New Ground*

*Enabling Adaptive and Affordable Housing Production on Pitched Roofs in Berlin through Computational Design & Fabrication

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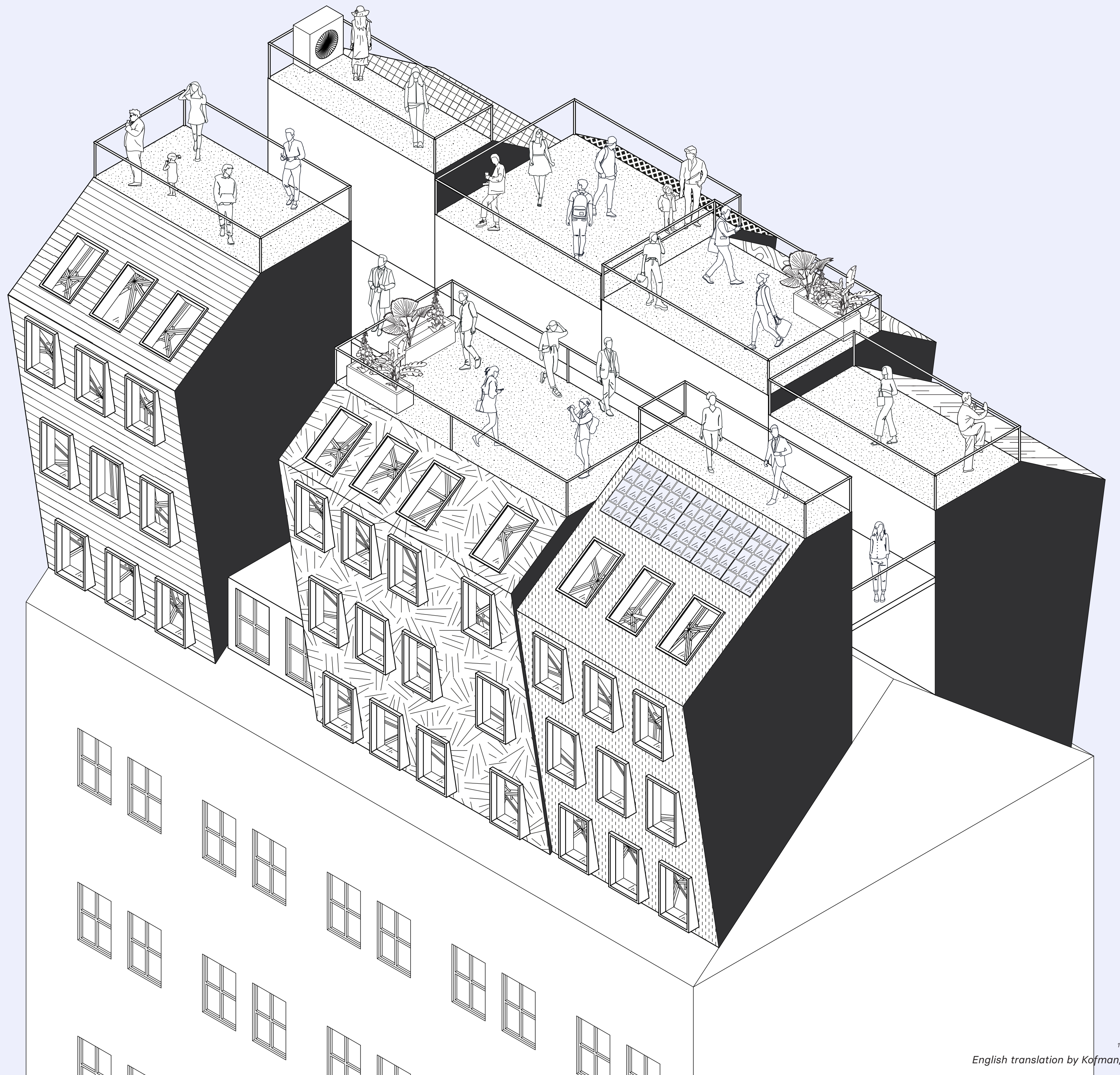
Abstract

In times of limited resources, growing cities, and a changing world, weeding out outdated answers to new questions is a cardinal task of architecture.

Especially in cities, the space is limited, and space does not equal space. Development in the outer parts with new infrastructure has vastly different consequences than densification on inner-city plots. In the case study city of Berlin, the population has continuously been increasing for the past decade while housing production has stalled and prices for land, real estate, and rented apartments skyrocket.

As a result, former inhabitants are displaced to less-connected areas, and new construction henceforth rarely targeted at the average citizen. Arguing in the lines of Lefebvre's *Right to the City*[1], the gentrification and commodification of space should be resisted and counteracted. Reshaping and creating new, affordable living spaces in the central districts is imperative to a healthy density, effective use of established infrastructure, and preserving the myriad of functions, demographics, and classes that constitute a vibrant city. While this is primarily a question of planning, regulations, and politics, architecture too can contribute to turning things around.

The thesis decidedly adds to this discourse by investigating the potential of living on pitched roofs - enabled through consistent application of digital design and fabrication. This unlocks a new way of densification inside the existing urban fabric across the whole city without further sealing soils - essentially creating *New Ground*.



[1] *Lefebvre, H. 1968. Le droit à la ville.*
English translation by Kofman, E. & Lebas, E. in Writings on Cities.

Content

Introduction

What if Berlin does not have to blacktop its unique *Tempelhofer Feld*, clear the *Grunewald* forest, or expand into the neighboring Brandenburg to solve its housing crisis? What if the necessary new construction could happen right in the middle of the city without sealing any of the much-needed compensation areas?

It is possible if we can open up *New Ground*: Offering new spaces through re-shuffling, re-use, re-zoning, and re-densification of existing residential or industrial spaces. This particular project follows an idea of cautious, vertical densification to create this *New Ground*. Letting several buildings grow one or two stories, scattered over the central city districts, to initiate distributed densification, dispersing its benefits and ramifications and generating the space where it is needed most. Acknowledging that this is easiest done on buildings with flat and empty roofs, the proposal at hand specifically investigates pitched roofs and their potential for a parametric design system that can be fitted to a multitude of otherwise unusable roofs. The combination of new opportunities, non-profit management, and governance leveraging directed building law exemptions for social housing with a scalable architecture can allow this development to produce affordable housing that fits citizens' needs.

The project is not meant to deliver the one answer to overheated housing markets in growing cities. Instead, it is a case study into what additional potentials can be lifted by consistently applying emerging technologies in computational design and fabrication. It should be seen as an augmentation of the discourse on how these cities, specifically Berlin, could develop. It should raise questions, stimulate a shift in the boundaries of what is conceivable and provide a novel tool in the arsenal to fight the shortage of well-connected space in the city.

The first chapter will introduce Berlin as the case study's site and illustrate the motivation for the project as a whole. Chapter 2.0 then explains the developed design guidelines and the resulting concept in a series of diagrams. The third chapter shows the design itself in-depth, with chapter 4.0 zooming in on the custom, load-bearing structure, and its prototype. Finally, chapter 5.0 presents the limitations, reflections, and possible future continuations of the project.

Chapter 1.0*

*Berlin - A story in two charts and three maps

After its reunification and a prolonged economic and demographic recession in the 90s and 2000s, Berlin grew steadily again since 2011. With only a slightly decreased acceleration due to the COVID-19 pandemic, it is expected to reach 4 million people by 2030 and has already gained 300,000 inhabitants over the last ten years.[1] Amplified by demolitions and sell-offs, the city has continuously been amassing a housing backlog, which the Senate expects to reach almost 200.000 in the year 2030.[2] However, just building more and faster is easier said than done. Especially the well-connected, inner-city plots are limited, finding available construction workers is an ever more arduous struggle, and just building any apartment misses the point. Berlin needs high-quality, affordable residences to ensure everyone has access to appropriate housing while keeping Berlin's alluring personality.

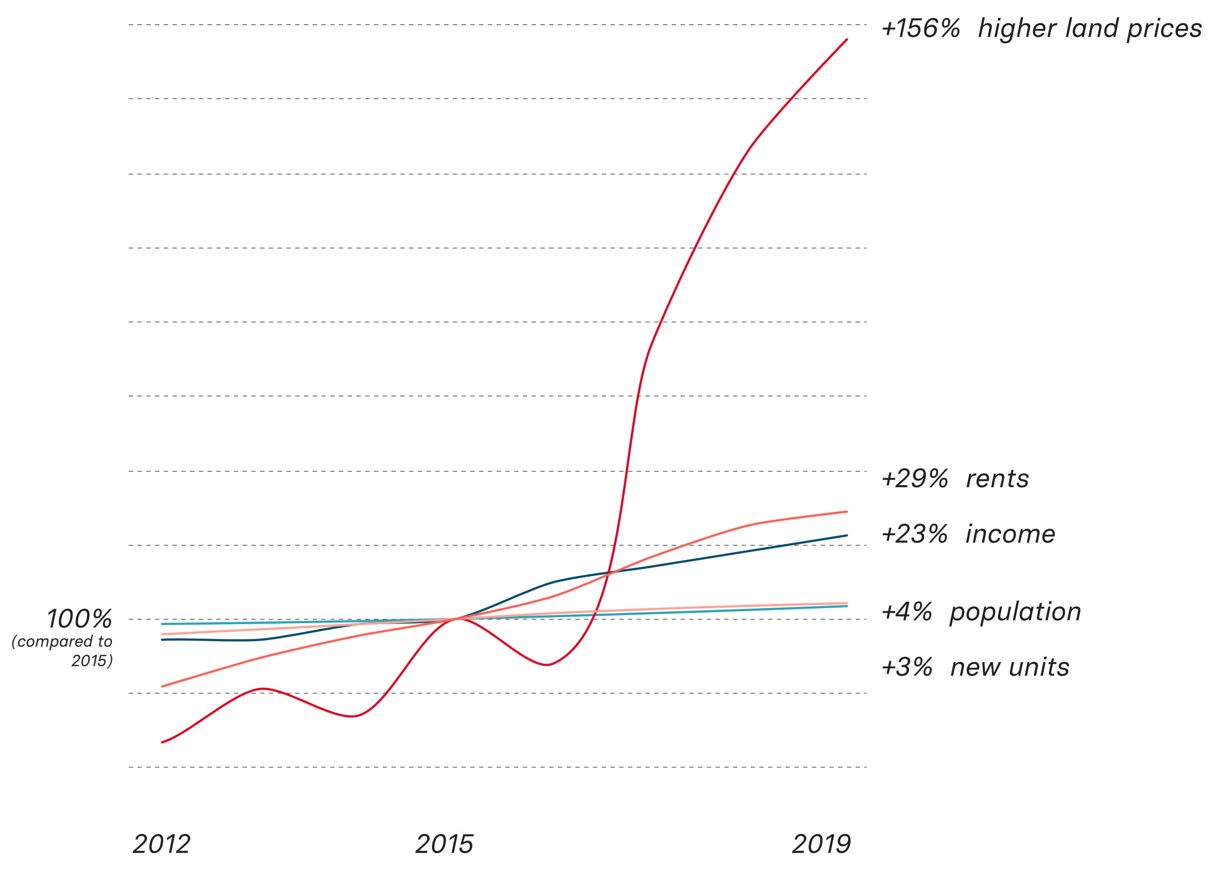
This situation is illustrated further in this chapter by analyzing two key statistics and shedding light on the spatial distribution of three more: Population, construction, and rent.

[1] *Population forecast Berlin & Amt für Statistik Berlin Brandenburg*
[2] *Marie Baléo in „Berlin: the challenge of affordable housing in a city of low-income tenants."*

1.1 Trends

The chart on the right summarizes the issues of Berlin's housing market almost too plainly: Land prices and rents increase, income and available housing not so much. While all metrics develop upwards, the divide between the metrics is immense and only seems to grow. Since 2015 the land prices in the city have more than doubled, and rents have grown by almost 30%. Admittedly the median income grew in the same timeframe, however, merely by 23 percentage points. The statistic does not state how much income was allotted to housing in the first place, but it is reasonable to assume that most households in Berlin have to invest a more considerable share now than in 2015 or before.

All this while the population influx is not declining and continually surpassing the number of newly available units. While Berlin should stay (or perhaps return to being) welcoming to new inhabitants, more units for existing Berliners and the newcomers undoubtedly have to be provided.



Charting Berlin - Comparing Different Trends in Berlin from 2012 to 2019 (in relationship to 2015)[1]

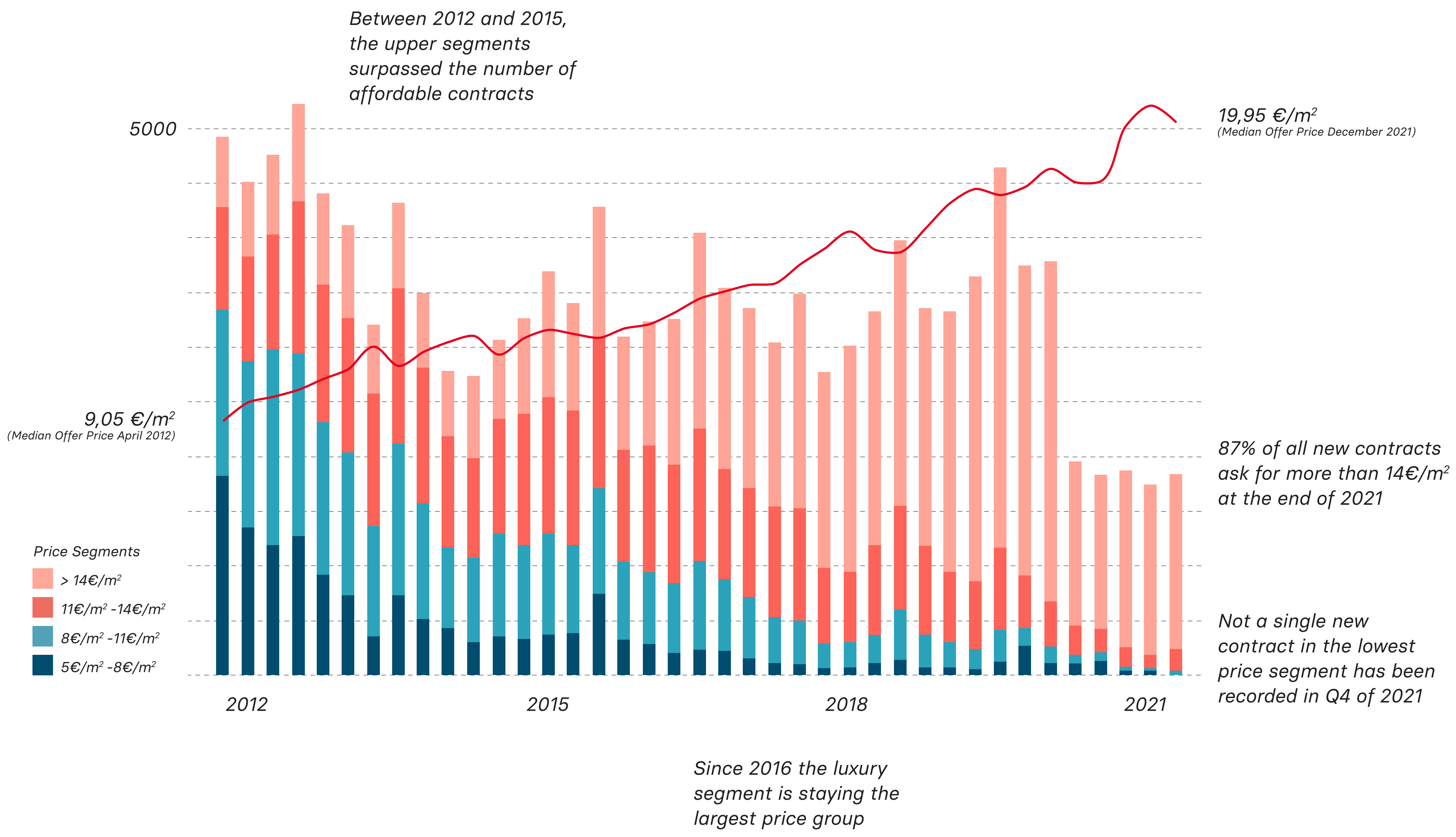
[1] *Based on IBB Wohnungsmarktbereicht 2020, Amt für Statistik Berlin Brandenburg and Guthman's Berlin Real Estate Report 2022*

1.2 Contracts

The second graphic dives deeper into the development of the rental market. It shows the number of contracts each quarter, distributed in four price segments, and the median offer price for units in new buildings.

In 2012, the lower price segments were still in the majority, and the most significant number of units would be rented out for less than 8€ per m². However, between 2012 and 2015, the number of low-cost units shrunk dramatically. While the total housing provision seemed to have declined, the higher-priced segments managed to surpass the lower ones. Since 2016, the luxury segment has continuously made up the largest group.

Coming to the present, we can see that the median offer price has more than doubled in the last decade, and almost all contracts are now concluded with a rent higher than 14€ per m². Even when assuming that income simultaneously grew across all citizens equally, the chart nonetheless shows a skewed market that no longer serves the public.



Charting Berlin - New Contracts & Median Offer Price for Rental Apartments in New Buildings per Quarter 2012-2021[1]

[1]*Based on Guthman's Berlin Real Estate Report 2022*

1.3 Population

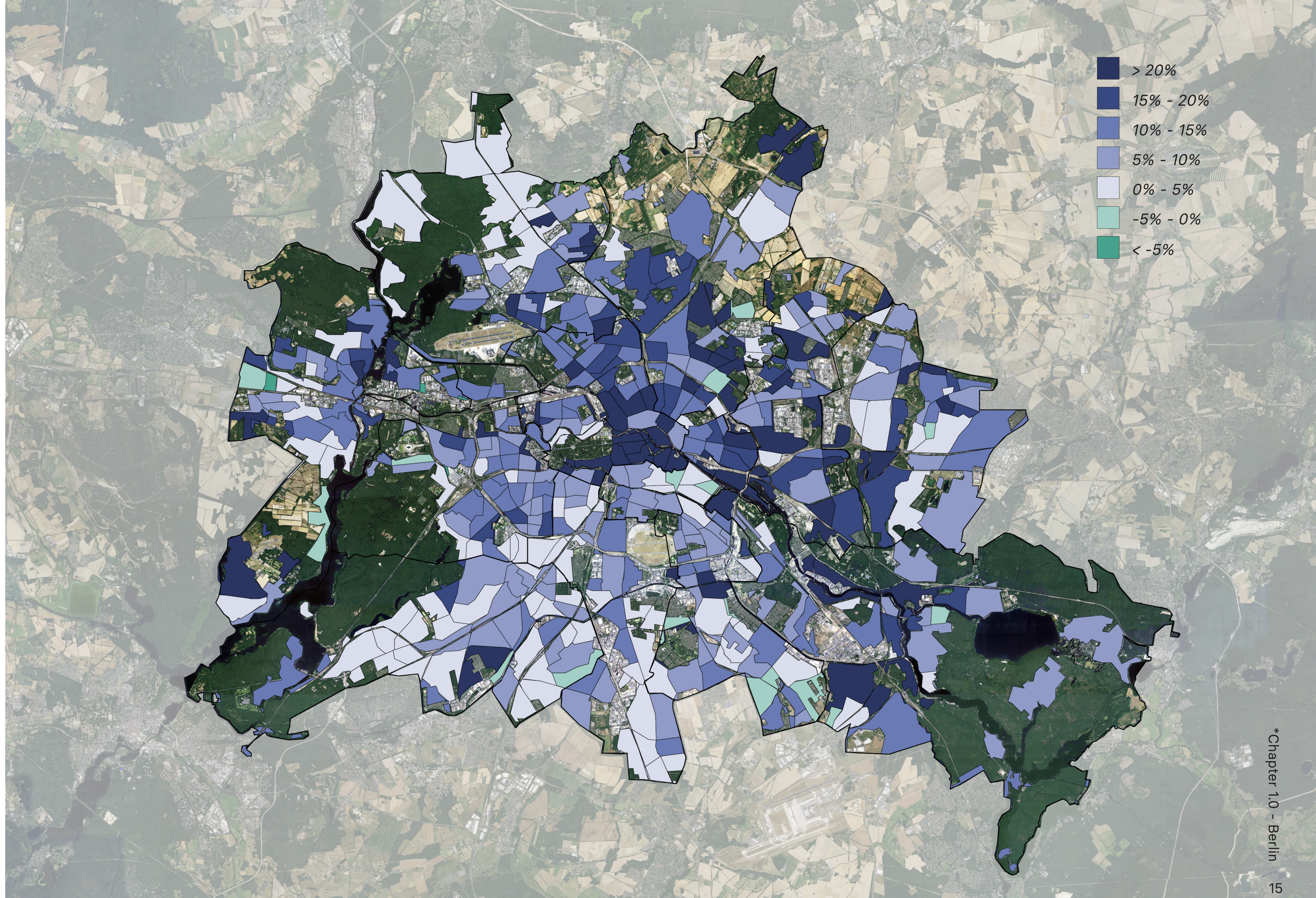
Mapping Berlin
Population Development 2010-2019[1]

The first map depicts the population development between 2010 and 2019 in Berlin's quarters. In line with the general trend, a population increase is registered almost everywhere while only a few lost inhabitants or remained unchanging. There is a clear tendency for accelerated growth in the very center and distinct development areas at the regional borders.

The map also shows that large parts of Berlin are not inhabited at all. These included forests, fields, parks, lakes, industrial areas, or the government district. One conspicuous assumption could be to use these lands for housing production. However, this is a naïve fallacy:

A city needs job opportunities to prevail, preferably mixed with residential areas, to maintain short distances. Open spaces and compensation areas are vital to increase the quality of life and air and lower the temperature in the urban environment. Arguing that other cities get by with fewer green spaces likewise comes to nothing. They, and possibly even Berlin, need more, not less, recreational and natural spaces. Moreover, conservation of a city's character should always be on the top of a planner's agenda, even those being progressive at heart.

In total, Berlin currently houses 3 775 480 residents.[2]



[1] Based on IBB Wohnungsmarktbericht 2020
[2] Statistic from 31 December 2021, Amt für Statistik Berlin-Brandenburg

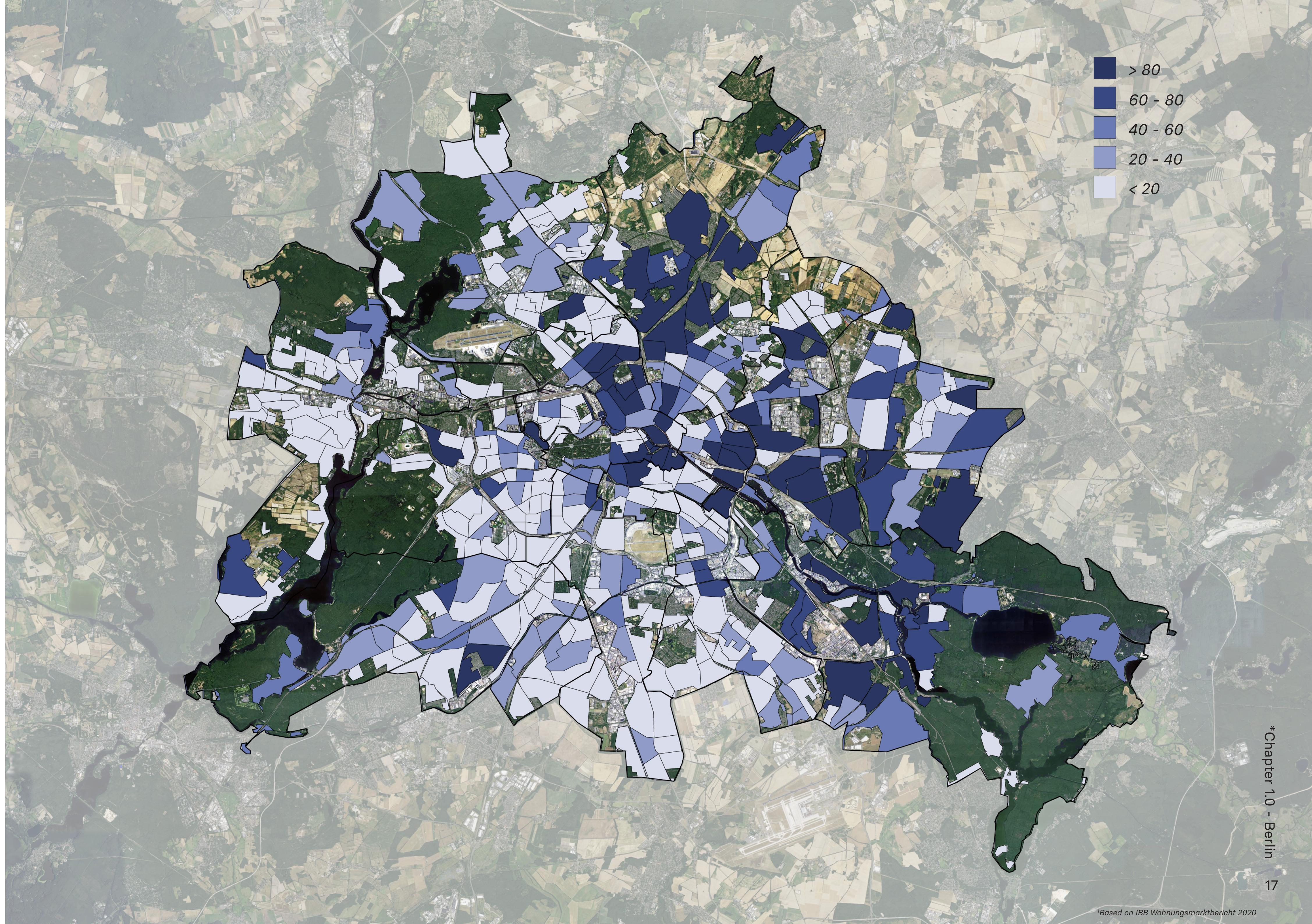
1.4 Construction

Mapping Berlin
Construction of new Apartments 2015-2019[1]

The second map shows new construction in Berlin in the same quarters. While also serving the center, the construction seems to be slightly more distributed with a trend towards the city's eastern parts. In that region, many former East German apartment blocks offer opportunities for densification and rebuilding.

Another striking feature is the generally low number of new units. In most areas, not even 80 new units have been erected in the four years between 2015 and 2019. Of course, it is hard to tell how many would suffice given that the absolute population development in the quarters is unknown. However, it feeds into the image of the prevalent development where the housing stock is growing slower than the population.

This might be an excellent point to mention that new construction is not the only way to provide more housing units. Repurposing, dividing, renovating, or redistributing the existing building stock are viable options and should be preferred whenever possible: We have already established that a city's space is valuable, and even the most sustainable building needs resources.



Based on IBB Wohnungsmarktbericht 2020

1.5 Rents

Mapping Berlin
Median Offered Net Cold Rents 2020[1]

On the last map, we see what might be the result of the previous two: The median offered rents (net cold) in a clear concentric pattern with the highest rents inside the S-Bahn Ring as well as towards the Southwest, where historically the more affluent quarters of Charlottenburg, Schöneberg, Grunewald or Zehlendorf are located.

Compared to the gradients of incoming people and new construction, which align as expected, the colors on this map are almost inversely proportional. Where there is no new construction but still high demand for land, office, and living space, the prices rise.

It is renownedly not possible for two people to occupy the exact same space, and it seems natural that everyone desires to live as centrally as possible, even though „central“ has quite a broad definition in polycentric Berlin. However, if the price is the only factor for selection, displacements and segregation by class are inevitable.

All of this suggests a twofold solution: Densify the inner city parts in a carefully distributed manner (no skyscrapers) with low-cost housing and improve the infrastructure and amenities in the outer parts. This could relieve the pressure on the most central quarters and ensure a continuous mix of backgrounds in the whole city.

[1]Based on IBB Wohnungsmarktbericht 2020

1.6 Politics?*

*or is this still Architecture?

Not everything mentioned in this chapter can be solved by architecture, architects, or any individual or group for that matter. Instead, they are societal problems and need political solutions.

However, they are spatial as well and demand spatial responses. This is where architecture has to become political by lobbying for improved legislation, proposing alternative plans, or at least informing and debating the inherent issues to not become complicit itself.

Of course, everyone should act within one's means, though it has to start now. Even with the best intentions, law-making, redistribution, expropriation, or rent control are complex endeavors with numerous actors involved on private, state, and federal levels and systems resemblant of slowly grinding mills.

Chapter 2.0*

*Design Guidelines & Concept

Following the analysis, the emerging proposal suggests purposeful, decentral densification across the inner city. Leveraging existing infrastructure and previously unused roof spaces, it consists of a design system that fits the concept onto numerous host buildings.

The concept pursues four design guidelines to ensure quality: First, the proposal is *Vertical* instead of promoting sprawl. Second, it is *Unobtrusive*. *Unobtrusive* to the city's character and *Unobtrusive* to the residents of the individual intervention sites: Cautious in its vertical ascend, limiting it to a few stories, and cautious in its logistics - all within the limits of the impact any new construction inevitably has. Third, the concept is designed to be *Scalable*. Starting from selected catalyst projects probing variations and the system in general, it should eventually be able to grow to an impactful scale. This directly ties into the last and fourth point, *Affordability*, where the key factors are economies of scale, a reusable design system, or non-profit management.

Concept Key Guidelines

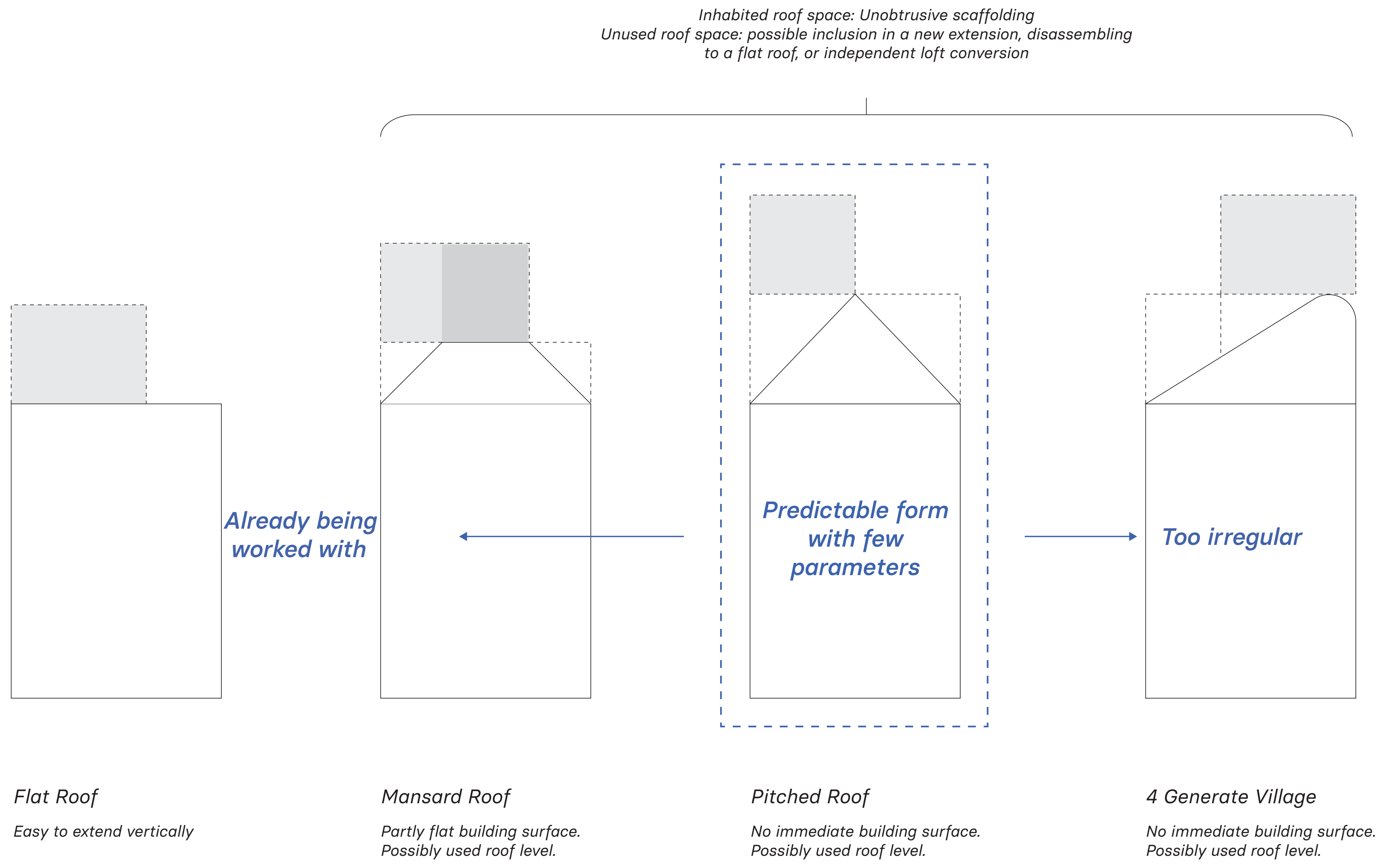
1	Vertical
2	Unobtrusive
3	Scalable
4	Affordable

2.1 Verticality & Pitched Roofs

When suggesting unimposing densification, vertical growth and roof conversions immediately come to mind. Acquiring additional spaces from the already prepared ground is an excellent deal. When done respectfully, and the building is heightened by only one or two stories, the impact from shading the surroundings is permissible. Especially in Berlin, most streets are wide and high ceilings up to four meters with respective windows are common and would still allow plenty of light to enter.

Following a similar argument, several proposals for roof extensions of different scales have been made by various architects[1]. However, they exclusively concentrated on flat roofs, preferably on standardized soviet housing blocks. To add to the discourse and include the additional aspect of digital design and fabrication, this project concentrates on pitched roofs: The prism shapes are similar enough in their parameters for a consistent design system but too complex to be regarded as sites by mainstream architecture.

Especially for roof spaces already being used for more than an attic, simply dismantling the pitched roof and building on the then flat roof is not an option. This proposal offers a solution for these cases and preserves the opportunity for a supplementary, conventional loft conversion for the others.



Roof Typologies

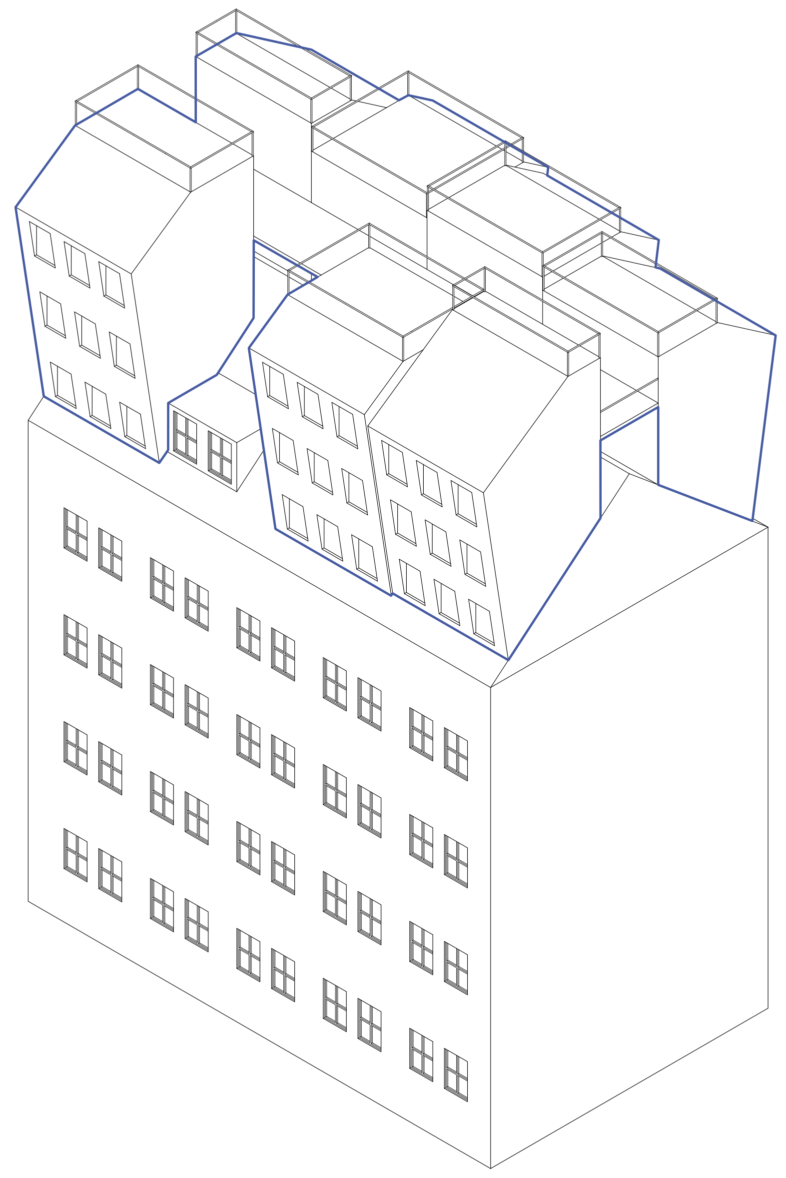
[1]For example Sigurd Larsen's „Dachkiez“ (http://sigurdlarsen.com/project/dachkiez_de) or „Roofs Of Berlin“ by Moritz Maier and Ruonan Wang, the winners of Buildner's Berlin Affordable Housing Challenge (https://architecturecompetitions.com/berlinhousingchallenge)

2.2 Host & Parasites

Attaching a new construction on the roof of an existing building might spawn the idea of a parasite afflicting an unconcerned host. While the proposal instead attempts to be symbiotic, let us indulge in this image for a second to determine the role of each actor involved:

The *Host* is the existing building, part of the urban fabric for decades. Foremostly, it provides the *Parasite* with *New Ground* to attach to. The *Host* also supplies access through its staircase and connection to building services like electricity, water, or sewage. While some of these might have to be augmented to serve the increase in consumers, they all can be replenished or compensated without a loss for the existing occupants. More parasitical and harder to equate is the blocked sunlight due to the height increase. However, considering the sun incidence, keeping height at a minimum and possibly leaving gaps can reduce this interference.

In return for its new home, the *Parasite* contributes new living space for the community and densification for the commercial surrounding. With Berlin once being a city of more than four million[1], most infrastructure should already be dimensioned for a higher population. Increased density itself is a catalyst for local economic activity and a vital ingredient to a vibrant and mixed neighborhood. The *Parasite* can also provide extra communal spaces in particular units or roof terraces for the whole house.



Host & Parasite

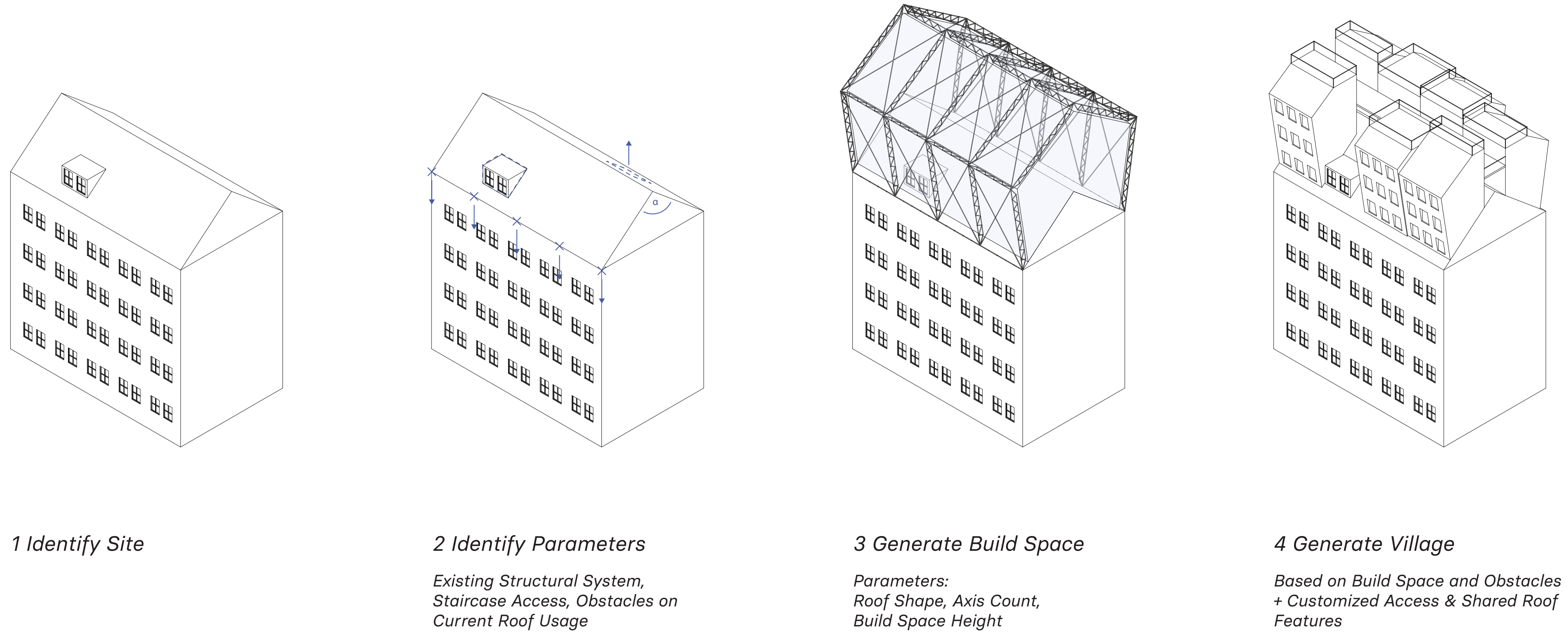
[1] *Herbert Schwenk, Topographie der deutschen Hauptstadt, https://berlingeschichte.de/stadtentwicklung/texte/4_13_bvoelent.htm*

2.3 Design System

To efficiently adjust the presented design to eventually all pitched roofs in Berlin, the proposal is based on a design system that generates a fitting scaffolding, a build space, and a *Village* of units atop the input roof.

After identifying the site and assessing the roof, structural system, possible accesses, and obstacles, the system first generates the scaffolding and the enclosed build space. The lightweight framework is compiled from a range of standard length girders to provide a reusable system. By defining the desired form and height, the configuration angles are calculated. Then, the *Cabins* are generated using the build volume and the *Host's* structural axes. Afterward, the individual units can be configured further with additional parameters depending on the particular users.

The system tries to automate as many steps as possible using the collected data of the host building. However, certain decisions still have to be made manually and designed individually. This includes the distribution of *Cabin* types or special features like additional staircases or added shared spaces, as well as connection details between scaffolding, units, and the *Host*, which depend on the specific roof structure present.



Design System Flow

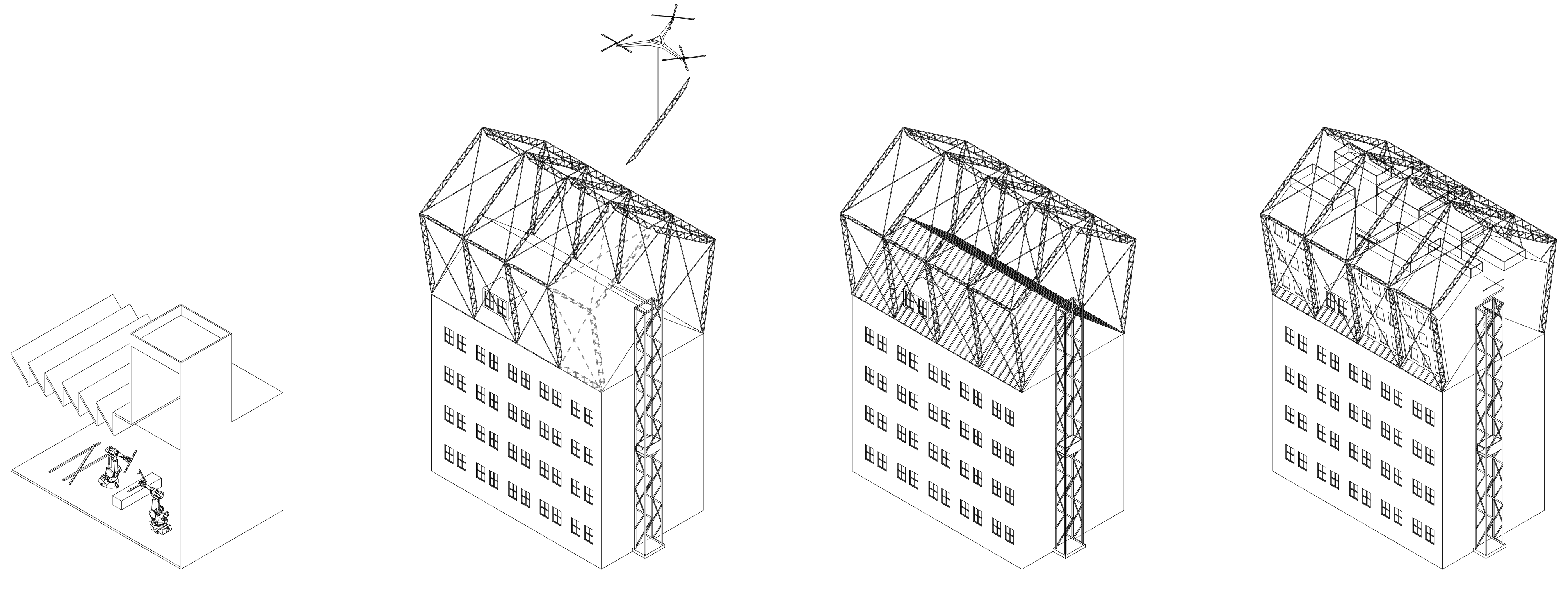
2.4 Construction & Logistics

To mitigate the increased complexity of construction in heights, a special focus has been placed on the logistics and construction processes covering the components' fabrication, delivery, and assembly.

The first aspect concerns off-site production. All necessary modules for the *Cabins* are fabricated in a controlled environment, aided by robotics and numerical control (CNC). The module size is kept small to allow easy transportation and handling on the roof, and predefined connection interfaces enable fast assembly.

The second aspect covers scaffolding on the roof. To be as unobtrusive as possible to the occupants of the host building, the scaffolding is designed to cover only the roof. It is a rigid framework fixed to the roof edges covered by a membrane protecting the whole build space from wind and weather and workers or objects from falling. Once the scaffolding is set up, the roof can safely be prepared and opened for more uncomplicated access.

When everything is prepared, the *Cabins* can be swiftly assembled and connected. After works are finished, the scaffolding is removed and can be reused for the subsequent intervention.



1 Off-Site Production

The Cabin's parts are prefabricated off-site. Robotic fabrication allows speedy production for the customized design of each building and unit.

2 Set Up Unobtrusive Scaffolding

Assemble the construction tent from fixed modules and fix it on the roof.
Once completed, roof works can be safely conducted.
To ease the delivery of girders, a drone could be used.

3 Prepare Roof

Open the staircase for additional access, remove roof tiling, and, if necessary, move chimneys and other roof installations.

4 Assemble Village

The small parts can effortlessly be delivered and assembled on the roof. After completion, the scaffolding can be disassembled and reused.

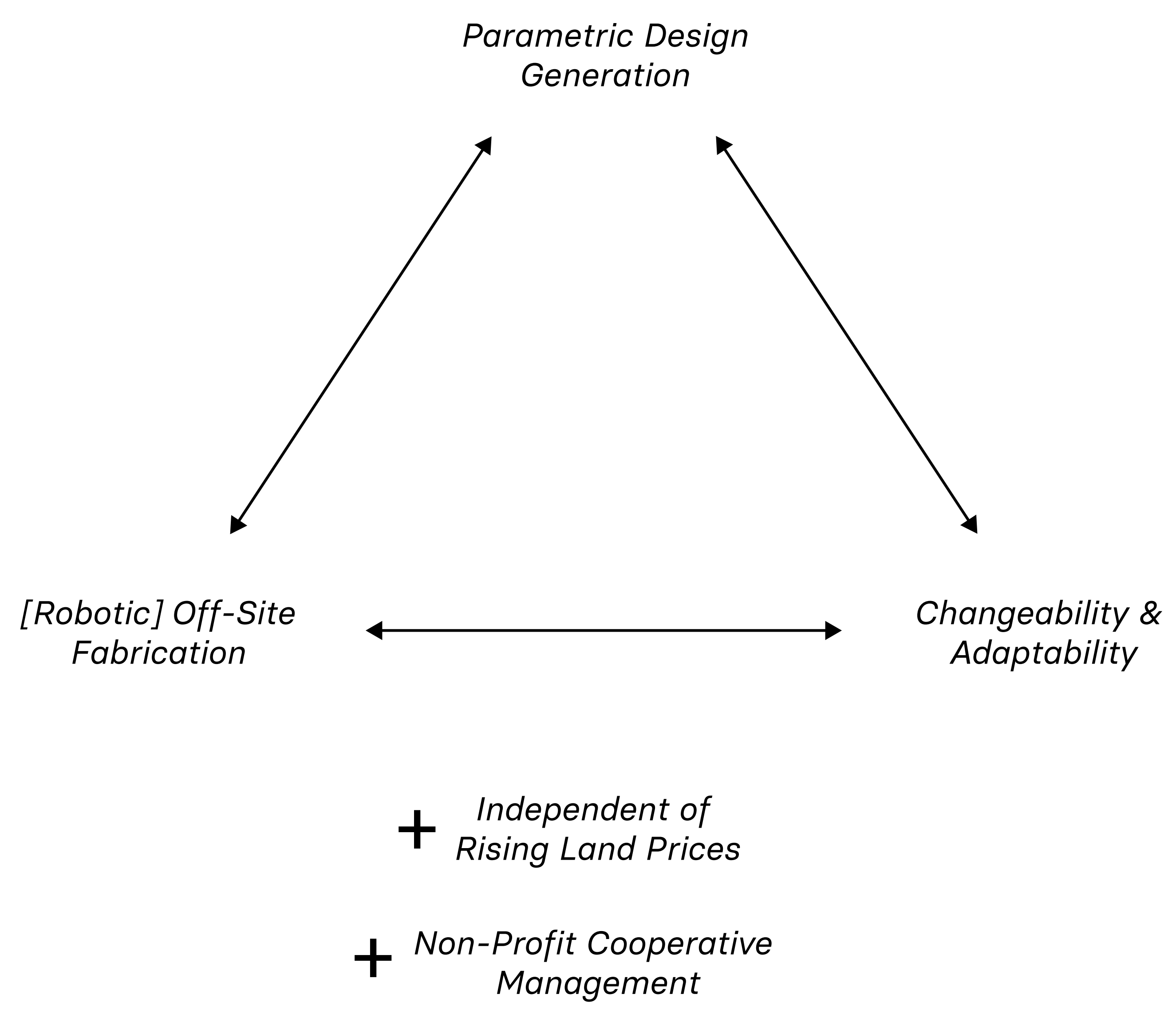
Production & Assembly

2.5 Affordability

Everyone who recognizes housing as a fundamental human right and believes people should be able to live close to their jobs, amenities, and infrastructure must consider affordability in residential and urban design. This project tries to do this justice by combining advanced fabrication techniques allowing minimal material use, generative design to simplify the planning process, and general adaptability to fit as closely as possible to changing users.

While implementing good or even tailor-made work at low costs is already an uphill battle, several decisive factors are beyond the designer's immediate control. For instance, rising land prices and possible taxes linked to them. Even though this project is theoretically independent of new land parcels, the owners of the host roofs might not. Another critical aspect is management. Housing should not be a for-profit investment, so the management of this proposal is intended to be handled by a non-profit cooperative. However, setting this up in reality and negotiating with the diverse ownership group of the *Hosts* is a different story and, again, abandons the classical realm of architecture.

Other obstacles are written into state or federal law and might take years of lobbying to change. A functioning rent control, for example. Or a right of first refusal for public authorities during land and housing sales. Enhanced zoning could allow more mixing of light industries and residential areas, opening up more land for development. One proposition by Arno Brandlhuber in the film *Architecting after Politics*[1] is especially fitting for this project: Allowing every landlord to build one extra floor if they rent out at least one floor of that building as social housing for 6,50€/m² - bending current building codes for cross-subsidization.



Affordability Drivers

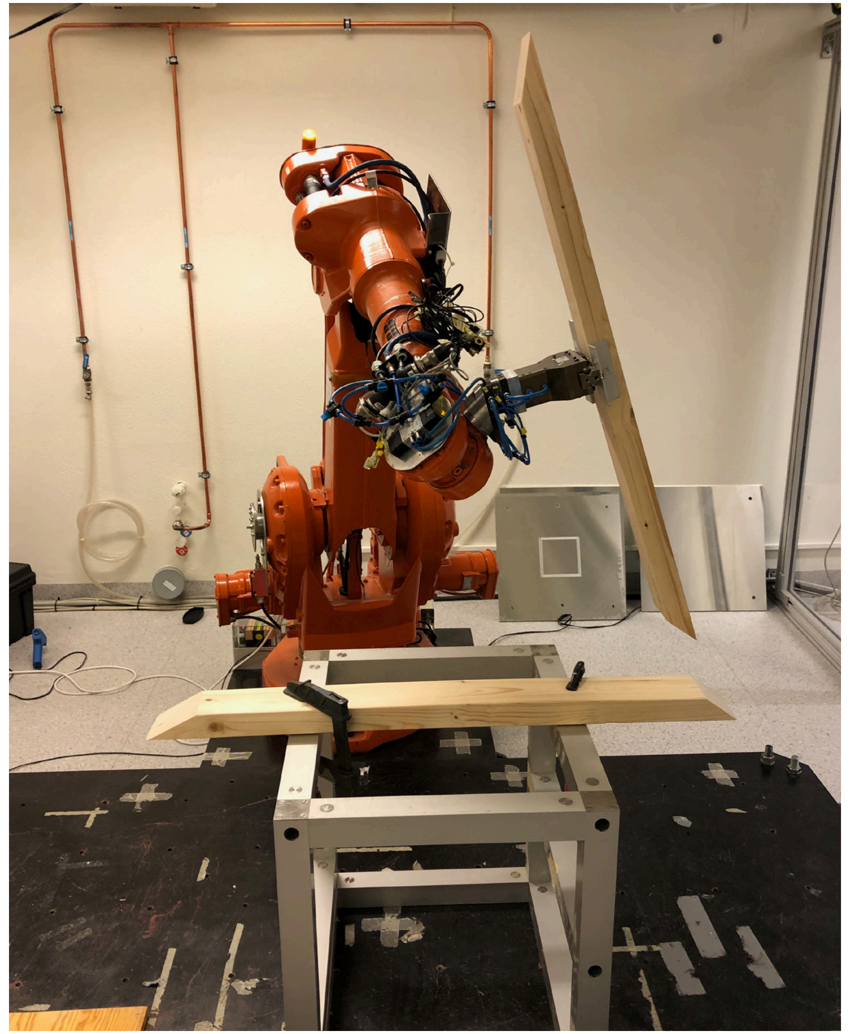
[1] *Available at https://vimeo.com/ondemand/legislatingarchitecture/304116817*

3.4 Why Robots?

Even though its strength is unparalleled, most tasks a robot arm can do could, admittedly, also be completed by a skilled human having the right tools. However, scaling up efficiently is virtually impossible with a solely human workforce, as acquiring the necessary skills takes time. In contrast, once a robot is programmed to perform a series of tasks, it can easily be copied and multiplied.

Additionally, the robot can be a tool and worker in one entity, increasing accuracy and control over a complicated workflow. Combined with an anticipated shrinking workforce and the generally physically demanding construction sector, it can be a valuable addition to building sites.

The proposed design suggests robotic fabrication for the complex timber structure made from individual triangles and a wood-only connection. Again, the modules could be manufactured by hand. However, an economical and affordable production could only be achieved using automation.



Chapter 3.0*

*Design (System)

The design starts from the question of how pitched roofs could contribute to a new wave of central space making, particularly when leveraging digital design tools to compensate for the higher complexity. It then focuses on a flexible and lightweight structural system constructed from timber and uses it to form *Cabins* fitted to each roof. To simplify the on-site assembly process and ease the burden on the current residents, the design suggests putting up a membrane on the roof as a first step to limit scaffolding to the part where it is needed. Then, after construction, it can be reused on a different roof to spread the vision.

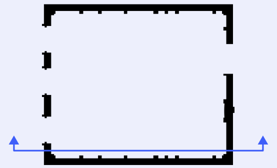
On the larger scale, the group of *Cabins* on the roof forms a *Village* community together with the already established residents, and from the *Villages*, throughout Berlin, a *City* on the city emerges.

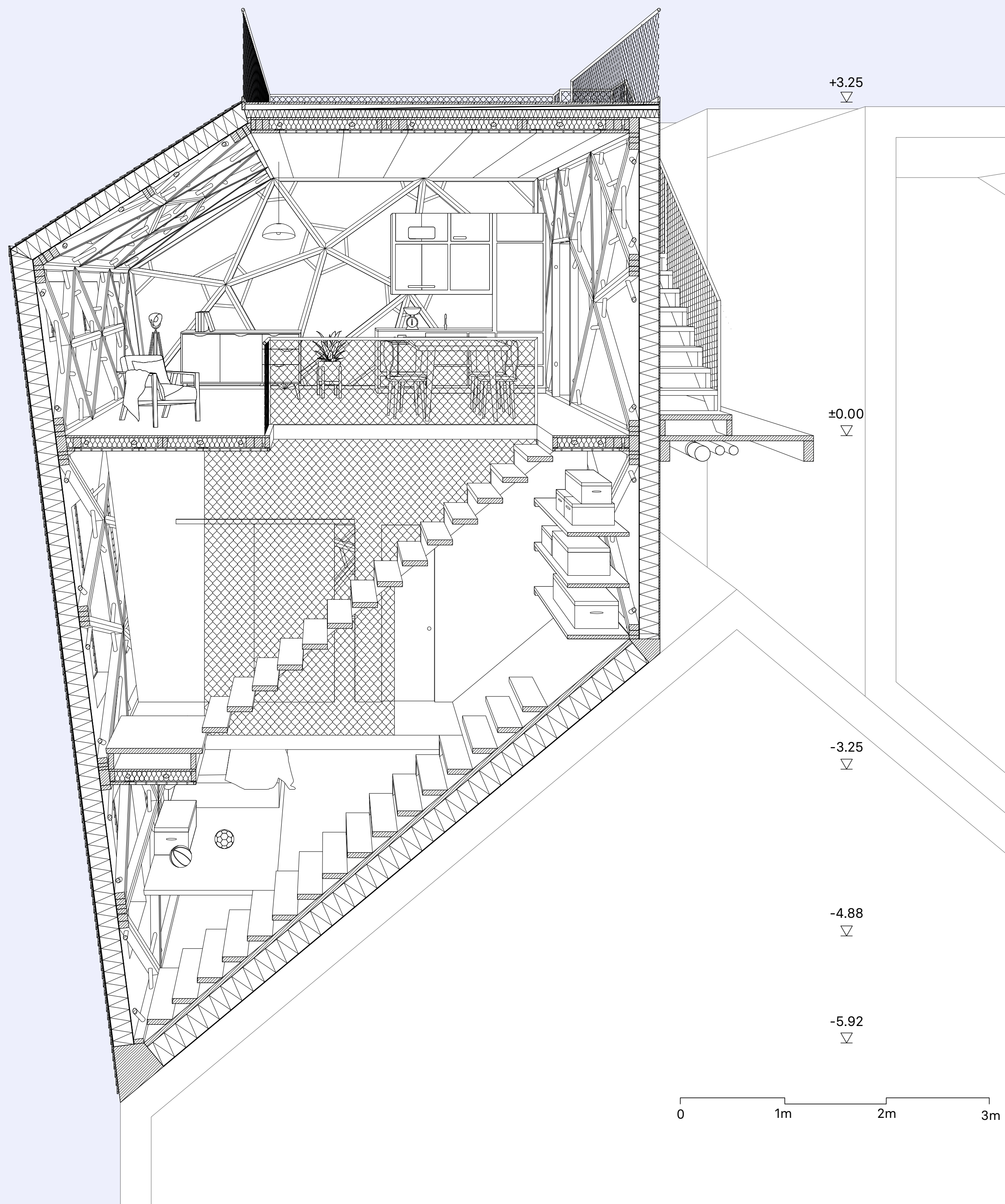
3.1 The Cabin*

*A Home in the Sky

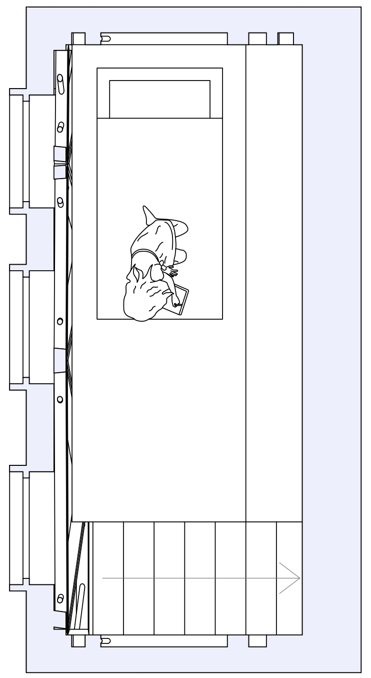
The *Cabin* sits on top of the host building, shaped by the angles of the roof and by maximizing space in the build volume. A generous shared living space welcomes visitors on the entry level with a head-on view of the city. The lower levels house the private functions: Bedrooms, bathrooms, some storage, and space for technical services. A cozy sleeping nook and additional storage in the residual spaces can be found in the „inverted attic“ on the lowest level. The presented *Cabin* type can house three to four people on 50m² over about 23m² of existing roof space.

The lightweight, triangular wood structure is the dominating feature of the inside space. It openly presents the *Cabin‘s* tectonics and invites appropriation by the inhabitants. Protected by a thin layer of plywood, rigid wood fiber insulation encompasses the whole *Cabin*. A final cladding made from overlapping larch wood boards adds a ventilation layer and protection from the weather on the outside. The floor slabs use the same triangular structure as the primary force-carrying layer. However, the beams are hidden by wooden floor panels on the top and a heating and cooling ceiling below. The gaps between the structure are filled with loose sheep wool insulation to help with sound and heat insulation. The air-handling ceiling is integrated into ready-made clay-fiber panels that are attached using a minimal, regular substructure. The staircase is made from solid wood, and to save space, all railings are materialized using wire meshes.

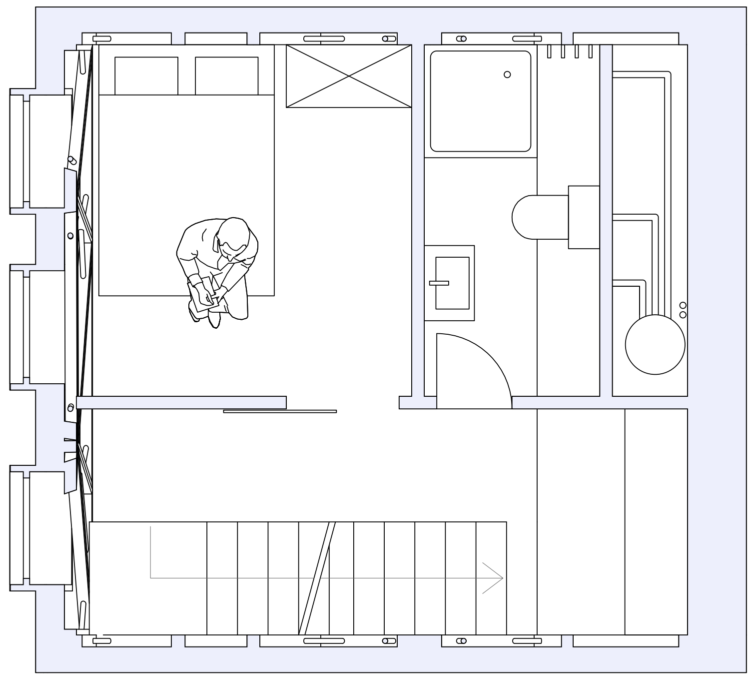




Cabin Detail Section, Circulation, 1:60



Cabin Floor Plan Lower Level (-2), 1:60

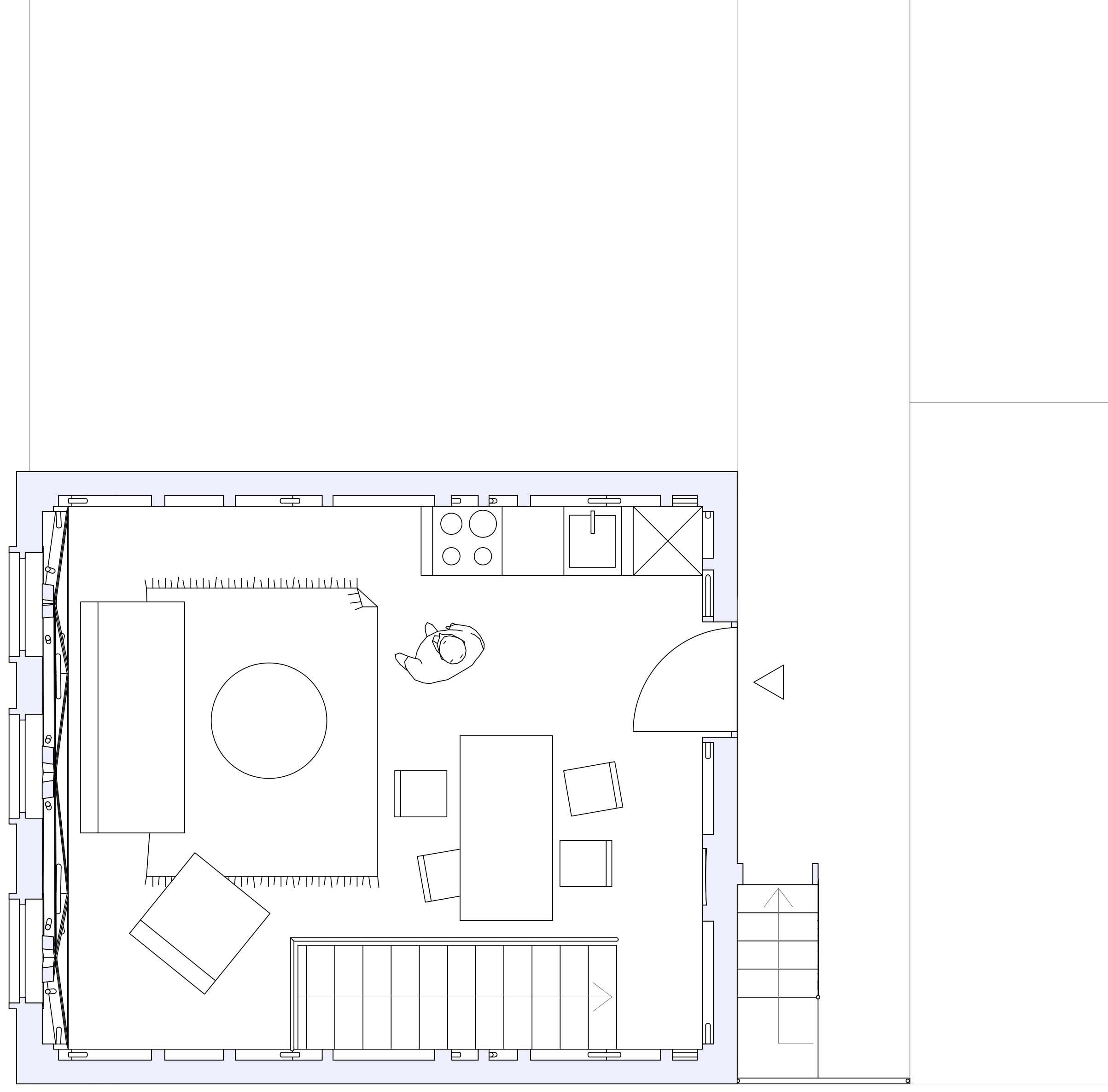


Cabin Floor Plan Lower Level (-1), 1:60

Each *Cabin* sits on one half of the pitched roof and is thus wholly oriented to one side of the host building and opened on that façade. Adjacent units are directly next to each other, and a central corridor connects them all with the main staircase and the host building.

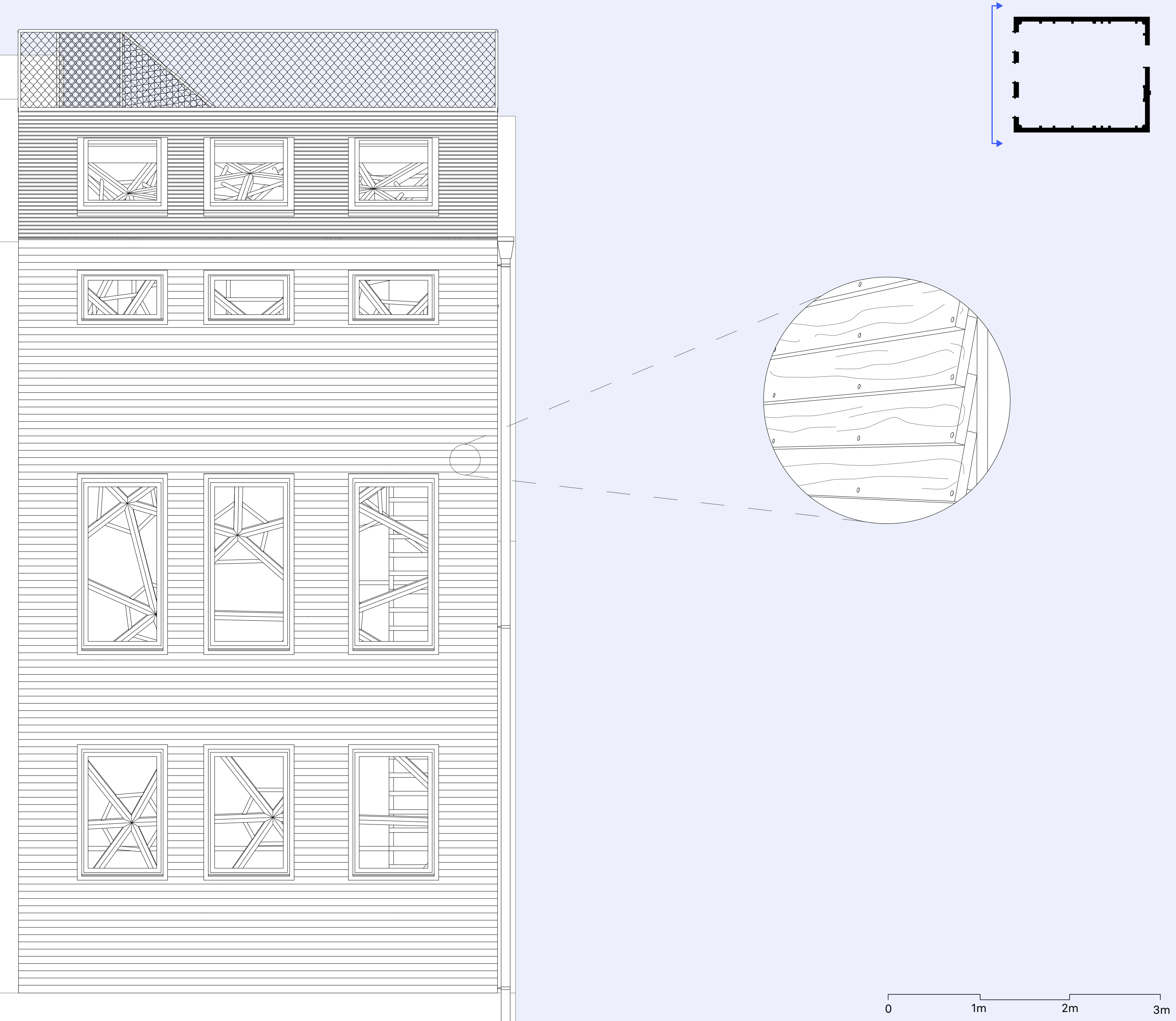
The floor plans are intended to be open and flexible. All internal walls are theoretically movable or removable. While customized furniture could maximize the use of the irregular-shaped space, the design enables off-the-shelf furnishing as much as possible to ease appropriation by possibly changing users.

All windows are placed behind the structure in extruding wooden frames. This allows the usage of straight, standard, rectangular windows and simultaneously reveals the striking structure on the exterior. The windows open to the outside and can be handled through the structure.

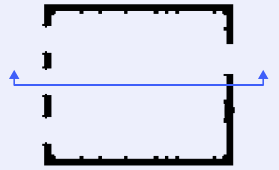


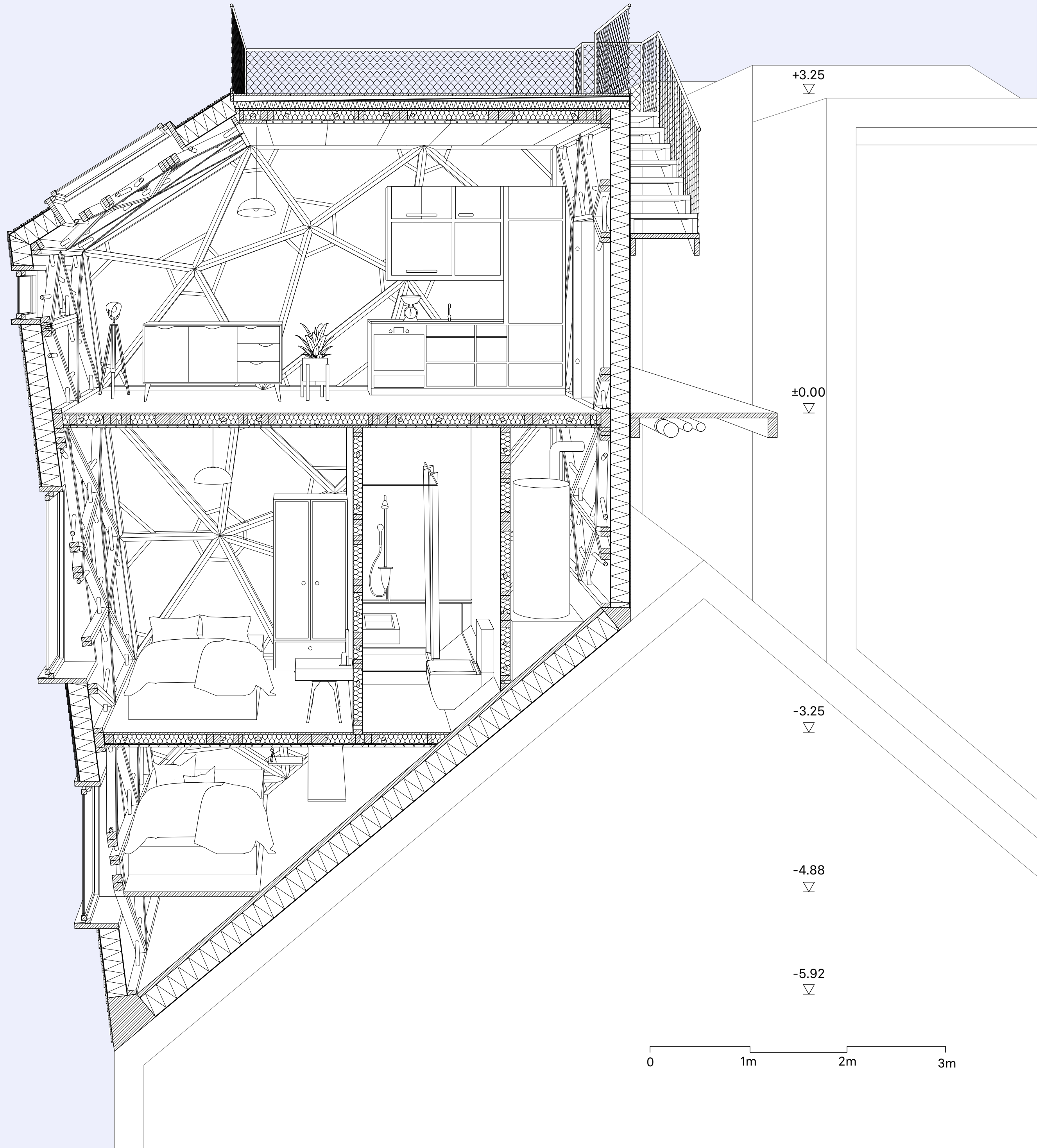
Cabin Floor Plan Entry Level (0), 1:60

VIew into the Cabin's Social Space



Cabin Street Side Elevation, 1:60





Cabin
Detail Section, Rooms, 1:60

The outermost layer of the *Cabin*'s wall structure is a cladding of long, overlapping, horizontal larch wood boards. Besides conveying the image of a roof covering, it actually provides excellent protection from precipitation. Moreover, it is a sustainable material that ages gracefully and helps bring out the natural character of the design. Still, the façade finish is not decisive for the concept. Instead, it would be one parameter that can easily change between *Cabins*, functions, and users - leading to a varied presentation of the design throughout the city.

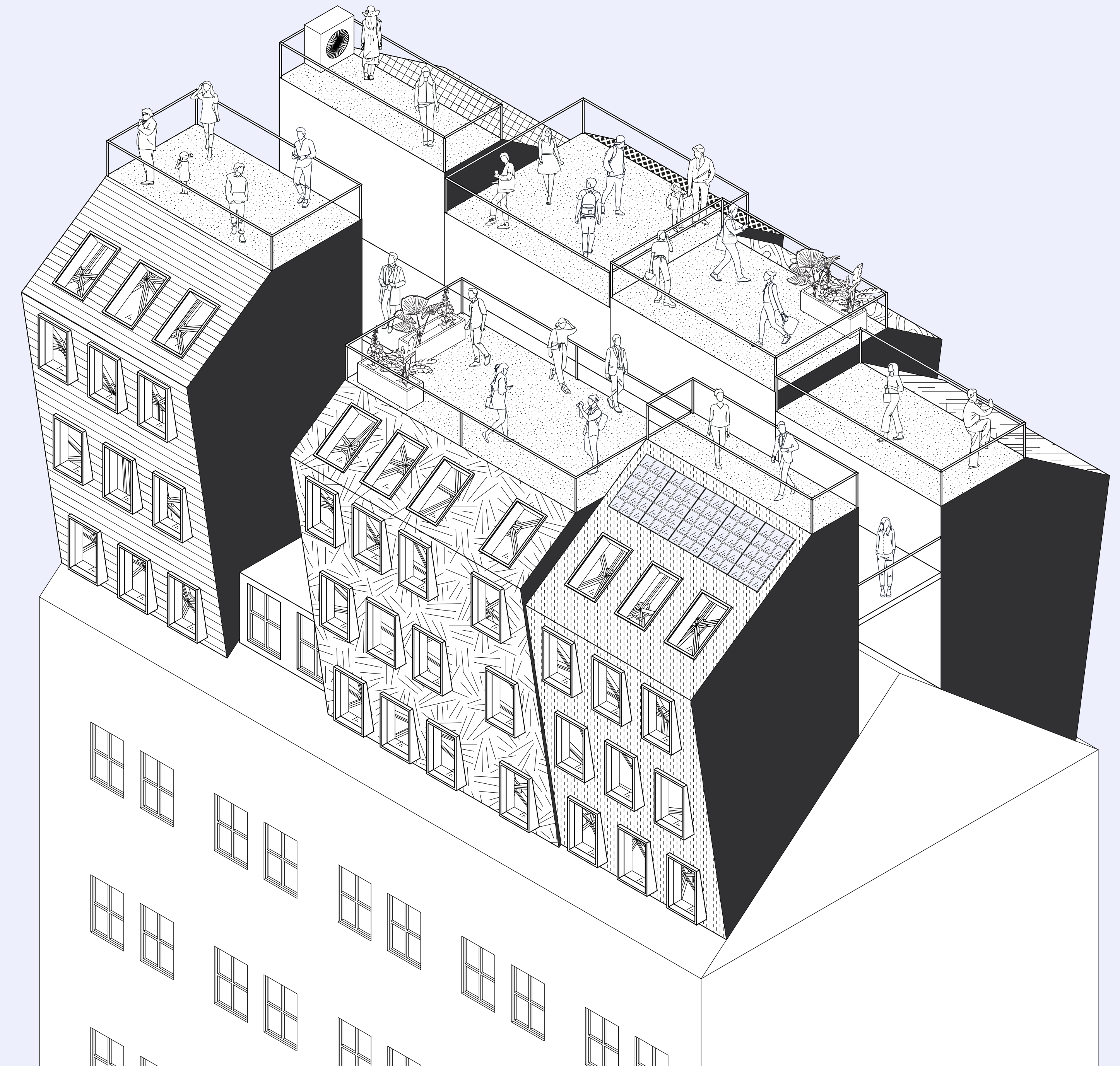
Each *Cabin* is connected to the building services and the municipal energy and water grids through the central corridor and the host building. The otherwise hard to use, small space atop the slope provides the service access room. The bathroom, as well as the kitchen, are positioned in the same corner to keep necessary plumbing short. As the primary connection lies higher than the bathroom's drainage, a pumping system is required, similar to inhabited cellar spaces. The water circulation for the air handling ceiling and the electrical wiring is laid underneath the carrying structure of the floor slabs. Sockets are incorporated into the flooring. Connections for overhead lights are integrated into the ceiling.

3.2 The Village

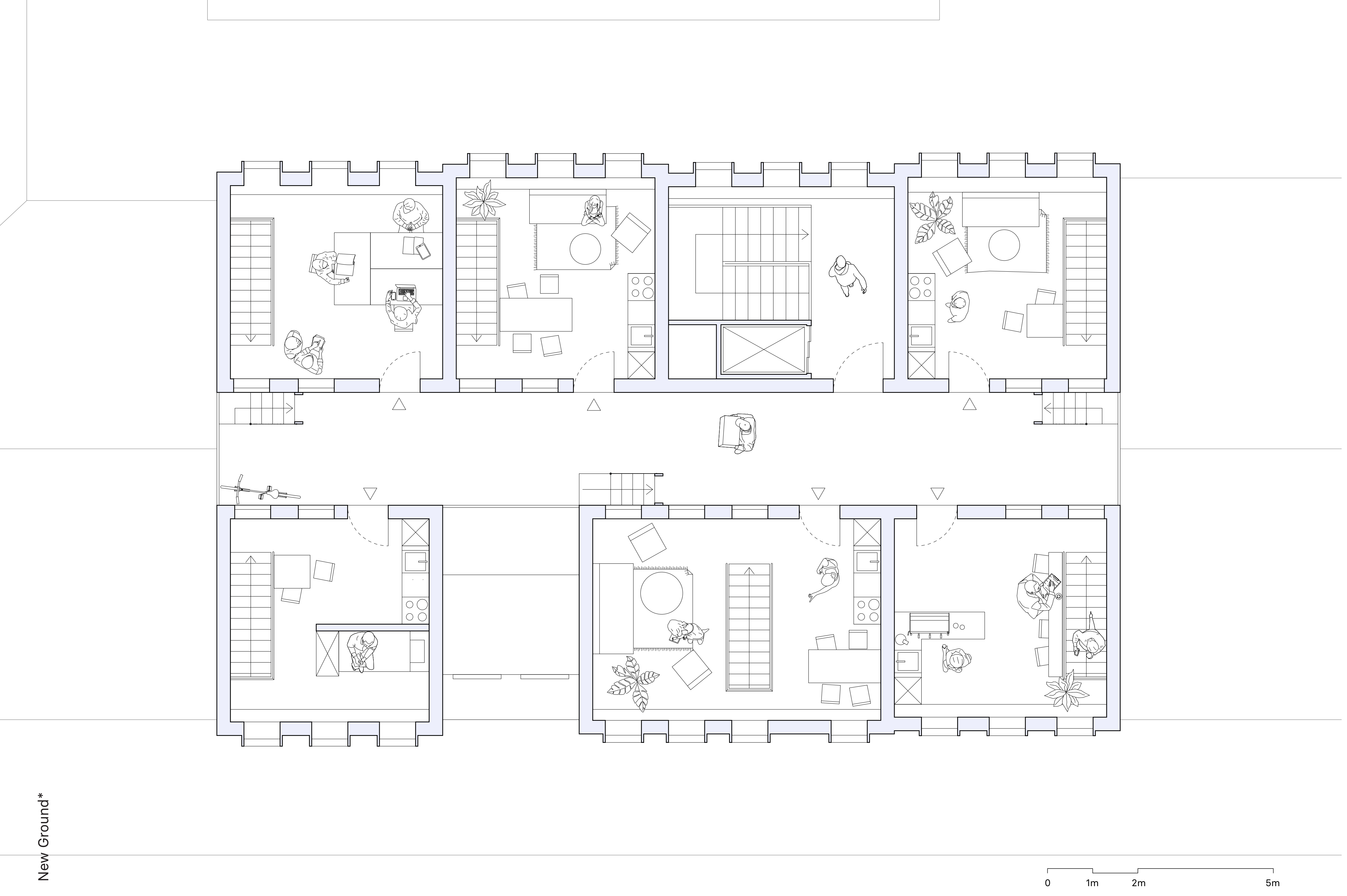
A *Village* is an arrangement that emerges from the group of *Cabins* on the rooftop of one host building. It is a small neighborhood of new occupants and is open to existing residents. The *Village* should give back for what it received from the *Host*: The roof space, light, and services, and compensate for the nuisance during construction.

Its central corridor acts as a bridge and connects each unit with the shared circulation and common spaces, like terraces, shared office spaces, guest apartments, or cultural and social *Cabins*. It is a communicative space that might become something like a *Village* square.

Each *Cabin* is slightly different, depending on hard factors like sunlight and space requirements or soft factors like the preferences of its users. However, they all share the skewed pentagonal shape that maximizes the available build space beneath the scaffolding system and atop the roof's slope. Next to the *Cabin* type presented in detail in the previous section, there should be a whole family of typologies: For singles, large families, flatshares, multi-generational living, as well as all the auxiliary functions.



A Village from Above



A Village's Floor Plan, Entry Level, 1:100

The floor plan shows the individual units and the shared staircase integrated into a circulation *Cabin* extending to the host building's main stairwell. This exemplary *Village* contains mainly residential spaces for different household sizes. However, it also provides space for an office or a café with its counter on the entry-level and additional seating below. While providing homes is its primary purpose, any space needed by the area or the *Village* itself could be included: Laundy facilities, guest apartments, a community kitchen, and more.

In the gap between the units, the existing roof apartment still has an unobstructed view. A unique *Cabin* fitted on top of the dormer could also tap into that potential. In return, the lowest level of a *Cabin* might be connected to the existing apartment inside the roof, giving that more space and light.

The City in the city
from Above

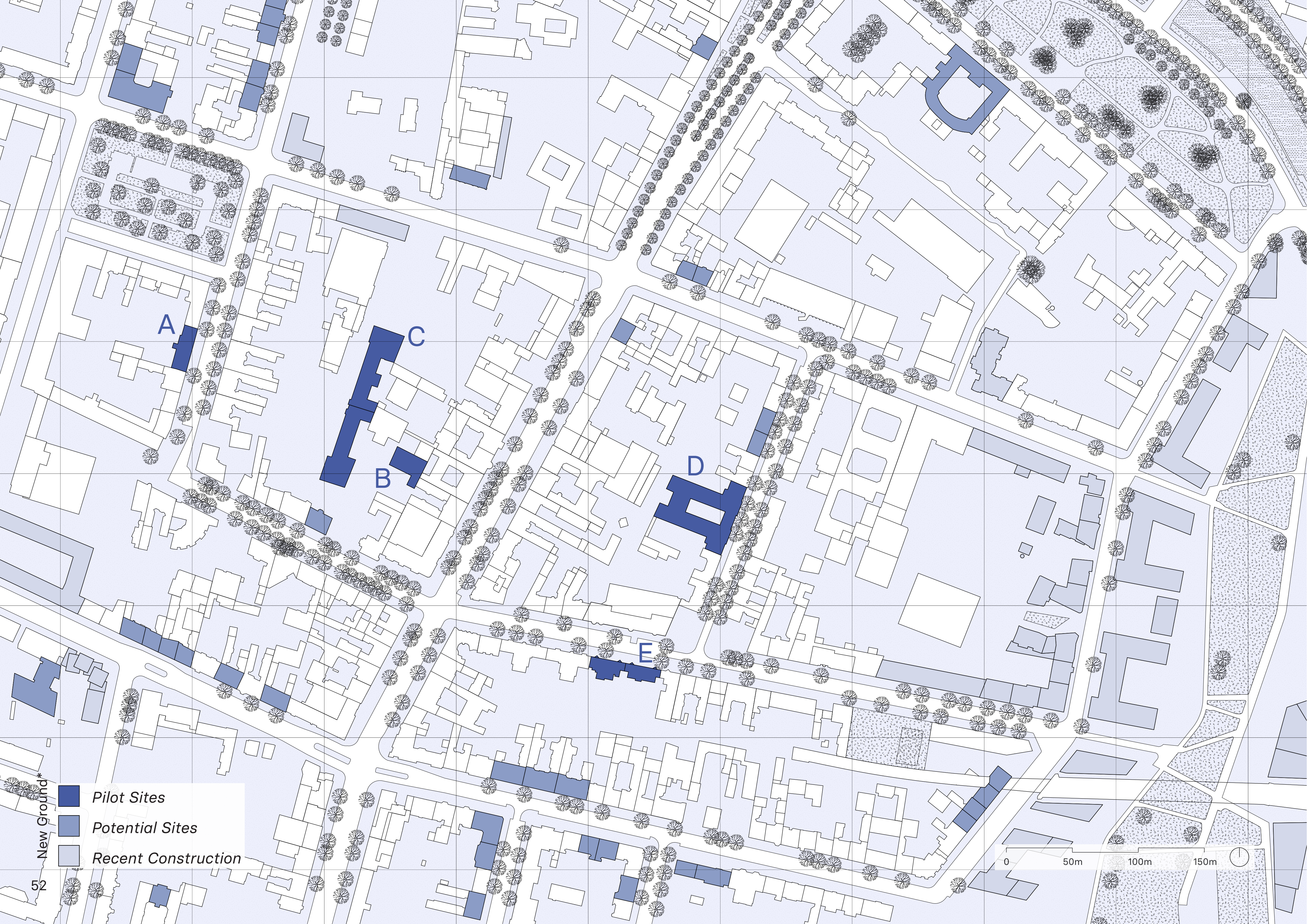
3.3 The City*

* and a Vision for the Future

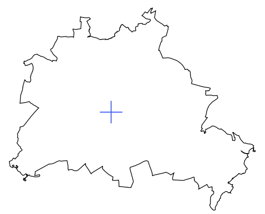
As soon as a growing number of *Villages* pop up all over the city's rooftops, a new *City* materializes above and throughout Berlin.

While only loosely coupled, the new residents share experiences and might become active in renter's unions, collectives, and the management of the *Villages* itself. The strong recognizability of the new superstructures across Berlin as a symbol of citizen-centered urbanism should facilitate the forming of a community of interested sympathizers and involved residents to promote the project's continuation as well as the general values of a city for all.

Moreover, the *City* stands for a network of production facilities and reusable construction tools, including the drones used for delivery or the scaffolding and membrane system. While in the beginning primarily focused on constructing new *Villages* with sustainably sourced local timber, it would grow into complete recycling centers for older *Cabins* reaching their end of life or other wooden structures - working towards a circular economy of local construction materials.



Pilot Area
between Schöneberg and Tiergarten



To illustrate and test the adaptiveness of the design system and get a glimpse of the utopian vision where the *City* occupies the whole city, a pilot area was defined around the northern Potsdamer Straße at the border between the districts Schöneberg and Tiergarten.

It is a central area, yet slightly secluded from the typical popular areas for tourists or new arrivals in Berlin. In fact, it is home to the infamous sex trade district around the Kurfürstenstraße, which might have spared it a bit longer from gentrification than the neighboring districts. However, being between two spacious parks (the *Gleisdreieck* and *Tiergarten* itself) and only a stone's throw from the Potsdamer Platz, Berlin's philharmonic hall, the New National Gallery, and the embassy district, development pressure was persistently high. Living there for over eight years between 2012 and 2020, I could observe live how parking lots, production facilities, parts of the *Gleisdreieckpark*, and any leftover brownfield slowly but steadily turned into upscale apartment blocks while elegant restaurants slowly crept South along the *Potsdamer Straße*, displacing established hairdressers, kebap shops and bakeries.

Welcoming the densification and increased variety of amenities, it is imperative to diversify the newly produced housing. This is where the proposed *City* steps onto the scene.

Several potential roofs were identified by analyzing the housing stock through 3D satellite imagery. Of these potential sites, five were selected to test the system on. They represent a cross-section through the years and typologies. The oldest one, now a primary school, was first constructed in 1880 (Pilot C). More importantly, though, they represent various shapes and sizes to ensure the adaptability of the algorithm and design system.

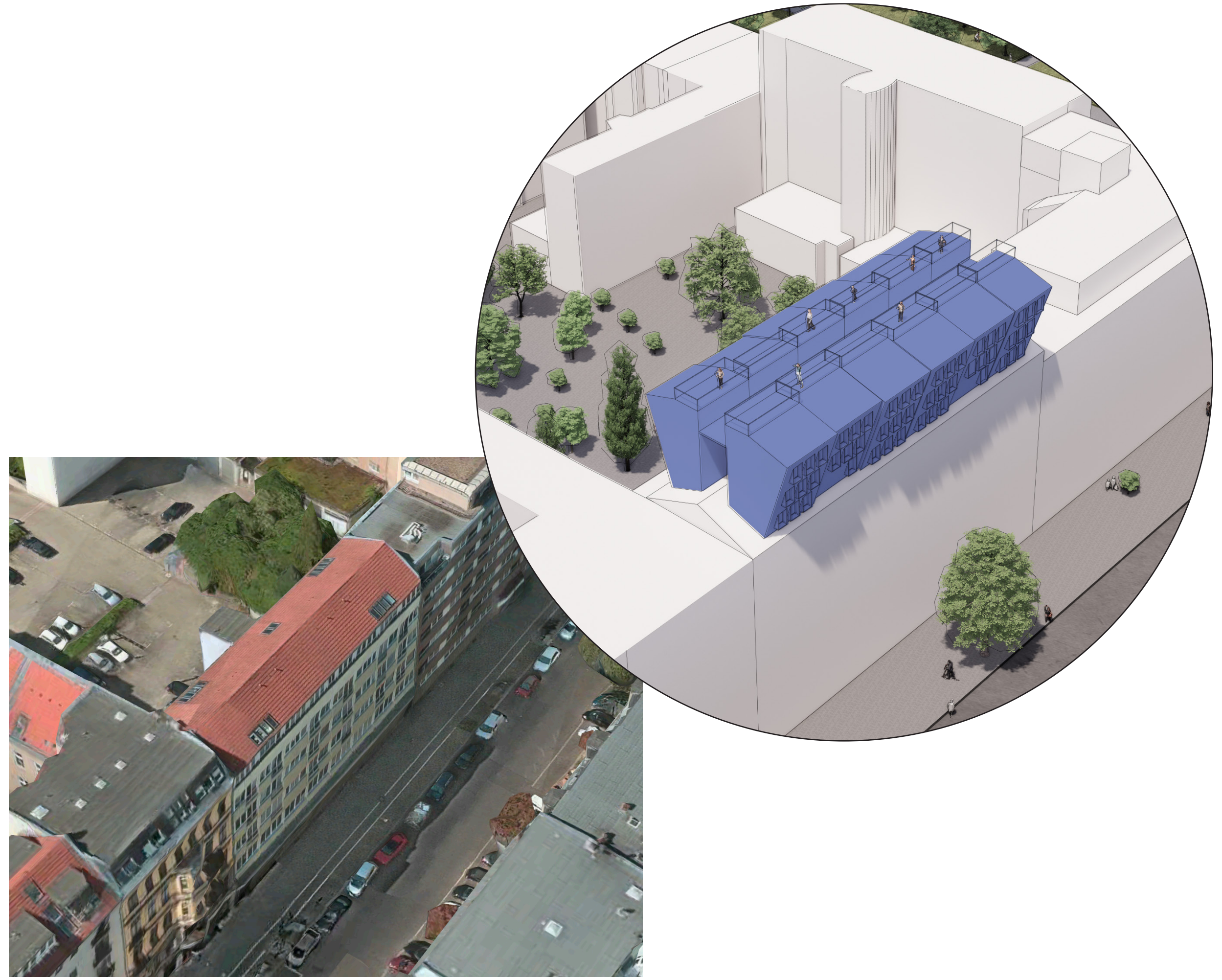
3.4 Probing the System*

* the Pilot Sites

The following section presents the individual pilot sites selected for testing the design system. Each had unique challenges and opportunities that helped refine the code and design but also tested the limits of the spaces the system might provide.

The first pilot site is a residential building on the outer block perimeter with a spacious courtyard behind it. The roof is partially used and relatively flat - leading to *Cabin* layouts without the lowest level or only a small storage space in lieu thereof. The lowest level should become part of the existing flats at the four positions where windows penetrate the roof to create a dormer for these units.

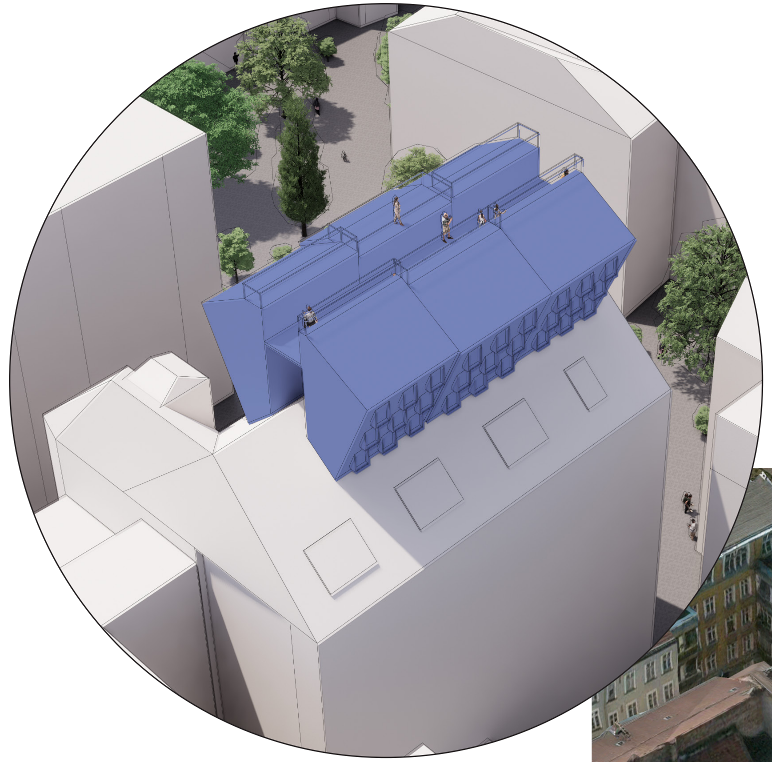
Thanks to the wide street in front and the large courtyard behind, the shading impact on the neighbors would be minimal. In addition, the already annexed staircase behind the building can easily be extended to also connect to the new *Village*.



A: Kluckstr. 32-34

Residential
350m² New Ground
Street Side
Feature: Flat angled roof

3D Satellite Screenshots from Apple Maps



B: Potsdamer Str. 98A

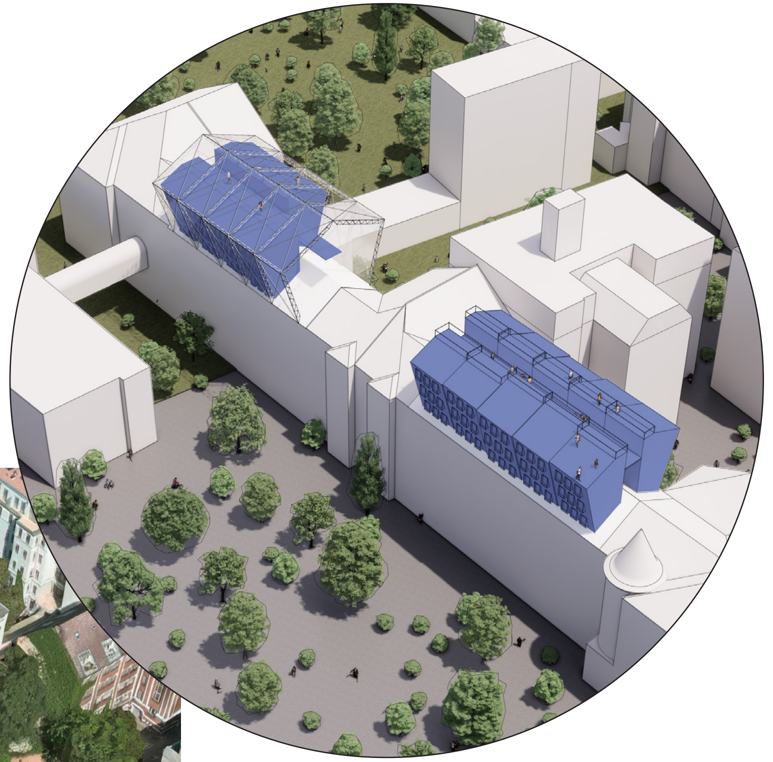
Residential
250m² New Ground
Block Center
Feature: Roof already converted

Pilot B is a residential building in the center of a more densely built-up courtyard. However, thanks to an orientation from East to West, the longest shadows again should have minimal impact on its surrounding.

This roof is much steeper, already used, and penetrated by windows and cut-out balconies over its whole length. To react to this, the *Village* sits only on the highest part of the roof and leans out further to make up for the smaller footprint. As visible in the rendering, the northern windows of the roof occupants are the most affected by shading.

The third pilot roof is on the *Allegro Grundschule* - an elementary school with a small campus inside a closed city block. The building was first constructed in 1880 and last renovated in 1991. Its older age should benefit roof superstructures as structural calculations and safety margins were less concise. However, it also means that the heritage preservation office would have to be convinced of the project.

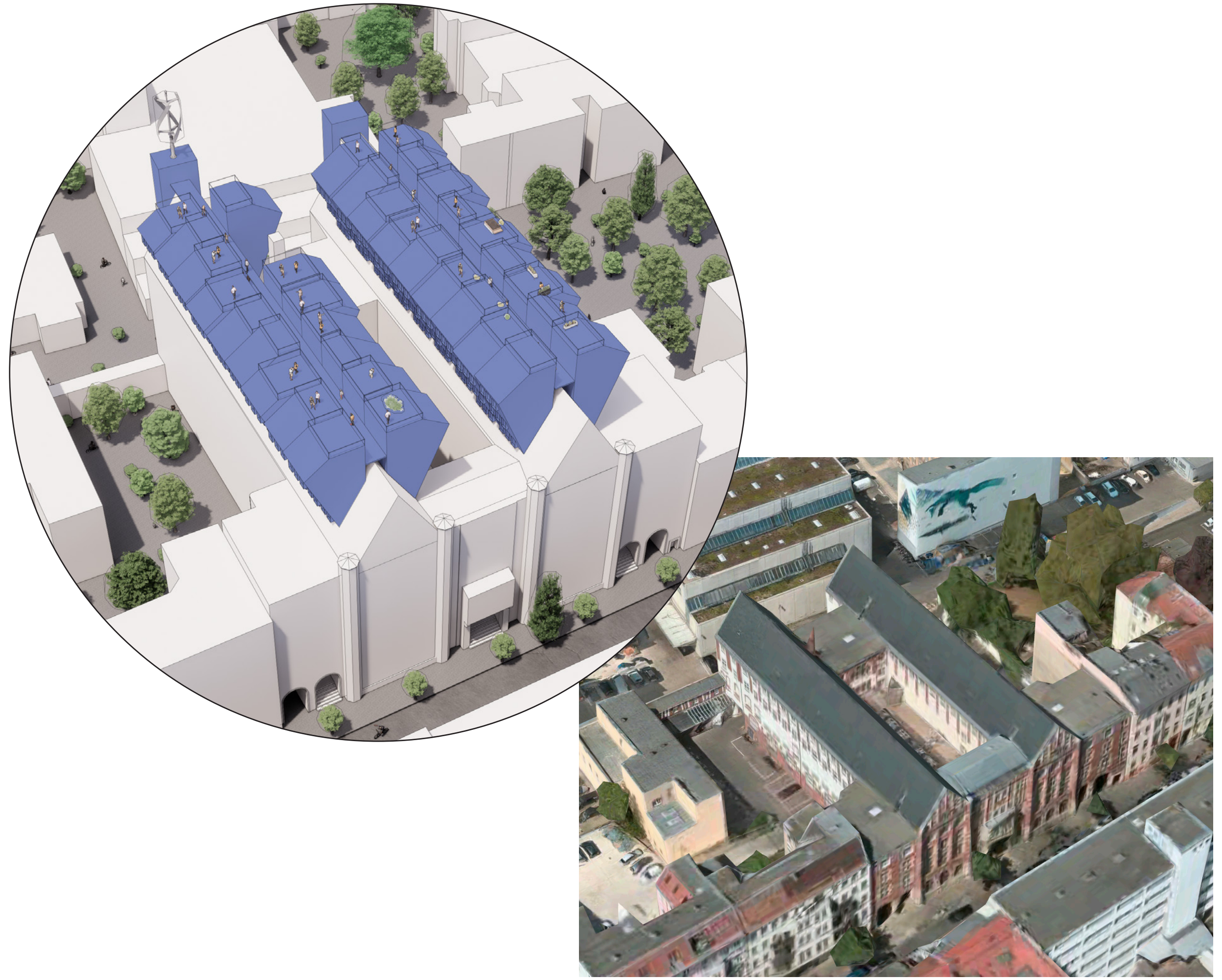
This pilot features a more flat roof divided into two long stretches by a central volume containing the circulation that would have to be connected to the new *Villages*. In addition, the spacious courtyard used as a school playground and the resulting distance to neighboring buildings would allow for a higher superstructure without shading the surroundings too much.



C: Lützowstr. 85
„Allegro Grundschule“

School
2x 350m² New Ground
Block Center

Constructed 1880



D: Körnerstr. 7-10
„Postamt W35“

Offices
2x 600m² New Ground
Steet Side and Courtyard
Feature: Access through back street possible

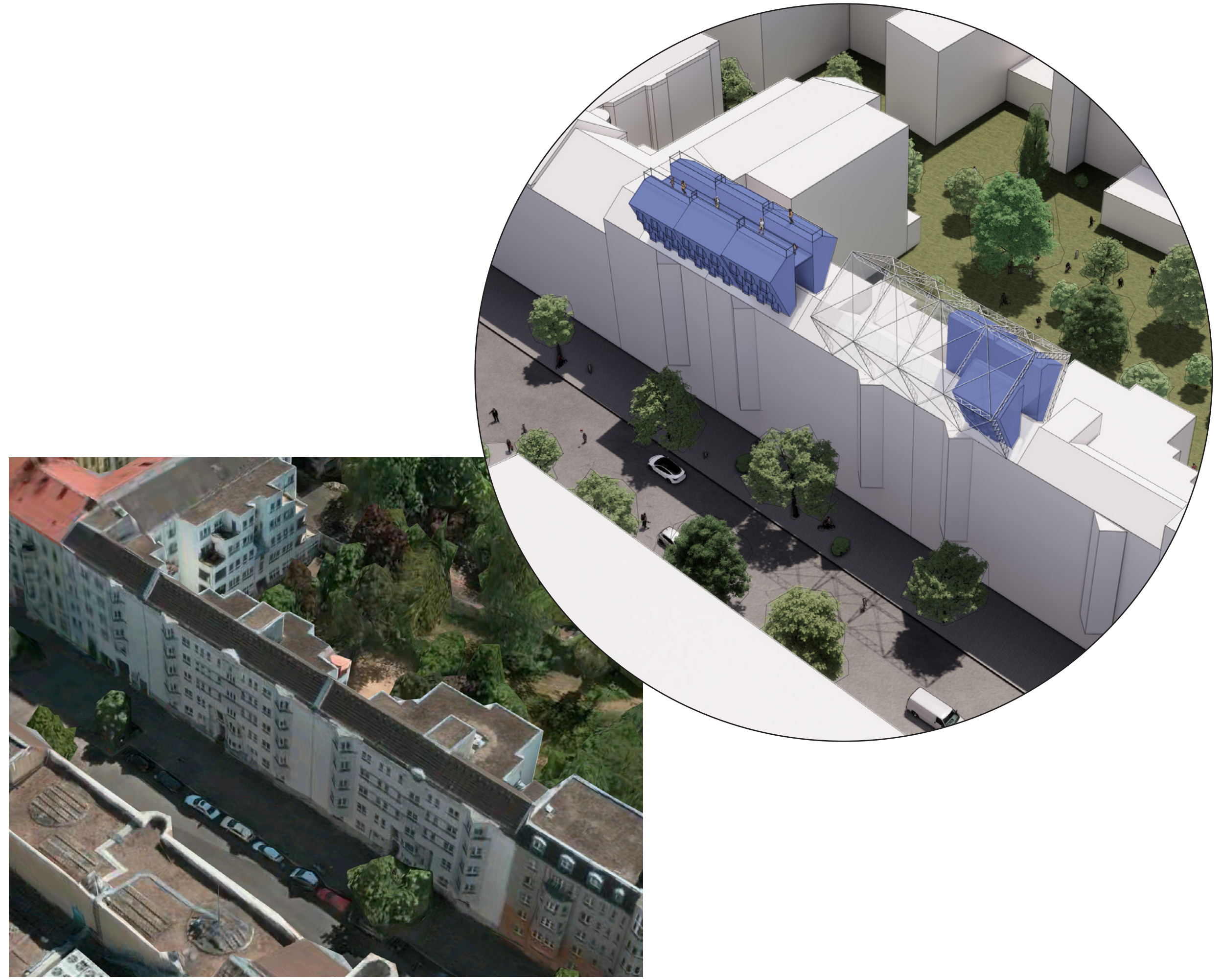
Constructed 1906

The *Postamt W35* is the host building for pilot D. Erected in 1906, this building is under heritage protection as well. However, given the two long, regular pitched roofs without any habitation and the commercial neighbors in its courtyard, it would be one of the best-suited *Hosts* for this proposal. The building is no longer used as a post office but instead offers office space to multiple companies.

One of the most significant advantages, is the direct connection to a backstreet in the block center. This allows to separate the *Host*'s office functions from the new residential *Villages* and removes the need to break open the host buildings roof to access the circulation. Lastly, it also eases the introduction of a second evacuation route following fire safety regulations.

The last pilot building is again a residential construction on its block's perimeter. The site itself is the roof space between three similar houses where the circulation cores do not obstruct the roof.

Similar to the first pilot, this building also separates a wide street from a spacious courtyard with a park inside. Combined with East-West orientation, this again should keep the shading impact to a minimum. A unique feature about this pilot, though, is its slimness. The relatively steep but slender roof will create rather small *Cabins* in the two *Villages* atop it. This means that the units would have to be wider or might be more geared towards smaller household sizes.



E: Pohlstr. 47-49

Residential
2x 115m² New Ground
Street Side
Feature: Especially slim

Chapter 4.0*

*Prototyping the Structure

In order to maximize efficiency and allow the most lightweight and thus most widespread employable construction, a bespoke structure has been developed: Triangular elements that perfectly fit into the polygonal-shaped walls and make bracing superfluous by being rigid in themselves.

The proposed structure uses two main experimental processes: Robotic fabrication and a wood connection only held by the forces of hygroscopic expansion. Especially the latter was inspired heavily by *Up Sticks*, a project of Gramazio Kohler Research, and the Master of Advanced Studies in Architecture and Digital Fabrication (MAS DFAB) at ETH Zürich[1], which uses a comparable hygroscopic connection and human-robot collaborative fabrication.

Both experimental processes have been tested on a prototype to demonstrate that the proposal is feasible. The prototype is a 1:1 model of one triangle of connected beams that carry the *Cabin*. The triangle's sides measure between 1 and 1.3 meters with a beam section of 45x95mm and dowels with a diameter of 27mm.

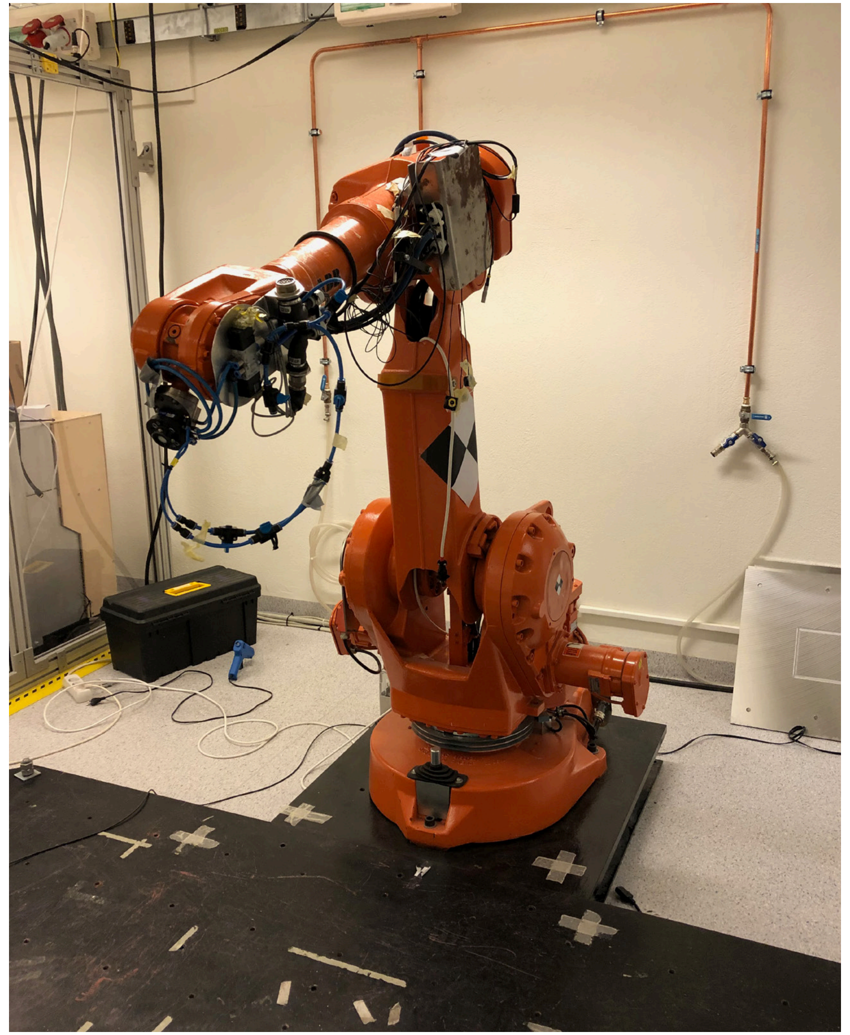
[1] *Availalble at https://gramaziokohler.arch.ethz.ch/web/e/lehre/375.html*

4.1 Setup

The tests were conducted with an IRB 2400 robotic arm by ABB with a reach of 1.55m and a handling capacity of 16kg[1]. A metal table frame was bolted in the build space to allow for easier collaboration during the drilling and insertion of the dowels. Using a vacuum gripper, the robot could pick up, position, and stabilize the individual pieces.

Because only a single-robot setup was available, only one task could be fulfilled by the robot. In this case, the wooden beams‘ handling, placing, and holding while the human collaborator connects them. For this setup, the pieces had to be prepared beforehand: The beams were cut in the calculated angles, and the dowels were dried to shrink in diameter.

Without a dedicated drying kiln disposable, the dowels were dried with conventional kitchen equipment. Two methods were tested: The microwave and the oven. The microwave was much faster, removing almost all moisture in 15 one-minute sessions over about one hour. However, it slightly burned the wood when the resin became too hot. The oven was gentler to the wood and refrained from producing burn marks. However, it took almost eight hours to dry to the same diameter. In both cases, the dowel diameter was reduced from 27mm to between 26.3-26.7mm, depending on the fiber direction.



[1]*ABB Product Specification IRB 2400*

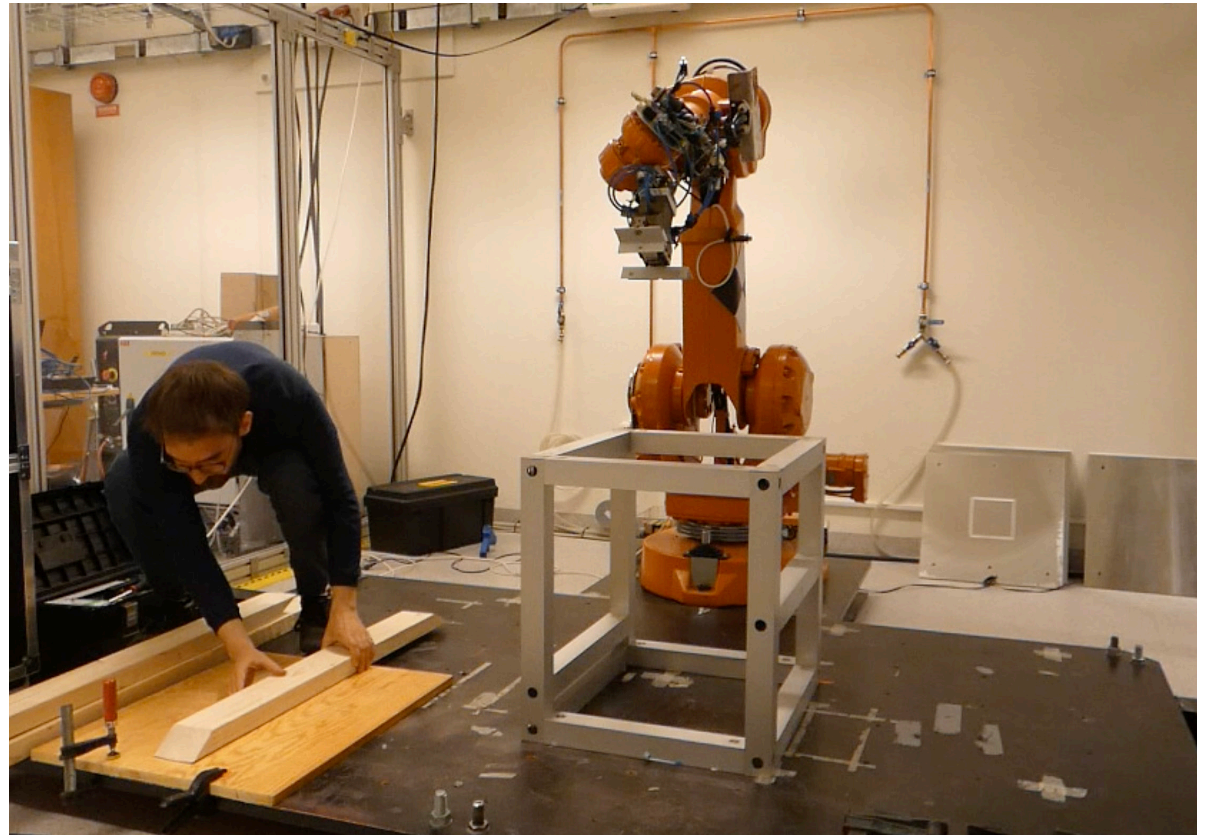
The robot was controlled with Grasshopper through COMPAS RRC and ROS using a python interface. Within this framework, a digital twin of the build space was created in Rhino + Grasshopper to determine the target positions of each execution step. This increased control was necessary to allow human-robot collaboration and intermediate adjustments, which would be impossible when simply running a predefined script.

However, the system first needed to be calibrated and the build space measured. Then, by approaching different points in space, the pickup space and the build table could be determined as frames in the robot's coordinate system. Subsequently, these positions could be used to find intermediate steps and define the conclusive path for each workpiece without interfering with each other or the robot itself.

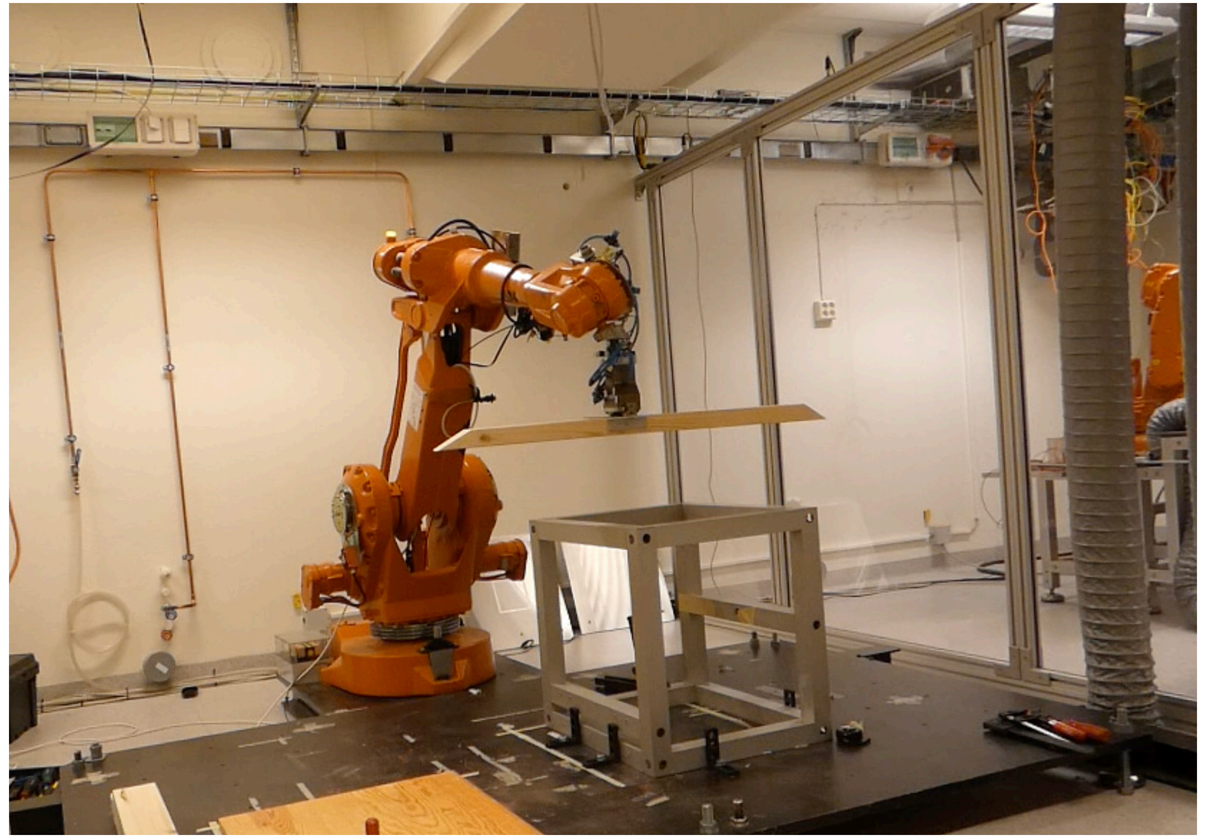
4.2 Execution

After calibration and several test runs over the course of two days, the final assembly took less than an hour and is documented in the following series of film stills.

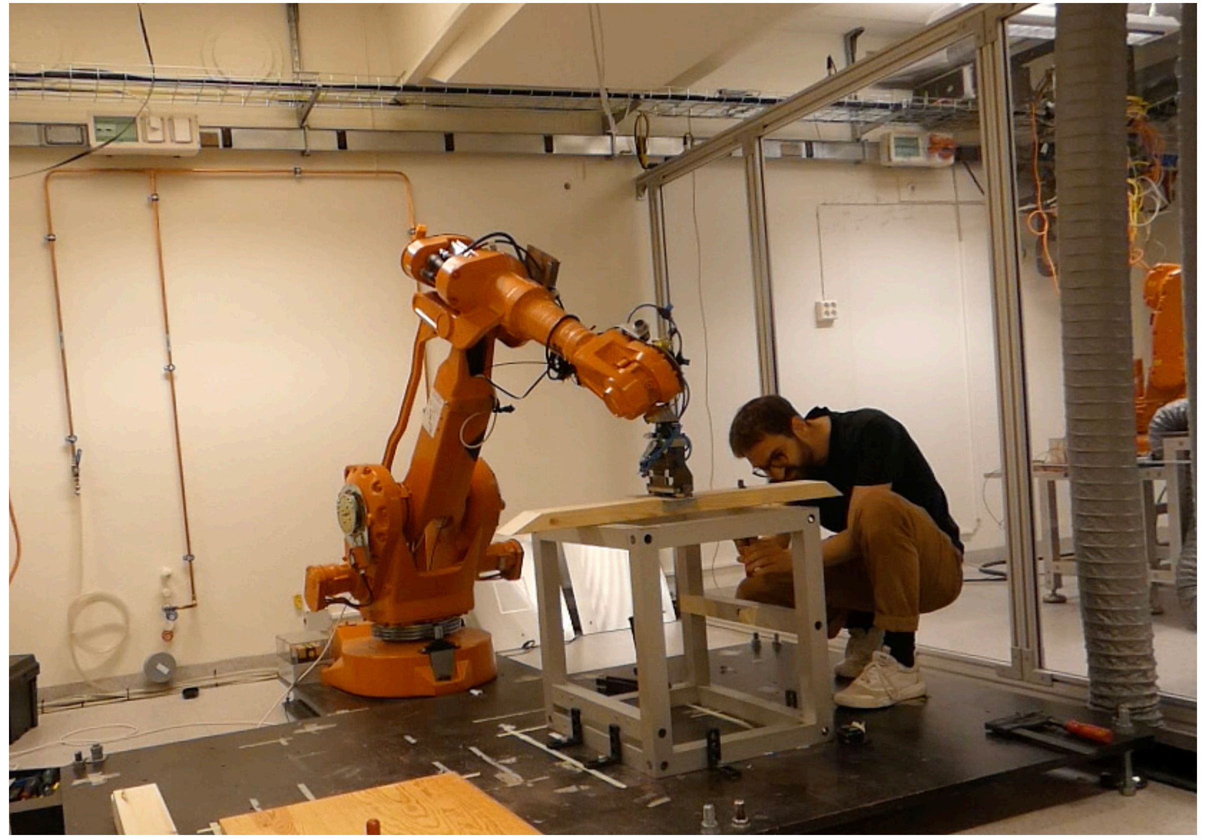
To see the film of the entire fabrication process, please follow the link in the QR code on the left (YouTube).



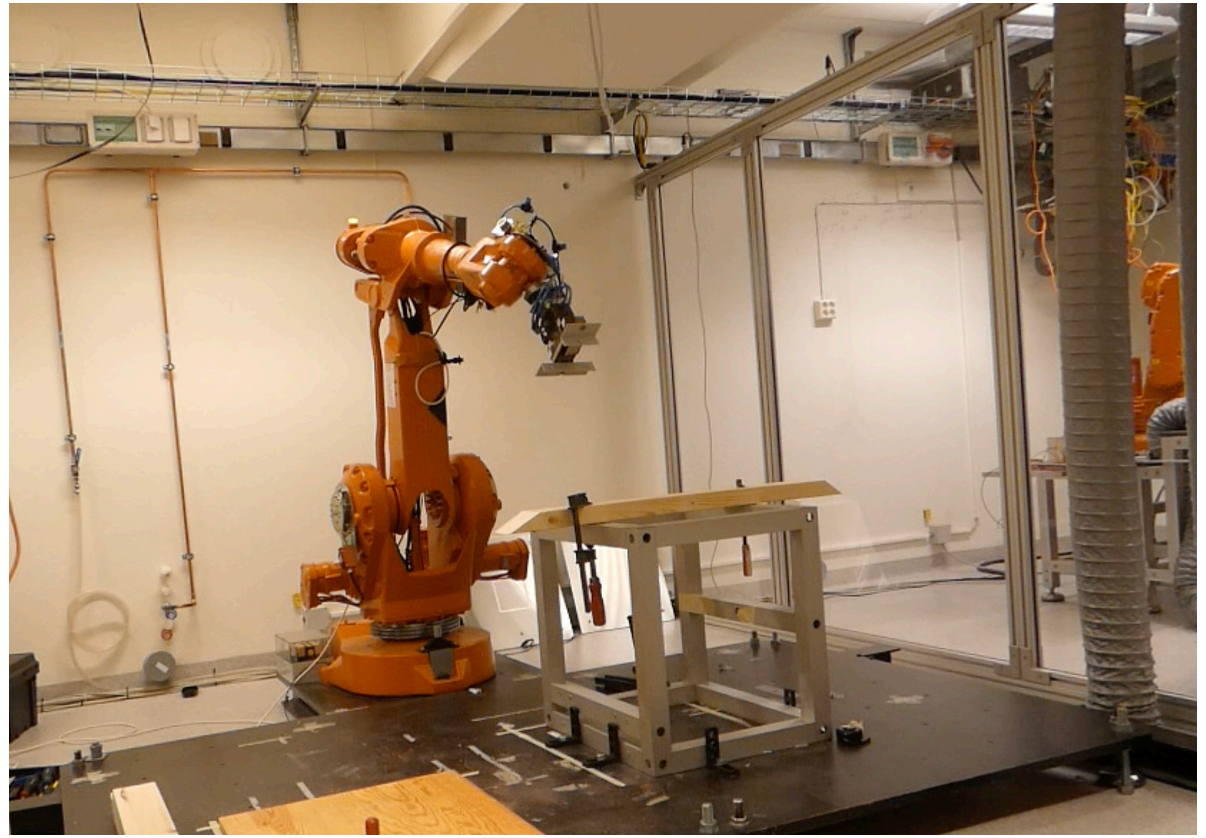
Step 1: Piece Placement at Marked Pickup Position



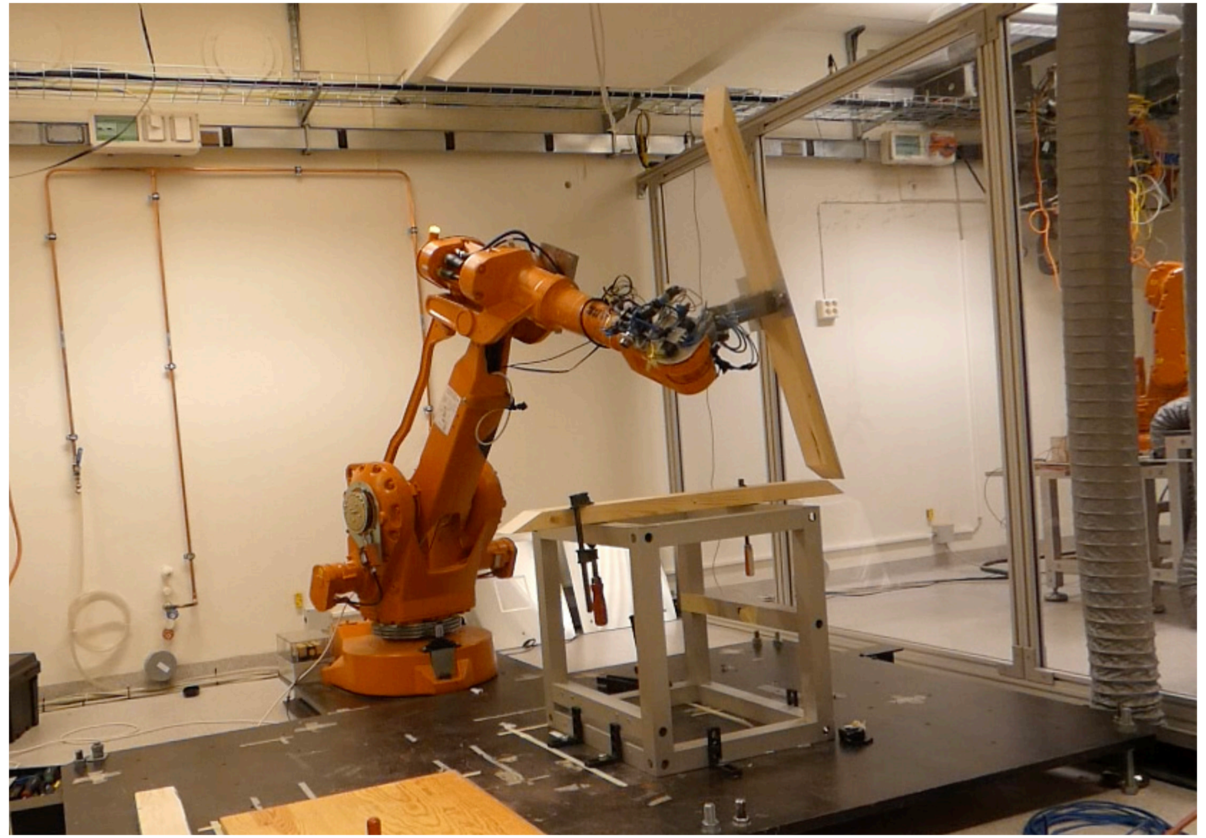
Step 2: Position Piece A



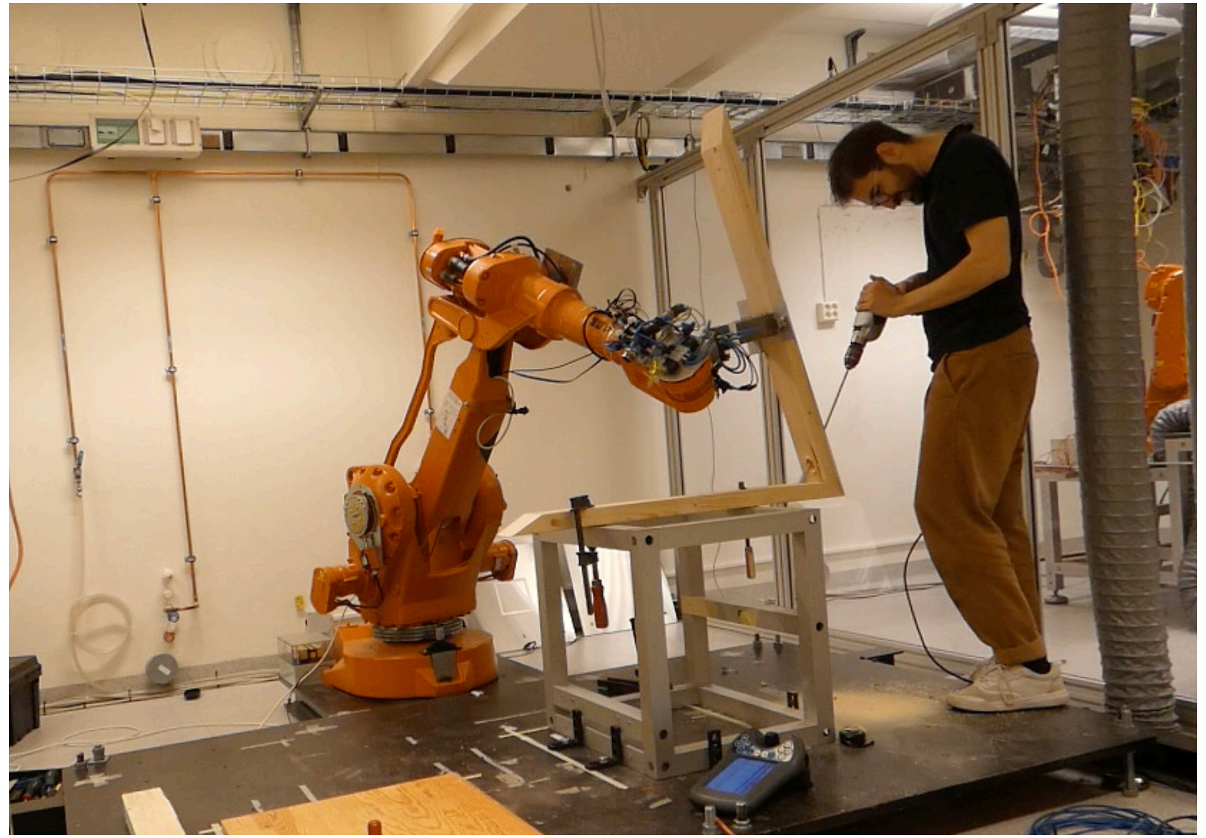
Step 3: Fasten Piece A to Build Table



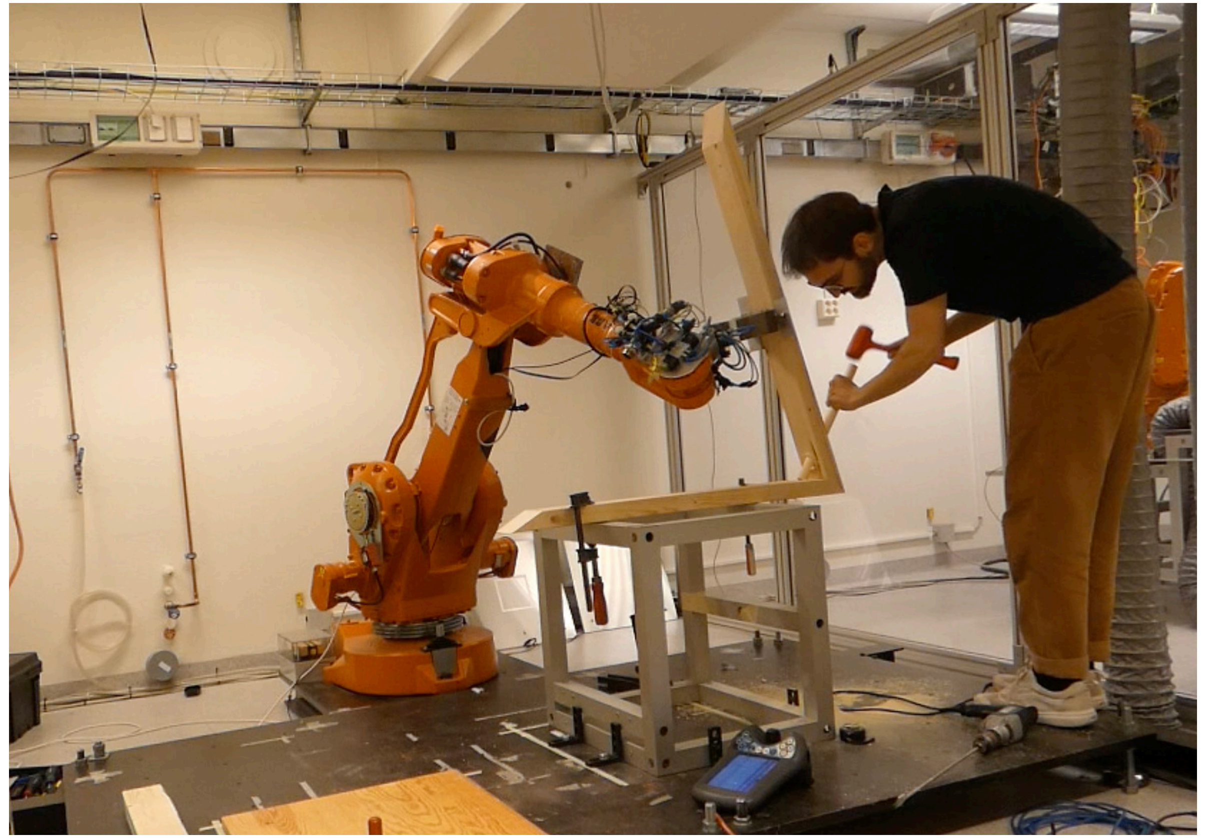
Step 4: Release and Reset Position



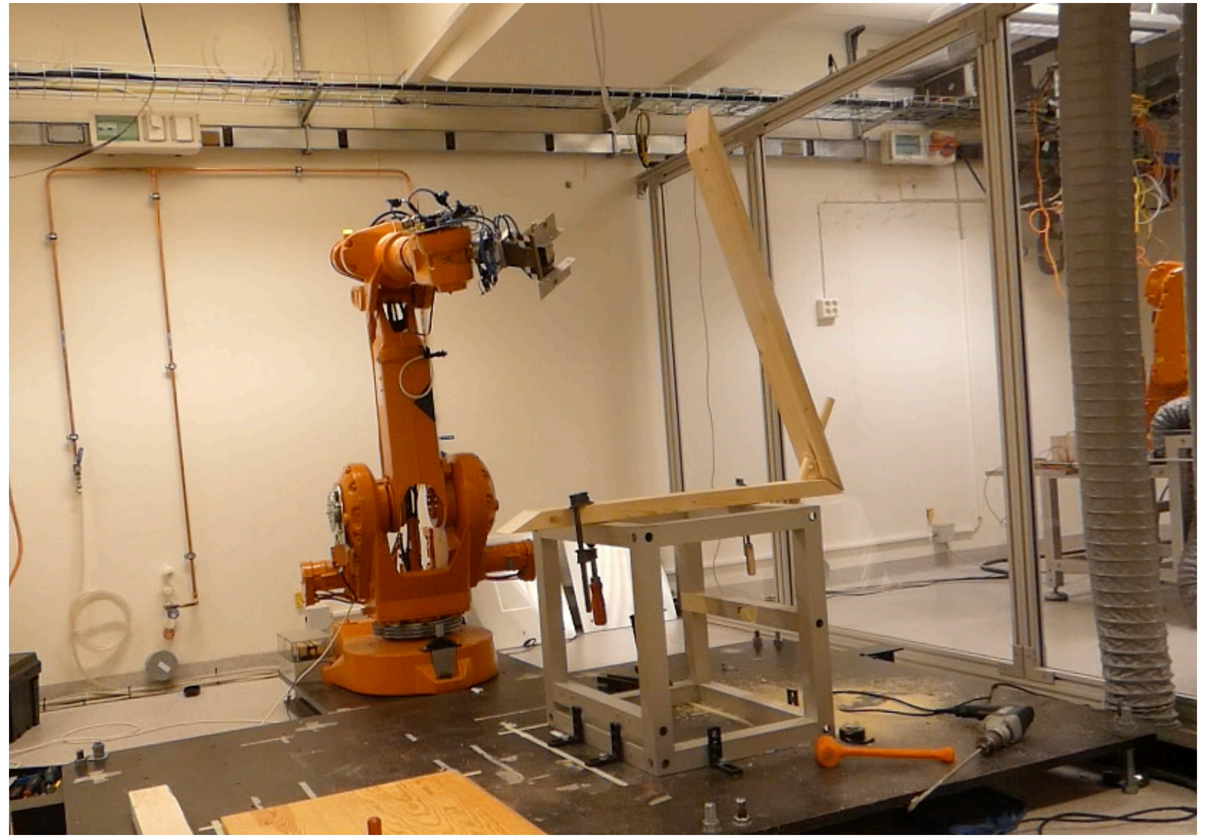
Step 5: Position Piece B



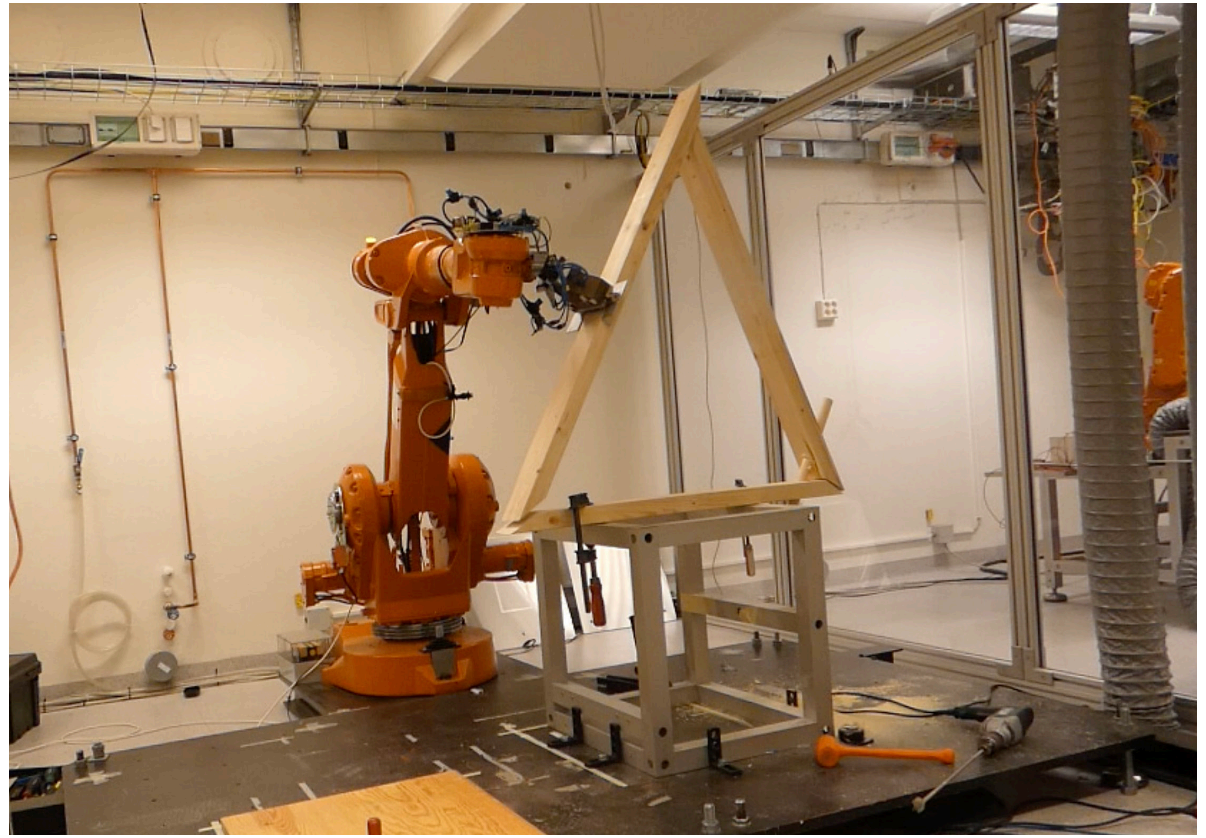
Step 6: Drill Hole #1



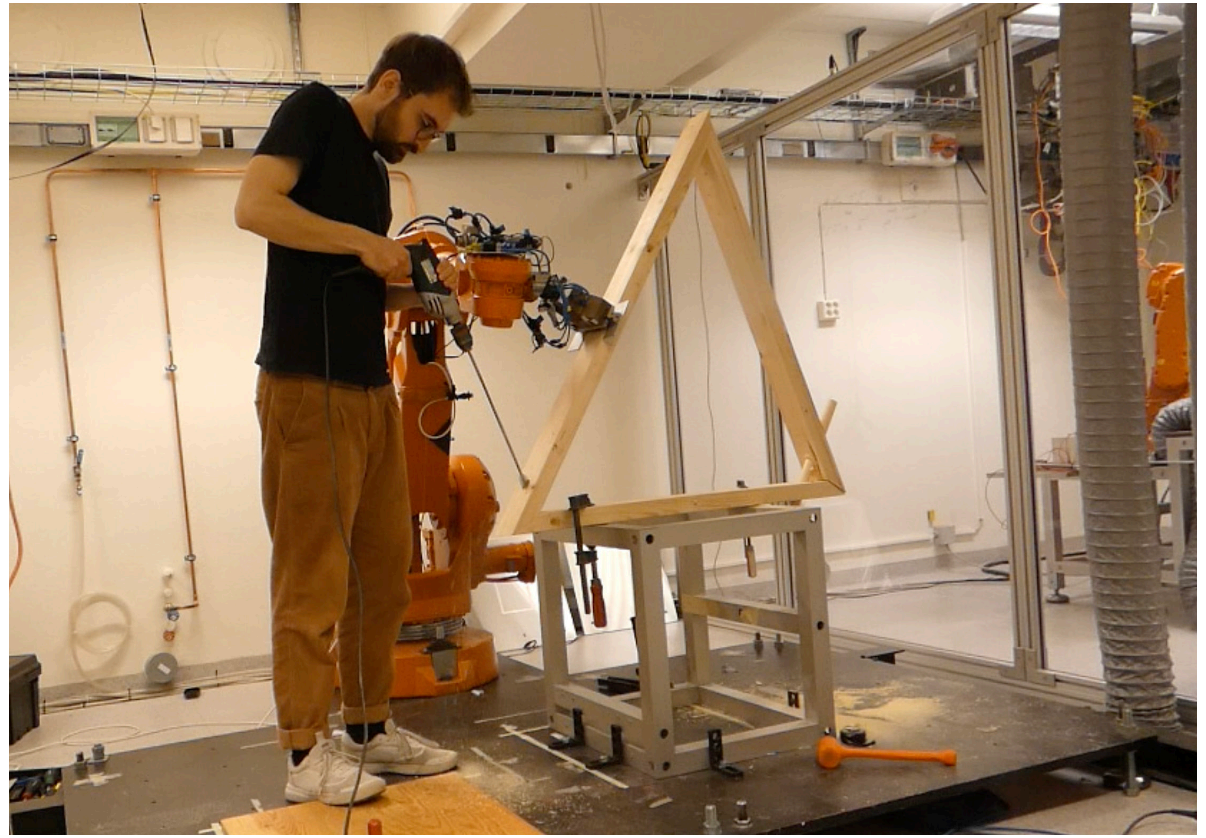
Step 7: Insert Dowel #1



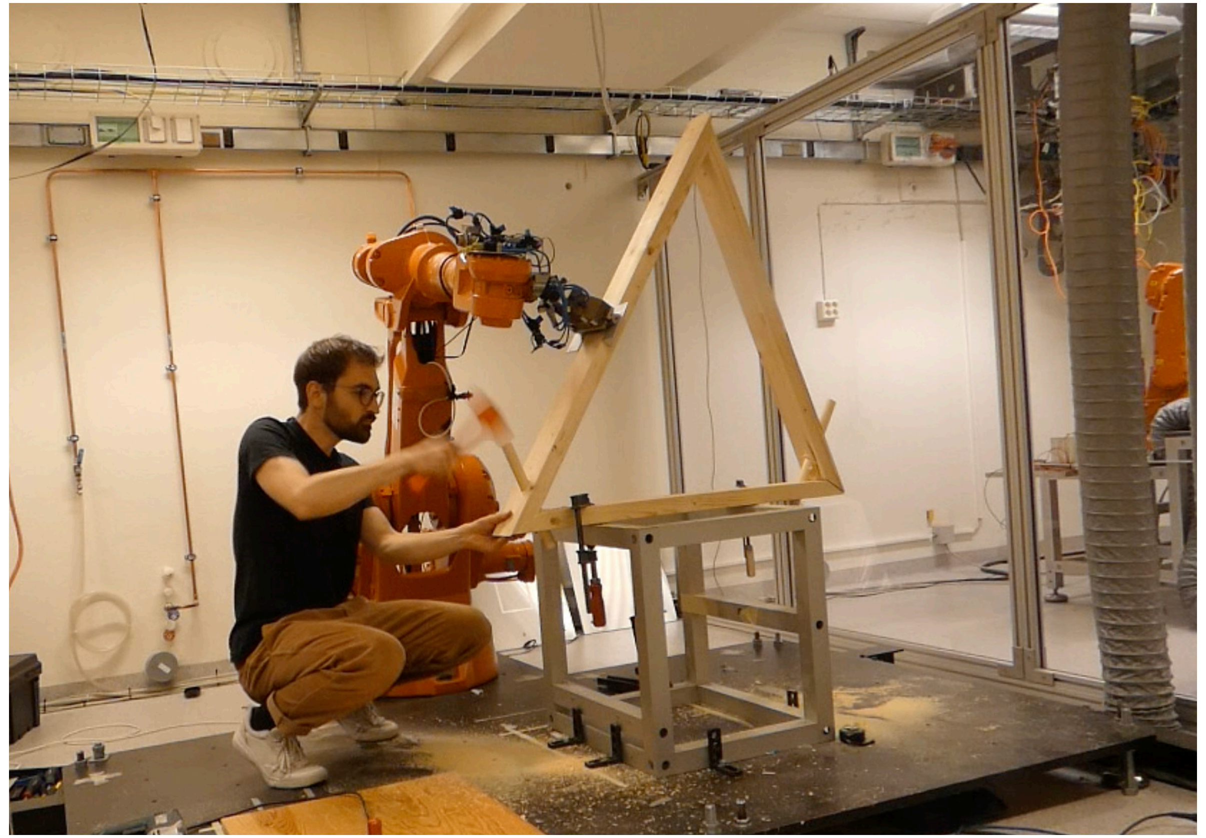
Step 8: Release and Reset Position



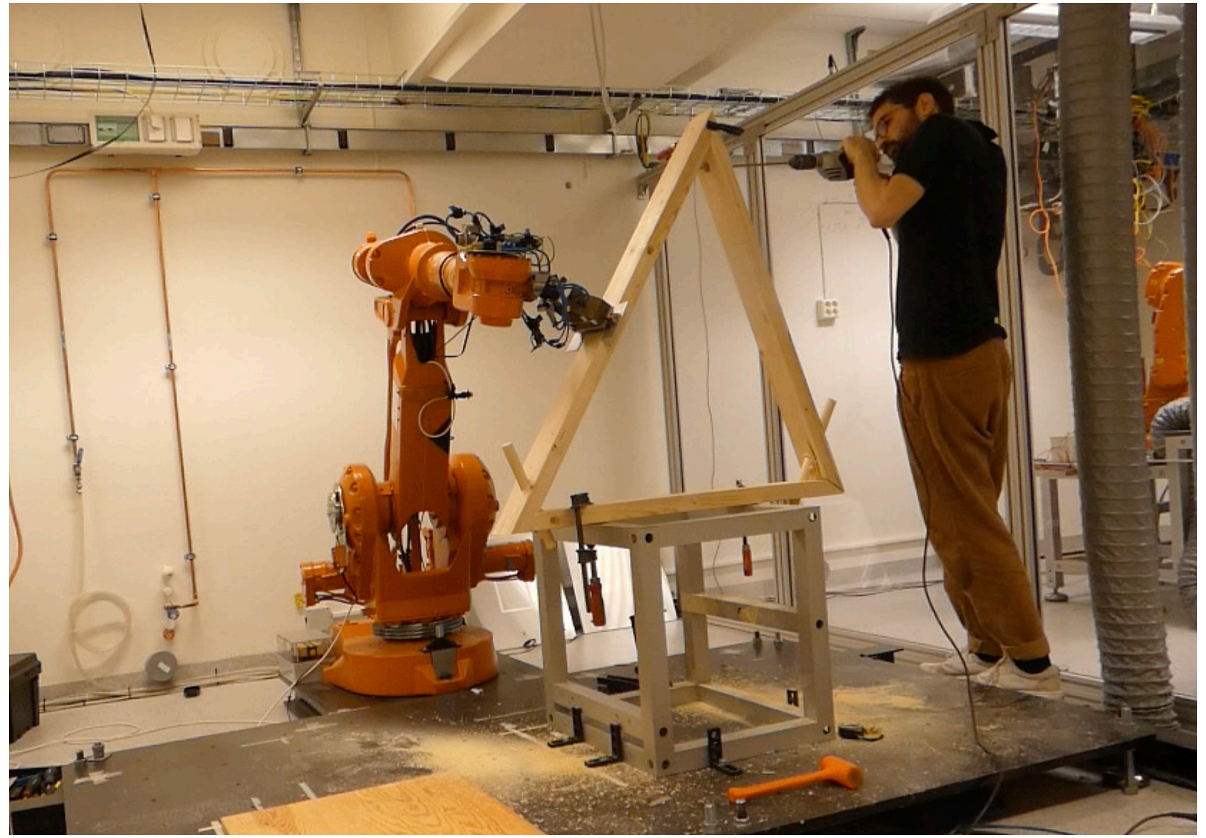
Step 9: Position Piece C



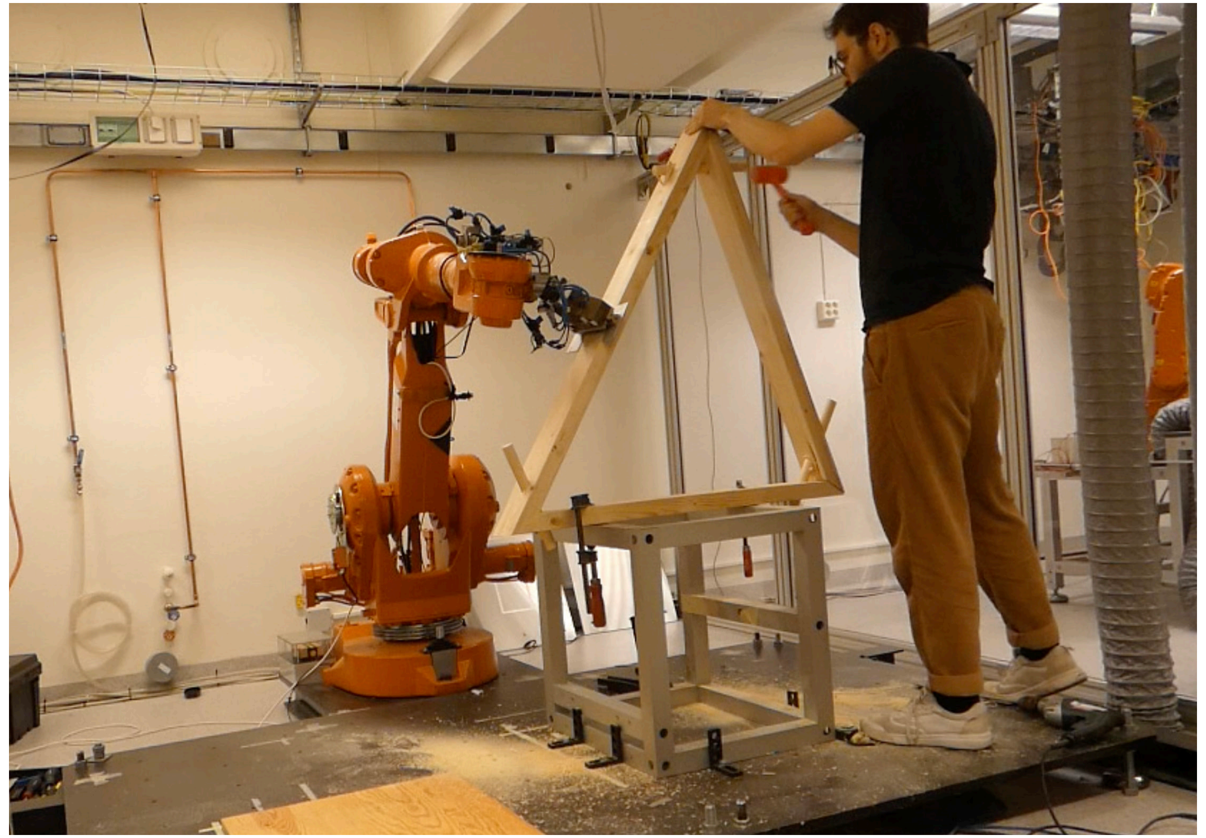
Step 10: Drill Hole #2



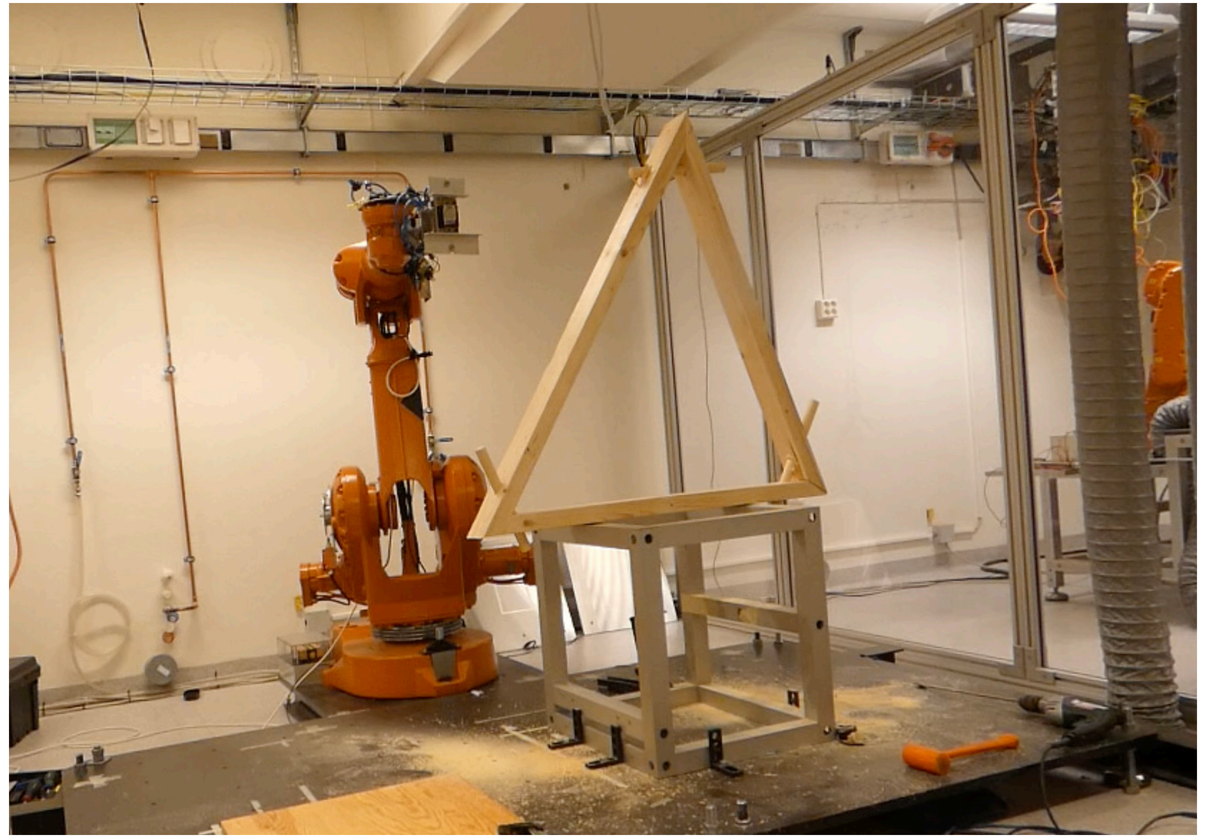
Step 11: Insert Dowel #2



Step 12: Drill Hole #3



Step 13: Insert Dowel #3



Step 14: Release and Reset Position

4.3 Results*

*and Adjustments for a Large Scale Application

The prototyping session demonstrated that a stable, triangular, structural element could be connected by kiln-dried dowels and fabricated in a robot-human collaboration setup. After sawing off the protruding dowels, the triangle could be connected to similar counterparts and integrated into a *Cabin‘s* structure. However, the overall accuracy and production speed should be improved. Due to limitations during the experiment, errors accumulated - especially on the human part and during the transition from the human to the robotic realm. Similarly, an improved setup could compensate for the wood‘s natural character, including unwanted twisting or bending in changing environments.

Thus, the final proposal suggests a multi-robot setup to cut, drill, and place in one flow. This reduces the risk of deformations during workshop changes and minimizes human errors. Furthermore, the increased control would allow pre-drilling of the holes. While the structural design is resilient to variability in hole angles and was factored in as such in the prototyped human collaboration process, the added control would enable additional optimizations and aesthetic intend in dowel placements.

The prototyping also showed that drilling in the air frequently splinters the wood when the drill exits. Additionally, aligning the holes between the two beams is not straightforward, even when drilling in one go. These issues are further arguments for pre-drilling the holes in a controlled environment, possibly through a second robot or a CNC machine.

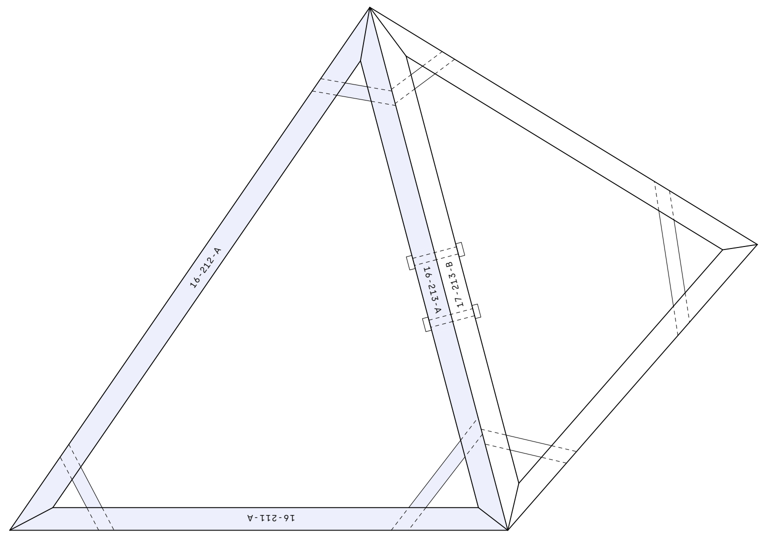
The beams used for the prototyping were standard C24 spruce beams from the hardware store. However, they were slightly warped, which complicated cutting them precisely and led to a mismatch between the digital model and the actual prototype. CNC-cutting and -drilling while ensuring the temperature and humidity are constant during the whole fabrication process could minimize these factors. However, in some cases, or to explicitly allow non-standard wood, 3D scanning of the pieces and machine vision for live adjustments could be included in the digital fabrication setup. Alternatively, processed wood like Cross Laminated Timber (CLT) or Glue Laminated Timber could minimize inaccuracies through warping.

Due to the dissimilar expansion in different directions of wood, and its general natural variability, the dowel drying process proved somewhat unpredictable. Additionally, the dried dowels were never perfectly round, which made drilling precise holes for them almost impossible. Even though the expansion was still substantial enough to make up for these inaccuracies, a reversed order of drying and shaping in the lathe could increase precision and produce perfectly round wood matching the desired diameter.

Finally, the prototyping revealed that the vacuum gripper was too weak, whereby the wood moved during drilling and inserting the dowels. Additionally, the test showed that the individual wood connections were not rigid until the whole triangle was completed. During the experiment, adjustments were possible between drilling each piece, but it showed that a stable tool and build surface are essential for robotic fabrication. With pre-drilling alleviating the need for upright assembly, which was introduced for more effortless drilling by the human collaborator, the modules could also be assembled flat on a higher build surface - further stabilizing the whole process.

All in all, setting up the automated workflow was much work and requires repetition in mass production or mass customization to be worth it. However, once the system is set up, a series of similar tasks can be significantly accelerated.

4.4 Final Structure

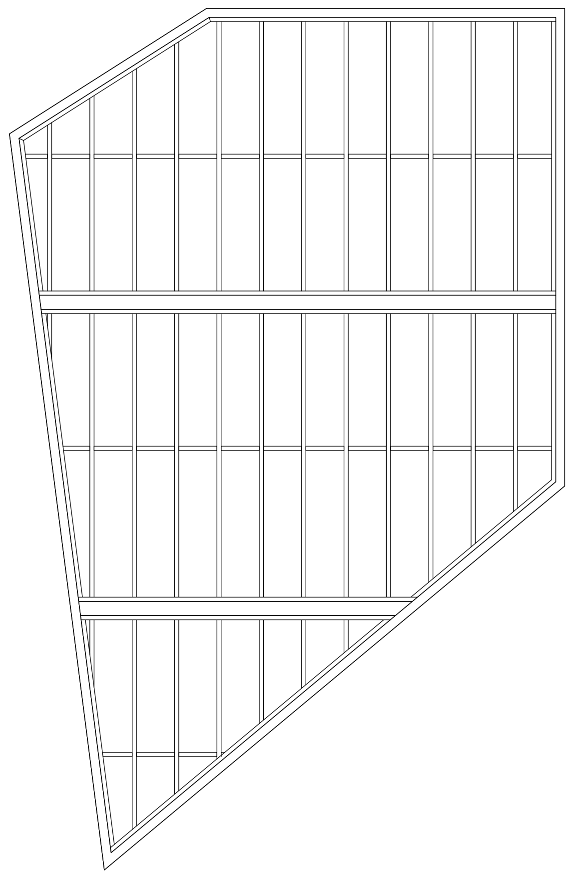


Before final assembly into a wall section, the fabricated pieces would be marked with their position and orientation. Next, the protruding dowels would be cut to allow a flush connection surface. Finally, the holes to connect the module to its neighbors are pre-drilled at the exact location.

The prepared pieces are now optimized for fast assembly on the roof with as few steps as possible. The workers simply have to identify the correct parts and join them by bolting them together. Augmented reality could further assist in this step to pick and place the correct modules even faster.

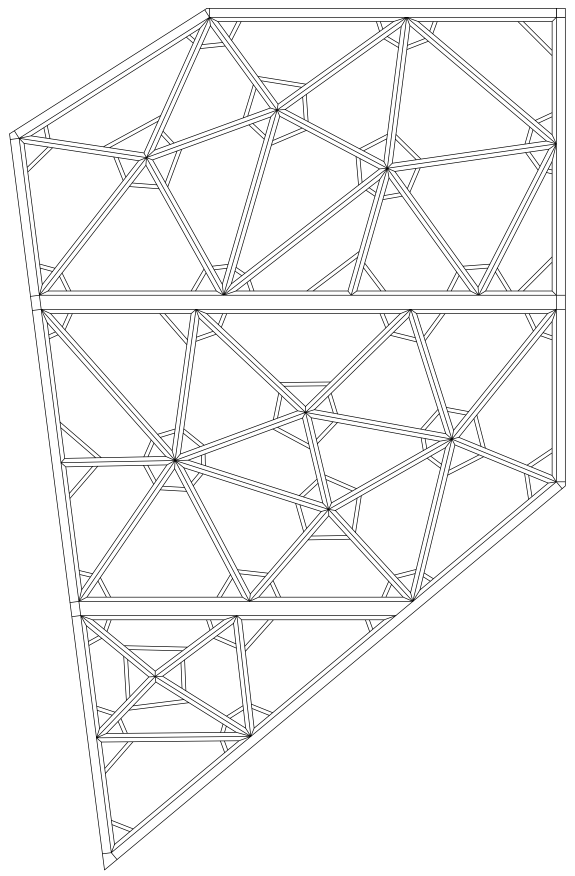
In an initial design, trying to follow the all-wood principle, the triangles were connected by wooden dowels and the same drying and expansion mechanism. However, the additional complication in assembly and a virtually impossible non-destructive disassembly led to the switch to conventional metal bolts and nuts.

Compared to a conventional timber frame, the triangular, robotically fabricated structure has several advantages: Due to the inherent stability of the triangles, no stiffening panels are needed, which saves material and provides additional aesthetic freedom. For example, to make it part of the interior furnishing. In addition, the proposed digital fabrication allows increased control and precise structural optimization, which again allows material efficiency. Lastly, the modular design eases transport and assembly on a pitched roof.



Conventional Timber Frame

Regular system in need of stabilizing panels.
Fails at angular walls / Needs adjustments.
Harder to assemble on a roof or in small modules.



Proposed Robotic Frame

Easily integrates non-standard cuts & profiles.
Inner rigidity removes the need for stabilizing panels.
Aesthetic integration is possible.
Precise structural optimization.
Modular design allows easy assembly.

Chapter 5.0*

*Future Work, Limitations & Other Reflections

The proposal described in this thesis is hypothetical and slightly utopian, with further research and design needed for its execution. While the necessary technologies exist today and construction planning could start tomorrow, several legal, organizational, and possibly societal hurdles would have to be taken. A few essential aspects of this path to realization, some limitations of the project at hand, as well as selected reflections are addressed in this section.

5.1 Limitations

Berlin's Building Heights

A principal element of Berlin's building code is a standard maximum building height of 21m measured at the structure's eave. For all selected pilot buildings, this would nip the implementation of *New Ground* in the bud. However, as previously mentioned, building codes can be changed, or concessions to it made in exchange for guaranteed affordable apartments - desperate times require desperate measures.

Weight Issues

Additional construction on roofs means an additional weight that has to be carried by the host building. While the whole design is set up to be as lightweight as possible, there is no way to prove it works for the pilot *Villages* and selected *Hosts* within the scope of this thesis.

Looking for at least a ballpark number, a leaflet on preliminary structural design and dimensioning published by Vienna's municipal building inspection department gave a hint to an answer. They set a threshold value of 720kg/m² for approving new superstructures on existing buildings without extra statical proof. This value is based on their experiences and only applies to *Gründerzeithäuser*, the typical tenement building built around 1900, which used to be the prevalent typology in Berlin as well and still makes up large parts of the housing stock.

In the absence of the possibility to measure and calculate the potential additional load of the host buildings, the proposal used this threshold to optimize the proposed structure, assuming that this could allow its application on most buildings, especially considering that pitched roofs and older buildings with additional leeway in their structure often correlate. Under these conditions, the proposed *Cabin* performs remarkably well, with an estimated empty mass of 350kg/m².

In a real-world application, of course, additional calculations or adjusted thresholds have to be considered. Consequently, some potential sites might have to be ruled out, or adjustments to the structure or amount of *Cabins* would have to be made. As a last option, structural reinforcements of the host building could be examined in particular cases.

Data-Driven Design

Albeit discreetly, the proposal and its design system see themselves following a data-driven design credo.
However, due to the scope of the project, as well as some genuine limitations, finding and utilizing enough meaningful data was impossible. Having complete information about the host buildings could have helped immensely to fine-tune the attachment structure, and knowing who and what functions might occupy the *Cabins* could have allowed a more bespoke interior. Additionally, data about available materials, distribution of the population influx, or climatic development, among others, could correspondingly inform the design system.

Data-driven design is the basis for true scalability in customizable designs. However, especially the first implementations will have to make additional manual adjustments to fine-tune the design system and collect, handle and apply more data as parameters. Concurrently, independent systems for the methodical collection, processing, and provision of the data, like a database for the structural qualities of the existing housing stock, should be developed. This would inevitably lead to higher costs and longer construction times in the adoption phase but amortize quickly when scaled up.

In the meantime, randomized inputs are used by the project to simulate customized parameters or to add additional variability to where data is never expected to be complete, but the design decision is not deterministic either.

5.2 Reflections

A Path to Realization

If this proposal becomes a reality, it would probably start somewhere else than the previously introduced pilot area. While the presented area is evidently in need of additional housing, it was foremostly picked for its familiarity to the author as a residential area exemplary for central Berlin to test the design on and to calculate its potential of pitched roofs. For the actual implementation, though, the most decisive factor would be the willingness of the host building's owner, the local administration, and the condition of the roof and structure.

Wherever this would first align, a real pilot could be developed with a progressive investor. This could be a municipal housing company with direct ties to the administration or a private investor or collective willing to test this concept out. In the latter case, exemptions from the building code, especially regarding height, could be granted in return for a guarantee to offer the units exclusively for rent under special rent control to maintain affordability. This would still be a better deal for many investors than just leaving the roofs untouched.

This first implementation would act as a testbed for polishing and evaluating the design regarding construction and user adoption. With positive feedback, it would become a catalyst that eventually spreads over Berlin and beyond. In this case, the initial design system could become a toolkit for the occupancy of pitched roofs. It should be augmented in competitions, inviting other architects to add their individual take to the concept - finally leading to a vibrant and diverse addition to the city's urban fabric.

A Proposal for Everyone?

While the project is intended as an inclusive development for everyone who might want to live in Berlin, the currently developed example *Cabins* are indeed geared more towards younger people, students, and small families. However, a part of this can be rectified through the idea of different typologies and adapted layouts. Special adjustments could also make the internal staircase and the circulation barrier-free and accessible for the disabled or the elderly population.

However, even then, not everyone will want to live in a rooftop *Cabin*. As no one solution can ever be the perfect fit for everyone, this as well is not meant as the one solution to completely solve Berlin's housing crisis in a top-down manner. Instead, it is supposed to be an addition, one puzzle piece in a series of interventions and developments that work side by side.

Alternative Materials

The proposal is very much set on wood as the primary material for the structure and tries to maximize it in all other parts of the construction as well - namely for the insulation, the cladding, and furniture.

Wood and timber are relatively lightweight materials, perfect for the application on existing rooftops. Furthermore, they are easy and safe to work with, both in the robotic pre-fabrication and on the construction site itself. Finally, being a natural material, each piece offers a unique final touch and always provides a warm and comfortable indoor atmosphere, not least because of its hygroscopic character.

Concrete would plainly be too heavy and require extensive alterations on the host building. More importantly, though, unsustainability due to the high CO_2 footprint as well as the complicated disassembly and hard recyclability ruled it out from the start. Steel, on the other hand, can be formed into highly efficient beams reaching a similarly low weight as wood. However, also steel is more difficult to adjust later and more expensive. Even with further rising wood prices, the externalized costs of steel through CO_2 emissions of its forging and extractive mining are likely always to be higher than those of local timber.

Conclusion

New Ground sets out with an ambitious goal: To find a new path for tackling Berlin's affordable housing crisis. Not to solve it all at the stroke of a pen, but to offer new ideas and tools to contribute to this seemingly sisyphean endeavor.

Utilizing computational design and fabrication and selecting a novel intervention area, the pitched roof, the resulting proposal suggests a combination of predictable and customizable robotic off-site fabrication, a framework for unobtrusive roof scaffolding, and an adaptive timber structural system to form a series of *Cabins*, *Villages* and eventually a whole *City* to populate Berlin's roofscape. The parametric approach allows the creation of a design system that adapts to each individual roof, enabling the scalability of the proposal. As a result, Berlin could be densified with cautious, distributed, vertical growth, honoring its current polycentric character. At the same time, the system strives for affordability by employing a lightweight, material- and cost-efficient construction supported by non-profit management.

Being at least a couple of further prototypes and trial implementations away from becoming a complete reality, the proposal could, for a good reason, be deemed utopian - not least because the political will in Germany has some catching up to do. However, I firmly believe utopian ideas are necessary to drive change: Think two steps ahead to perhaps actually move one forward. Or, as Joseph Grima puts it: „A fear of naivety [...] cannot continue to preclude the ambitious reinvention of architecture that will be required in order to construct a future of any kind.“[1]

„A fear of naivety [...] cannot continue to preclude the ambitious reinvention of architecture that will be required in order to construct a future of any kind.“

- Joseph Grima in
Design without Depletion:
On the Need for a New Paradigm in Architecture[1]

[1] in Space Caviar's 2021
Non-Extractive Architecture: On Designing without Depletion Vol.1
p.13

References

Literature & Data

ABB, 2021. *ABB Product Specification IRB 2400*.

Amt für Statistik Berlin-Brandenburg. Available at: https://www.statistik-berlin-brandenburg.de (Accessed: 06 May 2022)

Architecting after Politics. 2018. Film by Brandlhuber+ Olaf Grawert and Christopher Roth. Available at: https://vimeo.com/ondemand/legislatingarchitecture/304116817

Baléo M. for La Fabrique de la Cité, 2019. *Berlin: the challenge of affordable housing in a city of low-income tenants*. Available at: https://www.lafabriquedelacite.com/en/publications/berlin-the-challenge-of-affordable-housing- in-a-city-of-low-income-tenants (Accessed: 16 February 2022)

IBB (Investitionsbank Berlin), 2021. Berlin. *IBB Wohnungsmarktbericht 2020*.

IBB (Investitionsbank Berlin), 2022. Berlin. *IBB Wohnungsmarktbericht 2021*.

Guthmann Estate GmbH, 2022. *Berlin Real Estate Report 2022*. Available at: https://guthmann.estate/en/market-report/berlin (Accessed: 06 May 2022)

Lefebvre, H., 1996. *Right to the City*, English translation of 1968 text in Kofman, E. & Lebas, E.[eds and translators]. *Writings on Cities*.

Stadt Berlin, *Bevölkerungsprognose für Berlin und die Bezirke 2018 - 2030*. Available at: https://www.stadtentwicklung.berlin.de/planen/bevoelkerungsprognose/index.shtml (Accessed: 06 May 2022)

Schwenk H., 2004. *Topographie der deutschen Hauptstadt*. Edition Luisenstadt (Internet-Fassung). Available at: https://berlingeschichte.de/stadtentwicklung/texte/4_13_bvoelent.htm (Accessed: 10 May 2022)

Space Caviar (Editor), 2021. *Non-Extractive Architecture: On Designing without Depletion Vol.1*. Moscow, Berlin. V-A-C Press, Sternberg Press

Reference Projects

Dachkiez. 2017. Sigurd Larsen. Available at: http://sigurdlarsen.com/project/dachkiez_de/ (Accessed: 29 May 2022)

Up Sticks. 2019. Gramazio Kohler Research and MAS DFAB ETH Zürich. Available at: https://gramaziokohler.arch.ethz.ch/web/e/lehre/375.html (Accessed: 29 May 2022)

Roofs of Berlin. 2021. Maier M. and Wang R., First Price of Bee Breeders‘ Berlin Affordable Housing Challenge. Available at: https://architecturecompetitions.com/berlinhousingchallenge/ (Accessed: 29 May 2022)

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