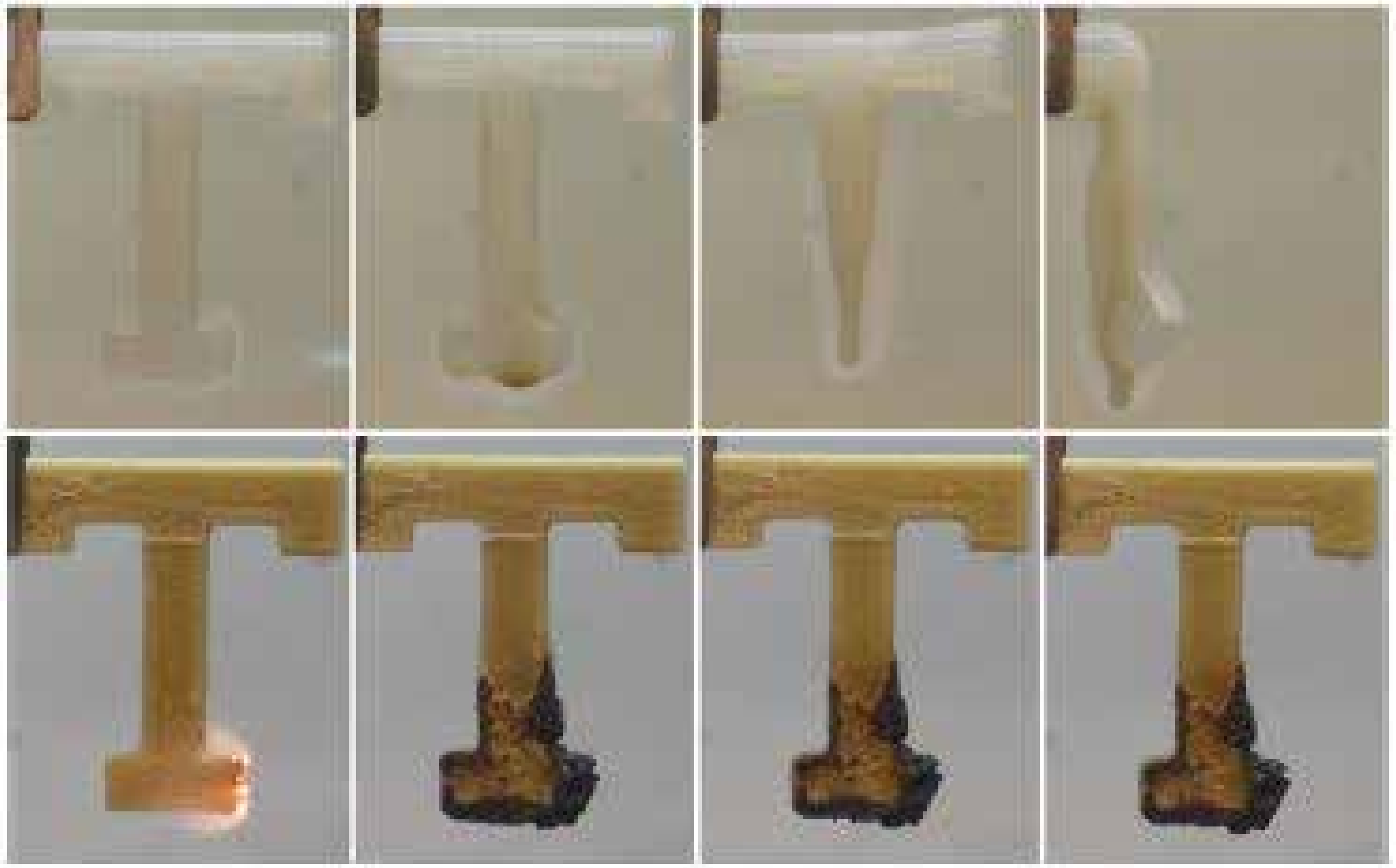


Figure 9: PLA that is more fire resistant and even self extinguishing (Kolibaba et al., 2019)

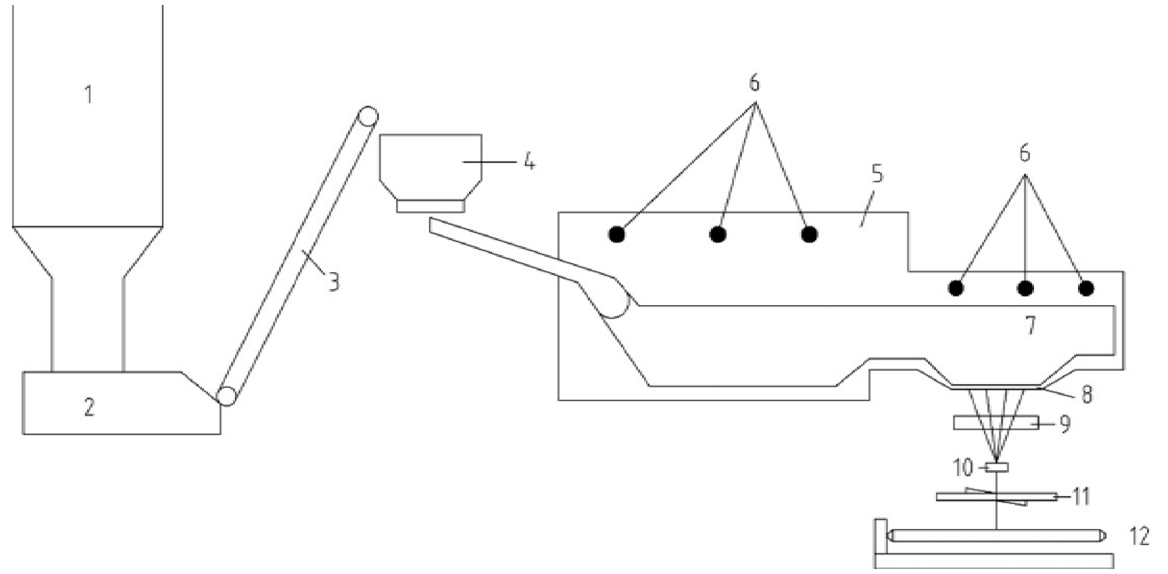
Basalt Fiber

BF: Winning + Processing

Basalt rocks are the most common rocks that can be found on earth. They take up about 33% of the earth crust (Dhand et al., 2015). Basalt is not a renewable source, however it is made from volcanic rock that is available almost everywhere around the world, so it can be considered as a natural material (Tábi et al., 2014).

In the process of making basalt fiber there are no other materials added, so it is a very straightforward and sustainable process which is in line with the creation of PLA. In order to transform the rocks to fibers the basalt rock is first washed and after that it is immediately melted at a temperature of 1500 degrees celsius. The diameter/thickness of the rock is reduced by drawing the rock over multiple rollers before winding it over a final spool (Dhand et al., 2015).

The last reason to use basalt fibers as a reinforcement for PLA is that basalt fibers have proven to have outstanding abilities for the reinforcement of thermoplastics (Dhand et al., 2015; Militký, Mishra & Jamshaid, 2018). In short, these abilities concern strength, durability, thermal resistance, water resistance and shall be discussed in paragraphs below.



1-Bin, 2-Feeder, 3- Lift conveyor, 4- Quantitative feeder, 5- Primary melting zone of raw materials, 6- Natural gas nozzle, 7- second stage melting zone (front furnace), 8- Platinum rhodium alloy bushing , 9- impregnating compound configuration equipment, 10- buncher, 11- Fiber tensioner, 12- Automatic fiber winding machine
Figure 2. Manufacturing process of Basalt fiber.

Figure 10: Basalt Fibers (Li et al., 2018)

Figure 11: Basalt Volcanic Rock (Sandatlas. (n.d.))

BF: Local Sources

The basalt rock can be found on all continents of the world, but the closest locations to graduation' project locations of Rotterdam can be found in Germany. In Germany there are a lot of quarries in the west side of the country, close to the Dutch border. That means transportation is reduced to a minimum. The worldwide availability also means this material can be used in other countries as construction material as well.

Figure 12: Basalt Fibers (Li et al., 2018)

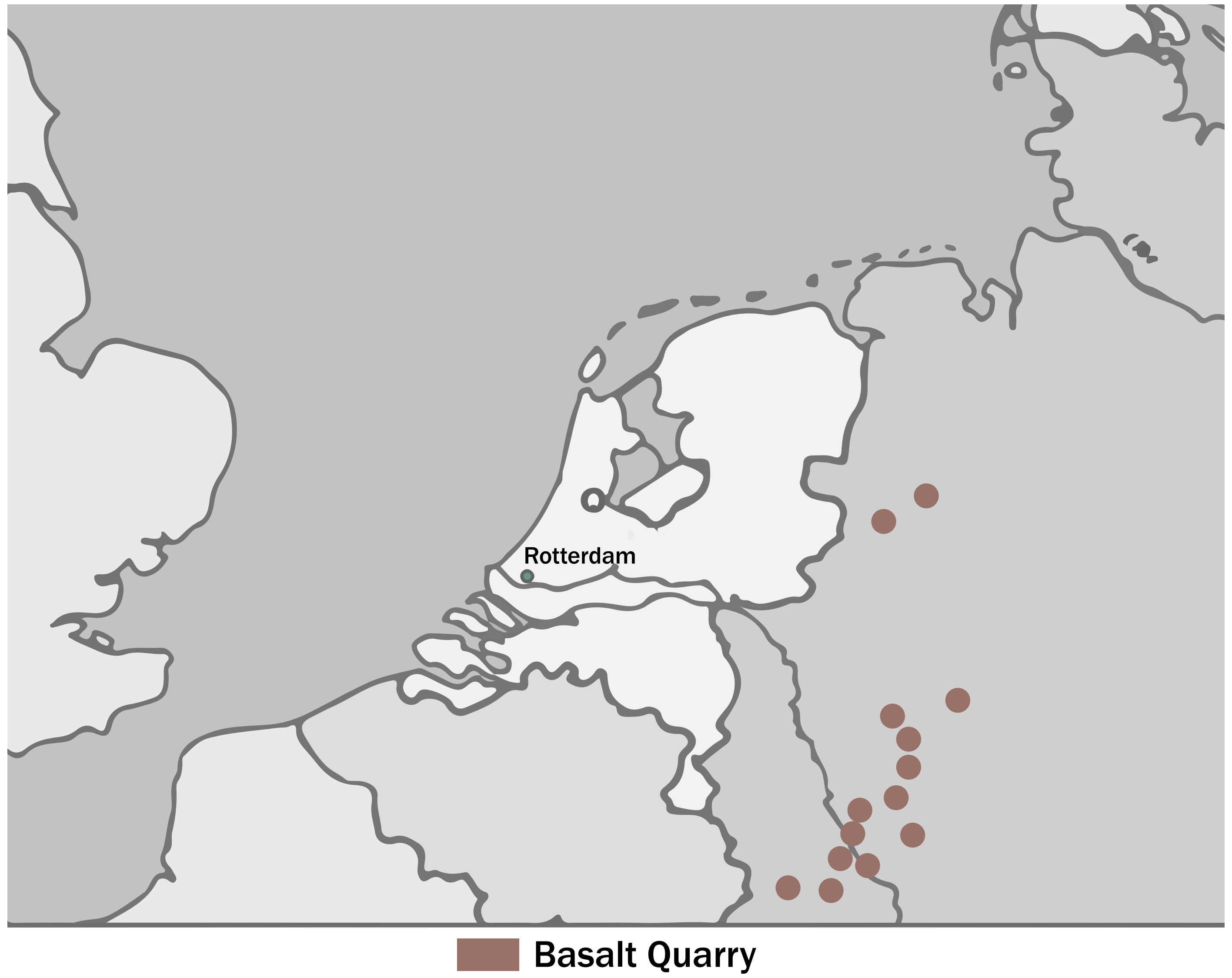


Figure 13: Nearest basalt quarries Rotterdam (own image)

BF: Structural Properties

Basalt fibers are known for their high strength and their ability to increase the strength of existing materials when combined. It is currently used in products like concrete and steel to reinforce bridges, buildings and other civil constructions (Militký, et al., 2018). There is a wide range of basalt fiber products as is seen in the image on the right (Smarter Building Systems. (n.d.)) These products can be used in different applications depending on both the strength properties of the fiber, as well as other positive properties that will be discussed below.

Figure 14: Products made from basalt fibers (Smarter Building Systems. (n.d.))

BF: Insulation & Heat Properties

Basalt fiber is a very good insulator, because of its porous structure and irregular arrangement (Li et al., 2018). Thermal conductivity values of 0.034 W/mK can be reached if this material is being used as insulation in a wall fragment. Besides the fact that basalt is a good insulator, the sound absorption is also very good. The material can therefore be used as both thermal and acoustic insulation (Li et al., 2018).

For the aforementioned reasons Buratti et al. (2015) created a rigid basalt fiber insulation board for high energy efficiency in buildings. In the production process of the board no additive materials are used, which contributes to the sustainable aspect of this product. Buratti et al. (2015) managed to achieve a thermal conductivity value of 0.0305 W/mK with only 9 millimeter in thickness. Sound isolation was comparable with standard rock wool. This basalt fiber insulation board will reduce heat losses from buildings and therefore save energy (Buratti et al., 2015)

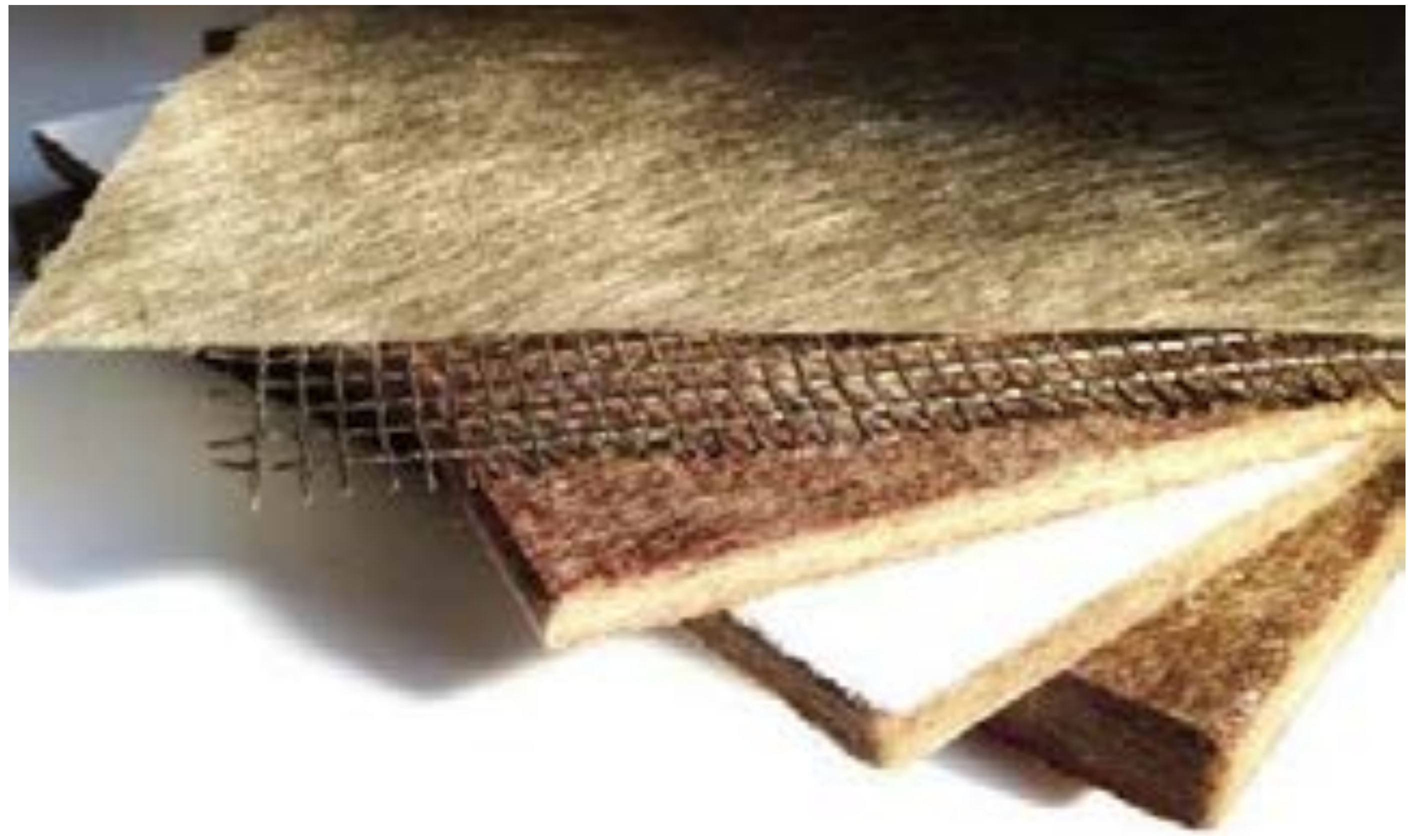


Figure 15: Basalt Rigid Insulation Sheets (Buratti et al., 2015)

Table 1
Comparison of various thermal properties of basalt fibers, fiberglass, and silica filaments [128].

Thermal properties	SI units	Basalt filaments	Fiberglass	Silica filaments
Maximum application temperature	(K)	1255	923	1640–2070
Sustained operating temperature	(K)	1093	753	1470
Minimum operating temperature	(K)	15	210	100
Thermal conductivity	(W/mK)	0.031–0.038	0.034–0.04	0.035–0.04
Melting temperature	(K)	1720	1390	2070
Thermal expansion coefficient	(1/K)	8.0×10^{-6}	5.4×10^{-6}	5.0×10^{-8}

Figure 16: Heat characteristics compared to other fibers (Dhand et al., 2015)

Beside the fact that basalt fiber is a good thermal insulator, its heat and fire resistance properties are also quite exquisite. Their very high melting temperature of around 1500 degrees (see figure 16) makes them very suitable for fire protection applications (Dhand et al., 2015). In a fire related event, these fibers will protect the structure behind the fibers'being it insulation or any other type of building component. This is also a huge gain when combining them with PLA, which has a very low heat resistance.

BFRPLA

BFRPLA Reuse Material Cycle Diagram

**Raw Material:
Basalt fiber & PLA
pallets**

Source: AI SpaceFactory. (2019b, May 22). TERA - How We Build Our Future Earth Eco-Habitat. Retrieved January 21, 2020, from https://www.youtube.com/watch?time_coninue=50&v=ZxEC5C8a0vE&feature=emb_logo

AI SpaceFactory. (n.d.-b). AI SpaceFactory (@AISpaceFactory) | Twitter. Retrieved April 02, 2020, from https://twitter.com/AISpaceFactory

AI SpaceFactory. (n.d.-a). AI SpaceFactory (@aispacefactory) | Instagram. Retrieved January 20, 2020, from https://www.instagram.com/aispacefactory/?hl=en

BFRPLA Material Cycle AI Spacefactory

This is a prototype from AI Spacefactory for the NASA Competition where they used basalt fiber reinforced PLA. It is printed indoors on an irregular surface, represents a house that is printed on scale, took about 30 hours and could withstand a 50% larger force than concrete.

Source: AI SpaceFactory. (n.d.-b). AI SpaceFactory (@ AISpaceFactory) | Twitter. Retrieved April 02, 2020, from https://twitter.com/AISpaceFactory

BFRPLA Material Cycle AI Spacefactory

The prototype is reused after the competition and broken down into smaller subparts. This can also be applicable in the building industry, where a building gets broken down and its material is reused for future purposes. But these smaller parts are still too large for reusing purposes.

Source: AI SpaceFactory. (n.d.-b). AI SpaceFactory (@ AISpaceFactory) | Twitter. Retrieved April 02, 2020, from https://twitter.com/AISpaceFactory

BFRPLA Material Cycle AI Spacefactory

Eventually the smaller parts of the building are grinded into smaller parts that can again be fed into a 3D printer to print another house, or something entirely different.

Source: AI SpaceFactory. (n.d.-b). AI SpaceFactory (@AISpaceFactory) | Twitter. Retrieved April 02, 2020, from https://twitter.com/AISpaceFactory

AI SpaceFactory. (n.d.-a). AI SpaceFactory (@aispace-factory) | Instagram. Retrieved January 20, 2020, from https://www.instagram.com/aispacefactory/?hl=en

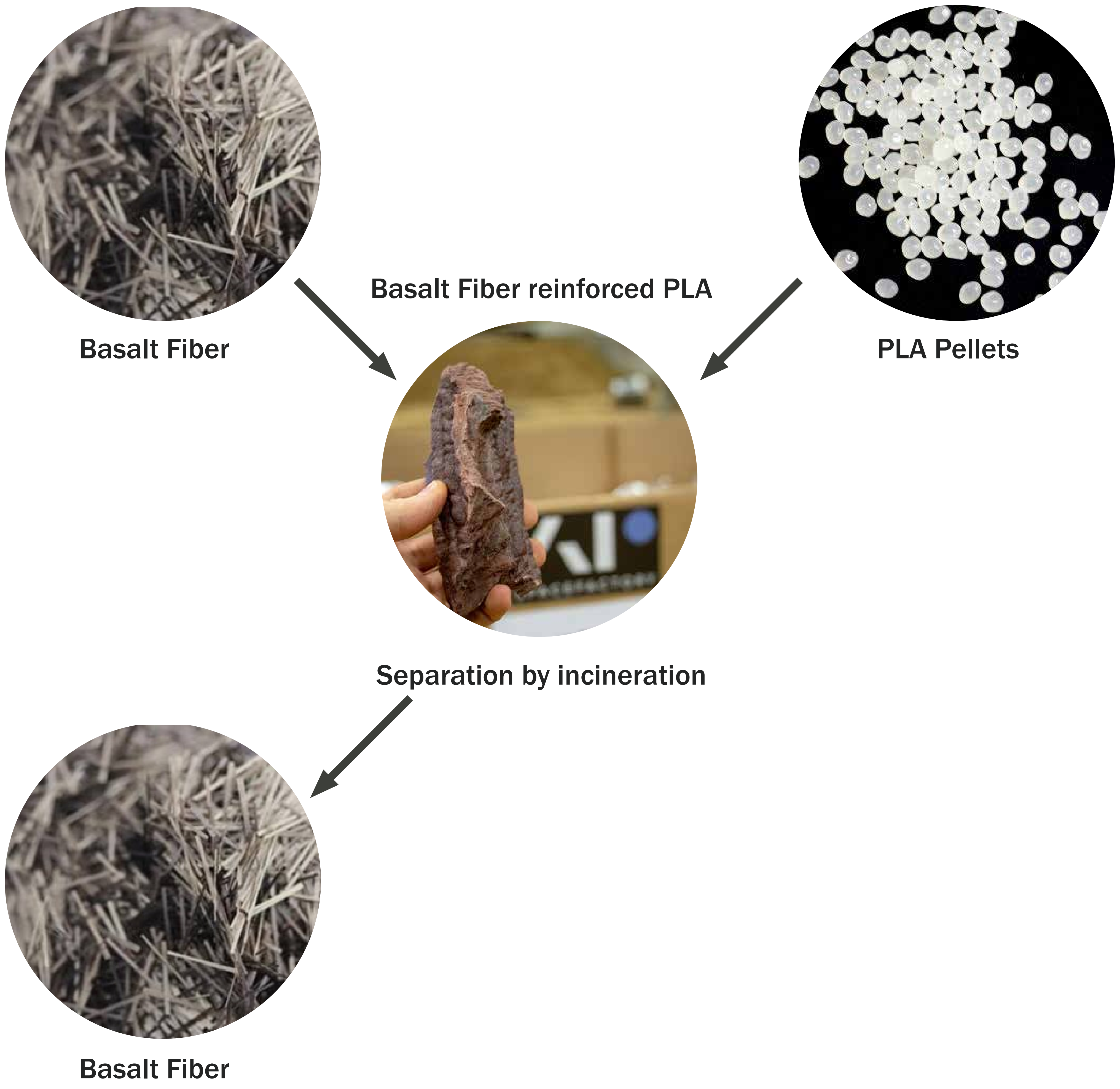
BFRPLA Material Separation After Use

The previous slides showed the reusability of the basalt fiber material. But it is also possible to separate the two materials into their raw materials. This process can be done by incineration and with more research maybe also in an compostable environment. . The process of incineration means that the composite material is incinerated in a very high temperature environment, just under the melting temperature of the basalt fibers. The PLA will be incinerated and the final product that is left, which are the unmolten basalt fibers, can be used again (Militký, et al., 2018).

Source: *AI Spacefactory. (2019b). AI SpaceFactory Wins NASA's 3D-Printed Mars Habitat Challenge [Illustration]. Retrieved from https://www.archdaily.com/916888/ai-spacefactory-wins-nasas-3d-printed-mars-habitat-challenge*

Li, Z., Ma, J., Ma, H., & Xu, X. (2018). Properties and Applications of Basalt Fiber and Its Composites. IOP Conference Series: Earth and Environmental Science, 186, 012–052. https://doi.org/10.1088/1755-1315/186/2/012052

Reprap World. (n.d.). Natureworks Ingeo 4043D PLA pellets [Photograph]. Retrieved from https://reprap.world/products/filament/pellets/natureworks_ingeo_4043d_pla_pellets_1_kg/



BFRPLA Structural Properties

When combining brittle PLA and very strong basalt fibers the resulting composite has very good mechanical properties (Tábi et al., 2014; Militký, et al., 2018). AI Spacefactory showed in the NASA contest that this material outperforms 3D printed concrete by being 50% stronger while also being 50% lighter than concrete (Youtube Originals, 2020). This phenomenon can be seen in the video on the next slide. While the material is stronger than 3D printed concrete the speed and material flow should be considered while printing because of the creation of voids as can be seen in figure 17 (Yu et al., 2019). These voids are found between layers and can be devastating for the strength of the composite.

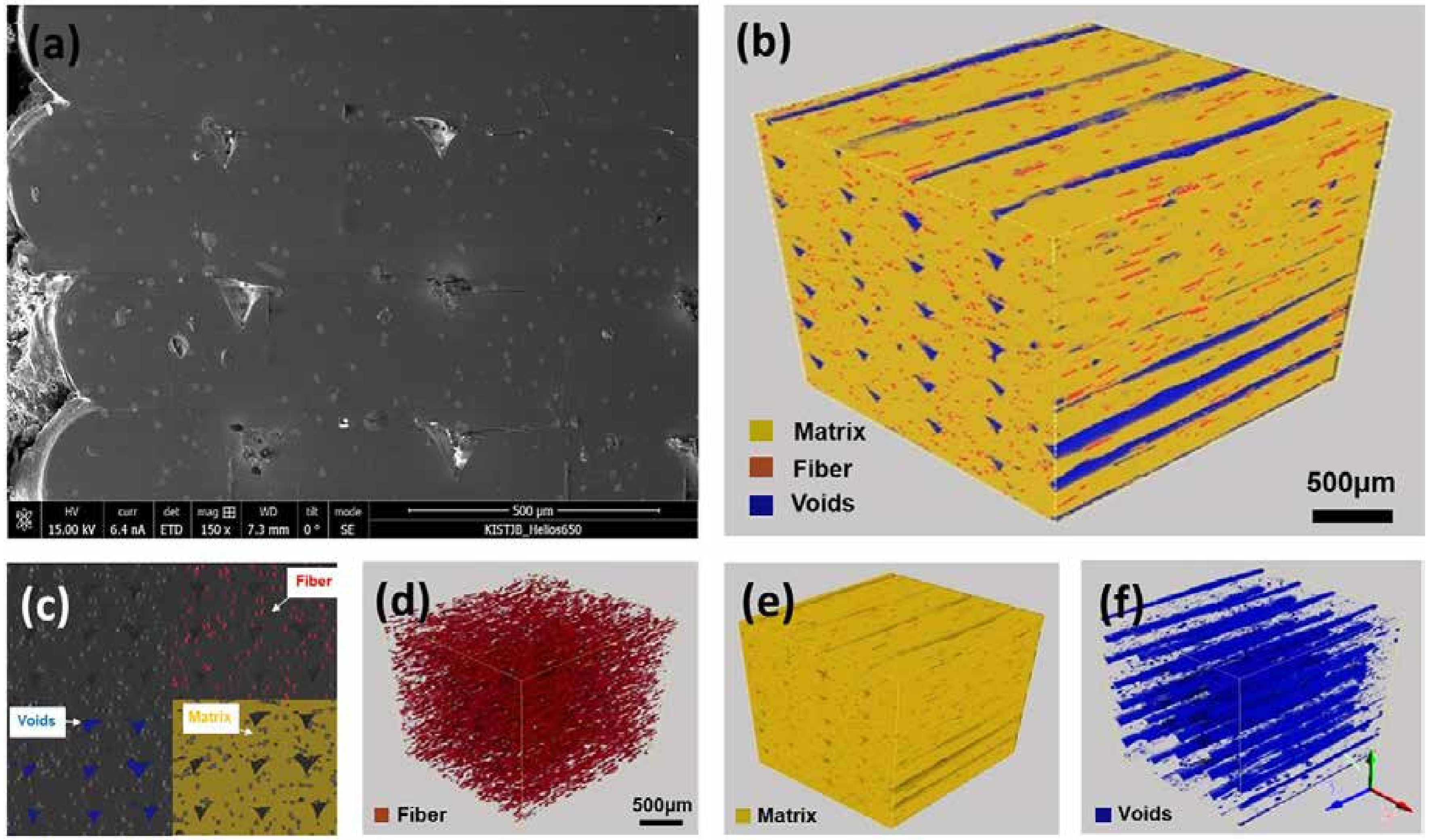


Figure 17: Voids and fibers when 3D printing BFRPLA (Yu et al., 2019)

BFRPLA Structure Test

Concrete vs BFRPLA strength test

Source: Youtube Originals. (2020, January 15). The "Space Architects" of Mars | The Age of A.I. Retrieved January 21, 2020, from https://www.youtube.com/watch?v=IIvrIKaNCRE

BFRPLA Insulation Properties + Calculation

Because of the excellent thermal and acoustical properties of basalt fiber and the low conductivity of PLA the composite of BFRPLA should have the best of both materials. This means a very good insulating material that also has a certain sound absorption due to the presence of the basalt fibers. In comparison with traditional insulation materials, which are mostly solely made to insulate the building, this material possesses also mechanical, and heat resisting properties. The calculation on the right shows that several printing layers of BFRPLA are enough to reach the insulation value of R=4.5 W/m2K that is minimally required. If higher insulation values are needed, or if the structure is more porous with severail voids, loose basalt fiber can be added which can add up to the total insulating amount. The creation of high performative exterior and interior skins make that there is less heat loss. Because of the basalt fibers, it is viable to say that contact sound will be reduced trough different housing units.

Basalt Fiber: R= 0.038 W/mK
Excellent thermal insulation value
Resistant to high heath
High sound insulation
Low water absorption

PLA: R= 0.110 W/mK
Low conductivity

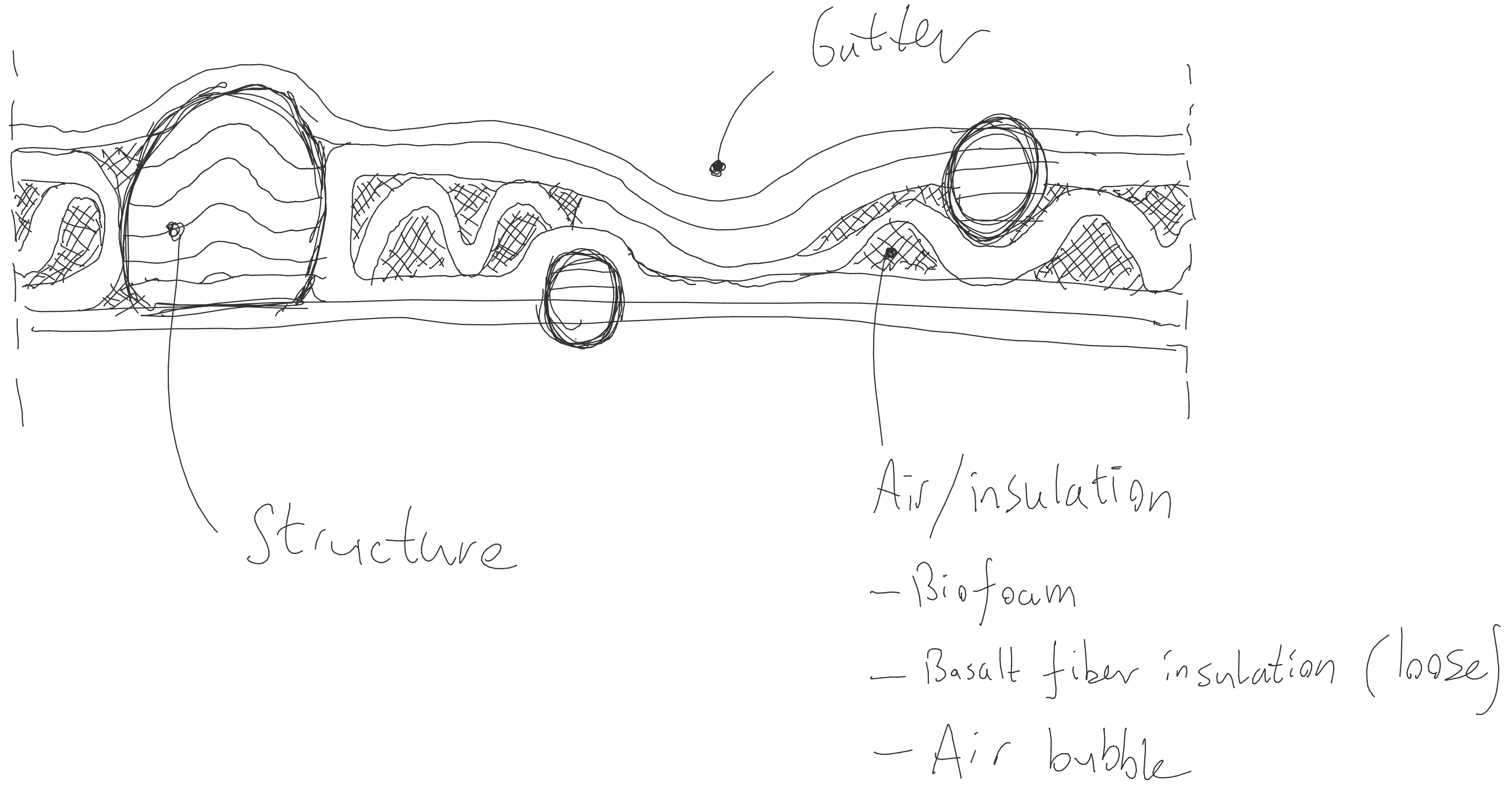
Available products from the Netherlands
(Loose) Biofoam: R= 0.034 W/mK
Basalt Fiber Panels: R= 0.035 W/mK

Exterior wall = 100mm of BFPLA (2 layers)
71% BF with a value of 0.038 W/mk
29% PLA with a value of 0.110 W/mk
(AI Spacefactory, 2019c)

Insulation (Basalt Fiber panels for calculation), thickness of 50mm with a value of 0.038 W/mK

Interior wall is the same as the exterior wall

Rc of wall on the right is: Rc=4.7 W/m2K



Rc on the location of the structure where no insulation material is used but rather more BFRPLA layers (300mm in total) Rc = 5.1 W/m2K

BFRPLA Heat Properties

When combining PLA and basalt fiber into a composite the glass transition temperature of PLA increases towards around 120 degrees celsius, which is a much more usable number (Tábi et al., 2013). This result can be seen in figure 18, whereas the numbers represent the amount of basalt fibers added to the composite. The letters BN mean normal untreated basalt fibers whereas BS is basalt fibers treated with silane. This means BFRPLA can be used effectively as building material because the deformation temperature of PLA is increased to a steady number by the addition of basalt fiber.

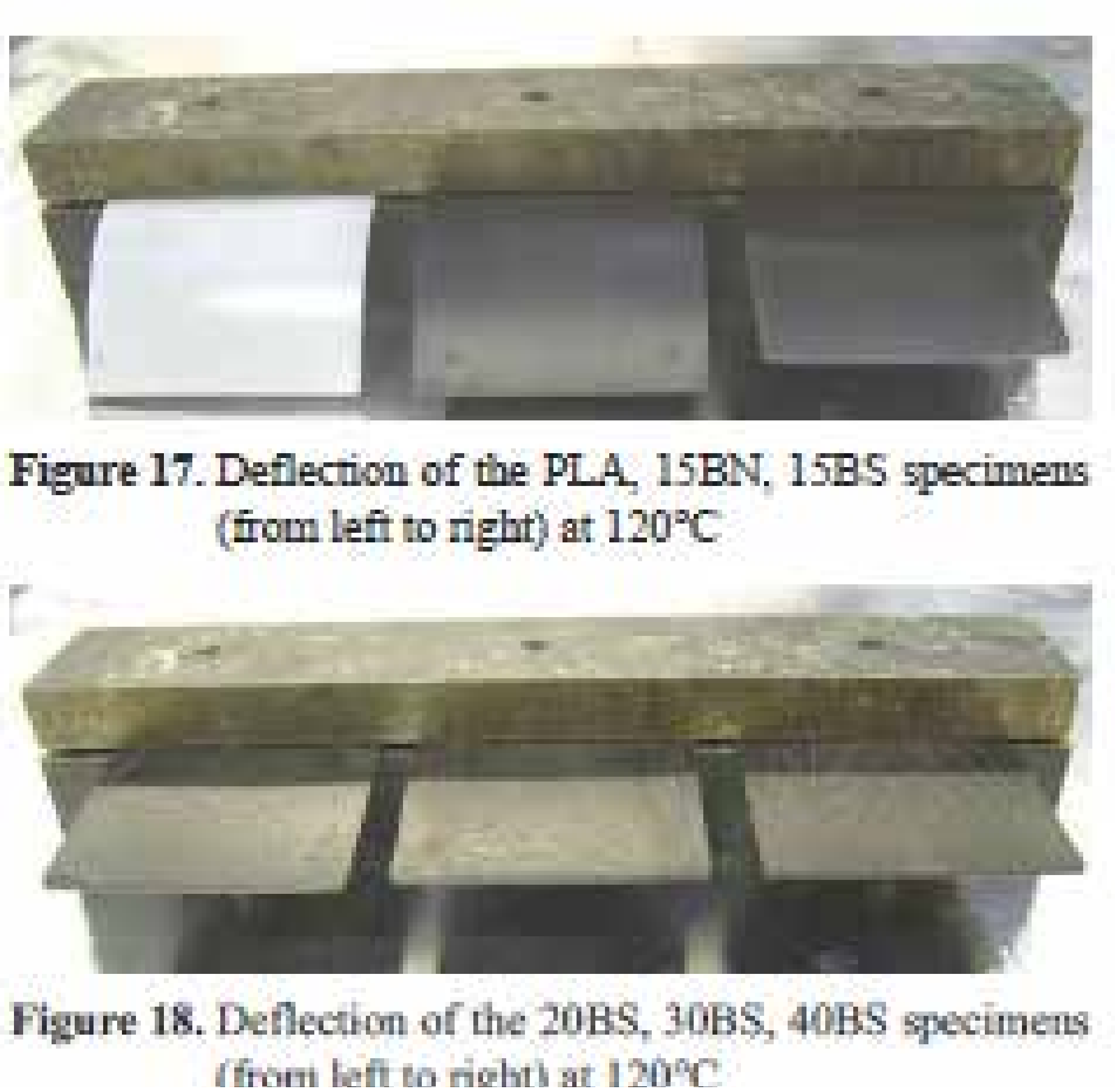


Figure 18: Deflection of BFRPLA with an increased glass temperature (Tabi, Tamas & Kovacs, 2013)

BFRPLA Fire Properties

When BFRPLA is exposed to fire, the basalt fibers will not take part in the combustion (Dhand et al., 2015). The addition of basalt fibers will create a layer of inorganic protection against heat and results in a flammability reduction of the original organic material (Barczewski et al., 2018). Dhand et al. (2015) also conclude that the backside of the material exposed to fire was much cooler than the one in contact with the heat. Finally, to show substantial images of how BFRPLA would perform in case of a fire, a research conducted to show the fire resistance of basalt fiber reinforced polypropylene will be discussed. Polypropylene (PP) is also a thermoplastic like PLA with high flammability. The results in figures 19-21 show that the basalt fibers made the dripping of the material stop completely (Tang, Xu, & Li, 2019). Furthermore did the addition of basalt fiber contribute to a large extension of burning time, meaning that the basalt fiber indeed improves the heat resistance and reduced flammability.

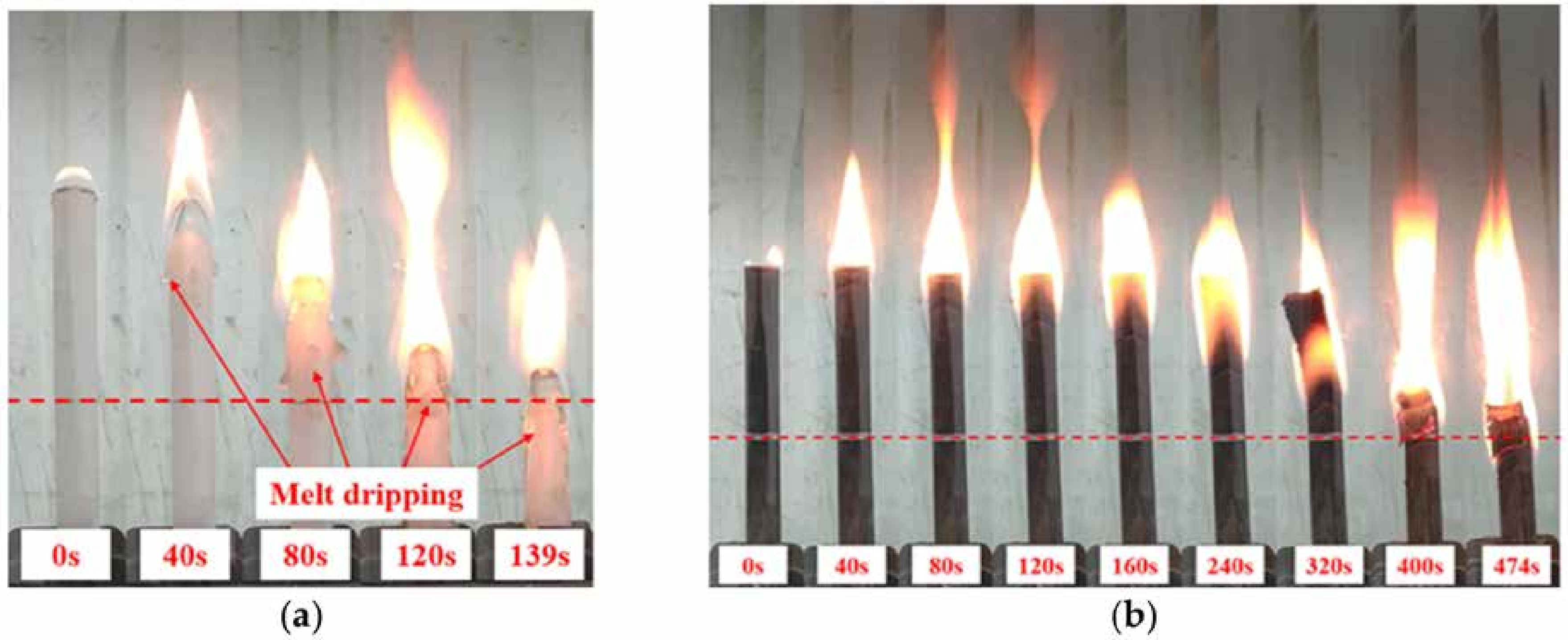


Figure 19: Dripping PP vs non dripping BFRPP (Tang, Xu, & Li, 2019)

Figure 20: Dripping effect of PP vs BFRPP composite (Tang, Xu, & Li, 2019)

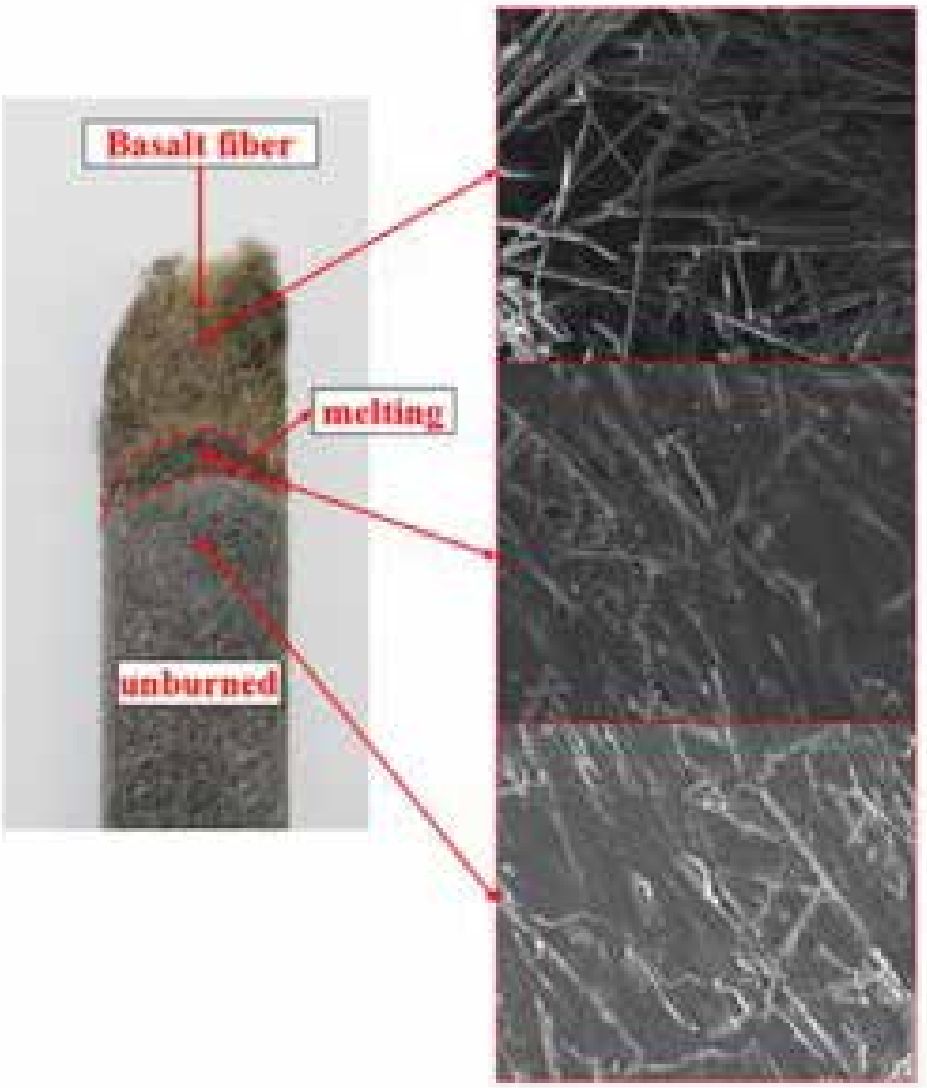
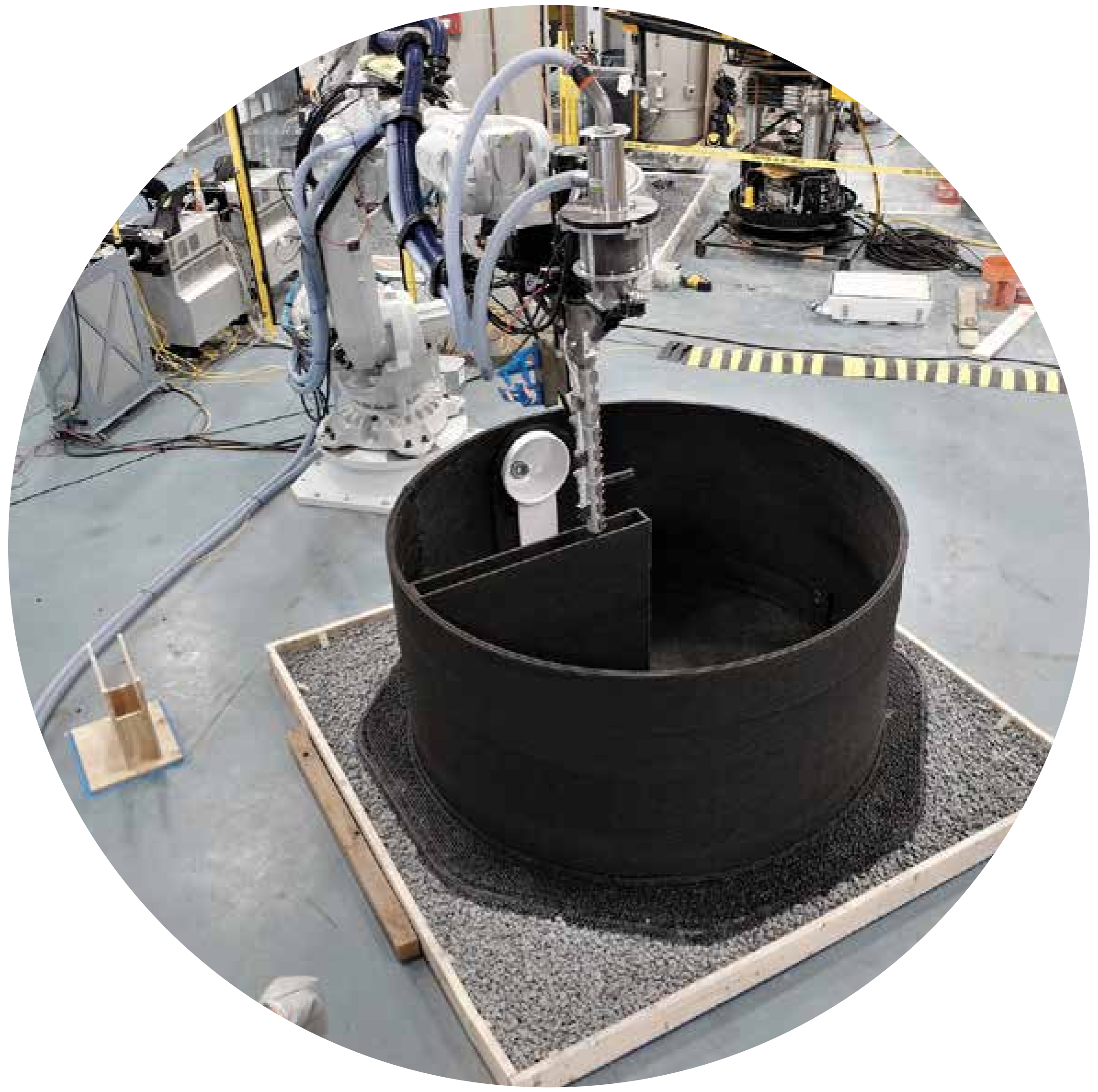


Figure 21: How BFRPP burns (Tang, Xu, & Li, 2019)

BFRPLA 3D Printing & Aesthetic



Source: *AI SpaceFactory. (n.d.-b). AI SpaceFactory (@AISpaceFactory) | Twitter. Retrieved April 02, 2020, from https://twitter.com/AISpaceFactory*

BFRPLA Printability Test

In this video the material is tested for printabitlity on irregular surfaces, a pressure test is conducted and it is shown how other robotics could be integrated in the printing process.

Source: AI SpaceFactory. (2019a, February 6). AI SpaceFactory - MARSHA - Our Vertical Martian Future - Part Two. Retrieved January 21, 2020, from https://www.youtube.com/watch?v=C_KxqCL5L5Q&feature=emb_logo

BFRPLA Calculation Material Amount

3400 kg PLA for 1 Tera House

3400 kg PLA = 0.34 ha = half a football pitch of sugar beets

The Netherlands in 2017 had 80 tonnes = 80.000 ha of sugar beets

3 Tera houses per ha = 80.000x3 = 240.000 houses per year (but no food, without taken any printing time into account)

3D PRINTING YOUR HOUSE, LAND USE (72)

DUTCH SUGAR PRODUCTION FROM SUGAR BEETS	Average Dutch sugar beet production 73 ton/ha (2013) Best locations can produce sugar beet up to 100 ton/ha Average Dutch sugar % in sugar beet is 16.88% (2013) Average Dutch sugar production per ha is 12.3 ton
PLA PRODUCTION FROM SUGAR	$C_6H_{12}O_6$ sugar -> $C_6H_{13}O_5$ PLA molecular weight ratio sugar/PLA = 182/165 85% yield to produce PLA from sugar Overall 1.25 kg sugar needed to produce 1 kg PLA Average Dutch PLA production per ha is 9.9 ton/ha
LAND USE TO PRINT A TOWN HOUSE	5,400 kg PLA needed Total land use 1 year **0.55 hectare = 5,500 m²** PLA produced from sugar beets grown in the Netherlands

Figure X: Amount of Sugar Beet needed for PLA (van Wijk & van Wijk, 2015)

Source: *AI Spacefactory. (2019b). AI SpaceFactory Wins NASA's 3D-Printed Mars Habitat Challenge [Illustration]. Retrieved from https://www.archdaily.com/916888/ai-spacefactory-wins-nasas-3d-printed-mars-habitat-challenge*

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Reflection

Reflection

This graduation project focuses on many aspects within the building environment. It is quite an ambitious project that investigates if inner cities can be densified by introducing both new construction techniques and new sustainable materials. By means of robotic fabrication (3D printing) as well as parametrically designed housing units I wanted to achieve a new architectural approach that is in contrast to the traditional approach we still know today. Because the introduction of robotics in the construction industry is something that is still not standardized in the day to day work I had to rely on a rather simple research and design method. State of the art examples became the main source of information whereas several assumptions, interventions and comparisons had to be made in order to make a comprehensive and executable design. The design process originates from those interventions (together with literature studies of the newly introduced material) the influence of the 3D printer can be seen throughout all the different scales of the final design.

The use of the 3D printer is one main focus in the graduation project. Another large portion of the research is done in favor of the sustainable goal that was apparent in the early stages of the design process: the introduction of a new, more sustainable material that can be 3D printed. Literature studies concerning my specific material of basalt fiber reinforced polylactic acid were hard to find. In recent years the attention for both PLA as a construction material as well as using organic and inorganic fibers in PLA has grown significantly. However literature related to the specific material that I used in the graduation project, namely basalt fiber reinforced polylactic acid, has very few research papers. Therefore I opted to define characteristics for both basalt fiber and PLA separately in order to gain information on their strengths and weaknesses. These aspects are compared with a reference of the 3D printing in-situ company that also uses this material in their prototypes.

I think the use of state of the art examples is the most viable way of researching the possibilities the examples could have in the design as well as provide a foundation to proof that the graduation project is not something quite futuristic, but can in a way already be implemented in the construction industry of today. However using this method also means that there is room for assumptions and scientific substantiated choices, which are in most cases just theoretical and not have been introduced in practice.

To see the research topics in a broader perspective of the studio of Architectural Engineering it can be said that my graduation project focuses on the main aspects of the studio. The search for innovative opportunities regarding circularity, digital manufacturing, material research and computational modelling are all aspects that are integrated in my graduation project.

Lastly, the topics of my graduation project also contain some serious ethical debates. It is made from renewable sources like PLA, but the main problem in the production process of PLA is that it is made from agricultural crops. Beside the fact that essential and precious food is used in the material production, the introduction of a robot on the construction site means there is a higher level of work to do for the construction workers. I would not say that all construction workers will lose their job, but they have to be more educated to work with and for the robot. The human-robotic collaboration is an important aspect in the graduation project and this requires new or other types of construction workers that can repair, manage, control and monitor what the robot is doing and what it needs. It would mean an entire shift in the type of people that is needed on the construction site.

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