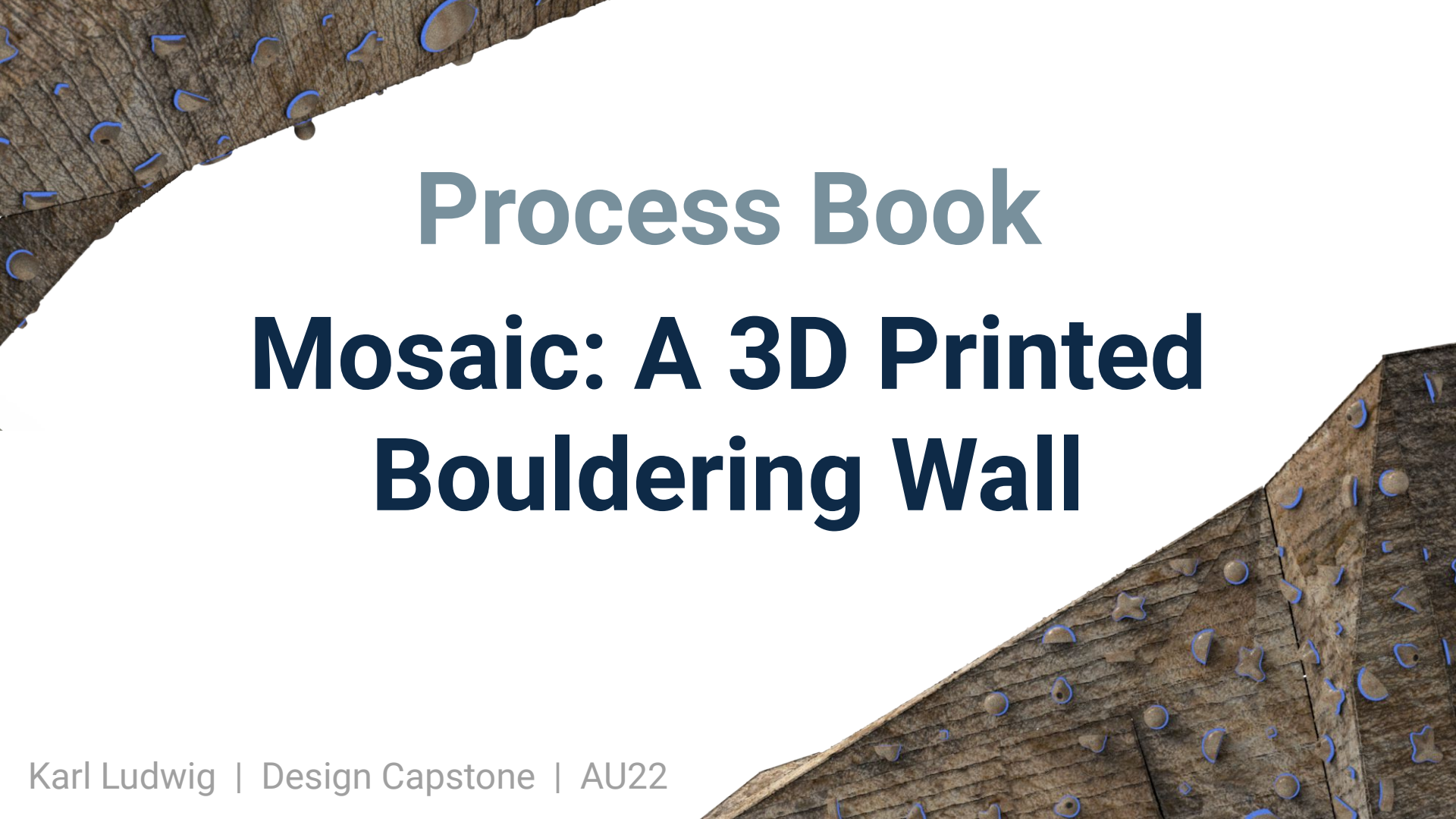

Process Book

Mosaic: A 3D Printed Bouldering Wall

Karl Ludwig | Design Capstone | AU22

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Project Abstract

Mosaic is an outdoor bouldering hub made from 3D-printed concrete. It facilitates diverse, readily accessible outdoor climbing and explores innovative use of 3D concrete construction printing.

Large-scale concrete printing is an emerging technology in which concrete is extruded in layers to create three-dimensional structures. OSU's Center for Design and Manufacturing Excellence is acquiring a cutting-edge concrete printer, and this project contributes to the exploration of its potential in creative manufacturing contexts, demonstrating how concrete printing can both be leveraged and complemented by other technologies to create ideal solutions for climbing.

The Mosaic bouldering wall utilizes molded components to create nuanced climbing features, radiant heat to maximize usability during colder weather, and integrated LED lights that allow climbers to build their own routes and use the permanent concrete features in an endless combination of ways. An accompanying app enables this customization with augmented reality while connecting climbers and their shared database of climbing routes.

Mosaic establishes a symbiotic relationship between rock climbing and concrete printing, resulting in a high-quality, resource-efficient outdoor climbing venue and thought-provoking insights about the capacity for integrated technology to activate printed concrete.

Introduction

Introduction

Rock Climbing is an incredibly popular sport and hobby. What is striking about climbing is how diverse the community is. It attracts a remarkably broad range of people. What each of these people share, though, is that in order to climb, they need a *place* to do so. If you live in, say, Colorado or West Virginia, you're in luck. However, for flatter areas with less dramatic geology like Columbus, Ohio, the question of where to climb poses a bit more of a challenge. When faced with a long drive to the nearest real rock to climb outside, many people resort to the convenience of indoor climbing gyms and the world of manicured plastic routes. That said, a new technology exists that could upend this paradigm by providing new ways for people to climb outside.

This Fall, Ohio State's Center for Design and Manufacturing Excellence (CDME) is acquiring a COBOD BOD2 large-scale concrete 3D printer. This machine represents the cutting edge on the frontier of efficient, more sustainable construction of concrete structures. However, as so often happens in the world of science, the technology has been developed without a clear vision for the range of possibilities that exist for its use. Engineers and architects are captivated by BOD2's ability to erect houses in a matter of days with little to no human labor, but the reality is this: we have barely scratched the surface of this technology's potential. It would be a complete shame if such a powerful tool were to be pigeonholed into operating in a single industry or context. This is precisely why, for my design capstone, CDME has asked me to expand this frontier of exploration to see how the world can make use of BOD2's talents in concrete additive manufacturing.

With a market for outdoor climbing infrastructure and a machine capable of efficiently producing massive rock-like structures, to me, rock climbing and BOD2 are a match made in heaven.

Research

Research

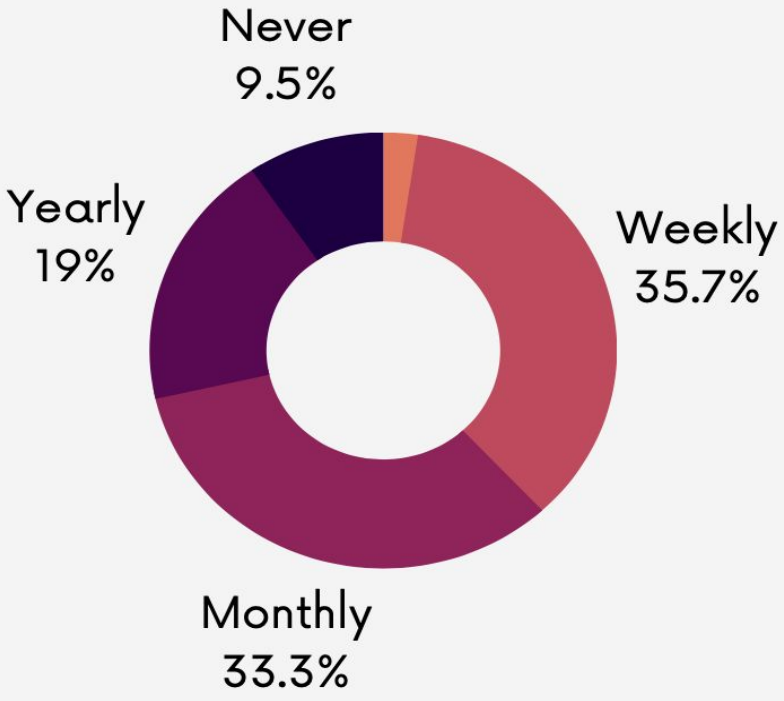
The concept of a man made outdoor climbing wall is far from a new concept. In fact, over a decade ago, the City of Columbus implemented a large outdoor climbing wall into their design of Scioto Audubon Metropark in the downtown area. It stands today as the biggest no-cost outdoor climbing wall in the United States. As one can imagine, this made it an ideal place to conduct my own primary research, not only about the wall itself, but about the people who use it and their experiences. What I learned from them was incredibly insightful.

The first thing I wanted to understand was where people climbed, and why. What draws people to that spot over the other options available to them? In the responses I got to this question, there was an overwhelming consensus. For starters, every person I interviewed cited convenience and proximity as the primary factor for their choice of Scioto Audubon. One young man named Jake said he had just come from the dog park and had some extra time, so he swung by for a session. Similarly, a woman named Michelle who was there with her two sons told me that they come there to get better at climbing with the hope of planning a bigger trip to climb at a real rock venue in the future. A climbing trip is an event that is planned for, but on an everyday basis, people look for a quick option that does not demand any thought in advance.

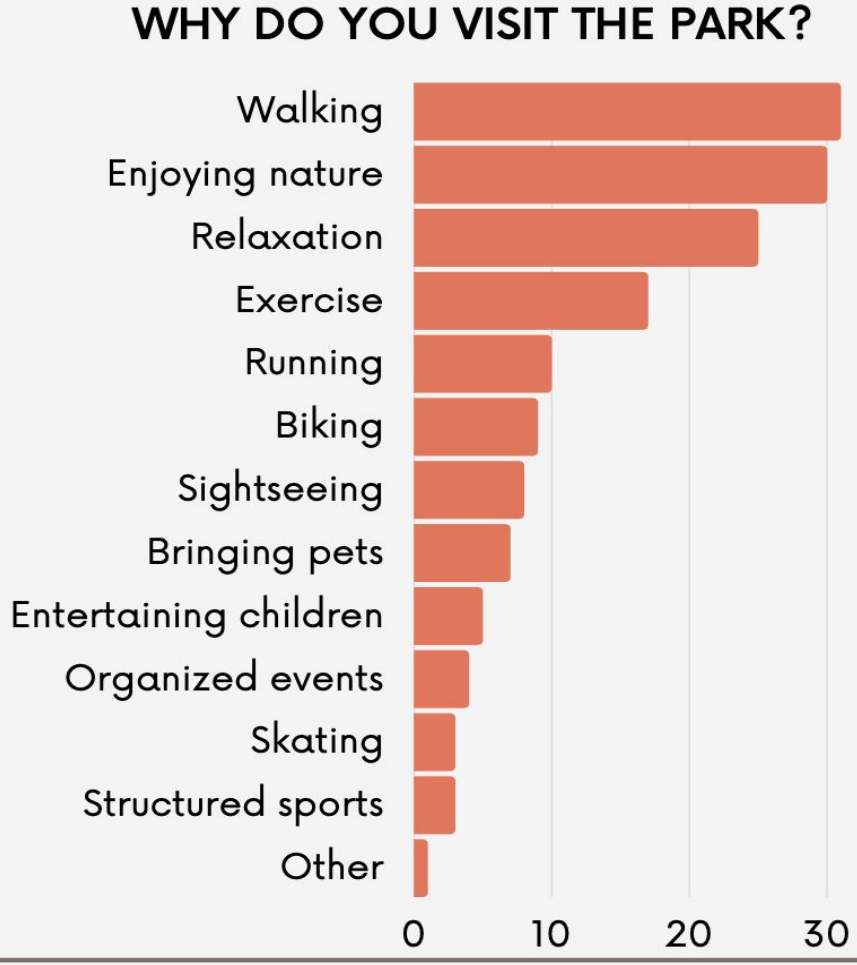
Research

If convenience is priority #1, though, I wanted to know why these climbers didn't just go to one of the handful of nearby indoor gyms. Aside from the obvious point that you have to pay for a gym membership, interviewees were quick to point towards a desire to be outside. Jake, the one who had brought his dog said this: "I'll get a gym membership when it gets colder here in a few months, but I like coming here when it's nicer because it gets me outside." Likewise, Michelle and her son said they climb at Vertical Adventures (a local climbing gym) sometimes as well, but they tend to enjoy the outdoor setting. Carson, a local high school student there with his friends, told me that being outside plays a huge role in his desire to get out and climb. Having gotten into climbing this year, he hadn't yet felt the urge to try an indoor gym.

As part of my primary research, I also conducted a more general online survey about the use and perceptions of public parks. In my results, I found that more than 71 percent of respondents listed "enjoying nature" as a reason for why they go to the park, which was more than almost any other reason people gave. These findings certainly seem to corroborate the testimonials from the climbers I interviewed.



HOW OFTEN DO YOU VISIT A PUBLIC PARK?



Research

Having established that climbers are drawn to Scioto Audubon for its easy access and outdoor setting, I next wanted to get a sense for the quality of their experience climbing on the artificial wall as opposed to real rock. It was clear that their decision was a pragmatic one: quantity over quality. So, what aspects of quality are sacrificed? This question, more than anything, is the crux of actionable design problems for my project. As expected, the park's public climbing is far from a perfect solution in the eyes of its users. With the more negative feedback, deterioration and durability were central concerns. The wall was built in 2010, so it has about 12 years of wear and tear, but for a project that large, you would want it to have a pretty long lifespan. Unfortunately, as Zach, age 20, pointed out, the outer composite material has worn down or broken off in countless places on the wall, leaving patches of exposed fiberglass, which would be very uncomfortable or even dangerous to contact. Carson said he actively worries about loose pieces breaking off while he's climbing, which impacts his mindset. When climbing real rock with too many loose or crumbling pieces, this issue is often enough to make climbers abandon a route and move elsewhere.

Research

I want to take a second to pause and recap what we've established so far. Climbers look for the closest places available to them to climb on a day-to-day basis and seek out outdoor options if they're available. While Columbus is lucky enough to have an artificial wall that meets these criteria, it falls very short of ideal on metrics like quality and durability. Furthermore, the very reality that Scioto Audubon is the largest installation of its kind in the country begs the question of how we can make it easier to produce climbing infrastructure like it.

This is an interesting project to explore the capabilities of COBOD's printer for two distinct reasons. On one hand, it leverages BOD2's strengths of efficiently constructing large-scale, durable structures with compelling rock-like textures and imperfections. On the other hand, a good climbing wall demands a level of geometric complexity, nuanced details, and pleasing aesthetic that are not current strengths of construction printing. By addressing the weaknesses of a technology, it opens up new possibilities for its application.

Research

It is no revelation that concrete 3D printing can construct faster and more efficiently than traditional methods at an impressive scale. That's what it was made to do. Organizations like Habitat for Humanity are starting to successfully test how the machines can drastically improve the rate at which they can construct quality, affordable housing for the people they serve (Taylor, 2022).

The durability aspect is also a promising dimension of concrete additive manufacturing. Concrete is already known for its solidity, but companies like Icon are taking it a step further by 3D printing "disaster proof" homes with a new concrete variant called Lavacrete. The resulting homes are supposedly built to withstand fire, flood, wind, etc. (Englefield, 2021).

One reality of 3D printing and concrete is that there is inherent imperfection in the resulting surface. Extruded concrete is rough, and 3D printing always shows the striations of each layer to some degree. While this could be a drawback in many applications, I was inspired by some cases where this quality was being leveraged instead. For example, in Sydney Harbour, researchers a installing "living sea wall" of concrete panels made in 3D-printed molds to "support easier attachment for barnacles and mussels" (Gillespie, 2022).

Research

My review of literature on concrete printing and adjacent topics also uncovered several main limitations of the technology. With a few exceptions, most projects I've seen BOD2 tackle deal with very vertical, simple-surface geometry, such as the walls of a house. This presents a serious problem when you're trying to mimic rock features. However, according to architect Jack Balderrama Morley in Op-Ed piece, we should not treat 3D construction printing as a stand-alone solution. He writes, "conventional buildings are not made by extrusion or casting or any other single manufacturing process; they are accretions of dozens of different techniques from cast-and-pour concrete to spot-welded steel extrusions to laminated glass. How could one process replace the dozens of others that we currently use?" (Morley, 2022). A part of expanding a technology's possibilities is exploring what materials and processes can complement it, and a climbing wall is a great venue to do so.

In the online survey I conducted, I also asked participants to share their perceptions of 3D construction printing. In my results, one perception stuck out: 3D printed concrete is not aesthetically pleasing. This is a huge design insight. To be widely accepted and reach its potential, printed concrete is going to have to move beyond its bland, industrial personality. This is especially relevant for use in public parks. In my survey, I asked participants to choose their favorite aesthetic from 3 different photo collages of parks. Only 52.4 percent of people opted for the collage featuring the most nature and greenery. How can we act on this information to effectively introduce a more natural aesthetic to printed concrete.

Research

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Research

Rock climbing and 3D construction printing have the potential to be a symbiotic relationship. With flat areas across the country in need of venues to climb, the BOD2 printer has the potential to provide just that. At the same time, COBOD and the additive manufacturing industry can benefit from tasks that push the boundaries of their capability in the interest of overcoming weaknesses and expanding functionality.

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Morley, J. B. (2022, June 1). *Architects: Here's the problem with 3D-printed buildings – architizer journal*. Journal. Retrieved September 29, 2022, from https://architizer.com/blog/practice/details/3d-printed-buildings-future-or-gimmick/

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Design
Development

Design Brief

Problem Statement

How can COBOD's large-scale concrete construction printing technology be leveraged and complemented to provide readily accessible resource-efficient, high-quality outdoor rock climbing experiences in areas that lack natural geologic features?

Specific Goals

Target Tactile Experience of Natural Rock

Artificial plastic climbing holds look and feel entirely different.

Minimize Material Input

Concrete is irreplaceable in engineering, but it’s better for the earth if we can use less.

Resolve Low Print Resolution

BOD2 prints layers 1”h x 4”w, and can’t print unsupported features. How can we bring the details?

Adapt to Seasonal Conditions

Climbers tend to be forced inside by cold/winter conditions. Can technology enable year-round use?

Afford Customization and Variability

Climbers want new options to keep things interesting and challenging.

Strategies

1. Test methods for creating climbing features in wet or cured concrete. These could include both additive and subtractive processes.

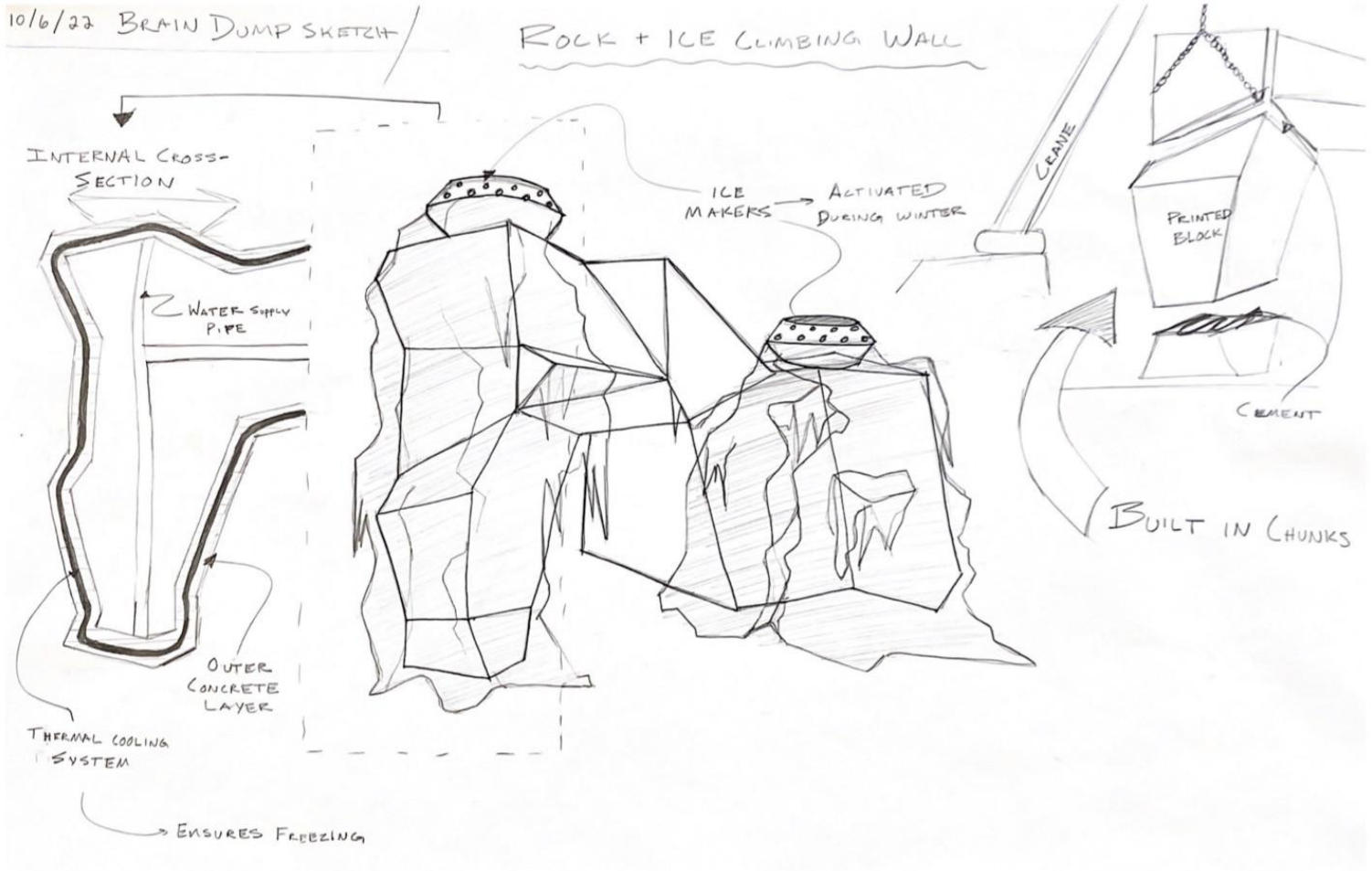
2. Explore ways in which integrated technology can either mitigate the effects of cold and winter weather or facilitate alternate functionality when traditional climbing is not possible, including–but not limited to–heating and cooling systems.

3. Design physical and system-based solutions through climbing routes can be altered.

4. Employ module components to increase diversity of use without requiring excessive material input.

5. Explore visual aesthetics that are attractive and functional without attempting to copy the look of natural rock.

Concept Ideation


10/6/22 BRAIN DUMP SKETCH
ROCK + ICE CLIMBING WALL
INTERNAL CROSS-SECTION
WATER SUPPLY PIPE
OUTER CONCRETE LAYER
THERMAL COOLING SYSTEM
ENSURES FREEZING
ICE MAKERS
ACTIVATED DURING WINTER
CRANE
PRINTED BLOCK
CEMENT
BUILT IN CHUNKS

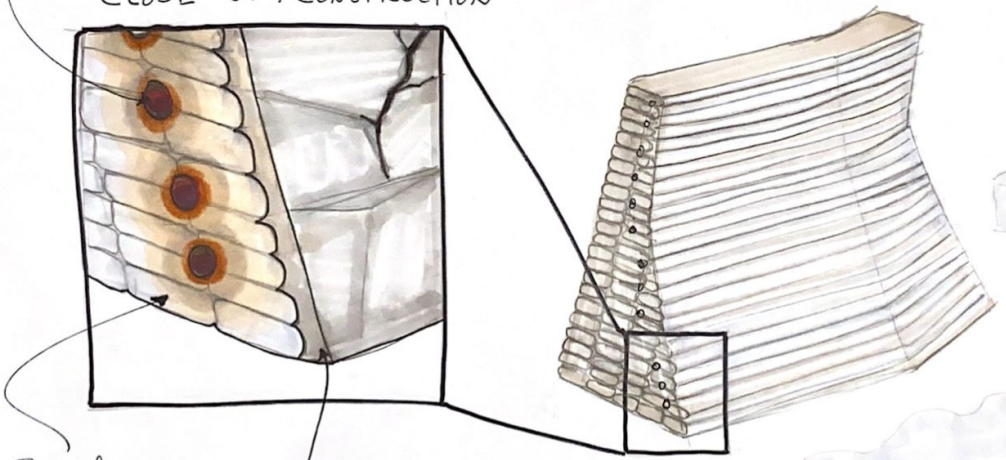
RADIANT HEATING

- MELTS ICE + SNOW
- KEEPS HANDS WARM ENOUGH

WATER PIPES FOR RADIANT HEATING

CLIMBING WALL SEGMENT

CLOSE-UP: CONSTRUCTION

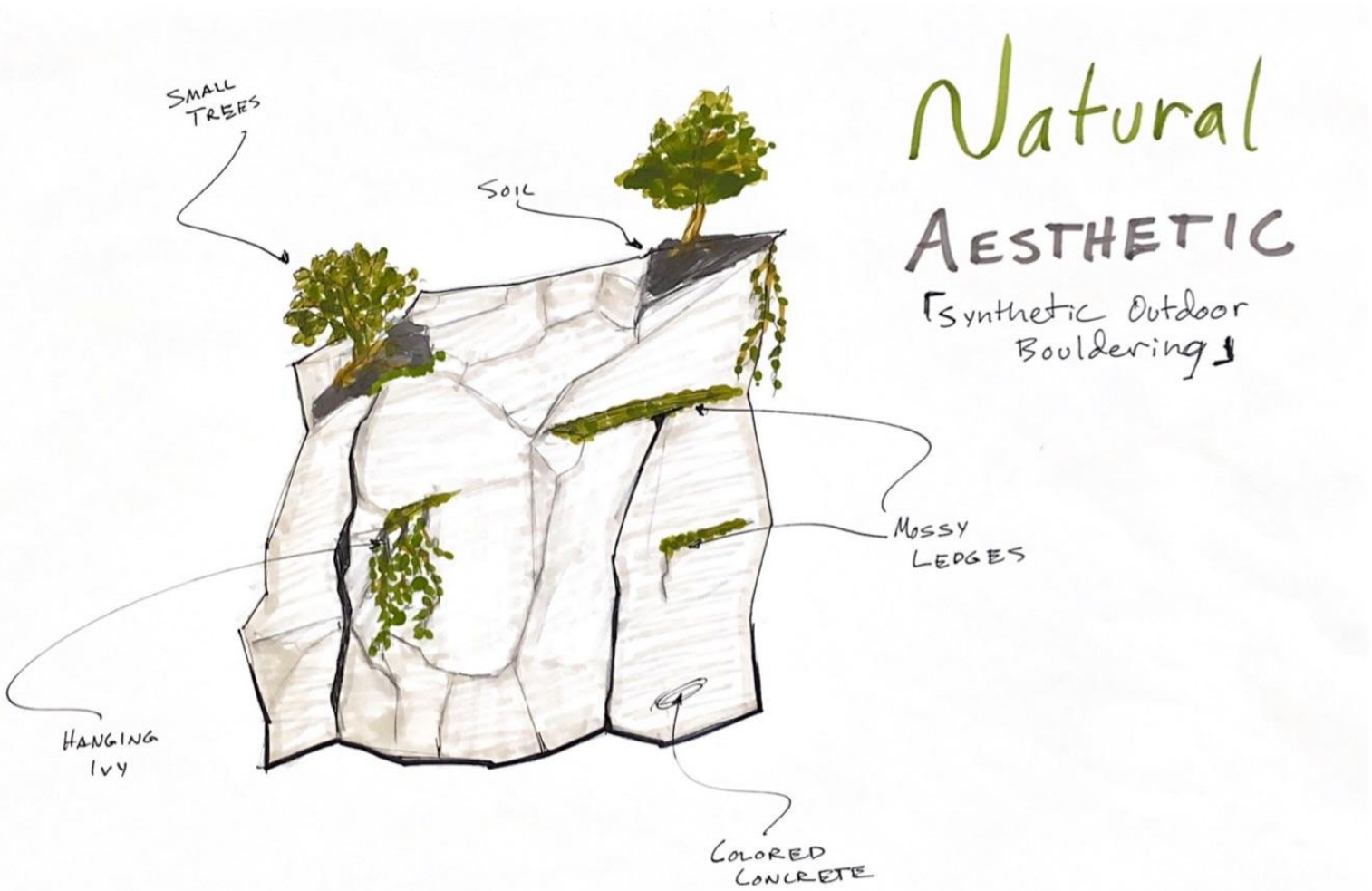


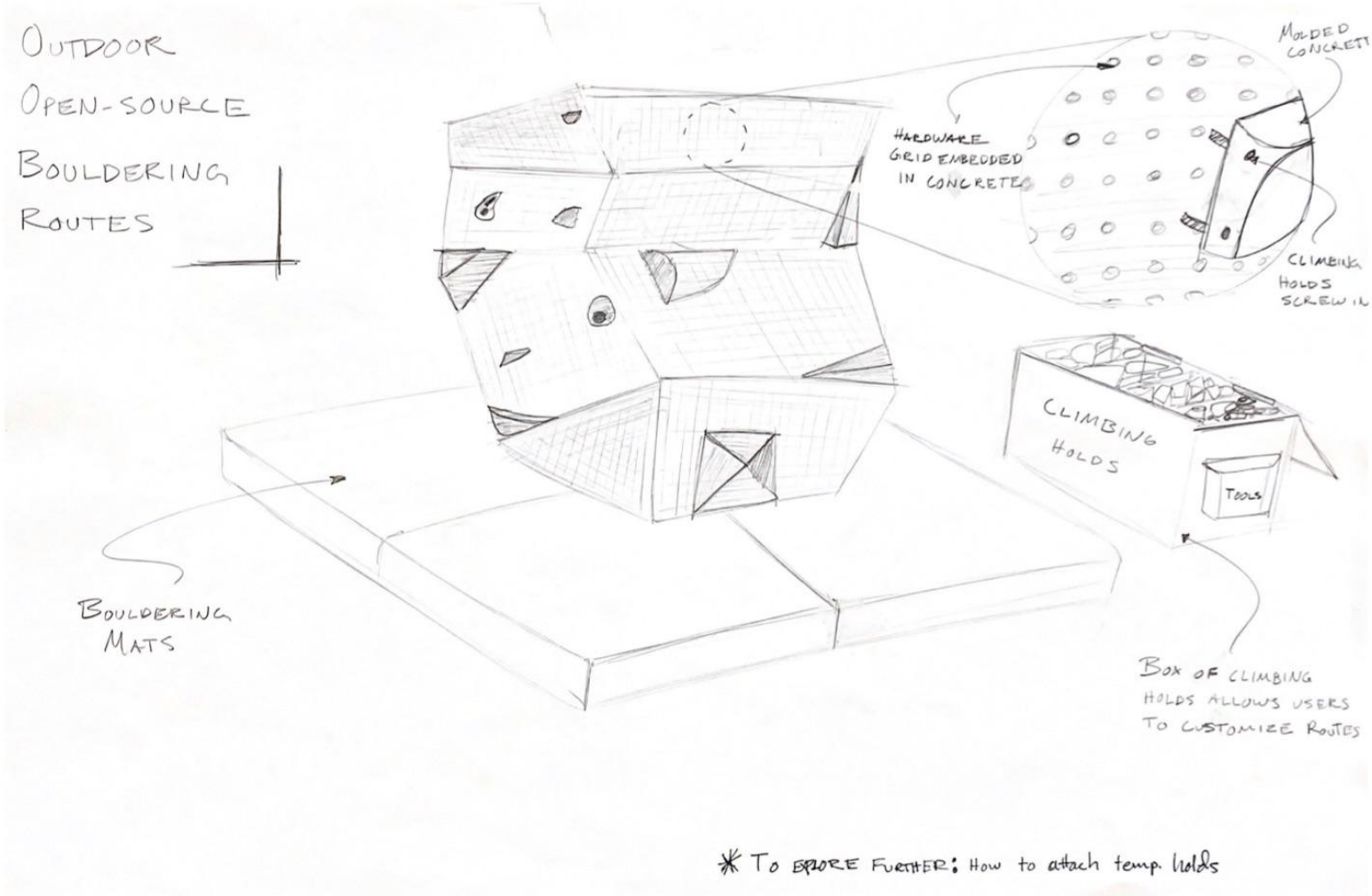
STAYS OPEN DURING WINTER

SNOW

Printed CONCRETE LAYERS – 1"x4"

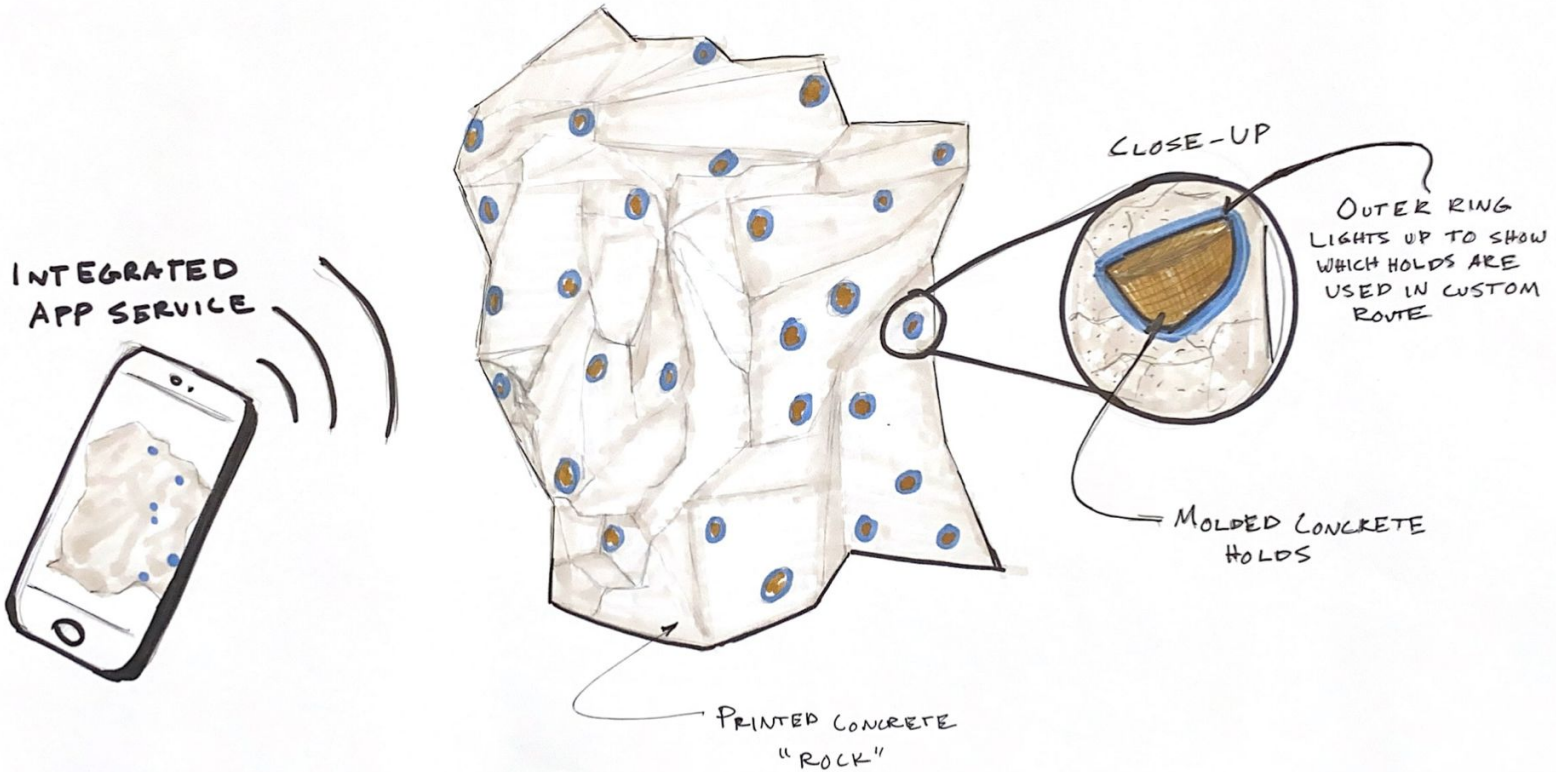
OUTER MATERIAL
- DEFINES APPEARANCE/GEOMETRY
- CONCRETE? Other?


SMALL TREES
SOIL
Natural
AESTHETIC
「Synthetic Outdoor Bouldering」
MOSSY LEDGES
HANGING IVY
COLORED CONCRETE


OUTDOOR
OPEN-SOURCE
BOULDERING
ROUTES
MOLDED CONCRETE
HARDWARE GRID EMBEDDED IN CONCRETE
CLIMBING HOLDS SCREW IN
CLIMBING HOLDS
TOOLS
BOULDERING MATS
BOX OF CLIMBING HOLDS ALLOWS USERS TO CUSTOMIZE ROUTES
* TO EXPLORE FURTHER: How to attach temp. holds

BOULDERING STRUCTURE

WITH LIGHT-UP HOLDS FOR CUSTOMIZATION



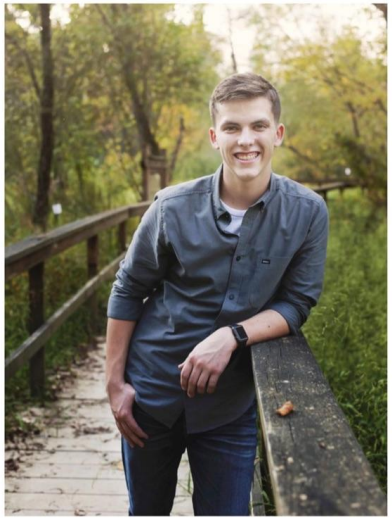
Persona

During my concept ideation, I created a persona to serve as inspiration. The purpose was to summarize key research insights in succinct and anctionable way.

PETER EKIN

PROFILE

Gender : Male
Age : 17
Education : High School
Occupation : Student
Location : Upper Arlington, OH



BIOGRAPHY

Peter is a student at Upper Arlington High School. He and his friends recently tried rock climbing on an outdoor field trip and want to get into it more. They've gone to a local climbing gym a few times, and their experience was decent, but they don't go often. After being in a classroom all day, Peter would rather be outside. Unfortunately, at his age it's hard to find the time, transportation, and coordinate with friends to plan a proper outdoor climbing trip.

PAIN POINTS

- Lacks transportation to outdoor crags to climb
- Would rather be outside, but most convenient climbing is at an indoor gym
- Forced inside completely to gym climbing in the winter
- Nearby Scioto Audubon Park nearest crags offer only a limited number of climbing routes

GOALS

- Wants somewhere convenient he can climb at more spontaneously
- Wants to prepare for bigger outdoor coming trips with walls that feel like the real thing
- Wishes the diversity and variability of gym climbing were available outside so there is always something new to climb
- Wishes the ice, snow, and cold didn't inhibit rock climbing during the winter months

Formative Assessment

Question #1

Would a radiantly heated climbing wall make people more inclined to climb outside in less desirable weather conditions?

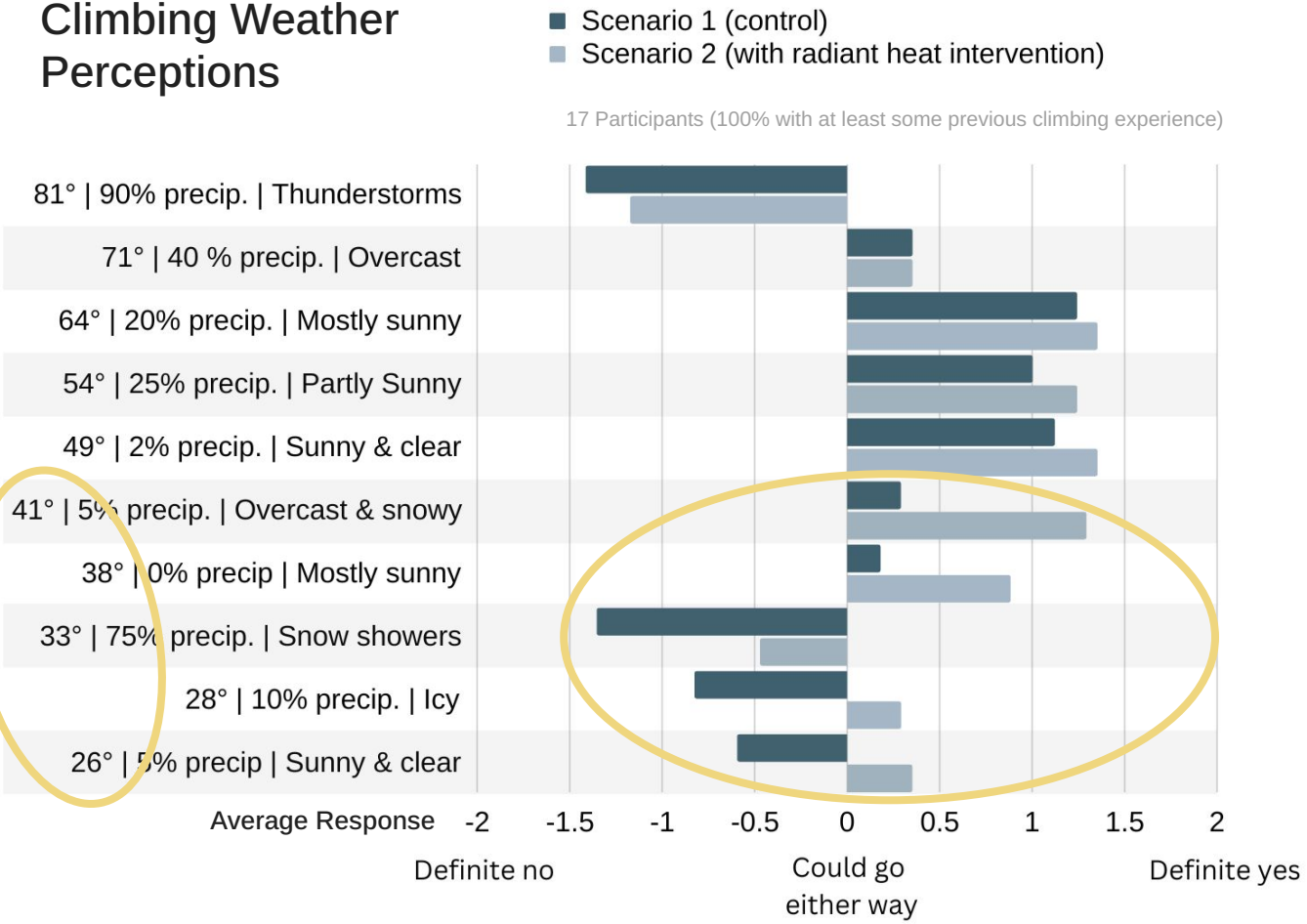
Q1. Methodology

- Survey format
- 2 hypothetical scenarios
  - Want to go bouldering at outdoor, artificial climbing wall
  - Same as above, but the artificial wall is heated internally
- For each scenario, I presented a series of daily weather forecasts that they might find on a weather app that shows temperatures, precipitation, and sun quality
- For each forecast, I asked people to rate the likelihood that they would go climbing on a 5-point scale from “definitely yes” to “definitely no.”
- After they answer, I will also ask why they chose their response.
- I will compare the responses with and without a heated wall.

Q1. Results

"Cold reduces dexterity, so the warmed wall would be perfect for climbing when conditions would otherwise be sub optimal"

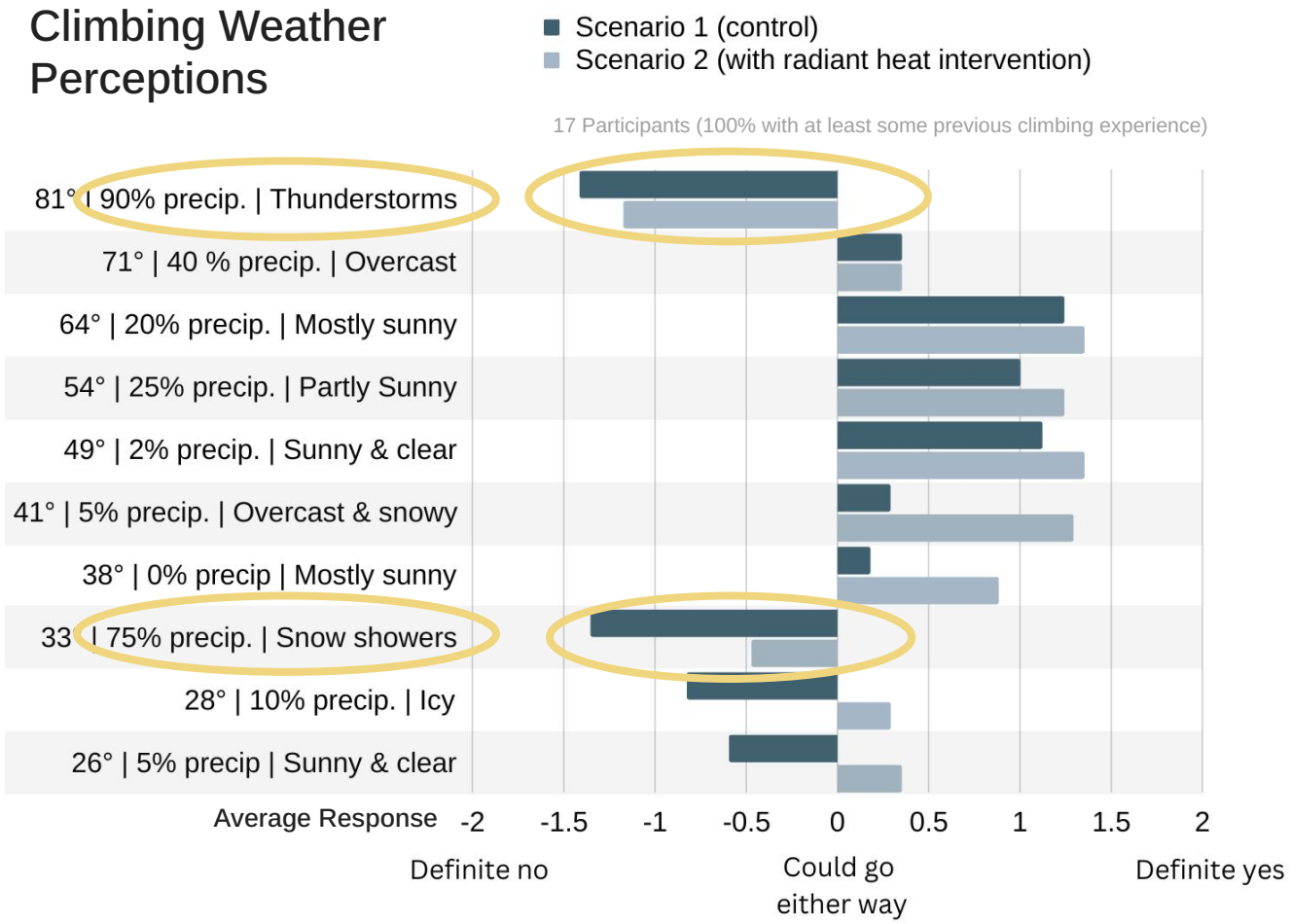
Climbing Weather Perceptions



Q1. Results

"Cold reduces dexterity, so the warmed wall would be perfect for climbing when conditions would otherwise be sub optimal"

"Even if there's a radiant heat design, the wall would still be wet, and I'd get rained on."



Q1. Results

“The heating would be nice but colder temps help with better friction on the skin so I wouldn’t want the wall to be too warm.”

“I think that it could be heat pollution.”

On keeping things dry: “A roof could help this?”

“I was more concerned with my time when off the wall rather than on it.”

Q1. Takeaways

Effective for Lower Temps.
The intervention noticeably increased the likelihood of use in colder temperatures.

Moisture
The presence of moisture is a make-or-break, and warming tech doesn't solve this directly.

Moderation
Not to warm for comfort, use only when necessary to prevent energy waste.

Auxiliary Infrastructure
Secondary interventions like physical shelter from precipitation could be beneficial.

Down Time
Can something be added to support comfort in between climbs?

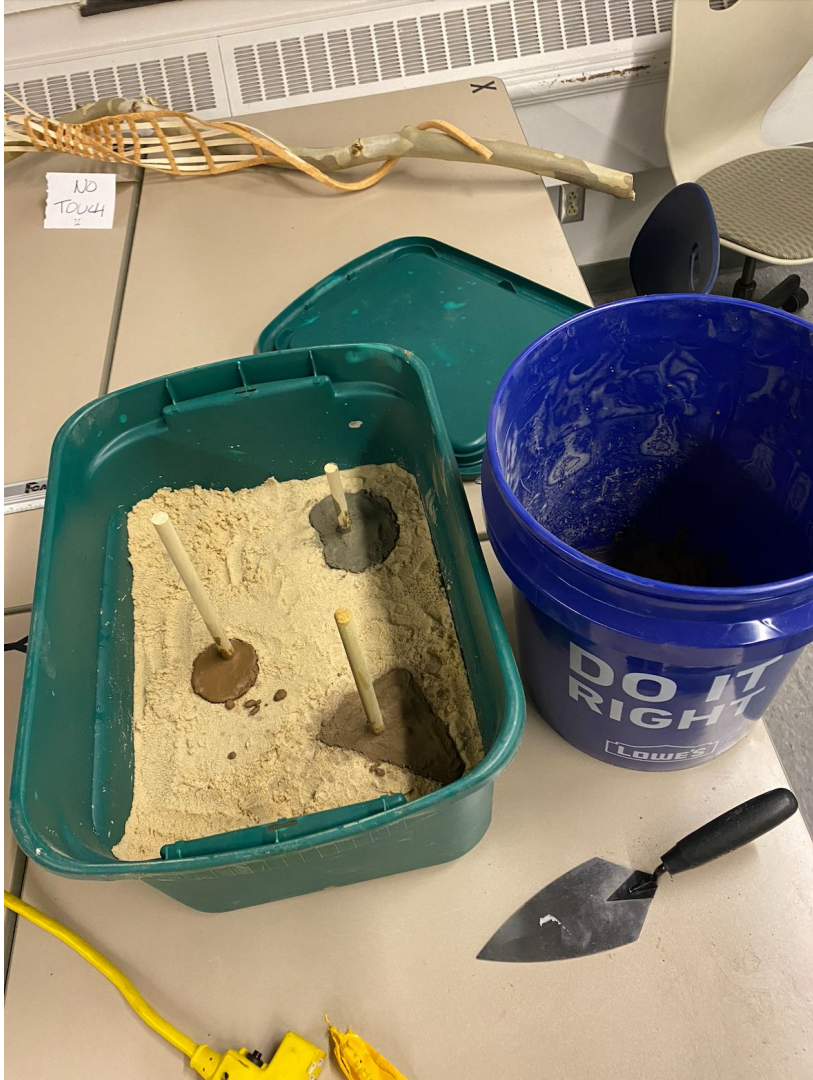
Question #2

Are concrete climbing holds strong enough to be viable for use in climbing walls?

Q2. Methodology

- Created taxonomy of different climbing hold types
- Created my own climbing holds by sand casting store-bought concrete.
    - Variety of shapes and sizes
- Anchored them to a fixed surface.
- Test the strength of the holds under increasing load conditions by standing on them.*
- To create higher forces if they withstood body weight, I created higher dynamic forces by jumping/bouncing.

* While this was not a highly technical methodology due to limitations in prototype production and strength-testing technology, it still gave me a lot of useful information



Q2. Results

Q2. Takeaways

Bolt Hole is a Weak Point

The smaller diameter, the better. Focus on finding better anchor solution.

Better Anchors

Ideal anchor should focus force towards wall, not the edges of the climbing hold.

Full Cure Time Matters

Concrete exhibited a tiny fraction of its true strength when tested too early.

Mix Concrete Wet for Molding

Too thick a mixture can leave pockets and weak points.

Successful Proof-of-Concept

I am convinced that, with further tweaks to the process and hardware, the prototypes demonstrated the necessary to strength to be viable.

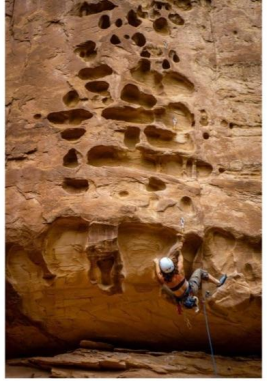
Aesthetic Language Exploration

Aesthetic Language Exploration

This mood board served as a reference for colors, shapes, patterns, and textures found in rock, printed concrete, and climbing tech.

ENTROPIC

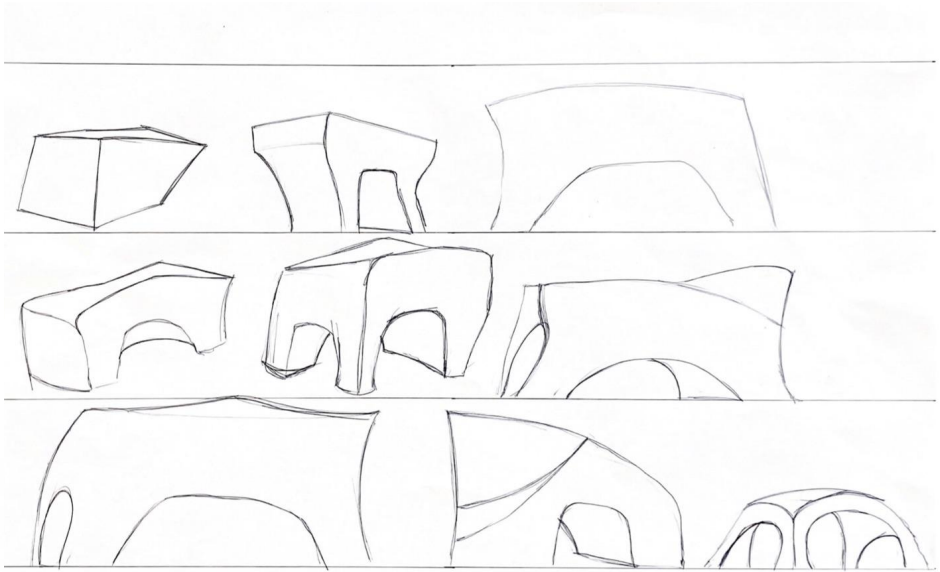
Geology

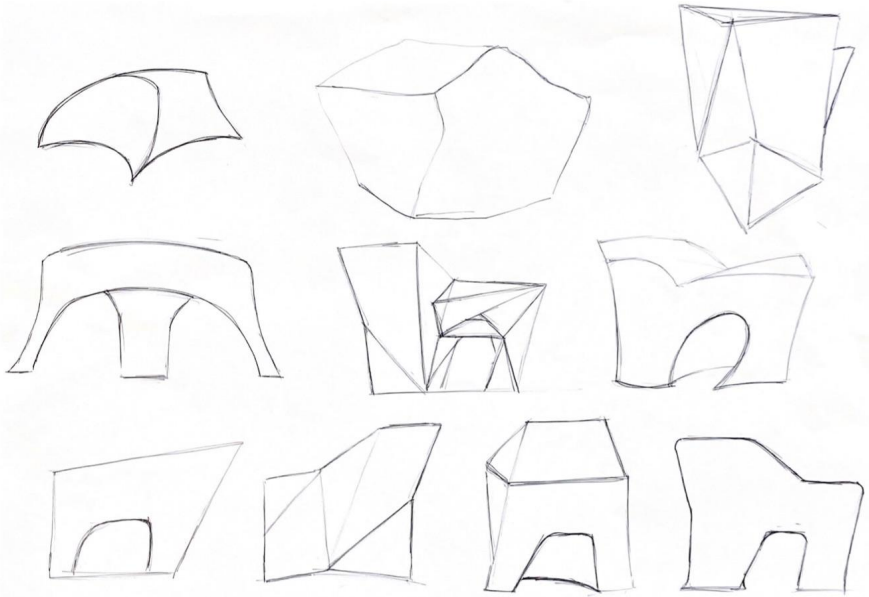


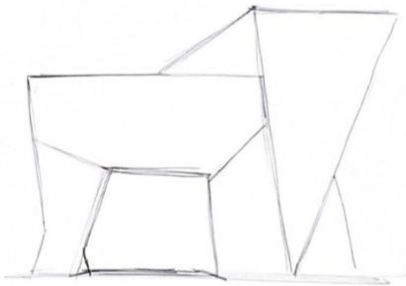
Form Iteration

Form Iteration

Thumbnail sketches exploring stable structure forms that incorporate a wide variety of climbing difficulties and styles.



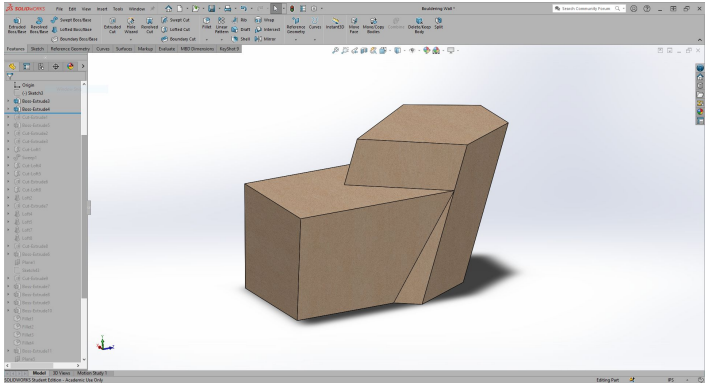


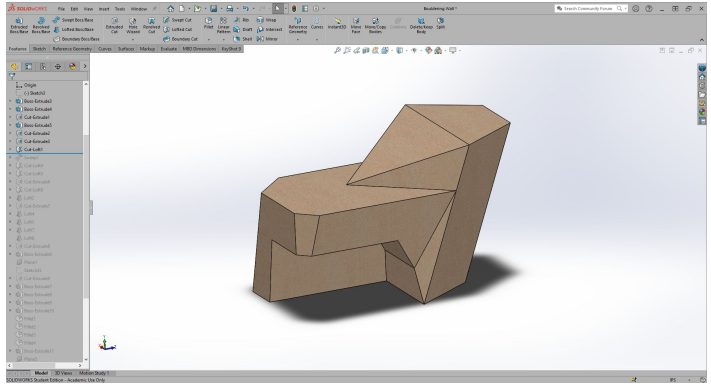


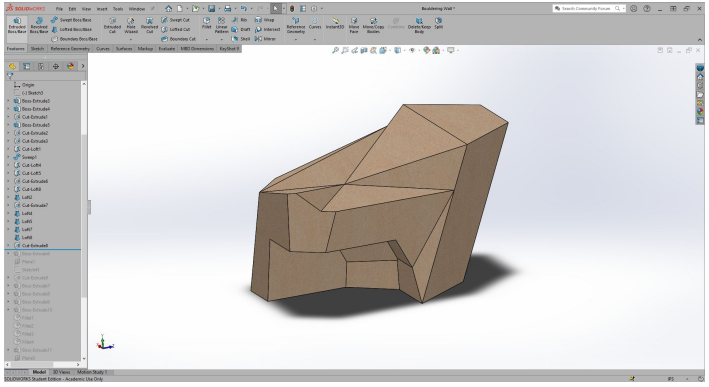
Form Development

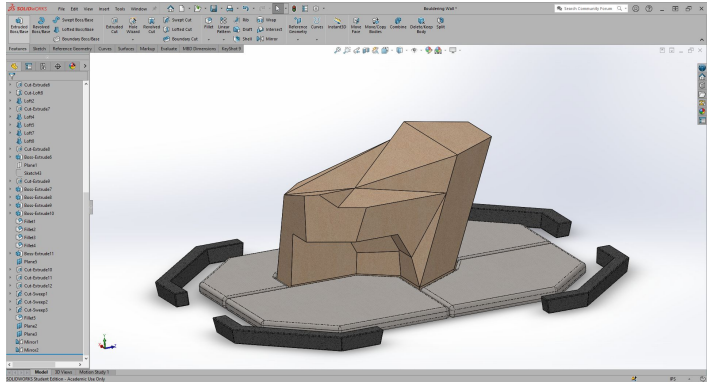
Form Development

Structure form explored three-dimensionally and refined in Solidworks.



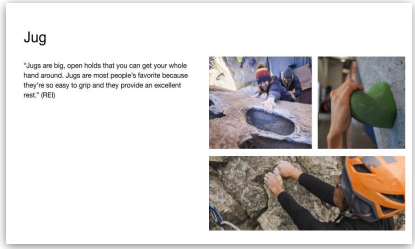


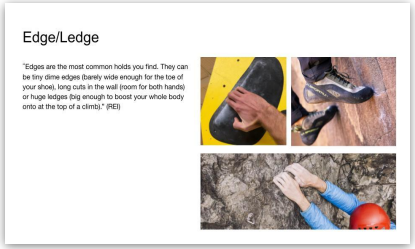


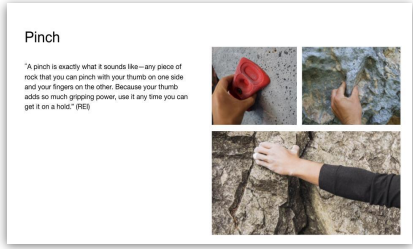


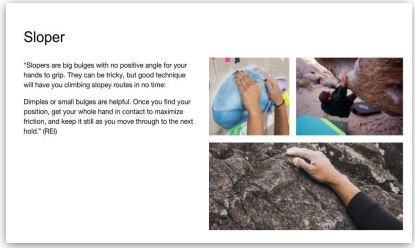
Form Development

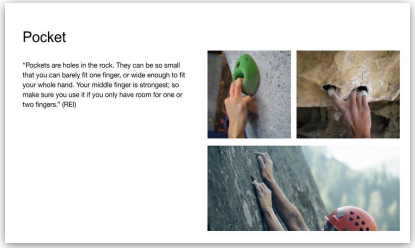
Created a visual and written taxonomy of different types of climbing holds to inform modeling and prototyping of my own.

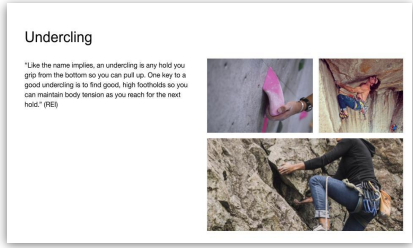


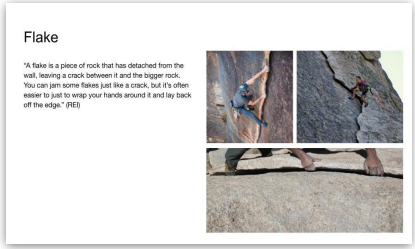


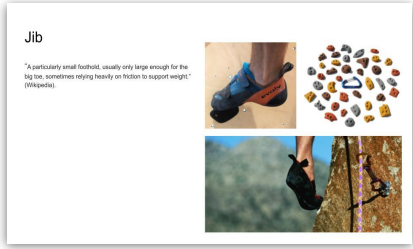






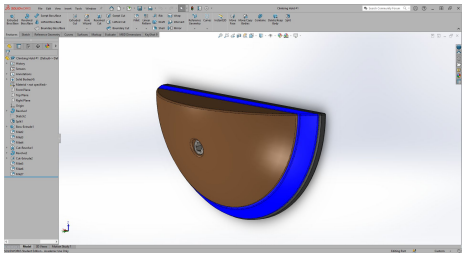
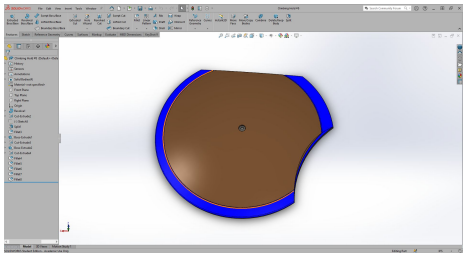
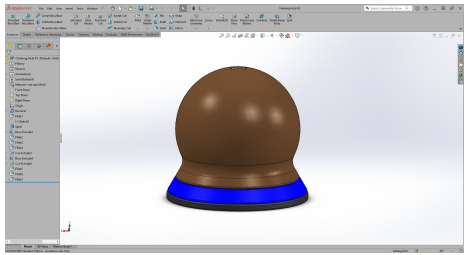
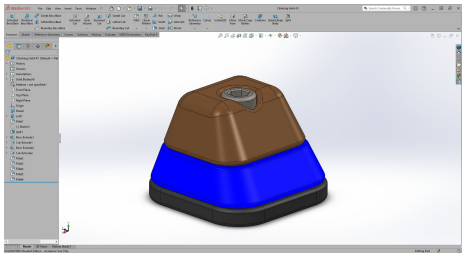
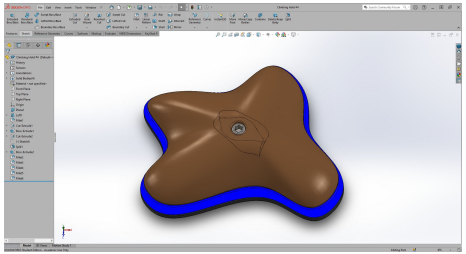
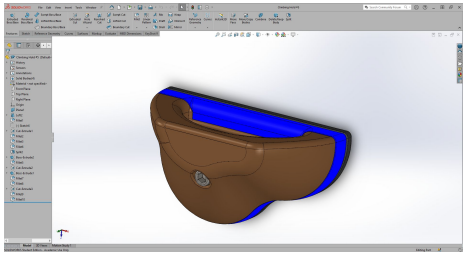
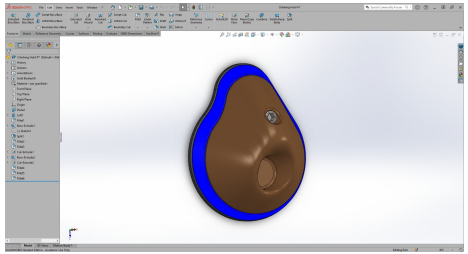
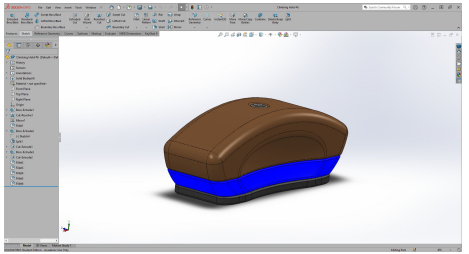


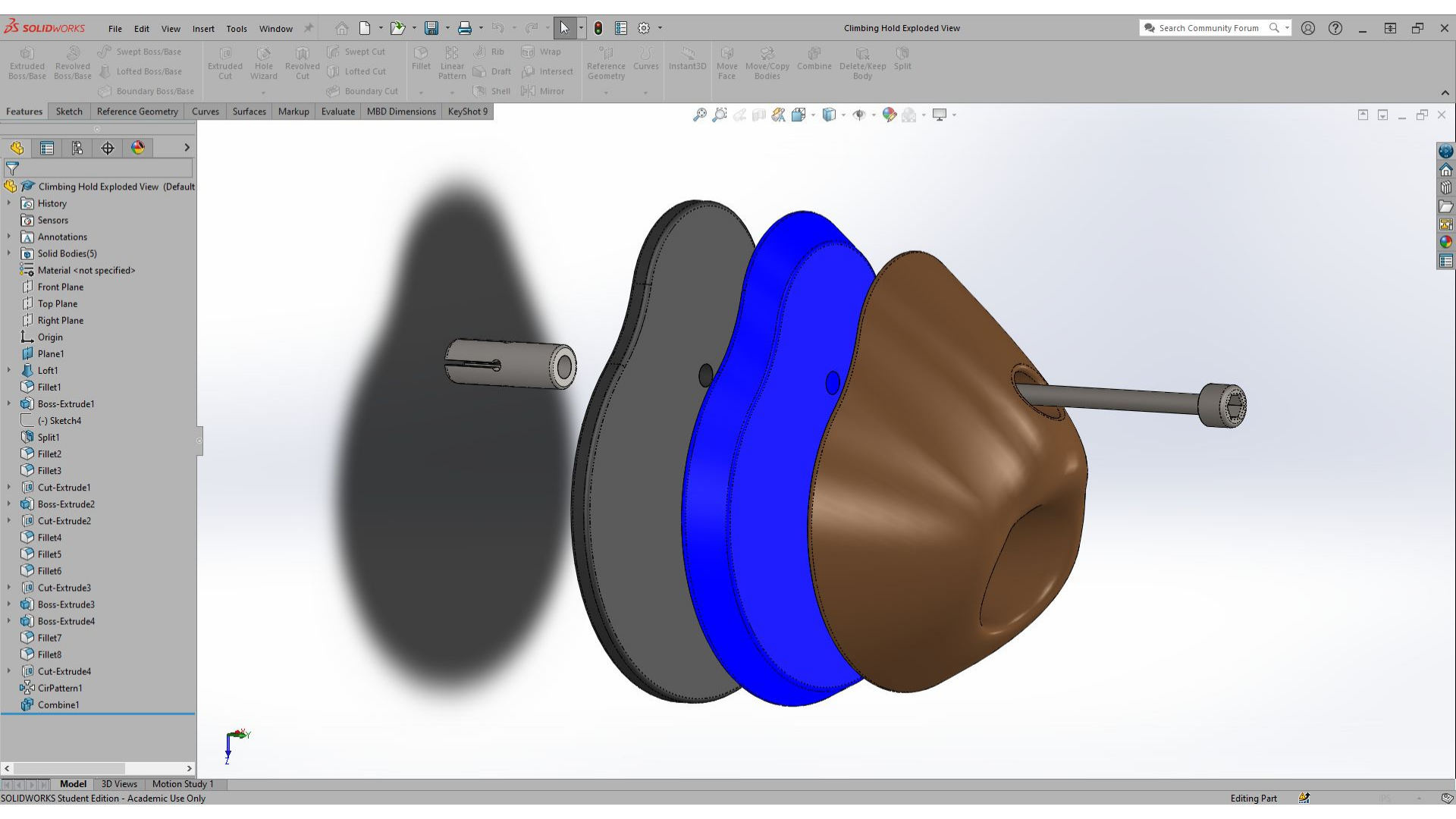




Form Development

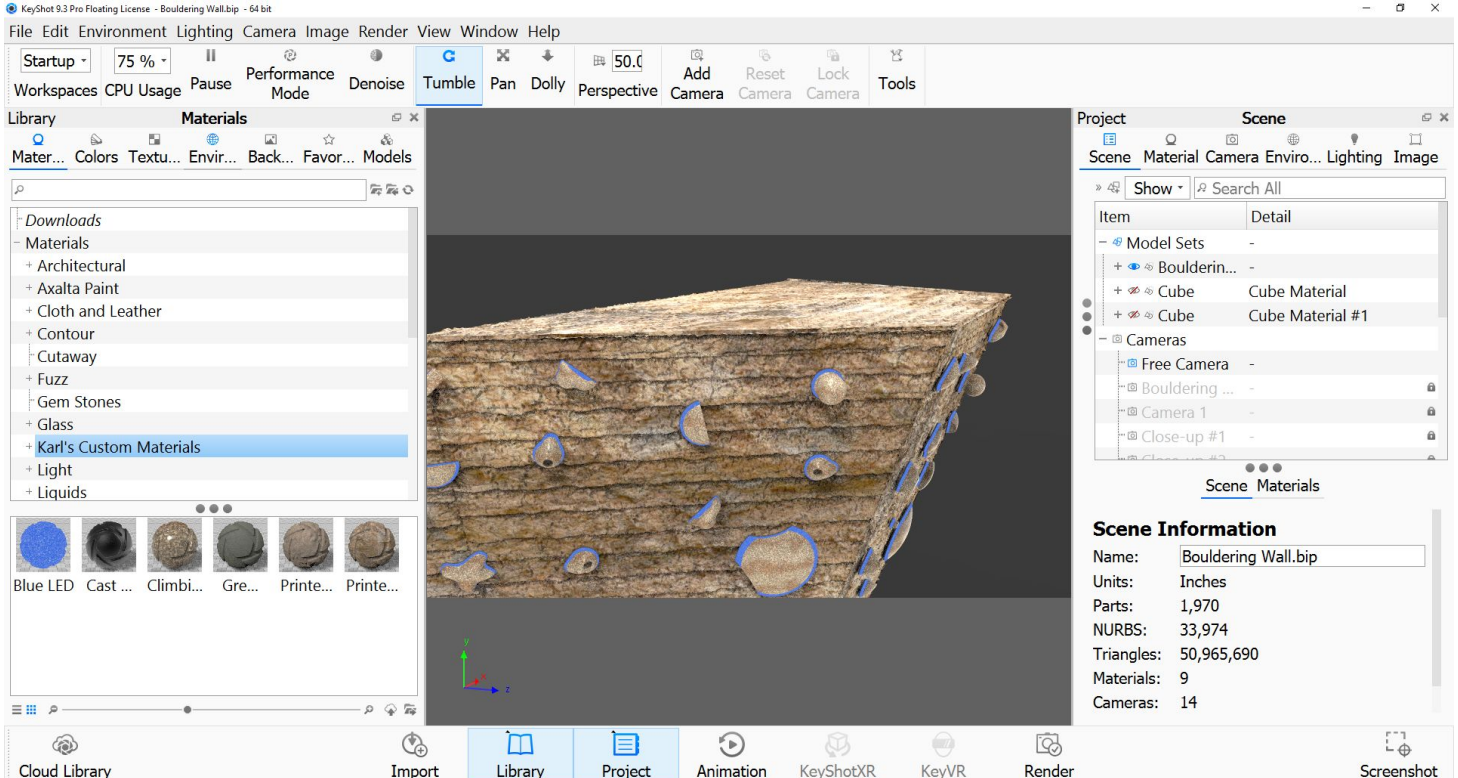
Modeled 8 different climbing hold forms to assemble on the climbing structure. They serve as examples of different possible geometry, but the options are limitless.


SOLIDWORKS
File Edit View Insert Tools Window
Climbing Hold Exploded View
Search Community Forum
Extruded Boss/Base
Revolved Boss/Base
Swept Boss/Base
Lofted Boss/Base
Boundary Boss/Base
Extruded Cut
Hole Wizard
Revolved Cut
Swept Cut
Lofted Cut
Boundary Cut
Fillet
Linear Pattern
Rib
Draft
Shell
Wrap
Intersect
Mirror
Reference Geometry
Curves
Instant3D
Move Face
Move/Copy Bodies
Combine
Delete/Keep Body
Split
Features Sketch Reference Geometry Curves Surfaces Markup Evaluate MBD Dimensions KeyShot 9
Climbing Hold Exploded View (Default
History
Sensors
Annotations
Solid Bodies(5)
Material <not specified>
Front Plane
Top Plane
Right Plane
Origin
Plane1
Loft1
Fillet1
Boss-Extrude1
(-) Sketch4
Split1
Fillet2
Fillet3
Cut-Extrude1
Boss-Extrude2
Cut-Extrude2
Fillet4
Fillet5
Fillet6
Cut-Extrude3
Boss-Extrude3
Boss-Extrude4
Fillet7
Fillet8
Cut-Extrude4
CirPattern1
Combine1
Model
3D Views
Motion Study 1
SOLIDWORKS Student Edition - Academic Use Only
Editing Part

Form Development

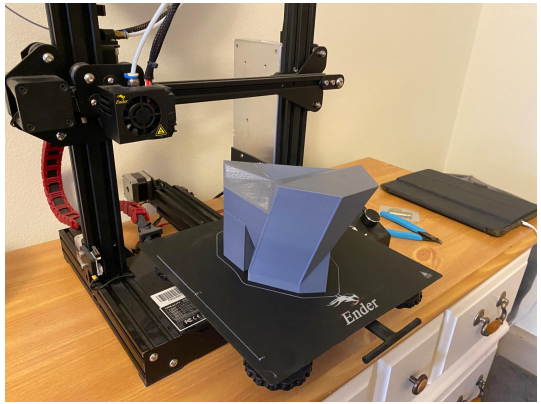
Created realistic custom materials and displacement maps in Keyshot, referencing aesthetic language exploration.

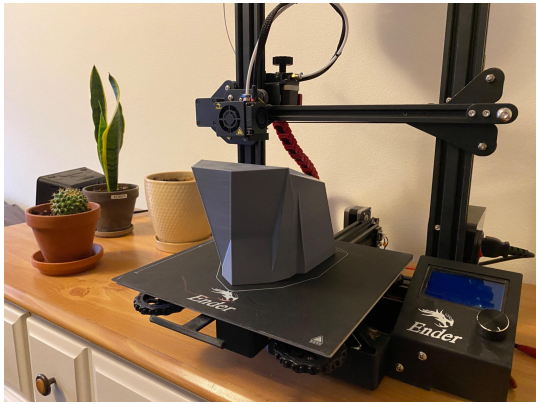


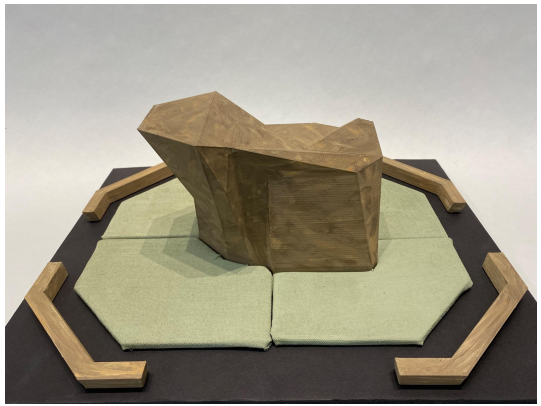
Prototyping

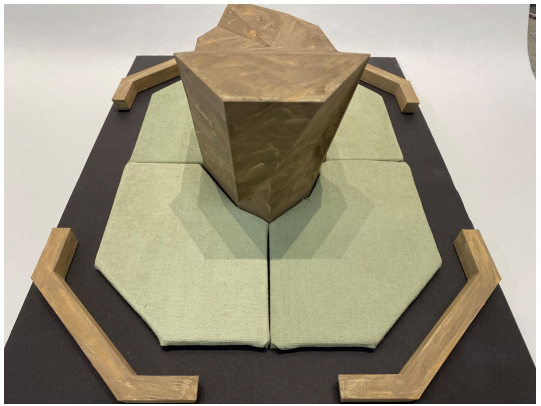
Prototyping

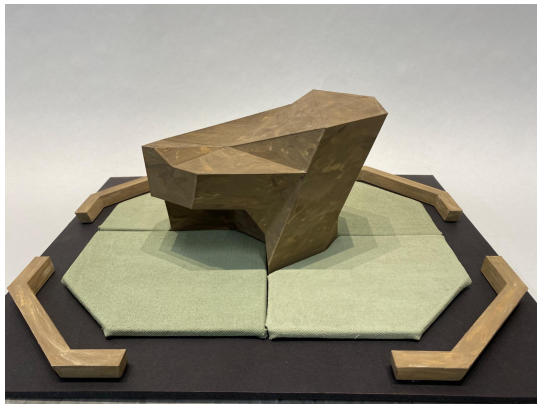
3D-printed and painted a 1 : 40 scale model





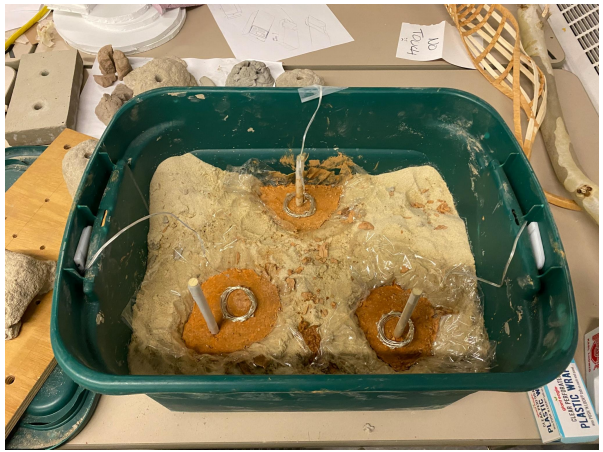


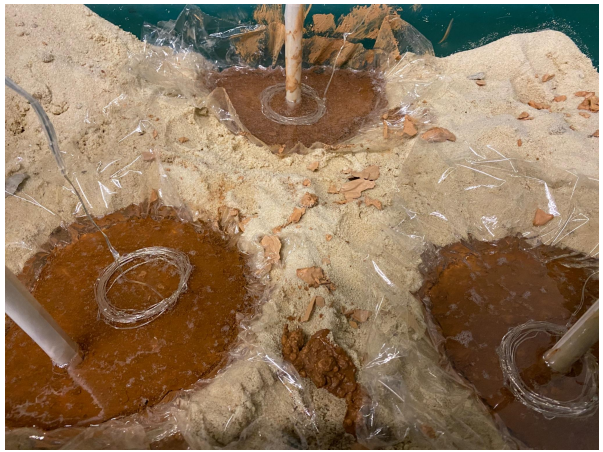




Prototyping

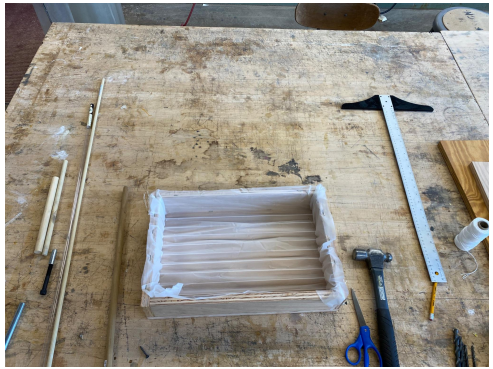
Cast climbing hold prototypes with embedded LEDs.

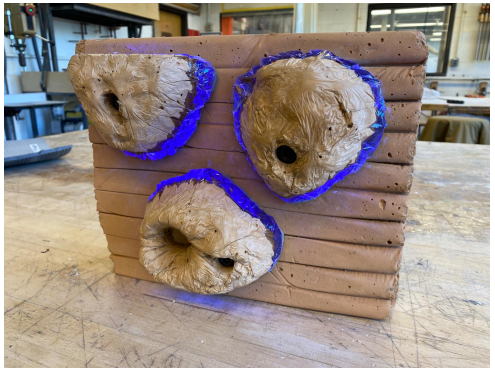




Prototyping

Built section of concrete wall showcasing concrete layers interfacing with custom LED climbing holds. Molded concrete block with taught string to create impression of printed layers. Drilled holes, placed anchors, bolted on holds, and wired the lights.

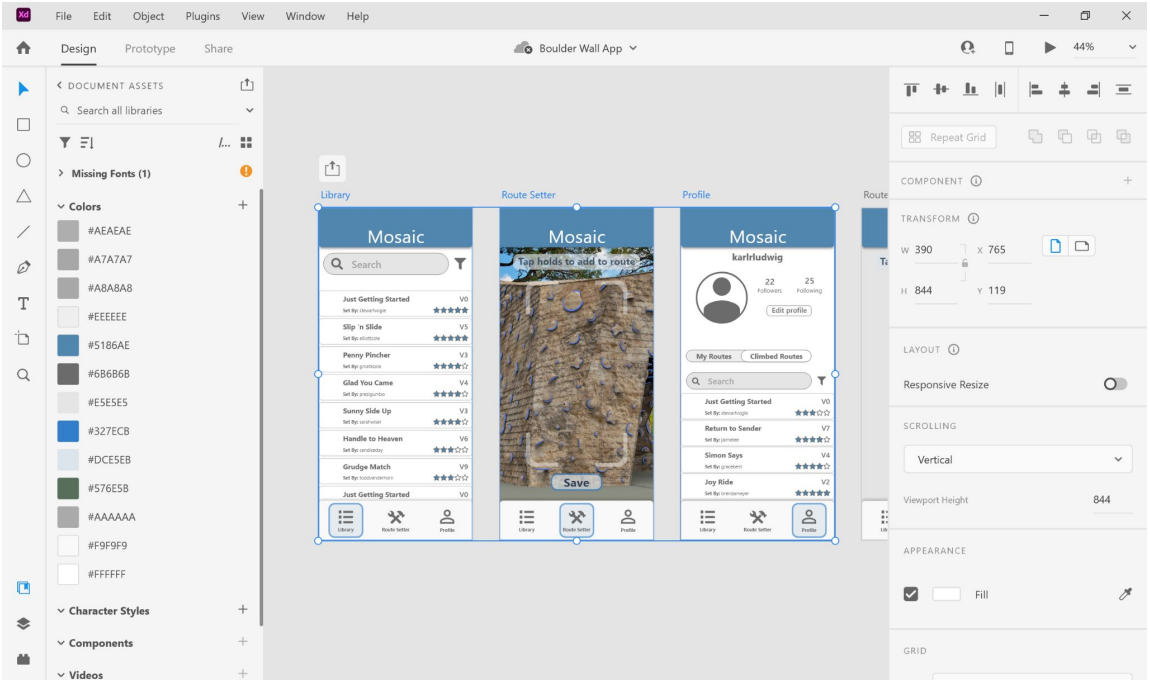




Back-End Design: App Creation

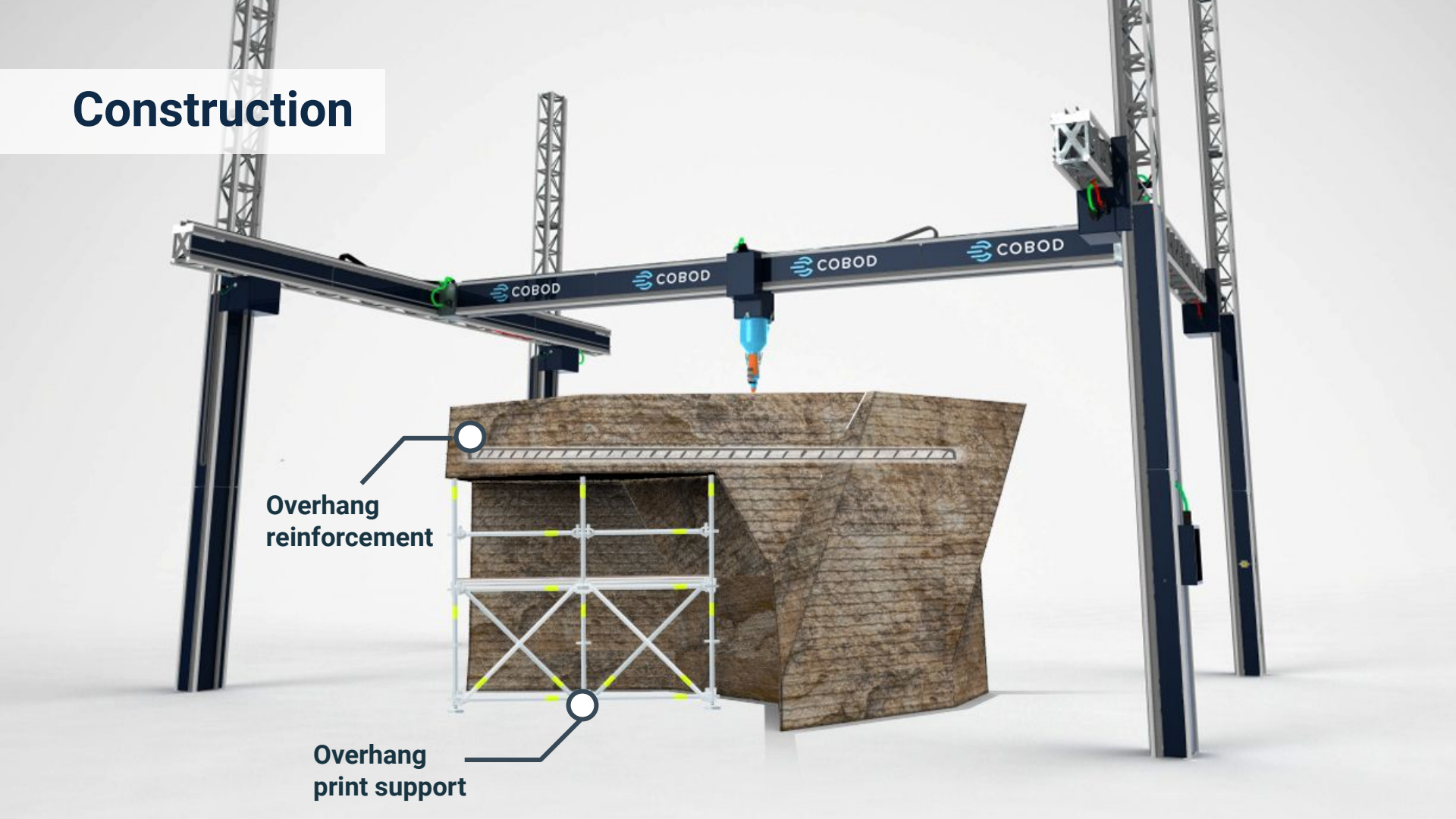
Back-End Design: App Creation

Developed basic app mock-up in Adobe XD, demonstrating how users would operate the wall's features and interact with an online community.

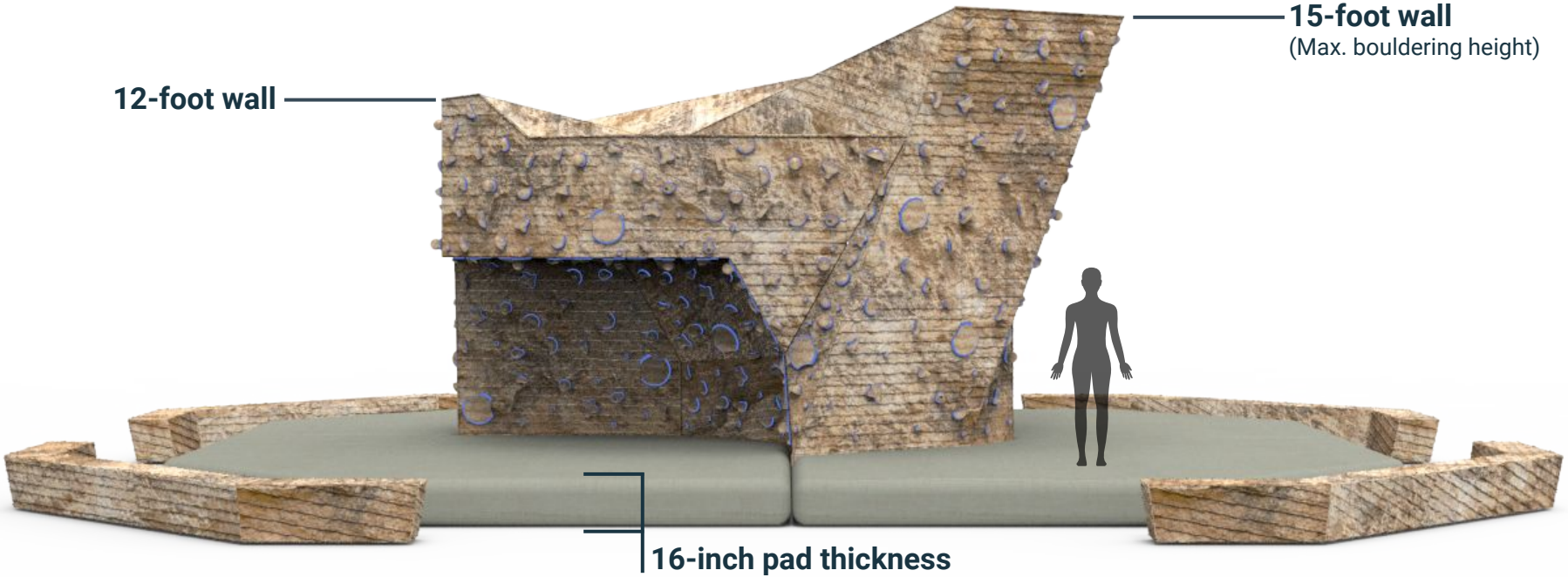


Design Solution

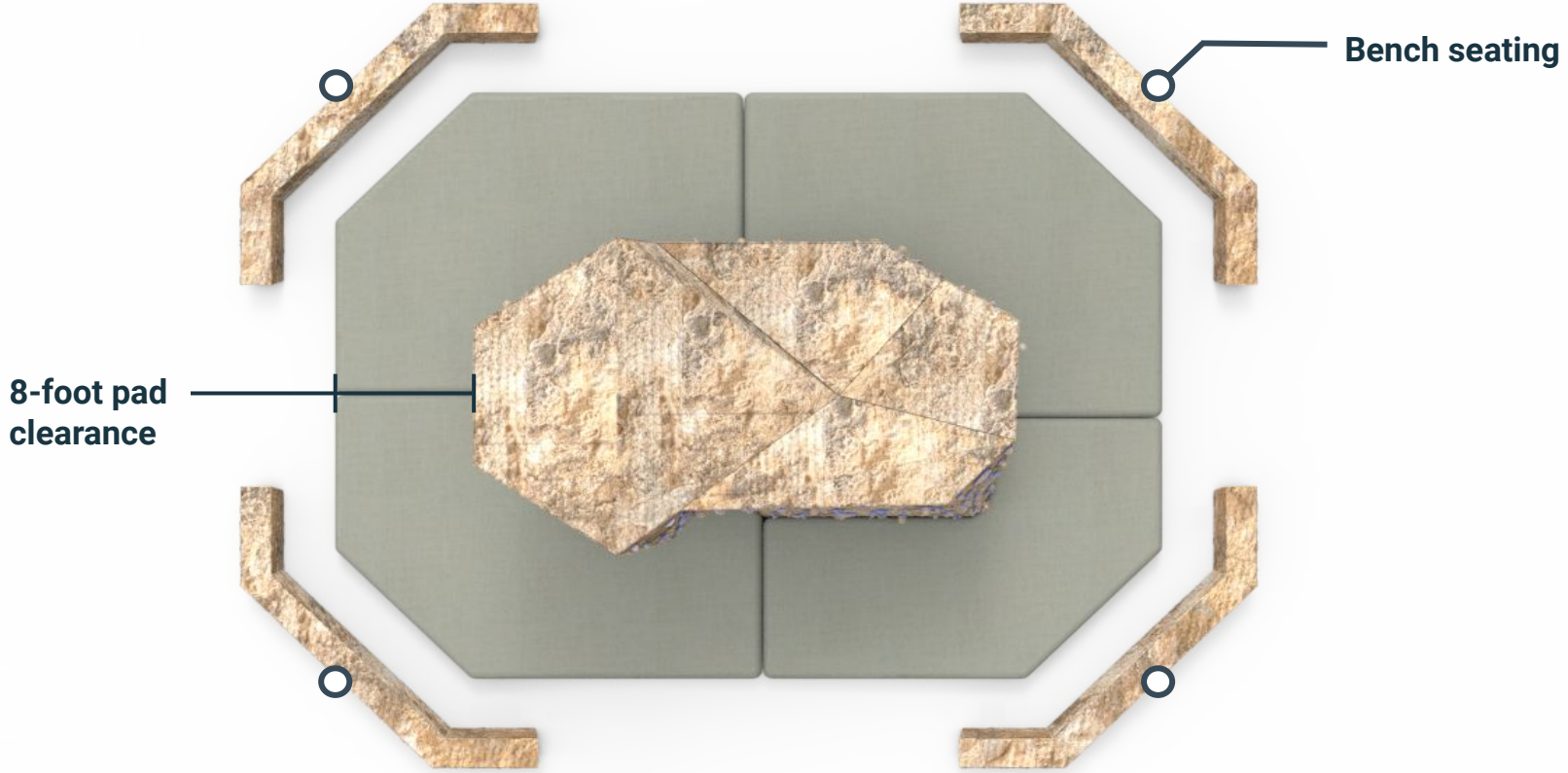
Construction



Structure Features

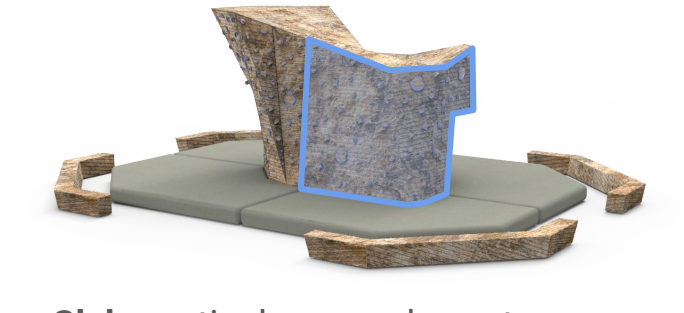


Structure Features

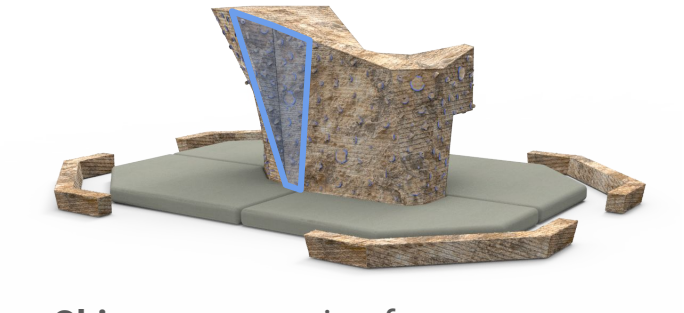


Wall Sections

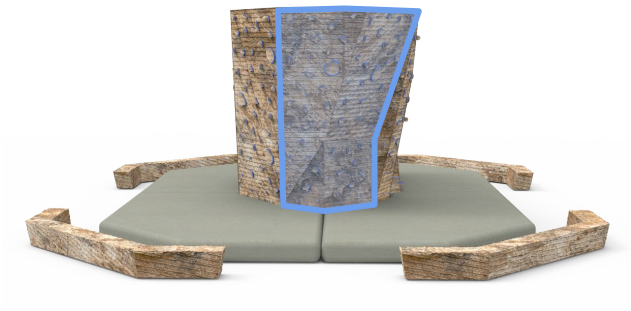
Designed to incorporate varying difficulty and climbing styles.



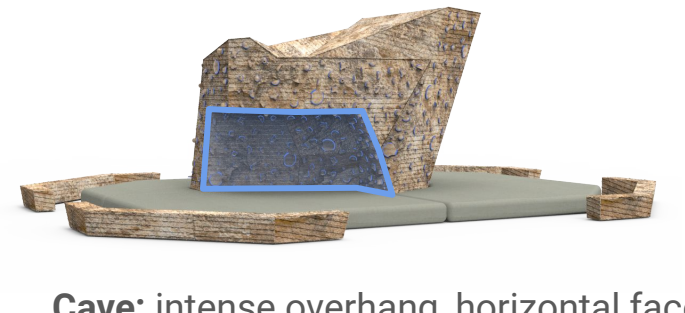
Slab: vertical or even less steep



Chimney: opposing faces

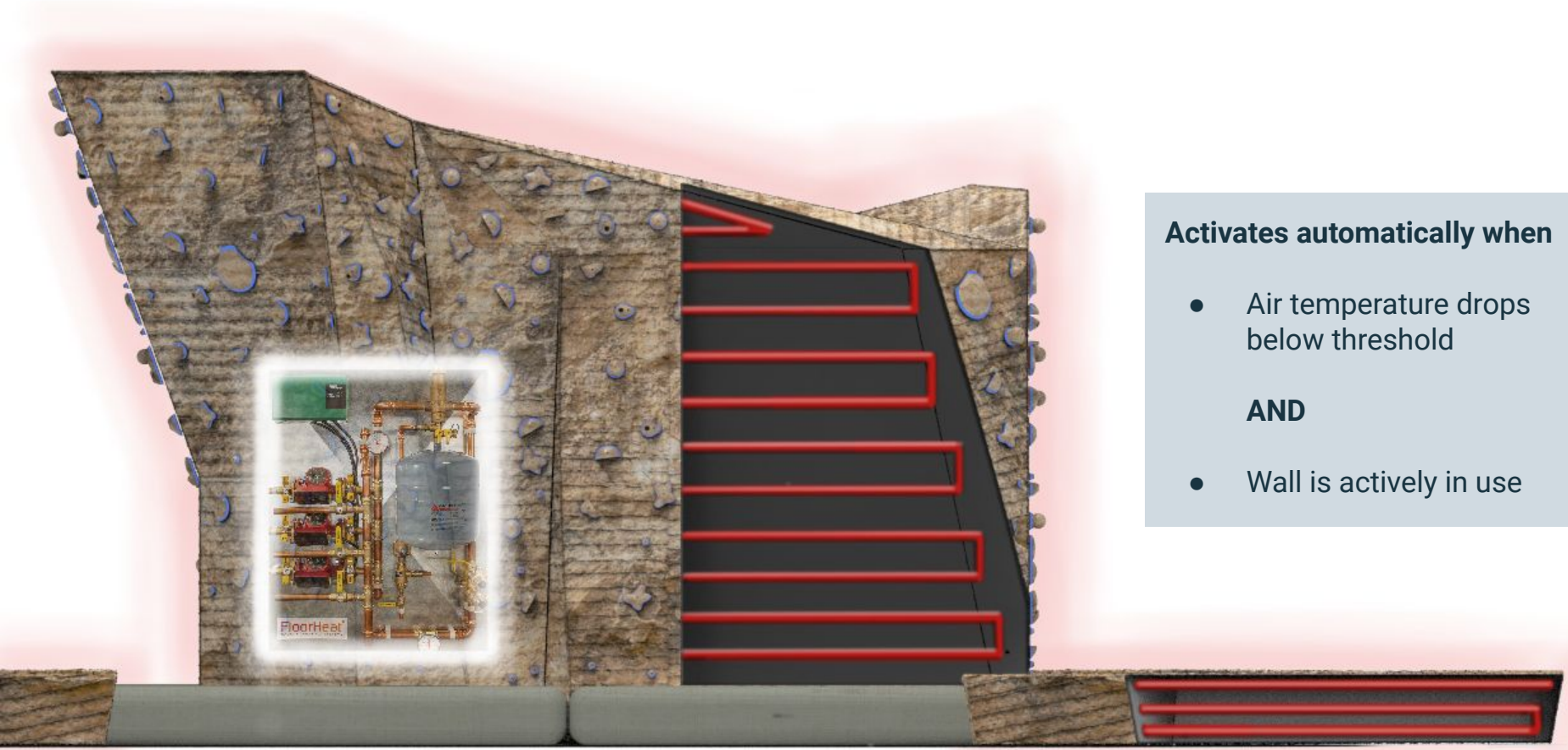


Moderate Overhang: up to 20 degrees



Cave: intense overhang, horizontal face

Radiant Heating

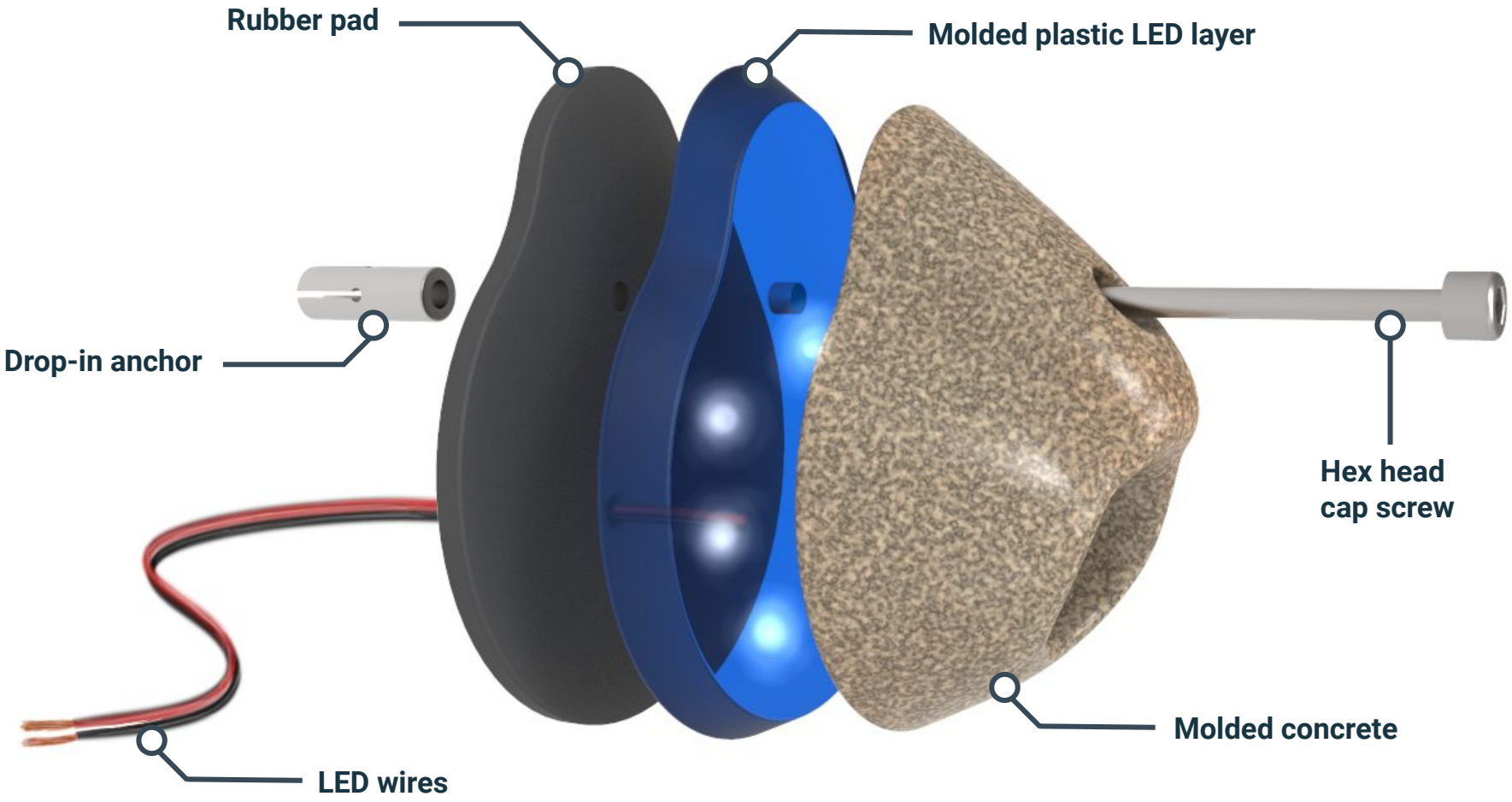


Activates automatically when

- Air temperature drops below threshold

AND

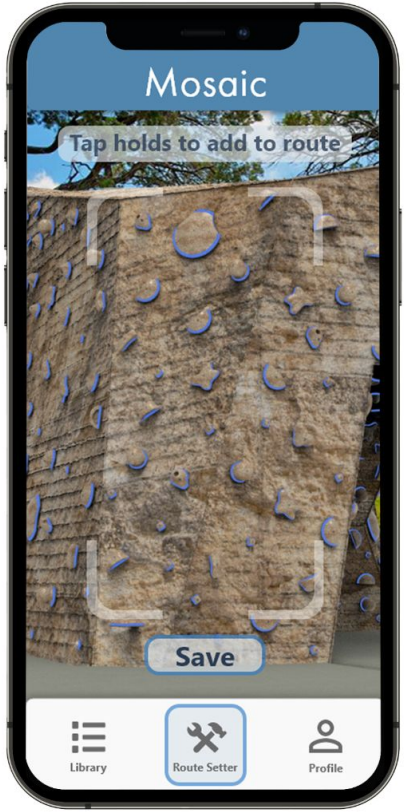
- Wall is actively in use

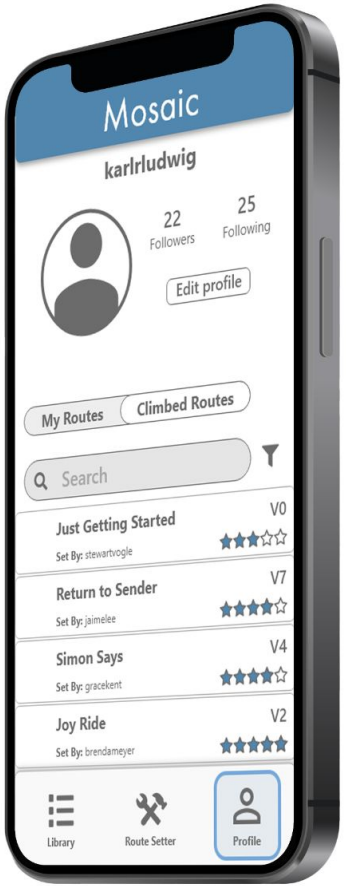

Rubber pad
Molded plastic LED layer
Drop-in anchor
Hex head
cap screw
Molded concrete
LED wires

Integrated LED prototypes

Mosaic App


Mosaic
Search
Just Getting Started
Set By: stewartvogle
V0
Slip 'n Slide
Set By: elliottcole
V5
Penny Pincher
Set By: gmafazola
V3
Glad You Came
Set By: prezigumbo
V4
Sunny Side Up
Set By: sarahwiser
V3
Handle to Heaven
Set By: candiceday
V6
Grudge Match
Set By: toddvanderhorn
V9
Just Getting Started
V0
Library
Route Setter
Profile


Mosaic
Tap holds to add to route
Save
Library
Route Setter
Profile

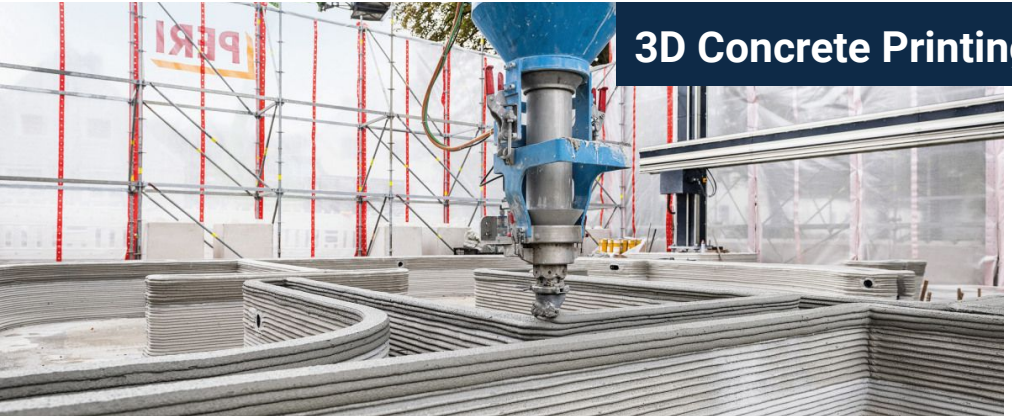

Mosaic
karlrludwig
22
Followers
25
Following
Edit profile
My Routes
Climbed Routes
Search
Just Getting Started
Set By: stewartvogle
V0
Return to Sender
Set By: jaimelee
V7
Simon Says
Set By: gracekent
V4
Joy Ride
Set By: brendameyer
V2
Library
Route Setter
Profile

Conclusion

The Impacts

Climbing

- Convient & accessible
- Scalable solution
- Enables time outdoors
- Better simulation of texture
- Provides endless diversity
- Encourages creativity



3D Concrete Printing

- Mixing form-giving processes
- Activating technologies
- Minimizing material input
- Frontiers beyond architecture

Potential Limitations

Material Durability

How would the structure, surface, and parts hold up over time?

Repairs

If components do break, are good methods for fixing them?

Cost

Would the cost of materials, parts, and operation be practical?