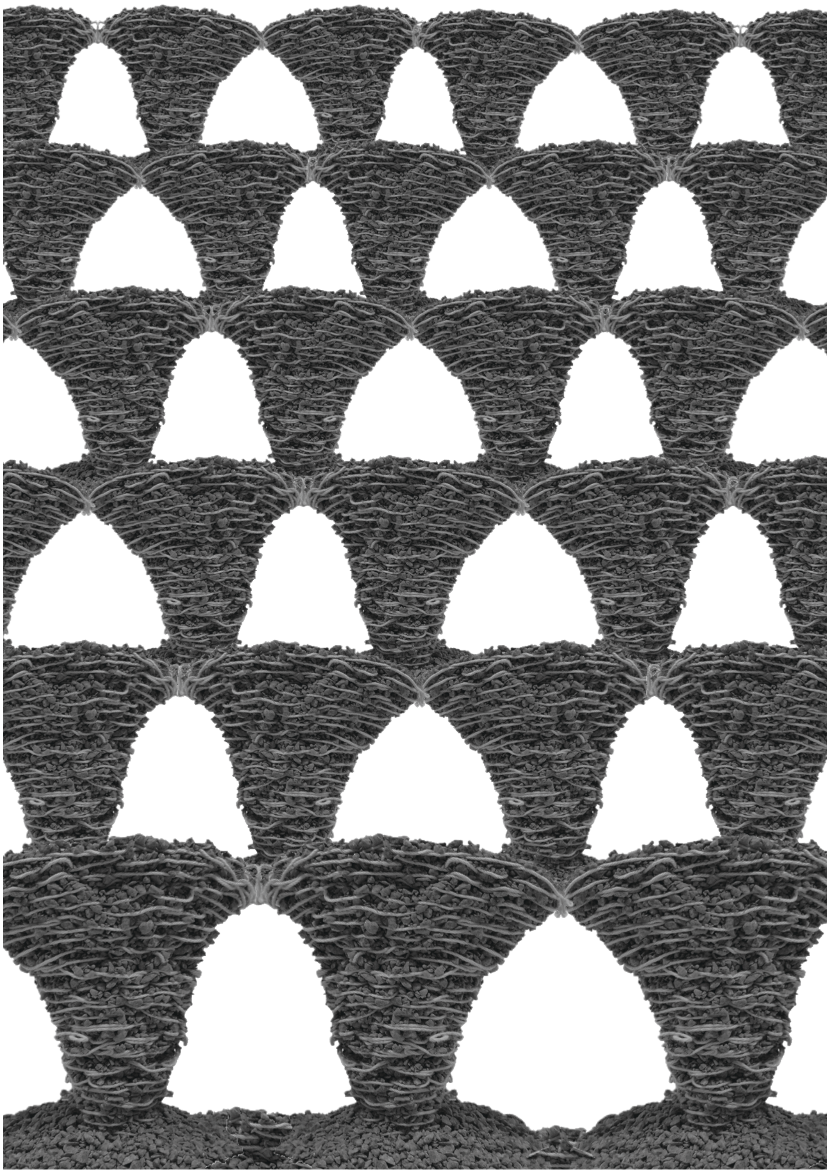
JAMMING STRUCTURES

Aggregations of Construction and Demolition Waste
Transforming over Time



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ABSTRACT

In 2012, construction and demolition (C&D) waste accounted for half of all the global waste that ended up in landfills. It is well-documented that materials used in the building process have a harmful impact on the environment. Most of the building waste ends up in backfilling operations or directly in landfills. Reuse of building materials is considered necessary for reducing C&D waste and material consumption. Despite its importance, the research of reuse has remained relatively unexplored to traditional construction methods in which elements are permanently joined together.

Granular jamming is defined as the transition from a collection of loose and unbound particles into a highly packed and rigid aggregation. In contrast to permanent bonding, the particles are stabilized through compression when packed within a confined space. The absence of any binding between particles allows the aggregated structure to be completely reversible. Over the last years, research on jamming and its possible application in architectural construction have pushed the boundaries of the material system. Instead of using external constraints, ETH developed a system in which string was used as confinement to create large scale aggregated structures. Alternatively, ICD designed a particle shape that interlocked with one another without any type of confinement.

This thesis project focused on the reversibility of aggregated structures and how they slowly changed over a long time period when subjected to natural processes and human intervention. Design speculation was used to investigate how C&D waste at SENT landfill in Hong Kong can be jammed together to create a landscape of aggregated structures that add to the currently low stock of open spaces in Hong Kong and shelter the visitors from overheating.

Taking its departure from research on granular jamming and its possible architectural application conducted at the ETH, the thesis also incorporates material experiments, design studies and precedence such as drystone architecture and aggregate studies in other materials in order to better understand the material system's capacity to function as a construction material. Ultimately, the thesis embodied the characteristics of granular jamming in a speculative design proposal that aimed to spark a discussion on the future implications of aggregated structures.

Key words: granular jamming, building waste, aggregated structures

TABLE OF CONTENTS

STUDENT BACKGROUND

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2020 — *Architectural consultant at Bostein & John*
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INTRODUCTION

GLOSSARY

GRANULAR MATERIAL — *A collection of loose macroscopic particles such as food grain, sand, earth and rock (Rusenova, 2020).*

DESIGNED MATTER — *Individually designed and prefabricated particles that can interlock without any fastening or bonding agent (Rusenova, 2020).*

NATURAL BULK MATTER — *Natural particles such as sand or gravel, that are readily available in large quantities. They are cohesionless materials and require external confinement to build freestanding structures (Murphy et al., 2017)*

JAMMING TRANSITION — *The transformation between a liquid-like state to a solid-like state (Rusenova, 2020).*

AGGREGATED STRUCTURE — *A structure that is mass composed of granular materials. The matter is crammed together in such a way that it holds its form and shape like a solid.*

PURPOSE AND AIM

The purpose of this thesis was to explore the possible opportunities and consequences of aggregated structures in architecture. The design proposal questioned if waste can be deposited in a way to form designed structures that have spatial qualities. Additionally, it focused on the reversibility of large-scale granular jammed structures and how they change over a long time period as they are subjected to natural processes and human intervention. The thesis project was a design speculation that embodied the characteristics of the material system into a design proposal. The proposal aimed to spark a discussion on the future implications of aggregated structures.

DELIMITATIONS

The thesis focused on construction and demolition waste found in Hong Kong, as the main building material for the aggregated structures. It was not within the ambition of this thesis to provide data on specific waste materials or investigate and design individual particles. Nor was it the ambition to provide building solutions to make the material system viable with today's building regulations. The design proposal did not investigate or propose a definitive program for the site but rather show possible scenarios that change over time.

THESIS QUESTIONS

How can aggregated structures change over a long period of time?

How can building waste be used in an architectural way by jamming?

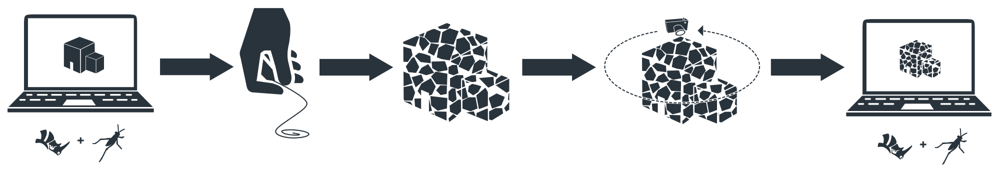
METHOD

Considering the specific behaviour of granular matter, different design tools were needed to explore the material system's properties. Following methods were combined to gain a broad understanding of the material system and to develop the design proposal: precedents studies, material experiments and digital design studies.

Precedents such as the research projects conducted by ETH, ICD and Jaeger Lab were investigated to understand the opportunities of granular jamming in architecture. The research projects established the theoretical foundation of the thesis project and set the limits for what was possible with the material experiments. Together with the master thesis project on granular jamming by Tuan Anh Tran, the precedents served as inspiration for the design proposal. Drystone architecture was explored to show historical examples of building structures without any binders. Land art was used as a design inspiration and to better understand the scale of the proposal in relation to the site.

Material experiments were used to establish proof of concept and to explore the strengths and weaknesses of different aggregated geometrical shapes. Different parameters such as size and shape of particles were explored. The experiments propelled the design project forward as they gave a comprehensive understanding of the shape limitations and characteristics of aggregated structures. Considering the reversibility of the material system, all experiments were dismantled so that material could be reused. The experiments were digitally documented with photogrammetry so that they could be studied after disassembly.

Digital design studies such as simulations in Blender and Unity were used as a drawing method to illustrate granular jammed structures. The design proposal was developed through a series of iterations in the 3D modelling program Rhino in combination with Grasshopper. Scripting in Grasshopper made it possible to take full advantage of complete iteration and automate the design process. Metaball scripts were used as a tool to simplify the representation of the aggregated structures and to create the landscape topography. Circle packing was used to distribute the structures on the site.



The method used for the material experiments

BACKGROUND

THE WHAT-IFS

Our actual world is surrounded by an infinity of other possible worlds
- Lubomír Doležel

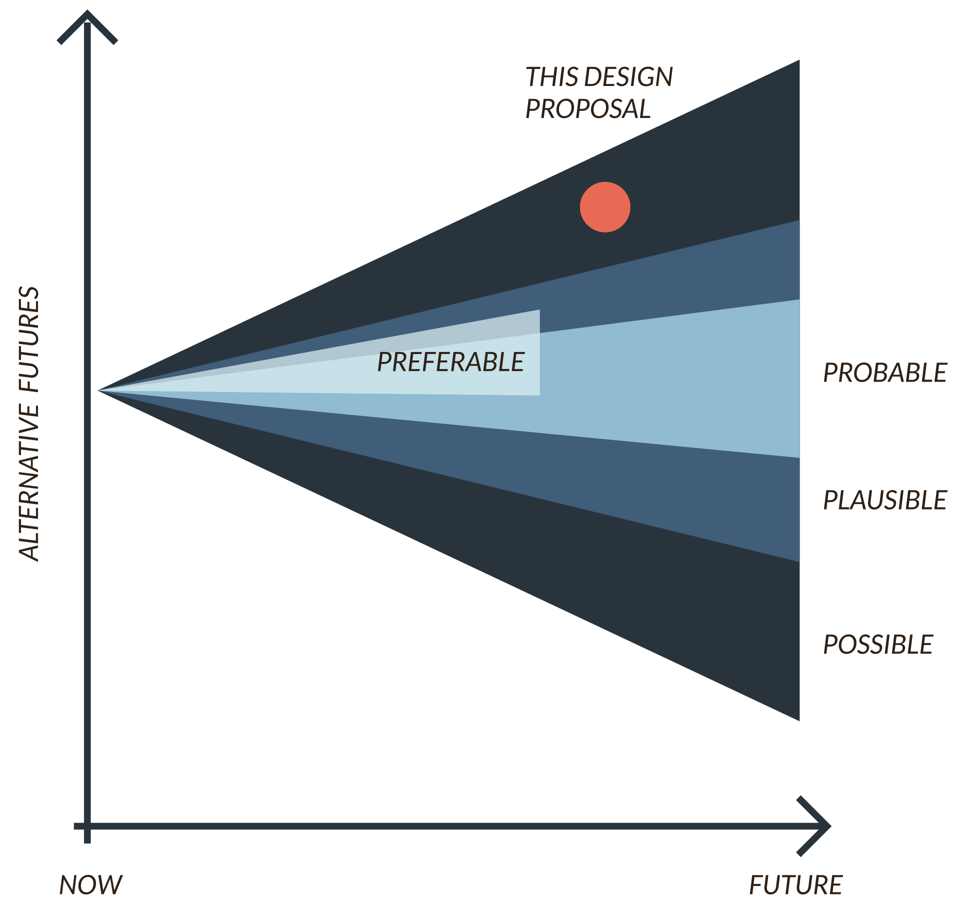
We are faced with many challenges like climate change, depleting natural resources and a pandemic to name a few. In Speculative Everything (Dunne & Raby, 2013), the authors described that the only way to overcome them is to change our values, beliefs, attitudes and behaviour. Design speculation can be used as a tool to speculate new possible futures of how things could be rather than should be. The alternative futures can be anything from delightful to concerning ones that should be avoided. Dunne and Raby acknowledged the importance to have a diversity of futures to better understand the present and to discuss the kind of future that we collectively desire and what we want to avoid. They described how their work operates in a space between reality and the impossible. It starts with a What-if question to open a space for imagination, discussion and debate. By speculating more, the possible impacts ideas might have can be determined and used today to increase the likelihood of for a more desirable future.

In their book Dunne and Raby redrew the Futures Cone to illustrate different potential futures scenarios fanning out from the present to the future. The first realm represents the probable that describes the scenarios we think are most likely to happen, usually based on current trends. Most designers tend to operate within this space.

The second one is plausible futures which is what we think could happen based on our current understanding of how today's world works. It is used by organizations to better be prepared for futures with different economic and political settings.

The third one is the possible that describes all the scientifically viable futures that might happen. The path that led up to the future scenario should be a credible series of events, that can be either fictional or real. This is where speculative design happens.

The final one is preferable futures, and it intersects the probable and the plausible. It describes what should or ought to happen and is mostly determined by government and industry.



Redrawn illustration of the Futures Cone adapted by Dunne and Raby (2013) from Hancock and Bezold (1994)

Considering the novel nature of this master thesis' topic, design speculation was used to explore the possible application of aggregated structures. It was grounded in current research and in today's world with increasing amounts of generated waste. Following Dunne and Raby's lead, what-if questions were asked such as what if structures were built with aggregated building waste, what would that look like? The questions helped to create the narrative that the master thesis was based on. The design proposal is located within the possible realm and investigated the design of aggregated structures and how the reversible nature of the material system allowed the structures to change over time.

THE TIMES ARE A-CHANGIN'

Architecture is but waste in transit

- Peter Guthrie

In 2012, construction and demolition (C&D) waste accounted for half of all the global waste that ended up in landfills. The waste from buildings has since increased and is expected to double to 2.2 billion tonnes by 2025 (World Bank, 2012). Today's waste management is highly linear and some of it is redirected into recycled products but more often they are used in backfilling operations or directly terminated in landfills. The linear economic model is based on the idea that natural resources are abundantly available, easily sourced, and disposed of. It is a model that is inherently unsustainable (European Environment Agency, 2020).

As the global building stock is expected to double by 2060, the embodied carbon is anticipated to only increase and be responsible for half of the entire carbon footprint of new construction from now to 2060 (World Green Building Council, 2019). Embodied carbon includes the emissions that is released during the material extraction, production of new materials, transportation and the construction process of the building. Addressing building waste as a viable material resource is essential for reducing the embodied carbon in future building stock.

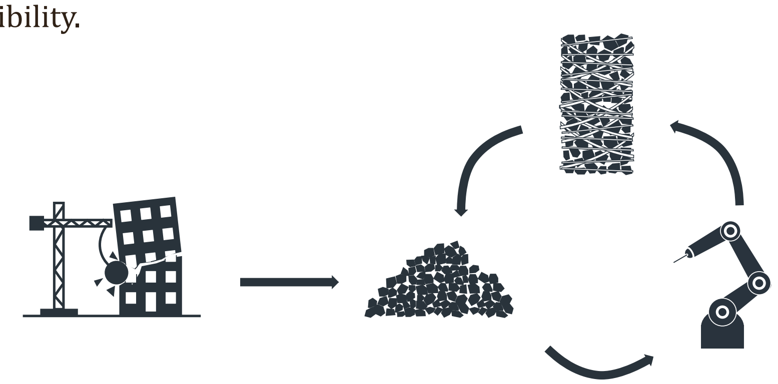
As described before, a vast amount of the building waste is dumped in landfills. There it is deposited into piles that form an artificial waste landscape. This thesis project wanted to argue that instead of viewing waste as a problem and a burden for the environment, it should be seen as an untapped material resource. In this thesis landfills are seen as repositories where materials can be mined and recycled or reused.

Landfills as material repositories (Photo: Fotoluminate LLC, n.d.)

GRANULAR MATTER

Granular material is defined as a collection of loose macroscopic particles such as food grain, sand, earth and rock. It is included within the field of material science. Granular matter has been studied to solve problems in other fields such as in road and tunnel construction and rock mechanics. Its behaviour differs from materials typically used in construction and it is not as well-studied as other traditional materials such as concrete or steel (Rusenova, 2020). In contrast to traditional construction techniques, in which fasteners or bonding agents are used to permanently join building elements together, particles are jammed into highly packed and disordered solids without any binders. The absence of any binding between particles allows the aggregated structure to be completely reversible. The jamming transition is described as the transition from unbound particles into rigid aggregation. The particles are stabilized through compression when packed within a confined space thus forming a rigid structure (Murphy et al., 2017). Compared to conventional construction in which each unit requires to be carefully placed and joined, each particle in a granular system randomly rearranges until all movement has ceased. Preplanning can be replaced by the self-organizing character of granular materials. Thus, granular materials can be seen as suitable for autonomous construction (Dierichs & Menges, 2017).

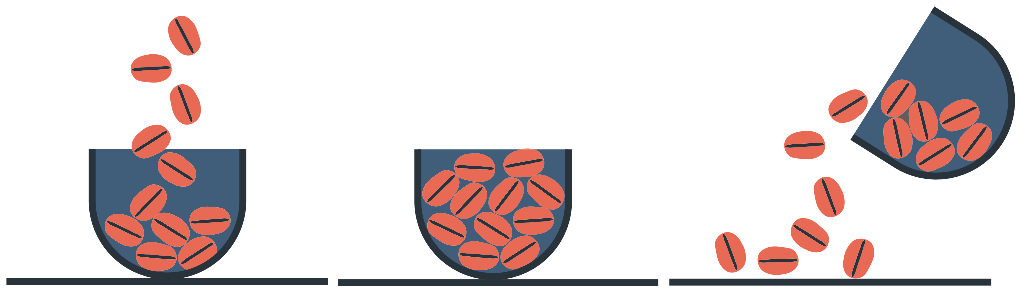
Waste in a landfill can be considered as granular matter. The waste particles can be thought of as unbound and distinct elements that are loosely grouped together. By defining waste as a granular material, it can be reimagined as a material system which inherently allows for self-construction and reversibility.



Building waste could be used to robotically construct rigid structures that can be disassembled and repurposed elsewhere

JAMMING GRANULES

Granular jamming is described as a common physical process that takes place in our everyday lives. For example, coffee beans being poured into a bag will flow like a liquid until the beans have settled into a stable and unplanned arrangement, a jammed state. Granular matter can be poured into any shape without any planning for the placement of every individual particle. The transformation between a liquid-like state to a solid-like state is called a jamming transition. The change takes place when the particles are put under certain external force conditions. During the change, the particles are rearranged independently to balance force and torque until they are jammed under their own weight. A structural solid-like state is achieved when every individual particle is confined locally and cannot move past one another. When that has occurred, a moment of stability has been reached globally. When jammed, the granular material performs as a solid body and is rigid to external forces. If the force conditions that hold the coffee beans together are removed, the beans will flow back to its liquid-like state (Murphy et al., 2017).



Coffee beans being poured into a bag will flow like a liquid

When settled in a stable arrangement, the coffee beans enter a solid-like state

When the external force of the bag is removed, the coffee beans will revert to their liquid-like state

Aggregated structures can be considered fully reversible as no binding agents are required. The properties inherent to granular materials have potential to be applied in architectural construction as it can be used to create structurally stable and non-permanent structures. Considering the reversibility of the material system, materials can be reused without any downgrading. Additionally, no curing time is required as the system becomes structurally stable immediately and is self-organizing (Aejmelaeus-Lindström et al., 2020).

The application of granular matter in the architectural field can be split into two research fields: designed matter and natural bulk matter (Rusenova, 2020).

Designed matter is individually designed and prefabricated particles that can self-construct by interlocking with one another (Rusenova, 2020). Research has shown that several designed particle shapes can self-confine but only a few of them are able to sustain loads beyond self-weight (Murphy et al., 2017). Most designed materials used in research projects have been either time-consuming and labour-intensive or expensive or used synthetic materials (Rusenova, 2020).

In contrast to designed matter, natural bulk materials are cohesionless and generally external confinement is required to build freestanding structures. They are made up of particles such as sand or gravel, that are readily available in large quantities. Different types of membranes are commonly used as external constraints in order to construct load-bearing structures. The aesthetics of the exterior is influenced by the type of membrane used. However, the reconfigurability and recyclability is partially limited when using external confinement. As opposed to structures with designed materials that can be fully reversed. Instead of external constraints, ETH developed a fully reversible system in which string was used as a reinforcement. With their system, large scale aggregated structures can be created without any constraining membrane (Murphy et al., 2017).

ROBOTIC AGGREGATION

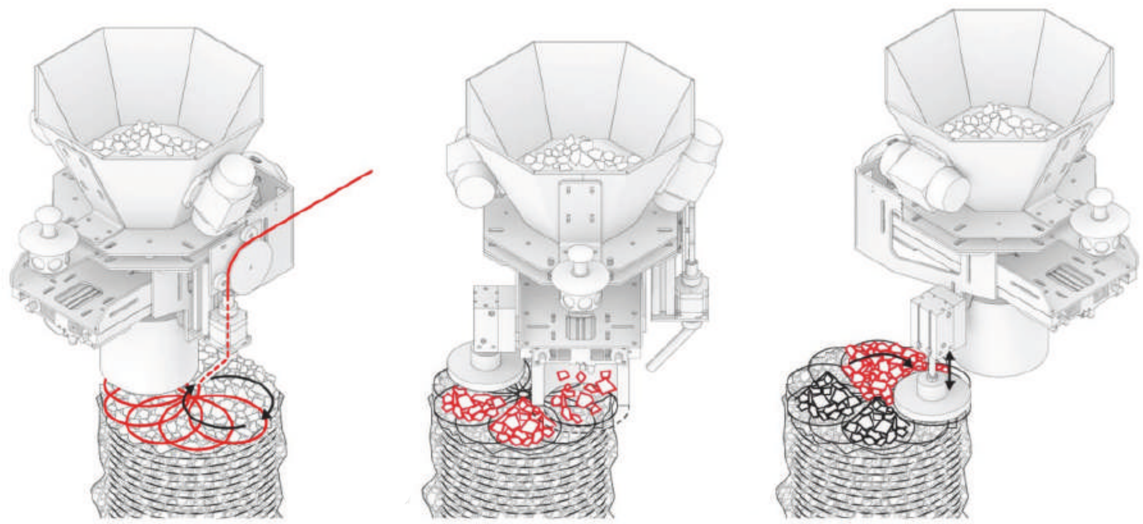
The self-organizing properties of granular materials lend themselves to autonomous construction. As the particle placement cannot be pre-planned or controlled with conventional construction techniques, another design fabrication method is required. One that is diverted towards controlled aggregations of granular waste and away from pre-planned production (Dierichs & Menges, 2017). Research conducted at ETH and ICD have developed novel robotic aggregation methods for building with granular matter. This thesis project focused on Jammed Architectural Structure (JAS) developed by ETH as the main method for constructing aggregated structures. For the reason that it was developed to build structures from locally obtained materials such as rock and concrete. It can be used to build directly on the construction site and is easily reversed.

The deployment of robots in architecture enables digital information and a range of construction principles to be connected directly to the fabrication process. Digital blueprints of the design are generated by algorithms and followed by the robots. The blueprints are flexible and can react to external inputs presented during the construction. This in turn let the blueprints to be digitally adjusted during the build-up. The robots are therefore allowed to directly interact with the formation of granular matter. Thus, the construction of large-scale non-standard structures can be made, directly on site and with local materials (Aejmelaeus-Lindström et al., 2016).

ICD used a custom-built cable-driven robot in the construction of the ICD Pavilion 2018. The robot was attached to the ceiling and was preprogramed to pick up designed particles and pour them at predefined location to build up the structure. The individual placement of each aggregate did not matter as they self-construct by interlocking (Dierichs & Menges, 2017).

Jammed Architectural Structure (JAS) is a novel robotic fabrication method developed by Gramazio Kohler Research group at ETH. It is defined as a material system that constructs freestanding and fully reversible jammed structures with robotically placed string as confinement. In contrast to the membrane constraints discussed earlier, no external confinement is required to construct large freestanding and fully reversible aggregated structures. Instead of a membrane, the structures are constructed with robotically placed string as confinement. String is placed in a circular pattern by a robot arm. Then material is directly deposited on the string where it is compacted by the robot. Tensile strength is provided by the string.

Its placement will decide where in the structure the material will hold and where it will not. The fabrication process is repeated until the aggregated structure is completed. When completed, the structure becomes loadbearing. The structure will increase its strength the more load it is subjected to. Geometrical articulations and openings can be created with this type of system. The research group investigated several possible material combinations to find the most suitable working with JAS. They found that the most optimal materials were crushed rock and standard concrete particles, as these were the hardest and most form-stable aggregates (Aejmelaeus-Lindström et al., 2016). JAS was used in the construction of installation Rock Print and Rock Print Pavilion by the same research group.



String is placed in a circular pattern by an in-situ fabricator

The bulk matter is deposited between the string layers

The material is compressed by a compactor and all steps are repeated until the structure is completed

Steps of the JAS fabrication process (Illustration: Aejmelaeus-Lindström et al., 2020)

DRY STONE STRUCTURES

To build without any fasteners or binding agents is not unheard of, there have been many examples throughout history showing the possibilities of constructing without any permanent bonding. One example of it is Dry stone architecture. It is a building method in which stone is stacked one on top of the other without any mortar. The construction technique has been around for millennia and can be found nearly everywhere in the world. From Etruscan walls in Tuscany to the settlements in Machu Pichu. They are usually built with locally sourced stone. Considering no binder is required, the structure can be disassembled, and the stones can be repurposed elsewhere. Creating friction between every piece of stone is needed for the method to work. The friction created between the stones prevents them from moving away from each other and the weight of them increases the friction (Dobbins, 2018). The key concept is very similar to granular jamming: when the stones are interlocked by friction, every individual stone piece stops to act independently and together they start to act like a solid body, like one large stone.

The drystone wall is considered one of the more familiar examples of drystone structures. It has a wider bottom with larger pieces of stone to provide support for the upper layers. The wall characteristically has a batter, where the top of the wall always becomes narrower than the bottom (Dobbins, 2018).

Pagghiare and Trulli are two other examples of drystone structures, and both can be found in the south of Italy. Despite being located in the same region, the two building typologies have ended up with a different structure, functionality and architectural complexity (Todisco et al., 2017).

The Pagghiare were used for temporary storage of farming tools. They were constructed as single enclosed cell with one dome without any cluster. In contrast to Trulli, the Pagghiare were only built with rough and semi-shaped stones found on site (Todisco et al., 2017).

Trulli (singular, trullo) only used hand-worked and well-formed stones. They have been used both as animal shelters, storage for agricultural tools and as housing. They are still being built today. The origin of the Trullo is unclear but one of the most popular theories is that they were built without any mortar so that they could be taken apart quickly to avoid visiting tax inspectors. The Trulli were distributed as clusters. Their spatial complexity varied from one single cell to multiple cells that are connected between different domes (Todisco et al., 2017).

Pagghiare (Photo: Psymark, 2011)

Trulli in Alberobello (Photo: Niels Elgaard Larsen, 2006)


SITE
HONG KONG
22° 16' 51.85408", 114° 16' 52.3913"

HONG KONG

Hong Kong is a high-density populated city where most residents live on only one-quarter of the city's land. In comparison to other major cities, Hong Kong's level of open spaces, that are accessible to the public, is very low (Lai, 2017).

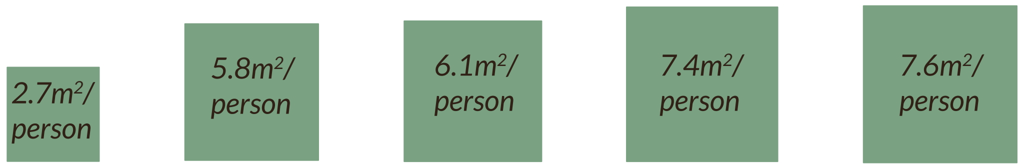
Open space is defined as a space that serves a recreational purpose in urban and populated rural areas. The residents in Hong Kong only have 2.7-2.8m² open space per person. In comparison to other Asian cities like Tokyo, Seoul, Singapore, and Shanghai, where people have between 5.8m² and 7.6m² open space per person (Lai, 2017). Compared to the population in the largest urban areas in Sweden, that have on average 183m² open space per person (Statistiska centralbyrån, 2015). The few open spaces that Hong Kong does have are poorly planned or not user-friendly (Lai, 2017).

The existing open spaces are often underused because of the unfavourable climate conditions caused by the urban heat island effect. The cities' built-up areas are exposed to excessive heat that increases the risks of heat strokes and exhaustion among the residents (The Hong Kong Polytechnic University, n.d).

These two existing conditions in Hong Kong established the foundation of the proposal's design program. The design proposal aimed to create a landscape of aggregated structures that add to the currently low stock of open spaces in Hong Kong. In addition to creating a sheltering landscape that shields the visitors from overheating.

INTERNATIONAL COMPARISON OF OPEN SPACE BETWEEN MAJOR ASIAN CITIES

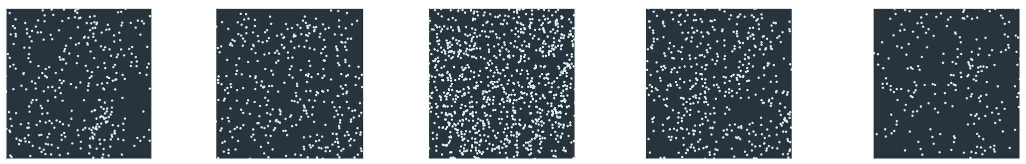
OPEN SPACE (Source: Lai, 2017)



HONG KONG | TOKYO | SEOUL | SINGAPORE | SHANGHAI

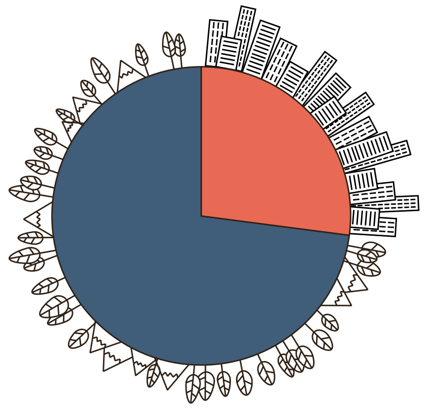
INTERNATIONAL COMPARISON OF POPULATION DENSITY BETWEEN MAJOR ASIAN CITIES

POPULATION DENSITY (Source: Wikipedia)

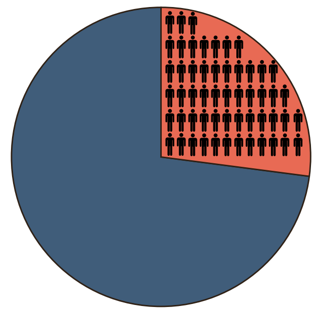


6,777/km² | 6,363/km² | 16,000/km² | 7,804/km² | 3,900/km²

LAND USAGE DISTRIBUTION IN HONG KONG



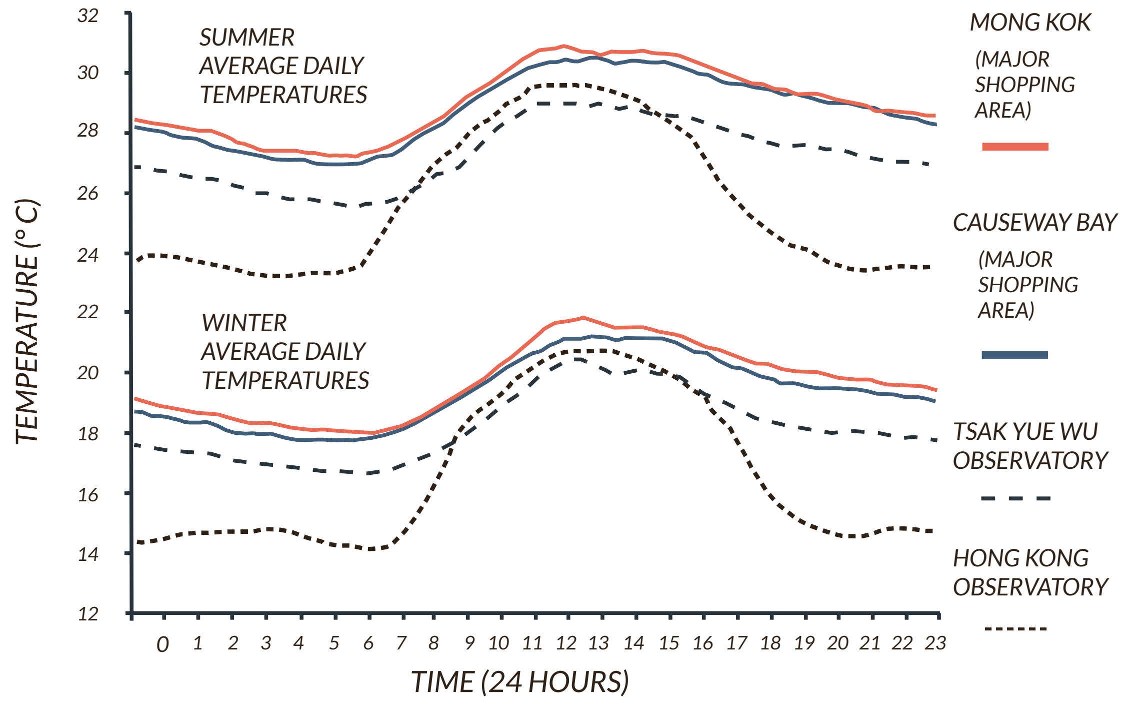
POPULATION DISTRIBUTION IN HONG KONG



(Source: Hong Kong Planning Department)

SUMMER AND WINTER AVERAGE DAILY TEMPERATURE MEASUREMENTS AT VARIOUS LOCATIONS IN HONG KONG

(Source: Wong et al., 2016)



URBAN HEAT ISLAND (UHI)

Occurs in a densely populated area with higher temperature than surrounding rural areas (Source: The Hong Kong Polytechnic University)

SENT LANDFILL

Hong Kong has earned a global reputation for its rapid construction of high-rise apartment blocks and office towers, but consequently, the high building activity has led to high levels of construction and demolition (C&D) waste disposed of at landfills.

Since the 1990s Hong Kong has had three strategically placed landfills that were designed to take care of the region's waste needs. However, today landfill space and public filling areas have almost reached their full capacities. The three landfills with their planned extensions are expected to meet Hong Kong's needs up to the 2030s. The Environmental Protection Department (2021) in Hong Kong estimates that even with reaching waste recycling goals, there will be a significant amount of construction and non-recyclable wastes that will end up in landfills.

The South East New Territories (SENT) Landfill is one of the three strategically placed landfills in Hong Kong. It is located in Tseung Kwan O at the south-eastern tip of the New Territories mainland. The landfill is wedged between the High Junk Peak Mountain to the east and the Tseung Kwan O industrial estate to the west. A popular hiking trail is located in High Junk Peak, and it overlooks the landfill along with the Clear Water Bay and the immense Pacific Ocean (Hong Kong Tourism Board, 2021).

Since January 2016, SENT Landfill has only received construction and demolition waste. Both inert and non-inert C&D waste is disposed of at the landfill. Inert waste is defined as waste that will not decompose or only decompose very slowly. Waste such as concrete, rubble and earth are considered inert substances. Over 90% of all C&D waste is considered inert. Non-inert substances are defined as organic materials such as bamboo, timber and vegetation. They are materials that will decompose or can easily be reused or recycled (Environmental Protection Department, 2020).

SENT Landfill is scheduled to be put out of commission within twenty years. It has been dimensioned to take the load of the disposed waste but not for any future large-scale buildings such as high rises. Currently, there are no definitive plans of SENT Landfill's future after its use.

However, there was a speculative proposal showing the possible development of the landfill and its surroundings. It showed the landfill as an open space for recreation and parts of its surroundings as reclaimed for more housing.

Panoramic of SENT Landfill from High Junk Mountain Trail (Photo: Minghong, 2010)

Current waste intake: *about 1,950 tonnes per day*
Area: *100 ha*
Capacity: *43 Mm^3*
Aftercare: *30 years after completion of operation*
Source: Environmental Protection Department, 2021)

Speculative proposal of how SENT Landfill and its surroundings might look one day (Photo: Farrells, 2018)

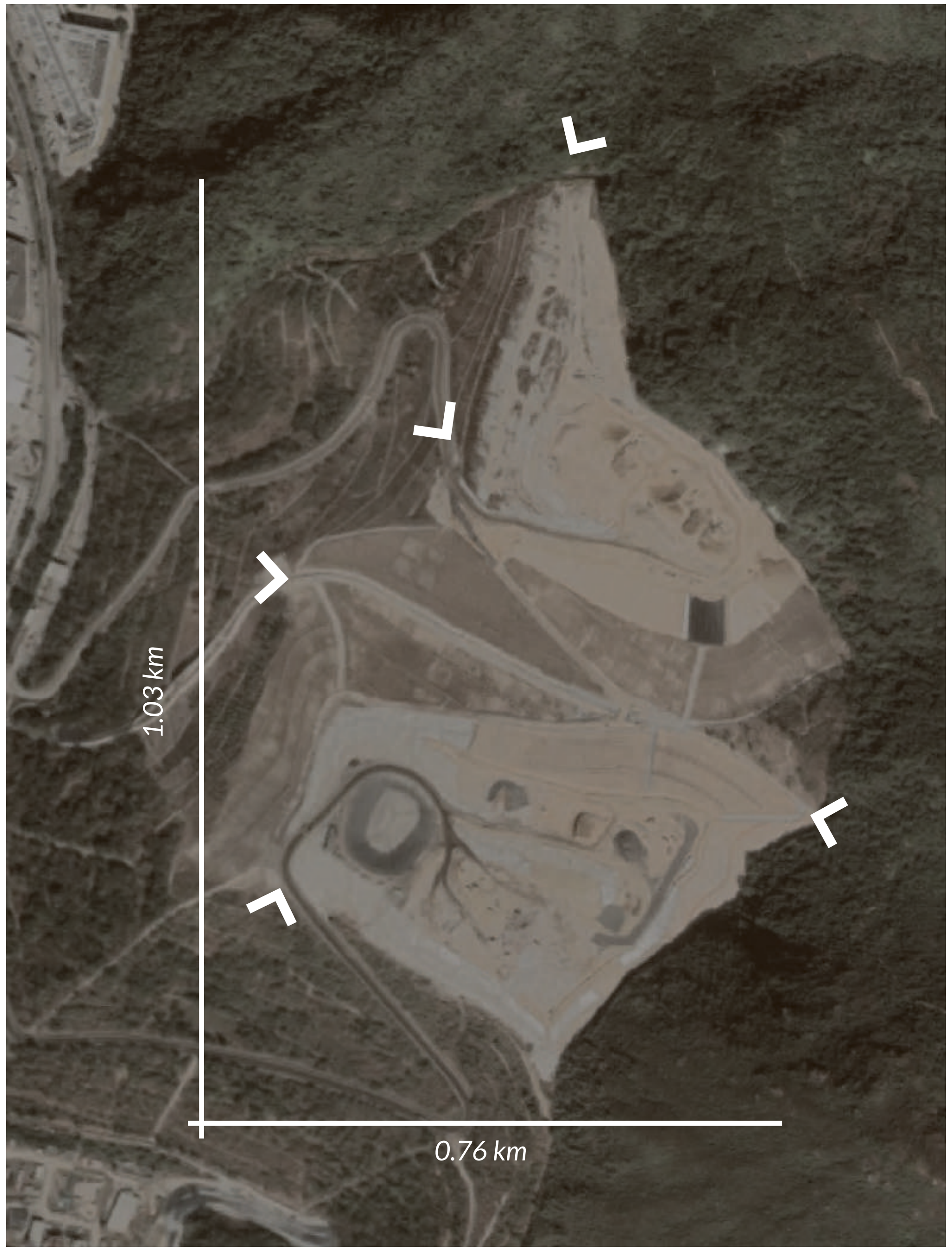
The location of the SENT Landfill in Hong Kong

Close-up of the site and its surroundings

The site and its relation to local attractions

SITE ANALYSIS

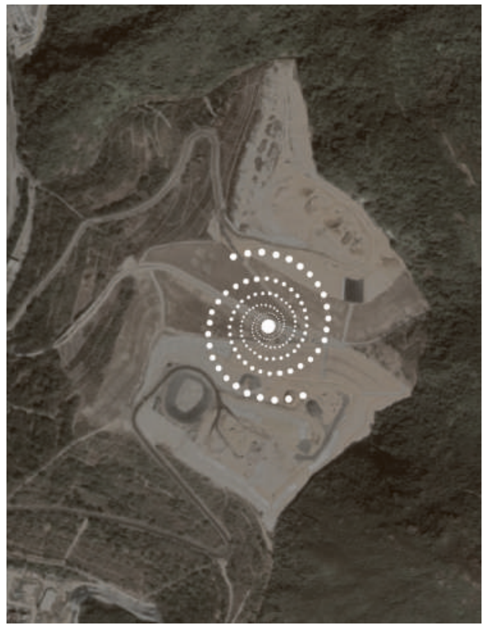
SENT Landfill is a large-scale site with five different entry points. The topography of the site itself is mostly flat. There are two entry points from the pathways leading up to High Junk Mountain trail. The other three are roads used to transport C&D waste into the site.



SITE COMPARISON

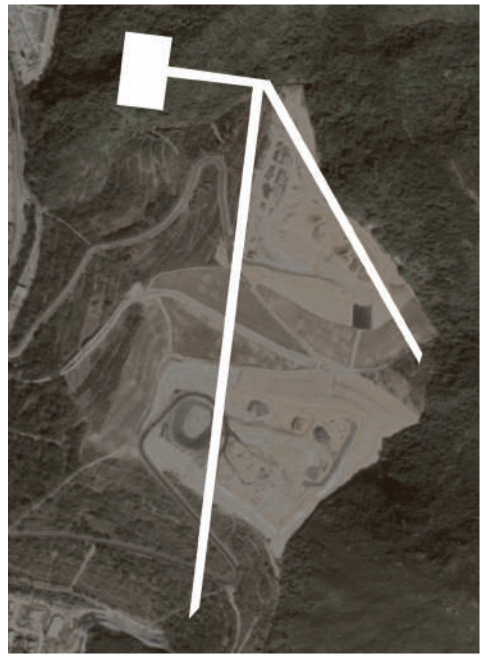
The actual scale of the site was difficult to comprehend. To better understand its amplitude, it was compared to four large-scale pieces of Land art. More on Land art can be read on page 68.

Spiral jetty



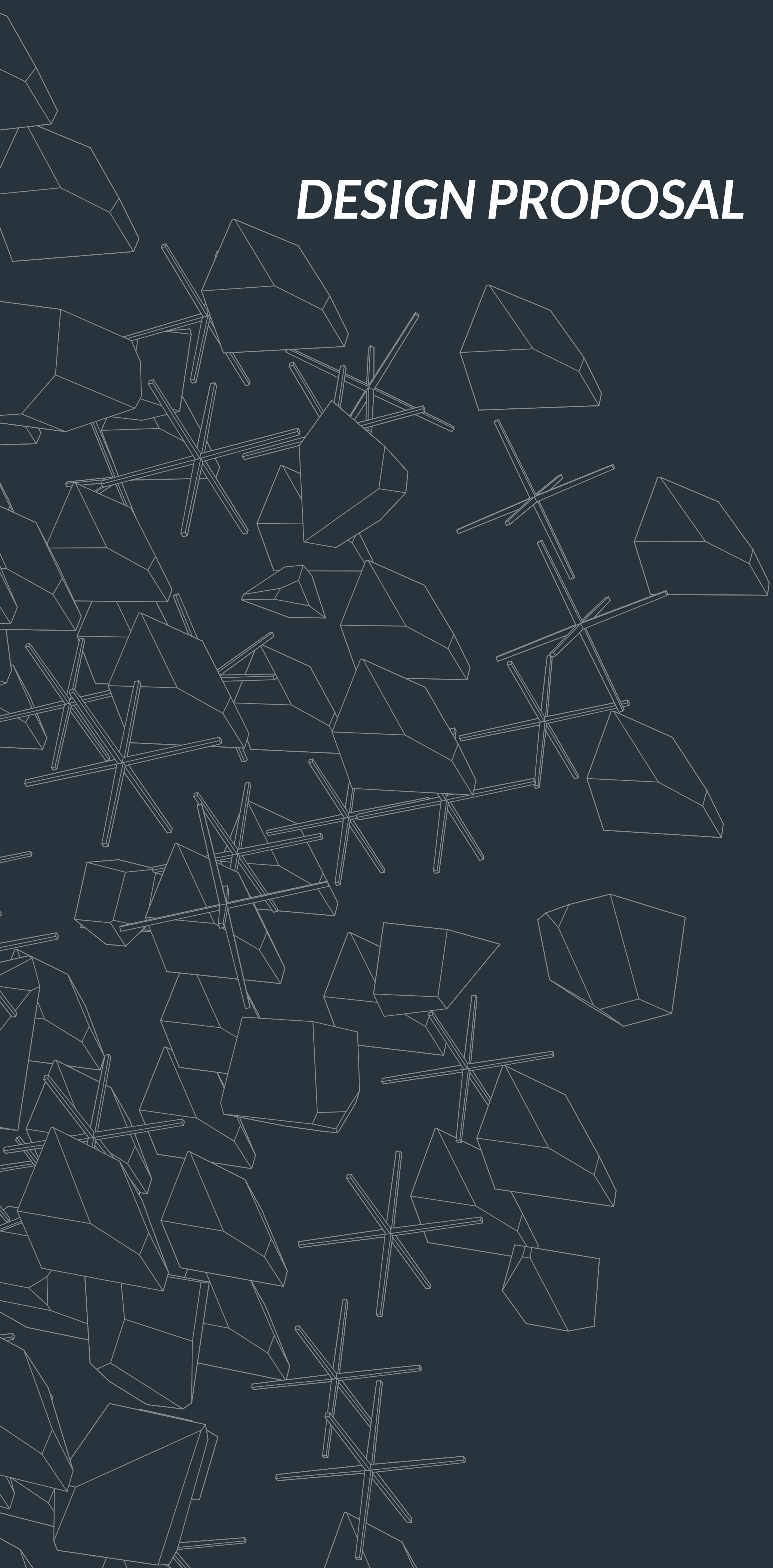
Desert breath

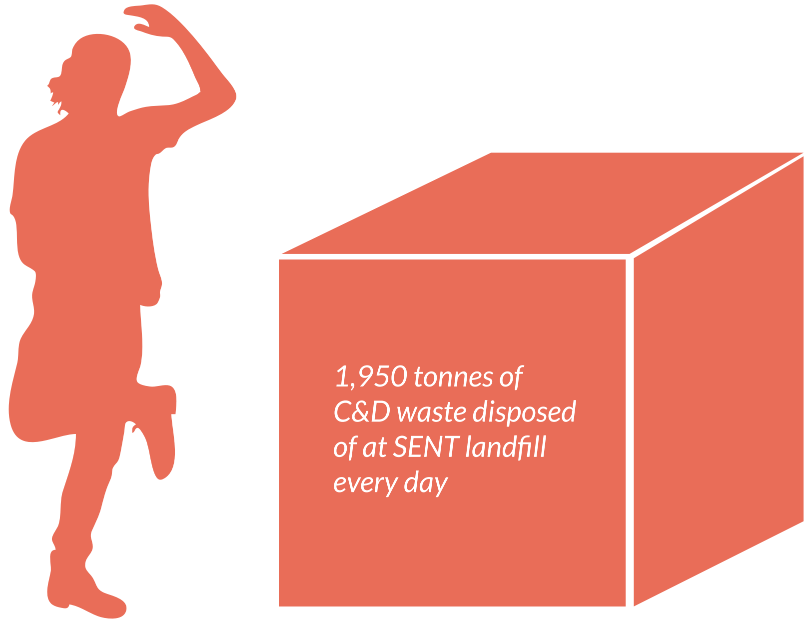
Cretto Di Burri



Floating piers

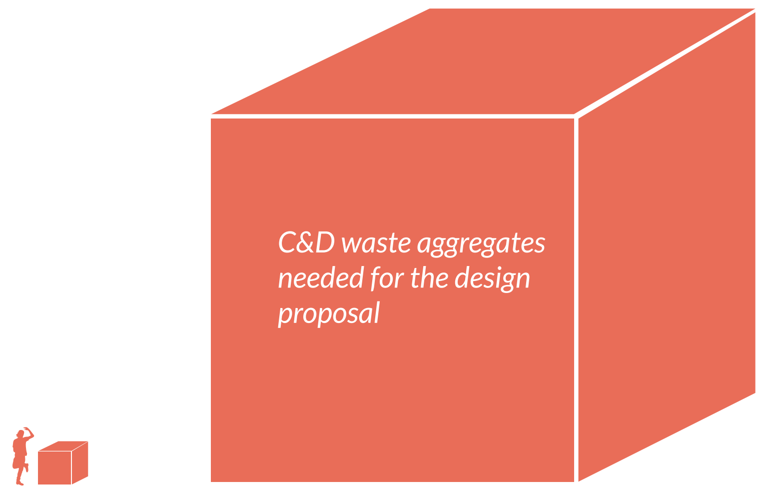
DESIGN PROPOSAL





The density of concrete (2400kg/m^3) was used to calculate and represent the cubic meter of received C&D waste

One cubic meter represents the daily amount of C&D waste that is disposed of at SENT Landfill



The cube to the right represents the five years of accumulated C&D debris needed for the design proposal

PANORAMIC VIEW FROM HIGH JUNK PEAK MOUNTAIN TRAIL

The landscape is situated between the mountain trail and the industrial estate down below. A panoramic view of Junk Bay and the skyscrapers of the Hong Kong Island can be seen at the site. Along with the vast view of the Pacific Ocean. The design proposal is a landscape created by aggregated structures that add to the currently low stock of open spaces in Hong Kong and shelter visitors from the heat. The structures are made from different types of waste, both biodegradable and nondegradable.

1. West Entrance
2. Visitor Center
3. Water park
4. Food court
5. Sports and event hall
6. South auditorium
7. North auditorium
8. Aggregated pavilions made from degradable and nondegradable C&D waste

YEAR 0 - 12 / THE BEGINNING

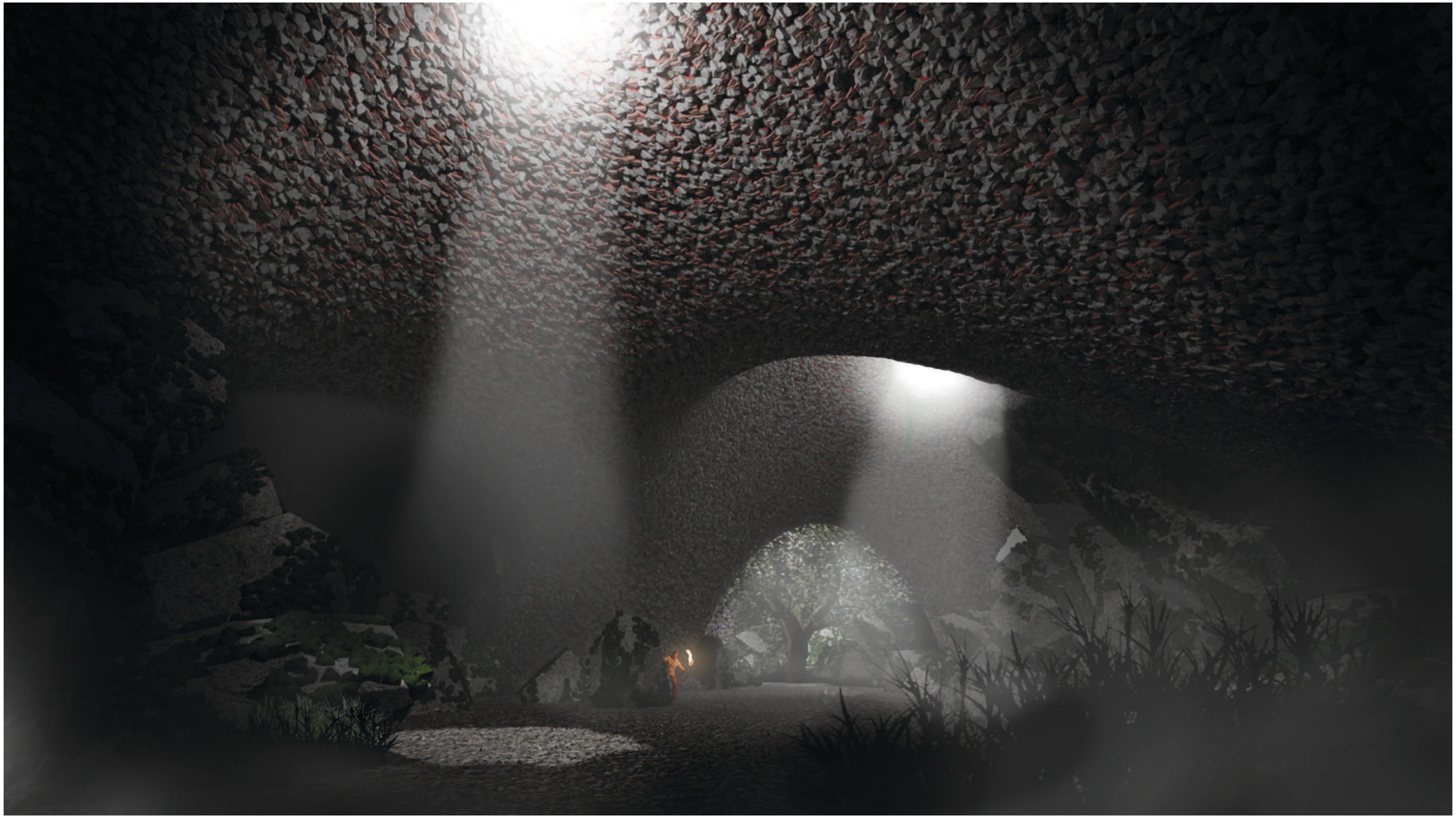
Construction of the aggregated structures seen from the west entrance of the design proposal. The landscape is slowly built from the bottom up by self-operating in-situ fabricators and landfill vehicles. The structures that formed the base of the landscape are made from nondegradable waste aggregates such as brick, concrete and tile. Different sizes and types of materials can be combined to create various surface finishes and effects.

The Visitor Center is seen from the west entrance. It is constructed with designed particles from bamboo waste. Since bamboo is biodegradable, the visitor center can be fully decomposed within months or years. The structure will break down into earth which could used for greenery. When the center has turned into earth, a new visitor center could be redesigned to take its place. This way, a new center can be created every other year to showcase new forms and ways of building with C&D waste.

YEAR 12 - 100 / A PUBLIC SPACE

The aggregated structures seen from the inside. The interior space becomes clearly defined by the dome construction of the aggregated structures. The insides of the domes are filled with different types of activities. Since the construction technique makes openings possible, daylight can be poured into the structure. The aggregated domes create a space that is sheltered from the outside heat.

Different types of C&D material can be assigned to different domes and activities to make it easier for visitors to navigate inside the structures. The domes in the foreground are made from a mixture of concrete and glossy red tile while blue tile is used for the dome in the background.



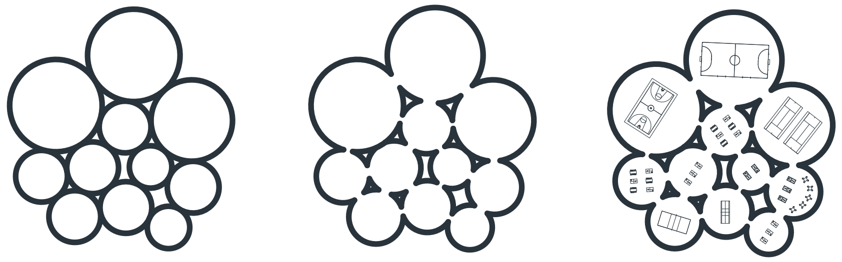
YEAR 100+ / PASSAGE OF TIME

The aggregated structures seen from the inside. The interior space becomes clearly defined by the dome construction of the aggregated structures. The insides of the domes are filled with different types of activities. Since the construction technique makes openings possible, daylight can be poured into the structure. The aggregated domes create a space that is sheltered from the outside heat.

THE AGGREGATED DOME

The design of the aggregated dome came as a result of the material experiments and research previously conducted. The material model with a symmetrical overhang showed the possibility of overarching and with that the idea of an aggregated dome structure was born. Using photogrammetry, the photos of the model were turned into a 3D-model. The model was digitally revolved 360° to show what an aggregated dome would look like.

The aggregated landscape is made up from various sized domes that are placed together to create a cluster. Connections are made between the domes and the interior spaces are filled with different public functions. Dome structures are placed on top of each other to create the topography of the aggregated landscape.



CLUSTER OF DOMES

A completed aggregated dome

Various spatial configurations are created by the domes placed together

The void between the domes is filled with earth and finer particles to create a ground for an upper level or for a park

An extra level of aggregated domes is placed above the structures below

DEGRADABLE AND NONDEGRADABLE DOMES

The various types of C&D waste decompose at different rates. Nondegradable waste has considerably longer decomposition time than degradable ones. The latter one can, given the right conditions, completely break down into earth. Their different character makes them suitable to be used in different parts of the aggregated landscape.

Since the nondegradable waste does not decompose, they are used to form the under-structure that supports the landscape above. Degradable aggregates are used above ground to shape temporary pavilions. Over time, these pavilions will decompose and create pocket parks.

Different C&D waste aggregates can be combined in various ways to create different façade expressions throughout the aggregated landscape.

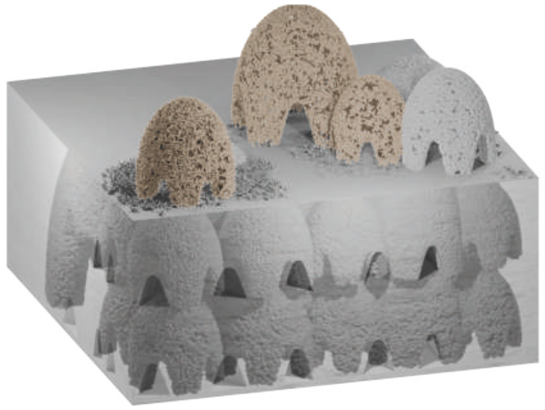
	WASTE ITEM	*DECOMPOSITION TIME*
Degradable	*Bamboo*	*4 months - 3 years*
	Plywood	*1 - 3 years*
	Lumber	*10 - 15 years*
	Rope	*3 - 14 months*
Nondegradable	*Monofilament fishing line*	*600 years*
	Plastic	*10 - 1000 years*
	Glass	*1 million + years*
	Brick	*n/a*
	Clay tile	*n/a*
	Glazed tile	*n/a*
	Concrete	*n/a*

(Source: Leblanc, 2021)

Regular and patterned tiles

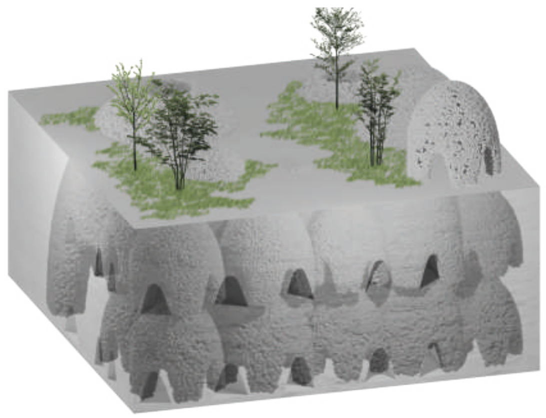
Plywood

Concrete



Degradable pavilions are placed above the nondegradable clusters of aggregated domes

After x amount of time, parts of the degradable structure have been broken down

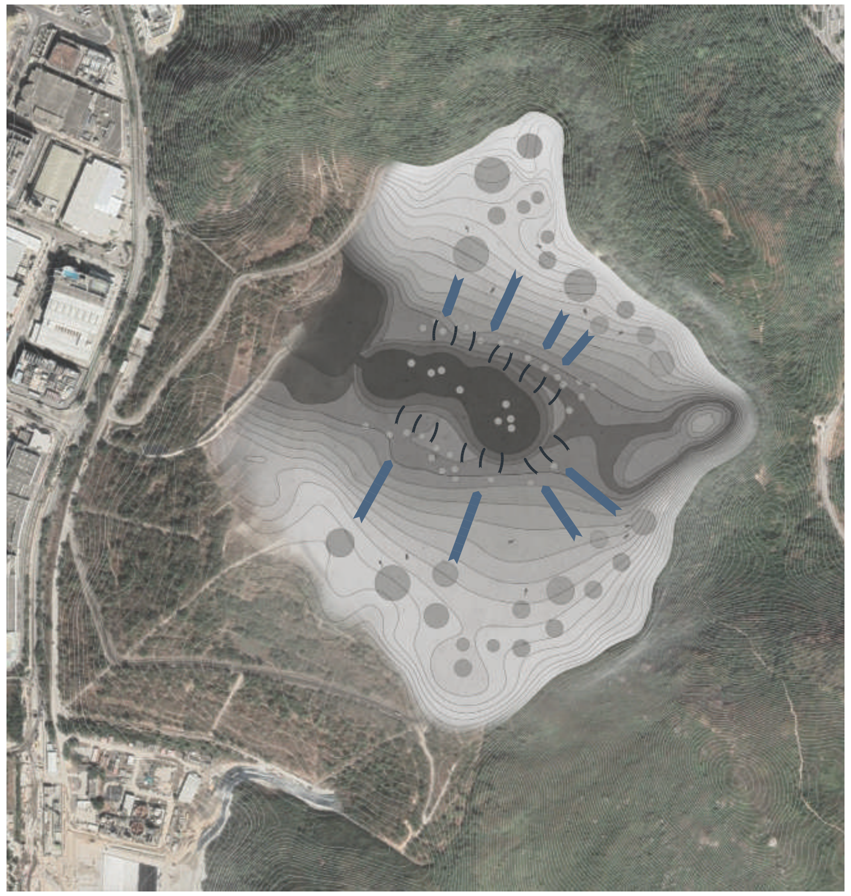


The areas in which the degradable pavilions have decomposed into earth, have turned into pocket parks

AS TIMES GOES BY

YEAR 0 - 3 / THE BEGINNING

The construction of the aggregated landscape is divided into different stages. This diagram shows the first phase in which the west entrance is built. The structures are assembled around the open space in which the Visitor Center will be placed. The landfill is still active during the construction and visitors are not allowed on the site. The C&D waste that is received is deposited in piles around the aggregated structures.



YEAR 0 - 3 / ROBOTIC AUTOMATION

The deposition of the aggregated structures is fully automated with self-operating in-situ fabricators and landfill vehicles. The diagram shows their function and how they are operated on site. Tasks are communicated and performed between the different operating machines using sensors. The in-situ fabricators are used to build the structures while the bulldozers, excavators and trucks are used to provide granular materials to the fabricators.

YEAR 3 - 6 / OPEN TO THE PUBLIC

In this phase the structures at the west entrance are completed and is open to the public. During construction, ramps were built into the landscape as a way for the robot arms to transport themselves around the structure. As the fabricators have moved onto a new area, the ramps are available and can be used by the visitors. The landfill is still active and the area outside the newly built structures is closed to the public as it is an on-going construction site.

DUMP TRUCKS

EXCAVATORS & BULLDOZERS

IN-SITU FABRICATORS

OFF-SITE SORTING FACILITY

Considering the automated setup, the tasks can be optimized to improve the workflow on the construction site. Since in-situ fabricators can handle precision-based work and be customized with different tools, they are used to construct the aggregated structures. Self-operating bulldozers and excavators are used to handle the granular material and provide it to the fabricators. Before arriving at the site by dump trucks, the C&D waste is separated and cleaned at an off-site sorting facility.

YEAR 0 - 12 / SECTION

Multiple self-operating machines are used to construct the West Entrance and the surrounding aggregated domes.

YEAR 6 - 12 / HALFWAY POINT

The landscape has reached a halfway point. The Water Park and North Amphitheatre have been added to the available public functions. Road connecting the landscape to the hiking trail have been made to allow visiting hikers a break for rest and play.

Aggregated structures made from biodegradable C&D waste are placed all over the landscape. They are degraded into earth and eventually become pocket parks. The biodegradable structures are continuously constructed on different locations around the site. Over time, the pocket parks will become bigger and form a continuous green space on the site.

YEAR 12 - 25 / COMPLETION

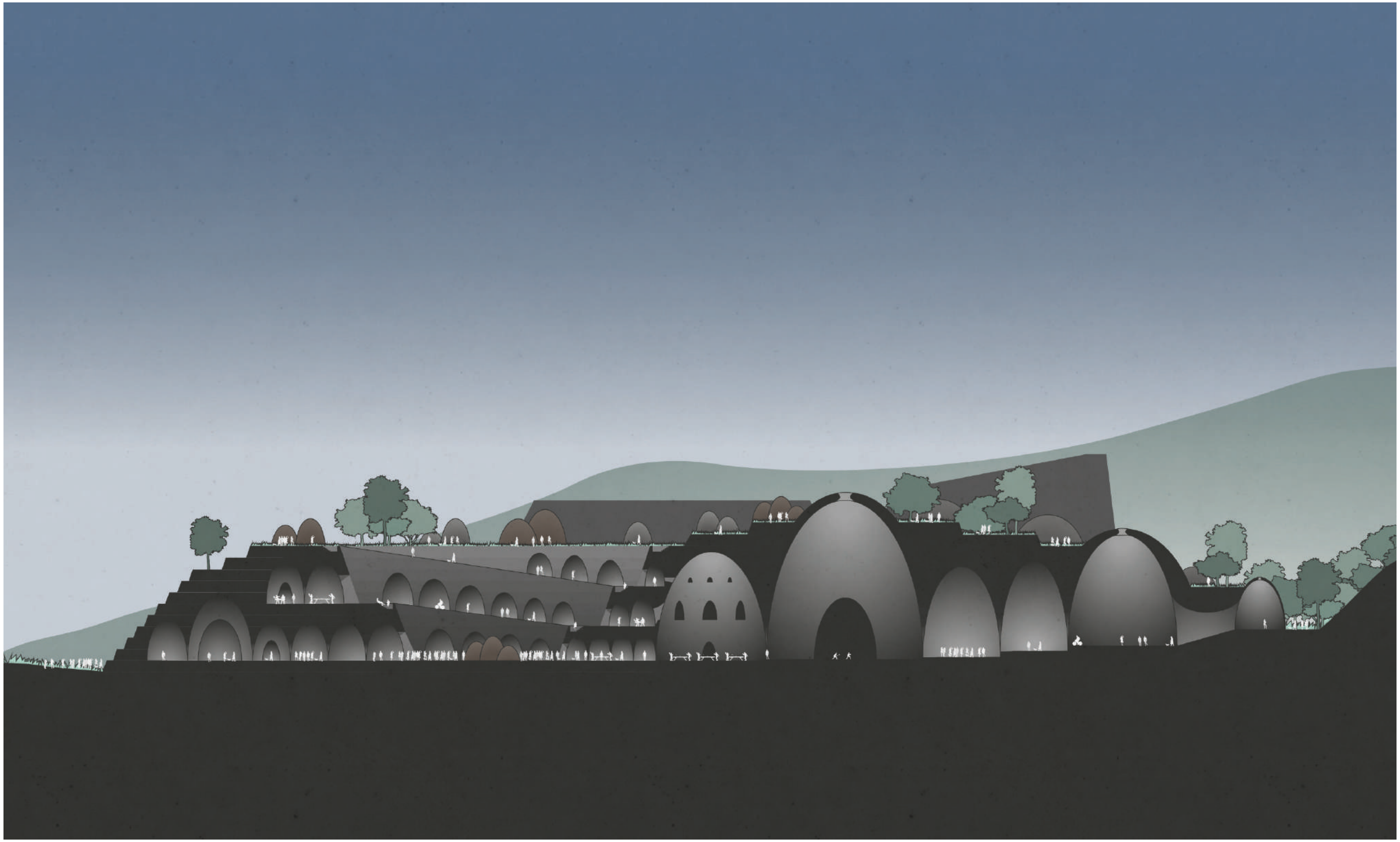
The landscape is finished. In this stage the landfill has become deactivated, and the in-situ fabricators and landfill vehicles have left the site. The whole site has now become available to the public. The site is covered with layers of aggregated structures that provide spaces for various activities.

A Sports and Event Hall have been added along with a South Amphitheatre. The west perimeter that is created offers a boardwalk along the border. The west perimeter is designed with spaces for seating and activities that offer a panoramic view of the Pacific Ocean.

YEAR 25 - 100 / REPOSITORY

Besides providing spaces for shelter and public activities, the aggregated structures functioned as a repository. As advancements in fabrication technology and sustainable materials have been made, parts of the aggregated landscape are dismantled to be used elsewhere, for example in another structure or as part of a new material.

In this diagram, the area south of the West Entrance has become an active repository. The aggregated structures have been disassembled by in-situ fabricators and the material have been transported elsewhere in Hong Kong.

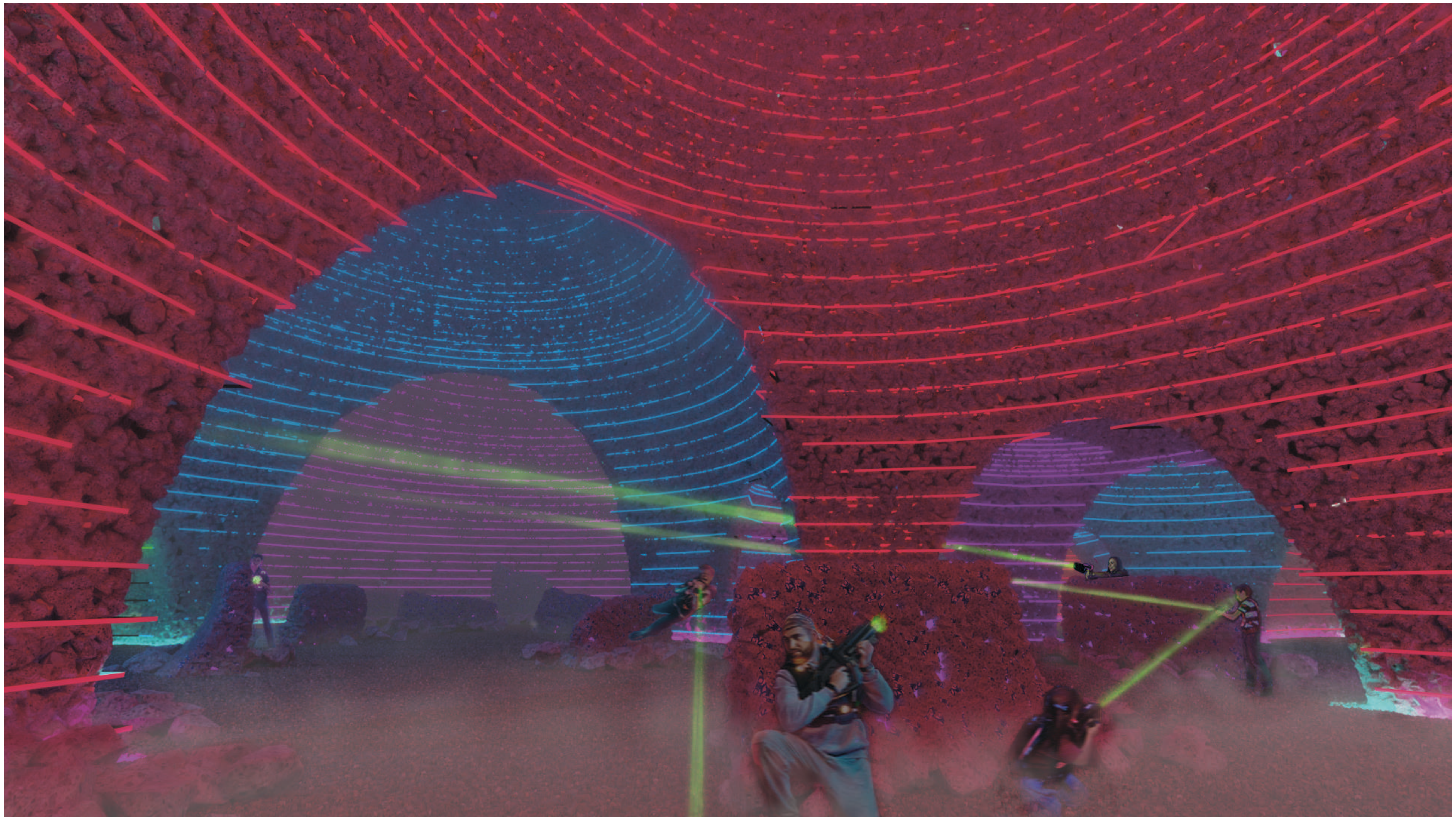


YEAR 12 - 50 / SECTION

The aggregated landscape is completed and can be accessed by the public. The site is covered with layers of aggregated domes that provide dynamic spaces for various activities and social settings.

YEAR 12 - 100 / OPEN SPACES

The aggregated structures are distributed around predefined open spaces. A variety of activities and functions are enabled by the open spaces. Some which are site specific to East Asia such as Tai Chi, dancing, sword dancing, calligraphy and wushu. High Junk Peak can be seen in the background.



YEAR 12 - 100 / MULTIPURPOSE

Different types of string, such as neon flex rope or others with built-in LED lamps, can be used to create dynamic environments inside the domes.

YEAR 100 - 300 / NATURE TAKES OVER

Nature has slowly taken over and the green spaces have been expanded from pocket parks into a continuous park space. The green spaces have become integrated with the surrounding landscape.

The roots from the trees have dug deep into the structure and made them structurally stronger. While in other parts, the string has completely eroded, and the roots have replaced it as reinforcement. Parts around the open spaces have eroded and created natural grooves that collect rainwater.

YEAR 300 - 600 / COLLAPSE OF STRUCTURES

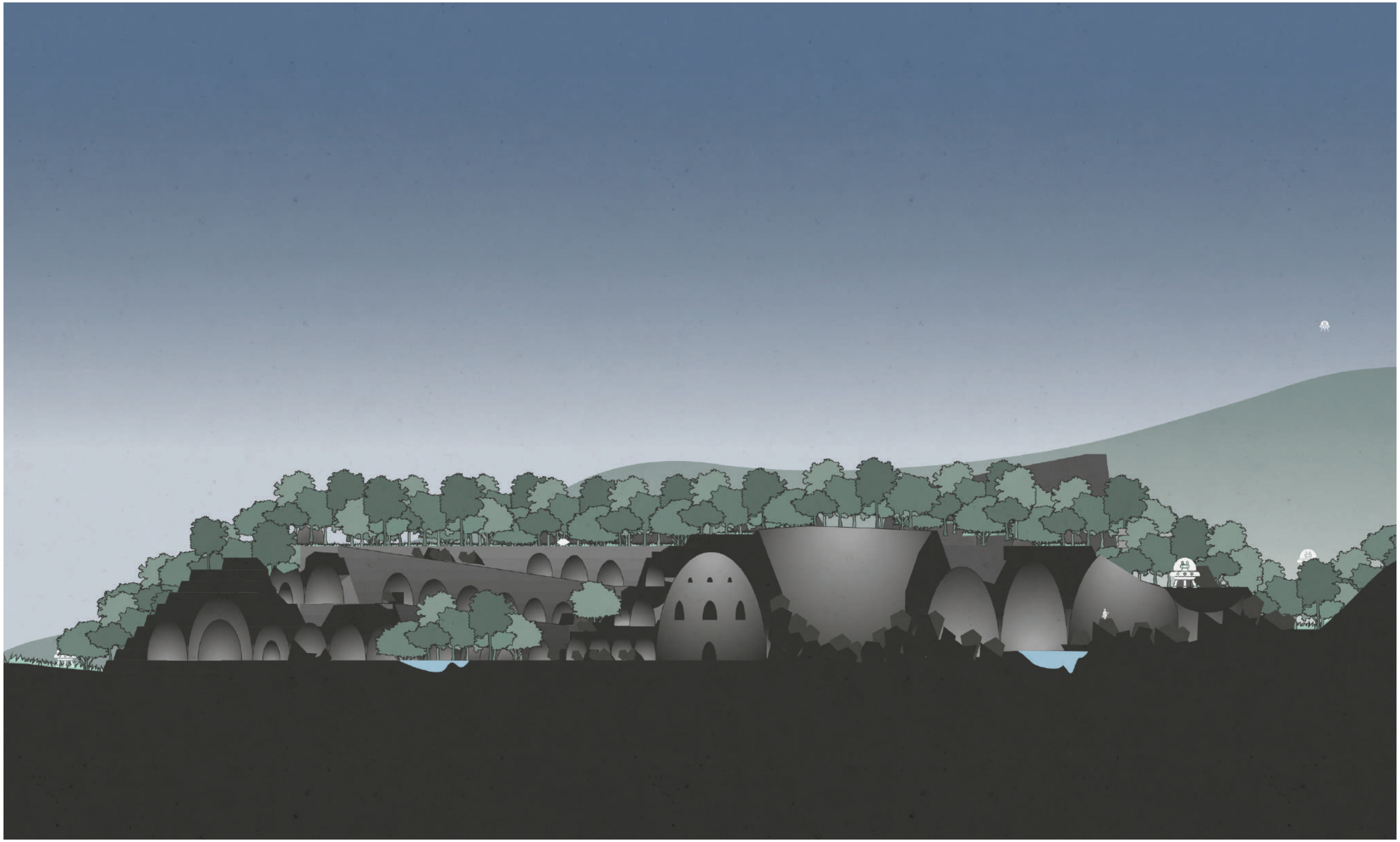
Over time parts of the aggregated landscape are broken down as the string and aggregates are naturally eroded by biological mechanisms or as the structures are subjected from wear and tear damage.

Some of the aggregated domes have completely collapsed and left gaping holes in the landscape. The structures below the surface of the landscape have been left empty since parts of it started to break down and collapse.

YEAR 600+ / REDISCOVERY

The landscape has stood empty for centuries. It stands as a reminder of an earlier civilization with an abundance of waste. It has become a ruin that is waiting to be rediscovered by someone or something.

In this diagram, the site has been re-colonised, and a new settlement has been integrated with the aggregated landscape. The long history of the site and the surviving aggregated domes can now be revived and become a part of something new.



YEAR 100+ / SECTION

Nature has reclaimed the site along with the aggregated structures. The site has become a ruin awaiting to be discovered.

YEAR 600+ / REDISCOVERY

After hundreds of years have passed, nature has spread and covered most of the site. Some of the aggregated domes have collapsed and left gaping holes in the landscape. While others have survived and been reinforced by tree roots.

The remains of the aggregated landscape stand as a reminder of an earlier civilization with an abundance of waste. It has become a ruin that is waiting to be rediscovered by someone or something. Far into the future the aggregates or the surviving structures could become a part of something else.

PRECEDENTS

LAND ART

Land Art is an art movement that emerged in the late sixties and seventies. It took its inspiration from the environmental movement of the sixties and the growing awareness of the human impact on the planet. The artists of the movement made their artwork outside gallery and studio spaces, directly involving the landscape and often in remote locations. They often made use of natural materials found in the landscape in their work (The Art Assignment, 2018).

This master thesis looked into Land Art to explore the potential of working with a waste landscape as both site and material. The transient qualities found in some of the Land Art references were used as an inspiration to understand the design proposal as a landscape that experiences the passage of time. A landscape that could change over time as it is subjected to the natural processes and human intervention. Additionally, the references helped to better understand the scale of the design proposal in relation to the site.

Spiral Jetty by Robert Smithson is considered one of the best-known works of the movement. The spiral was constructed in 1970 on the shore of Great Salt Lake in Utah. Over 6,000 tons of earth and black basalt rocks formed the coil. The visitor is invited to take a walk along the spiralling pathway and directly experience the lake from different viewpoints. The sculpture was submerged in water a couple of years after its completion, but it re-emerged in 2004 when drought made it visible again. Spiral Jetty fades in and out of the landscape as it is subjected to the constant flux of nature and time (The Art Assignment, 2018).

Some of the Land Art were monumental and aspired for permanence such as Alberto Burri's Cretto di Burri in Gibellina, Sicily. Cretto di Burri was built on the ruins of the small town Gibellina that was destroyed in the earthquake of 1968. It is in essence a memorial place that conceptualizes the trauma and loss of the disaster. Burri created a white concrete landscape labyrinth that spanned over 85,000 square meters. The concrete landscape mirrored the old town's city plan. The visitors are invited to walk around on the lost streets (Cao, 2021).

Similar to Spiral Jetty, Desert Breath by D.A.ST. Arteam worked with the passage of time in their installation. Since its completion it has slowly started to disintegrate due to natural erosion (D.A.ST. Arteam, n.d). Other artwork in the movement were light and ephemeral installations such as Floating Piers by Christo and Jeanne Claude (The Art Assignment, 2018).

Spiral Jetty (Photo: George Steinmetz, 2002)

Desert Breath (Photo: D.A.ST. Arteam, 1997)

Cretto di Burri (Photo: Getty Images, n.d.)

Floating Piers (Photo: Linoolmostudio, 2016)

ROBOTICS IN ARCHITECTURE

Robot - ro·bot
Machines that resembles a living creature in being capable of moving independently and performing complex actions.

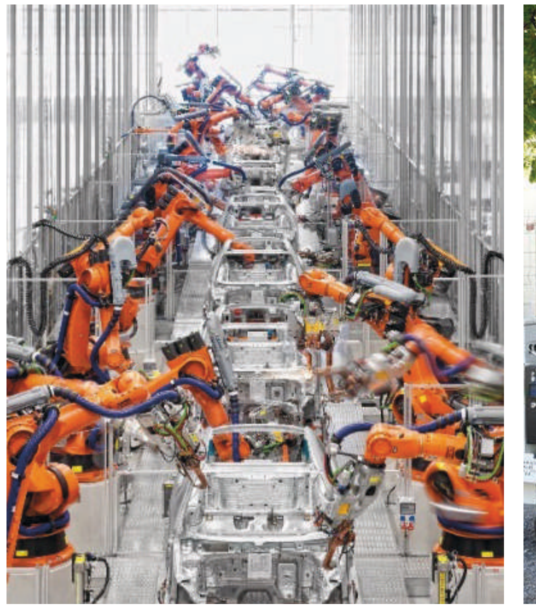
- Merriam-Websters dictionary

In architecture robotics is more often referred to as programable automated machines such as robot arms, CNC milling machines or 3d printers. Robots come in a wide range of shapes from large scale industrial robot arms to in-situ fabricators working directly on the construction site to humanoid robots to collaborating drones like the Fiberbots by MIT. Some robots have even become a part of our homes. From automated shading systems to smart home assistance. The advantages of robotics in architecture are vast. Not only have they lead to substantial time and cost savings in fabrication, but they enable digital information and a range of construction principles to be connected directly to the fabrication process. Ultimately, as the field of robotics has evolved rapidly over the years, it has become easier to re-imagine a future in which the robots of science fictions are realized.

The robots are controlled by algorithms that can generate digital blueprints. The blueprints are flexible and can react to external input received by sensors. Thus, the robot can get precise readings of the construction site in real-time, and the blueprints can be digitally adjusted to correct any possible building error.

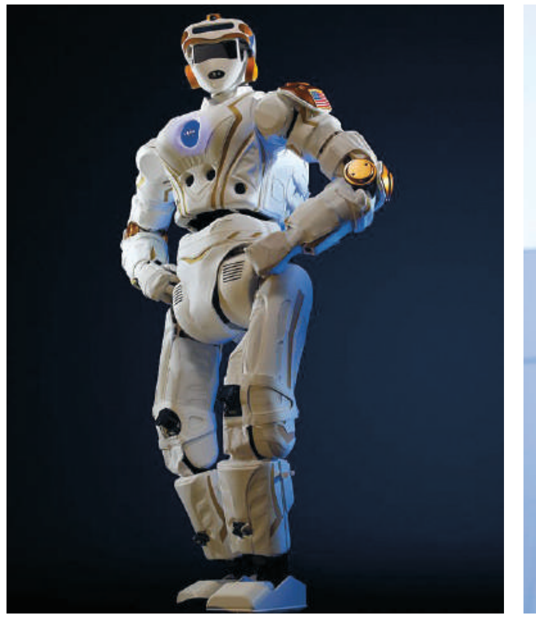
This thesis project explored how the deposition of waste at a landfill can become fully automated with self-operating in-situ fabricators and landfill vehicles. Tasks can be communicated and performed between the different operating machines by using sensors. Considering the automated setup, the tasks can be optimized to improve the workflow on the construction site.

The in-situ robot arm developed by ETH, was used as a reference in the design proposal. Since in-situ fabricators can handle precision-based work and be customized with different tools, they were used to construct the aggregated structures. Self-operating bulldozers, excavators and trucks were used to provide granular materials to the robot arms. Additionally, they were used to deposit the C&D waste into piles until the materials were needed elsewhere. If building materials stored in the aggregated structures were needed elsewhere, the structures would be reversed by removing the string.

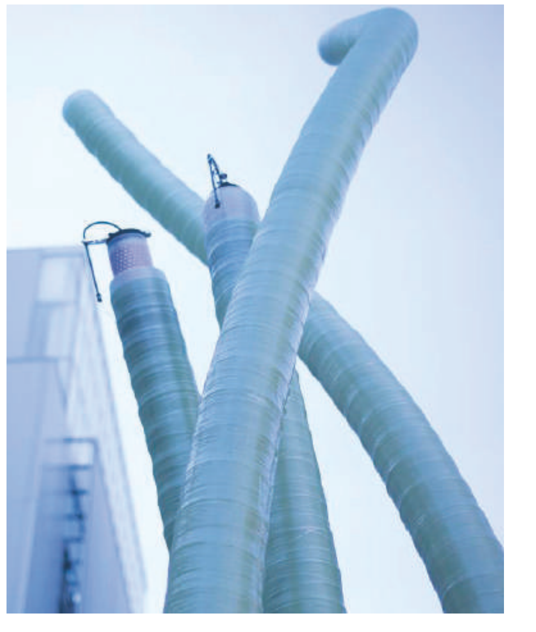


Industrial Robots (Photo: Audi, n.d.)

In-situ Fabricator (Photo: Gramazio Kohler Research, 2018)



NASA's Humanoid Robot Valkyrie (Photo: NASA, n.d.)



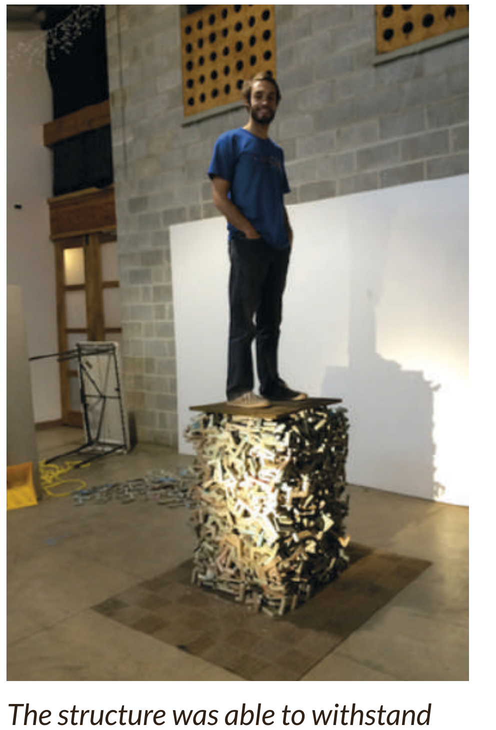
Fiberbots (Photo: The Mediated Matter Group, n.d.)

DESIGNED MATTER

Designed granular materials are individually designed and prefabricated particles that can self-confine by interlocking with one another without any fastening or bonding agent. Research conducted at ICD Stuttgart and Jaeger Lab has explored its possible architectural application. Different spatial forms and porousness can be created by modifying the shape of the aggregate and the deposition method (Rusenova, 2020). For example, specific light transmissions be achieved when the concentration and flow of the aggregates are varied during the constriction process (Dierichs, 2015). Large quantities of designed particles are required to build on an architectural scale. The particles used in research projects have either been time-consuming and labour-intensive (laser-cutting and gluing) or expensive (3D-printing or injection-moulding) or used synthetic materials (Rusenova, 2020). Research has shown that several particle shapes can self-confine but only a few of them are able to sustain additional loads beyond self-weight (Murphy et al., 2017)

Designed particles were investigated in Project Z-Form, a collaboration between the Jaeger Lab at the University of Chicago and artist Dan Peterman. The project used non-planar Z-shaped particles to create structures such as an arch and column. The Z-shape was used for its ability to withstand compression, torsion, shear and inter-particle tension. Variations of the particle and their ability to withstand load was investigated in computer simulations before a final Z-shape was chosen and fabricated. The particles were cut from recycled plastic planks, then heated and twisted to create the non-planar Z-form. The jammed structures were created by pouring the particles into a wooden mould and removing the formwork to reveal the freestanding structures. When poured, the Z-shapes entangled and self-arranged under gravity until finally jammed under their own self weight (Murphy et al., 2017). The Z-form project also showed that if structures built with granular matter are pre-stressed through compression, they will jam more deeply and thus become more structurally stable (Rusenova, 2020).

One of the structures in Project Z-form (Photo: Dan Peterman, 2017)



The structure was able to withstand load (Photo: Dan Peterman, 2016)

The designed Z-particles (Photo: Dan Peterman, 2016)

ICD AGGREGATE PAVILION

Another example of designed granular matter was explored in the ICD Aggregate Pavilion in 2015 and 2018 at the Institute for Computational Design at the University of Stuttgart. In both pavilions non-convex particles from recycled plastics were used. The aggregates were shaped like spiked stars that geometrically interlocked without any binding agent. In the first pavilion the particles were designed to shape vertical structures and to avoid the angle of repose that characteristically occurs in granular systems like sand or gravel. To construct macro-scale spaces a custom-built cable-driven robot was built. In both examples the preprogramed robot was used to pick up the particles and pour them at predefined locations to build up the structures (Dierichs & Menges, 2017). Their second pavilion was constructed with two interconnected vaults. It was the first enclosed architectural space created only with granular matter. Inflatable yellow spheres were used as temporary supports, onto which the particles were poured. The spheres were deflated and removed after the form's completion. Even though the ICD Aggregate Pavilions were built to be temporary, they demonstrate how granular matter can perform as construction materials in macro-scale architecture (Rusenova, 2020).

Add caption (Photo: ICD University of Stuttgart, 2015)

Add caption (Photo: ICD University of Stuttgart, 2018)

Add caption (Photo: ICD University of Stuttgart, 2018)

NATURAL BULK MATTER

Natural bulk matter is the other type of material included within granular matter. It is described as natural particles that are readily available in large quantities such as food grains, sand or gravel. Unlike designed matter, external confinement is required to build freestanding structures. Without any confinement, these materials are naturally only suited for slopes as in mounds, dams or embankments (Murphy et al., 2017). Loose natural particles are researched in areas such as: form-finding, formwork for geometrically complex element and as a filling material for sound isolating units (Rusenova, 2020).

An example of building full-scale architectural elements with natural particles can be found in earth-bag houses. Granular properties such as jamming can be displayed with unsaturated earth. The houses are constructed from bags layered and filled with locally available granular material such as earth, sand or rice. The unbound material is confined within the bag's membrane into units that can be stacked. Minimal formwork is needed as the bags can easily be formed into vertical walls, domes or vault structures. The construction method is expected to become a fully regulated building method in many parts of the world as it is inexpensive, easy-to-build, environment-friendly and earthquake resistant (Rusenova, 2020).

Structures with natural particles can also be found in gabions. Typically, a gabion is filled with crushed rocks in a wire cage. They are usually used as a noise barrier in the areas of landscape architecture, civil engineering and road building. Gabions became a prominent architectural feature of Dominus Winery by Herzog & de Meuron (Rusenova, 2020).

In both examples the membrane played an important role in creating freestanding and structurally-sound constructions. The membranes also became an essential part of the exterior's aesthetics. However, the reconfigurability and recyclability is partially limited when using external confinements. As opposed to structures with designed particles that can be fully reversed. Instead of external constraints, ETH developed a system called Jammed Architectural Structure (JAS) that is fully reversible. Large scale aggregated structures are formed using string as a reinforcement. JAS was used in the construction of Rock Print and Rock Print Pavilion (Murphy et al., 2017).

Construction of an earthbag house (Photo: California Insitute of Earth Architecture, n.d.)

Gabian walls as a as a architectual feature in Dominus Winery (Photo: Margherita Spiluttini, n.d.)

ROCK PRINT

Lightweight gravel was chosen for the installation Rock Print at the Chicago Architecture Biennial 2015. It became the first large scale example of the construction technique's architectural potential. The system confined the gravel with string that was placed in a preprogramed pattern by a robot arm. The string was placed in a circular pattern to provide tensile strength. The bulk matter was deposited between the string layers. The string's placement decided where the gravel would hold the material and where it would not. The fabrication process was repeated until the structure was completed. The structure became stronger the more load it was subjected to (Aejmelaeus-Lindström et al., 2017). Rock Print was built with formwork which was removed after the structure's completion. When removed, the structure's true form was revealed as the gravel that was not held together by the string's reinforcement, fell off (Rusenova, 2020).

In 2018 Gramazio Kohler Research group exhibited the Rock Print Pavilion as the first architectural space created using JAS. The project investigated how the material system could be used to create spaces that are structurally-sound and load bearing. The pavilion was placed outdoors and constructed with a mobile robotic arm. The robotic arm was designed with customized end-effector including a gravel dispensing tool, a compacting tool and a reinforcement-laying tool (Aejmelaeus-Lindström et al., 2020). The gravel was directly deposited without any formwork. After each layer of string and aggregate, the robot compacted the gravel and flattened the top surface twice (Rusenova, 2020). The compaction increased the density of the material system and created an even top surface that is good for laying reinforcement. Depending on the geometry about 10-30% of the material fell of the structure during compaction.(Aejmelaeus-Lindström et al., 2020).

In situ robot depositing string (Photo: Christian Beutler, 2018)

Rock Print
(Photo: Gramazio Kohler Research, 2015)

Construction of Rock Print Pavilion
(Photo: Gramazio Kohler Research, 2018)

COM-PACKING COMMONS

In the thesis design project Com-packing Commons, Tuan Anh Tran explored the concept of building with waste aggregates. Loose waste materials were chosen to be upcycled in order to reduce the carbon footprint of the structure. The project envisioned what kind of enclosed architectural spaces could be created with aggregated waste materials.

The proposal took its departure from the design research conducted by ETH and the ICD. The thesis project used both designed and natural particles to build aggregated structures. Their different characteristics were combined to construct various spatial element and qualities. The designed particles were given a longer shape to achieve higher and greater arches. Considering their load limitation, they were placed on a base of natural particles. JAS with gravel was used to form the foundation. The gravel also functioned as a filler material to fill the in between spaces of the structure. When the in between spaces were filled, the construction became more packed and thus more rigid. Different sizes of gravel were envisioned to create a sensory experience for visitors.

The thesis heavily relied on physical models to form the spatial configurations and to test the stability of the structure (Tuan Anh Tran, personal communication, February 20, 2021).

Models from com-packing commons (Photo: Tuan Anh Tran, 2019)

MATERIAL EXPERIMENTS

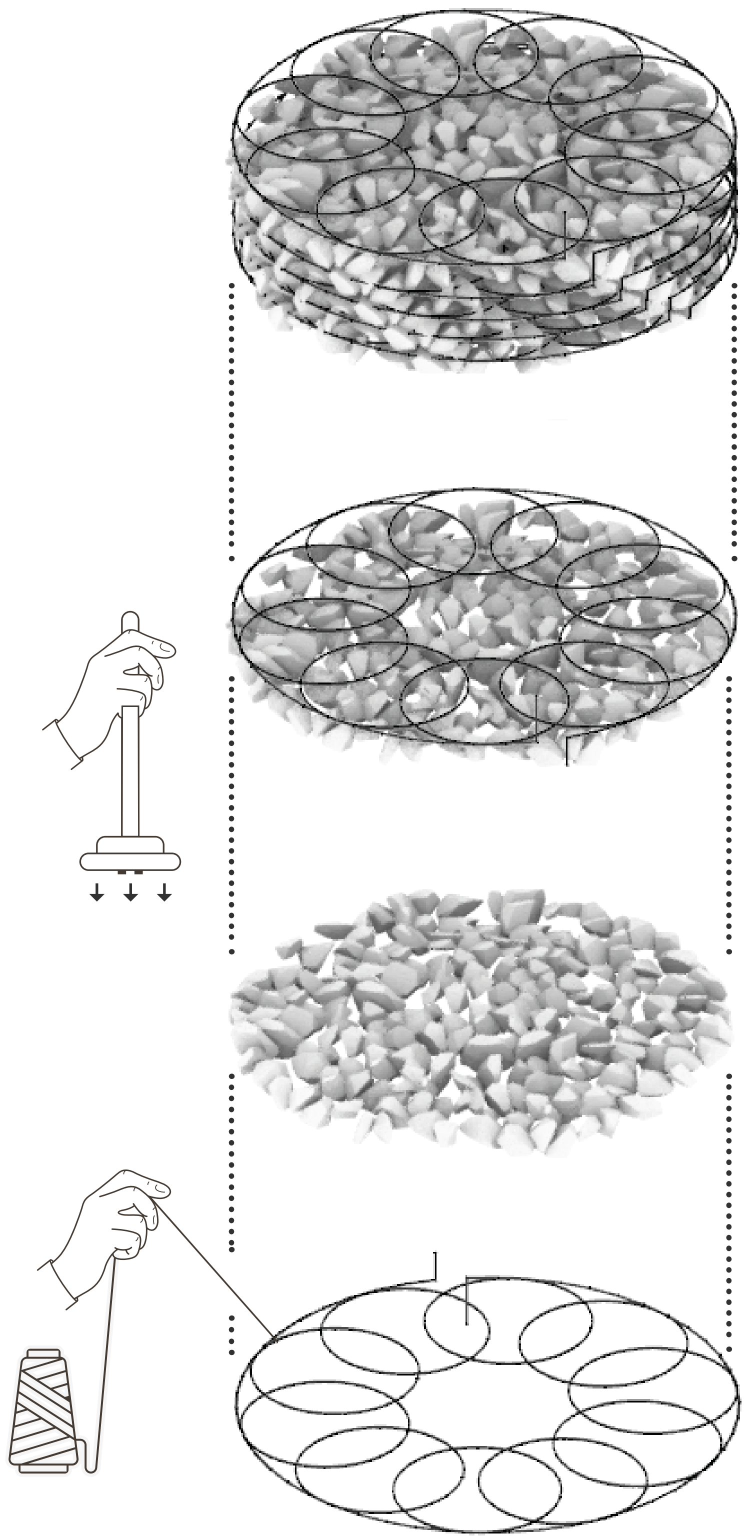
JAMMING BY HAND

A starter kit for jamming by hand

Most of the examples of granular jamming conducted in the earlier research projects, used robotic fabricators to construct aggregated structures. Unfortunately, due to limited time for the thesis project, the material experiments could not be conducted in the robot lab at ACE. As a result, the material experiments were made by hand. There are clear advantages of using robots for jamming such as a high level of toolpath precision. A robot arm can create more complex geometries and material models that closely resemble their 3D counterparts. In contrast to working with a robot arm, one can expect a higher likelihood of human error when jamming particles by hand.

When jamming there are a few pieces of equipment one might need, such as working gloves, protection glasses and most importantly a mask. The mask and glasses help to prevent any irritation caused by dust particles when constructing and disassembling the aggregated structure. Besides the gravel and string, a tool for compacting the aggregates is needed. In this case a dumbbell without the weight plates were used to flatten the top layers of gravel.

ASSEMBLY



For the technique to work optimally, the string needs to be tensioned. This naturally happens when it is compacted by the additional gravel that is stacked on top of it.

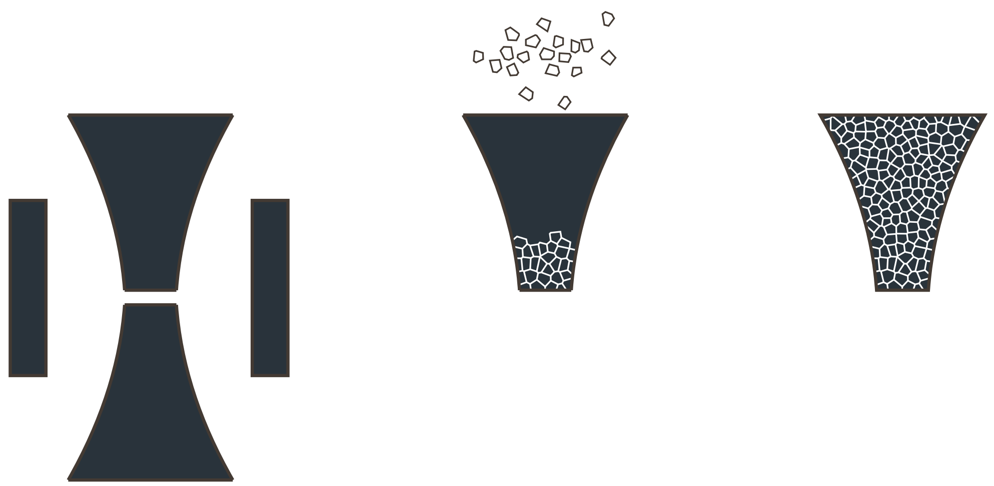
Firstly, the string is placed in a circular pattern. The string should have a low amount of stretch but still be capable of being deposited in a circular pattern. This step is difficult to achieve when jamming by hand, but it is still possible to create an aggregated structure manually if the circles are not perfectly round.

Secondly, a layer of gravel is deposited onto the string. The layer height is dependent on the size of the aggregate. A rule of thumb is that the layer height should be one and a half times bigger than the size of the gravel. This is because the aggregates will be compressed by the compactor and under the weight of the additional particles.

Thirdly, the aggregates are compressed by a compactor. When compressed, some of the aggregates will fall off and create a flatter surface for the string to be placed on.

All the steps are repeated until the structure is completed.

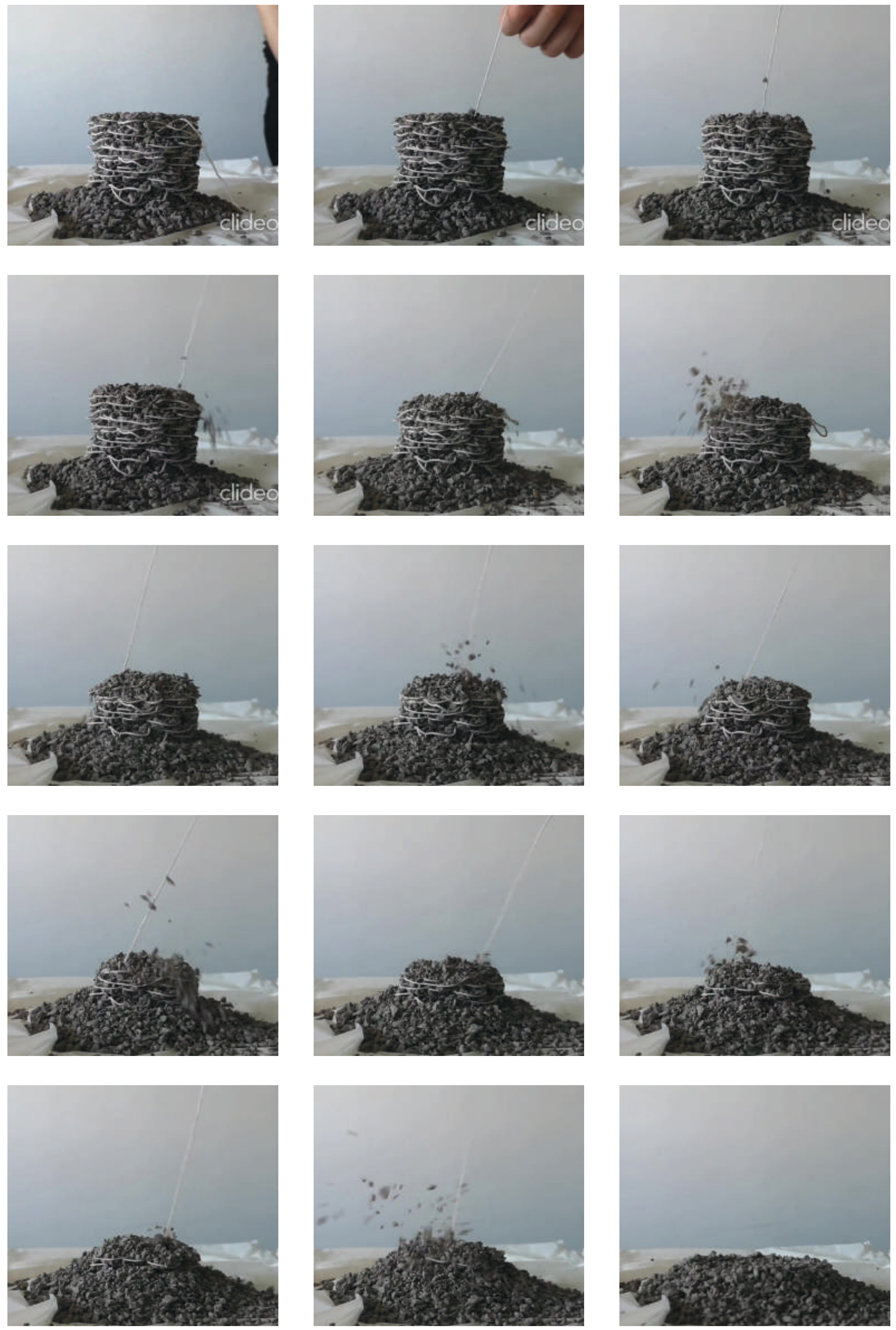
Moulds were used to make the construction of the aggregated models easier. The moulds made it easier to achieve various shapes. Firstly, the desired geometry was designed in Rhino and unrolled into surfaces. The surfaces were printed and put together with tape into paper moulds. Thereafter, the gravel was jammed inside the mould as described earlier. When the structure was completed, the mould was taken apart to reveal the finished aggregated structure.



Developed surfaces were put together with tape into a paper mould. The gravel was jammed inside the mould

When the structure was completed, the paper mould was removed to reveal the finished aggregated model

DISASSEMBLY



When disassembled, the aggregated structure completely reverts into its previous state

AGGREGATIONS

01. COLUMN

Column made with string that was deposited by hand. The structure became more stable when more weight was applied to it.

02. ARCH

Two-legged arch made with a paper mold. A pile was created by the feet when the mold was removed. The small rock size created a nice surface texture.

03. SYMMETRICAL OVERHANG

A gradually increasing overhang. 30 degrees were achieved. The structure was unstable and collapsed when lightly poked.

04. UNEVEN OVERHANG

Overhang was too great and resulted directly in a collapse when the mold was removed.

05. LONG-SPAN ARCH

Overhang was too great and resulted in a collapse when the mold was removed.

06. DESIGNED AGGREGATES

The aggregates easily interlocked with one another and created an undefined geometry.

07. AGGREGATED STRUCTURE WITH DESIGNED PARTICLES

It was easy to construct a predefined geometry with the particles, but when weight was applied to the structure it instantly became unstable and collapsed.

08. BIGGER ROCKS

Larger pieces of rocks were used with the same mold method and scale as earlier experiments. It resulted in a rougher surface texture.

09. BIGGER SCALE

Bigger structures were built to create spatial qualities. Freehanded without any mold. The string was deposited quickly and generously

10. AMPHITHEATRE

It was shaped to function as either a small scale urban furniture or as a large scale arena. The smaller particles were placed on top to create finer surfaces.

11. MOUNTAIN TOPS

When vertical structures were shaped, they always ended up having an angle of repose.

12. UNFINISHED DOME

An ambitious attempt at 1:10 dome but it was left undone because it was too time consuming and a lack of mold made it difficult to create overhangs

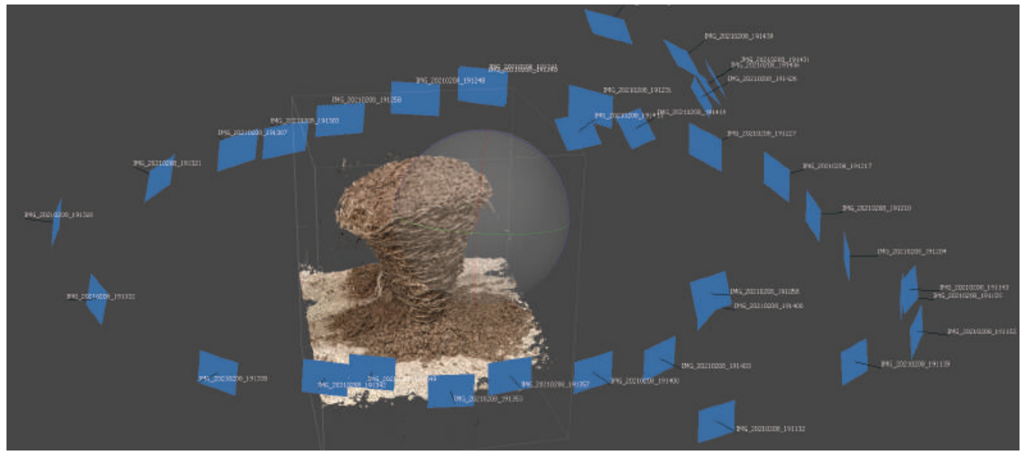
DIGITAL EXPERIMENTS

PHOTOGRAMMETRY

Photogrammetry is almost as old as photography itself. In its essence it is the process of acquiring information and measurements about physical objects from photographic images. Since the advancements in computer sciences, most people today associate photogrammetry with the processing of two-dimensional pictures to produce three-dimensional models with photogrammetry software. This could be used to import three-dimensional objects from the real-world into its digital counterpart (Aber et al., 2010).

Photogrammetry has been used in a multitude of fields such as architecture, mapping geographic information, game development and in special effects. Its main advantage and disadvantage are the raw amount of data that is obtained. On the plus side, the vast amount of information makes it possible to create a three-dimensional model without the need for extensive modelling. On the other hand, the amount of data can be overwhelming to process for computers, which means the process of interpreting a real-life object can become time consuming.

The material experiments shown in the previous chapter were made into digital models through photogrammetry for documentation. Due to the limited amount of gravel available in the experiments, the material models were all reversed when completed and the particles were reused in other models. Because all models were disassembled, they were documented through photos, videos and digital models. The photos were used to turn the material models into digital models. Some of the digital models were later used in the earlier design stages to propel the concept forward.



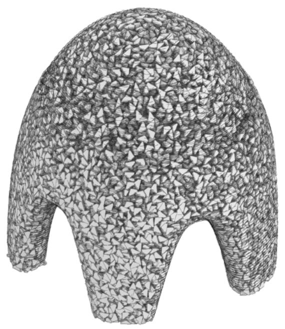
The inserted photos were turned into a digital model in Agisoft

The photos were used to create the 3D-model on the right

SIMULATIONS

A simulation is a way to predict real-world behaviour by imitating the operation of a system or environment. The research conducted at ETH and ICD used discrete element method (DEM) simulations for modelling granular jamming. DEM is a method that can simulate the granular flow by computing the motion and effect of a large number of small particles. A DEM simulation is a time-consuming and complex computing task that usually requires a specific software. Instead of using DEM to digitally explore granular jamming, simpler physics simulations were conducted in Blender and Unity. Rigid bodies were used to simulate the gravitational force on the particles.

As a result of the limitations in time, processing power and the simplification of the particles, the simulations became an oversimplification of the real-world behaviour of granular jamming. Therefore, the simulations became a way to represent the aggregated structures instead of predicting their load-bearing capacity.



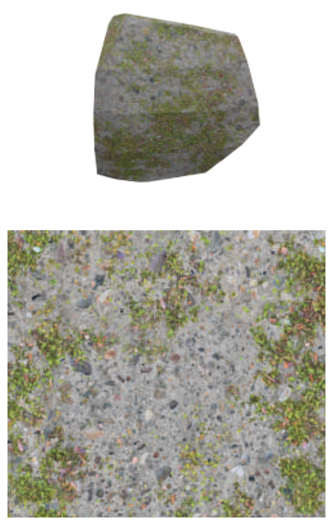
Simulation made in Unity

Early simulation trying to test the load-bearing capacity of an aggregated structure

PARTICLES

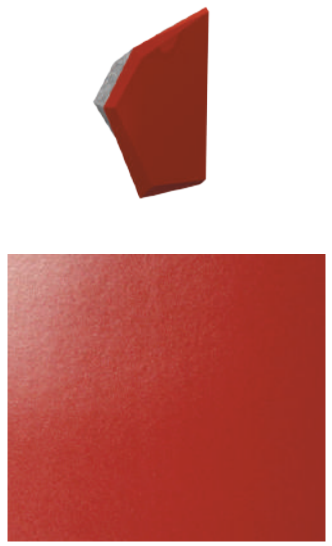
For the perspectives, different types of particles were modelled and given a material in Blender. Various types of common building waste were chosen to give the exterior and interior of the aggregated domes different surface expressions.

Brick

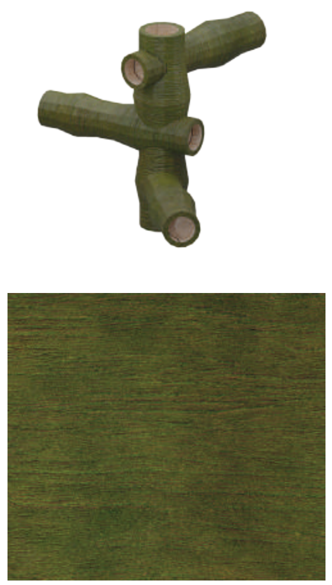


Concrete

Moroccan tile



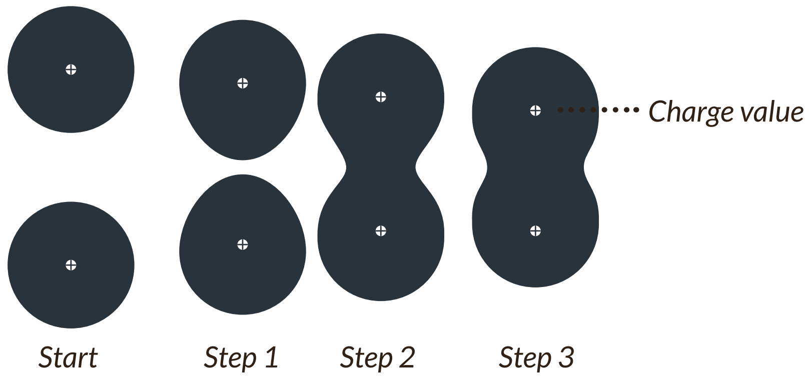
Red glossy tile



Bamboo

Wood

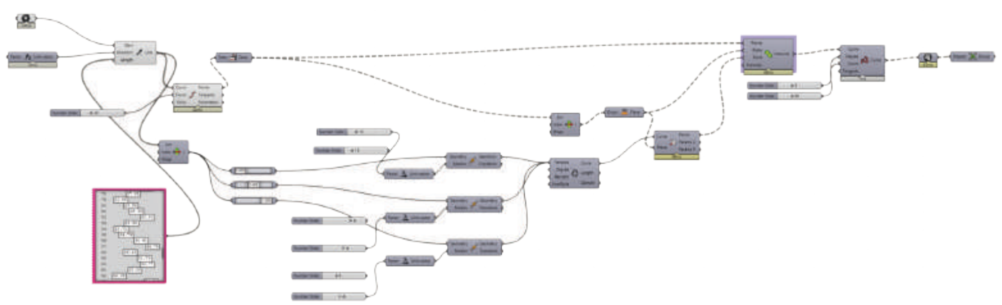
METABALLS



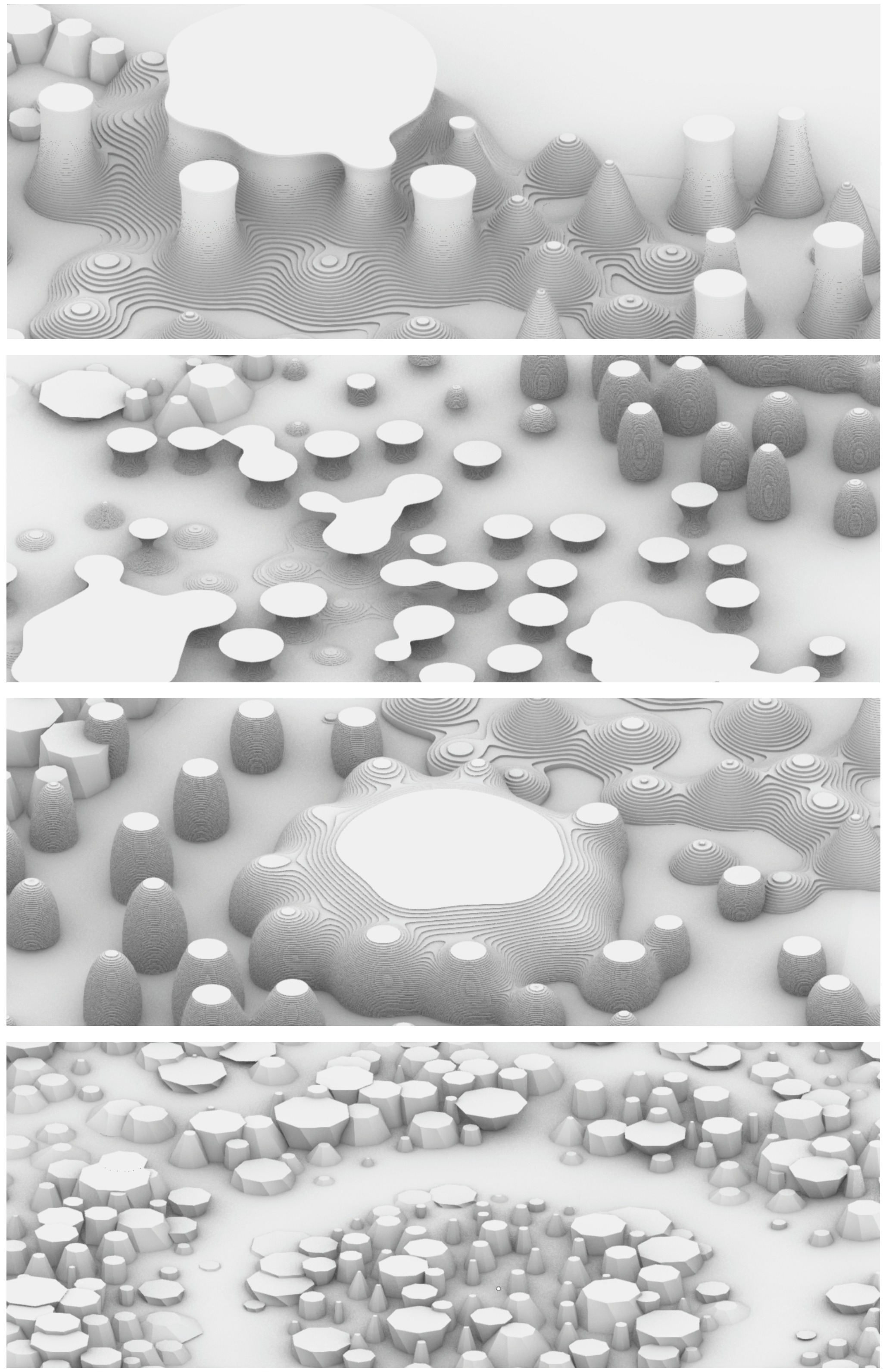
In computer graphics, metaballs are n-dimensional objects that can merge into an organic-looking shape. When two objects get near one another, they start to attract one another. They blend together to create a "blobby" appearance that is distinct for metaballs (Blender Documentation Team, n.d). How well the objects merge depends on the charge strength assigned to each object. The charge is located in the centre of the object and decreases as it moves towards the outside edge. A higher charge means the object has a higher level of attraction.

Metaballs were used in the design proposal to represent the shape of the aggregated domes and to create the topography of the aggregated landscape. The plugin Cocoon was used in Grasshopper to create metaballs. Inputs such as points, lines and charge values were used to control and create a high variety of metaball geometries.

As digital simulations are time consuming and CPU-intensive, metaballs were instead chosen as a method to represent the aggregations. Previous material experiments and design research formed an idea of how an aggregated dome would look like in real life. As such, iterations of metaball geometries were done to come as close to that idea.

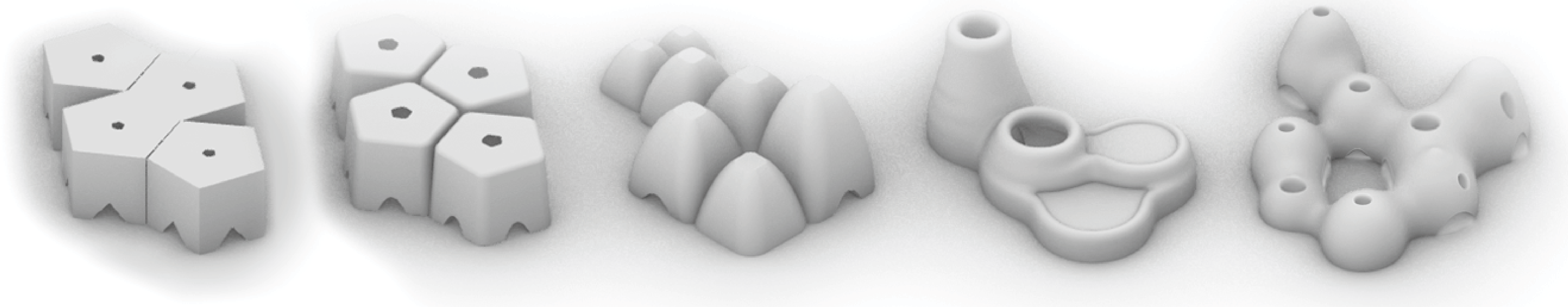


An earlier metaball script in Grasshopper



Earlier experiments on representing different aggregated structures and on how their configuration can form various landscapes

EVOLUTION OF THE AGGREGATED DOMES



GENERATION 01.

The interior of the aggregated structure was created with a 20-degree slope to simplify the shape of a dome. The exterior walls were designed to be vertical to make it easier to place them next to one another in design iterations.

GENERATION 02.

The inside was vaulted to portray the interior space of a dome more accurately. The outside was bevelled to look like the rounded edges found in aggregated structures. As it is not possible to create 90-degree angles with JAS.

GENERATION 03.

In this iteration, the outside was designed to follow the interior shape. The exterior slope started to resemble the angle of repose found in aggregated structures.

GENERATION 04.

A metaball script was used in this iteration to create free formed structures in which the exteriors resembled the organic look of aggregated structures.

GENERATION 05.

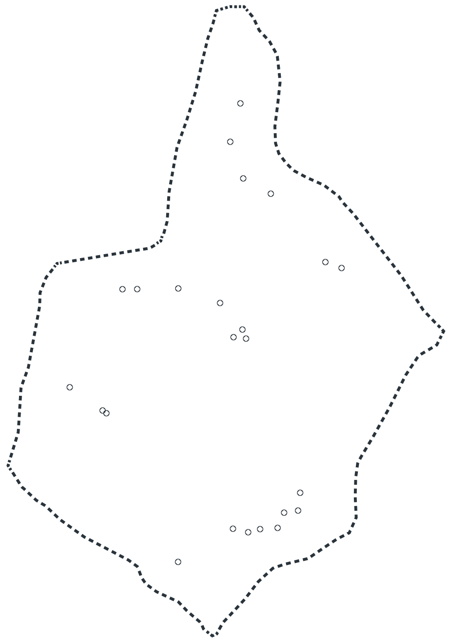
In the final iteration both the inside and outside look more like a dome. The metaball script generated a variation of structures that merged like it would have if it was built.

TOPOGRAPHY

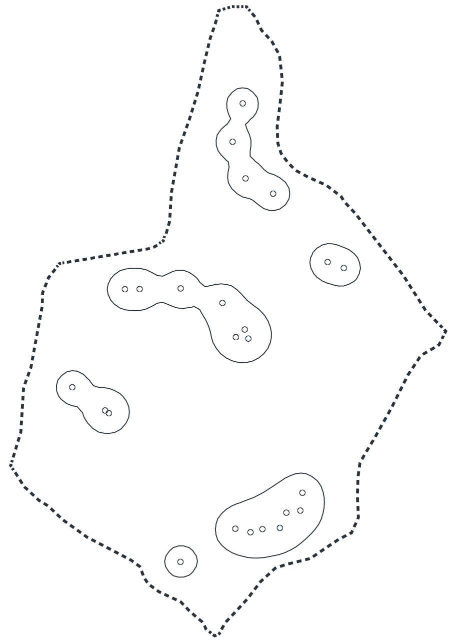
The organic patterns are exhibited in some mines such as the Kalgoorlie Super Pit mine (Photo: unknown, n.d.)

Inspired by the organic patterns left by mining vehicles, the proposed landscape was formed with metaballs. The organic look was achieved by using a two-dimensional metaball script in Grasshopper.

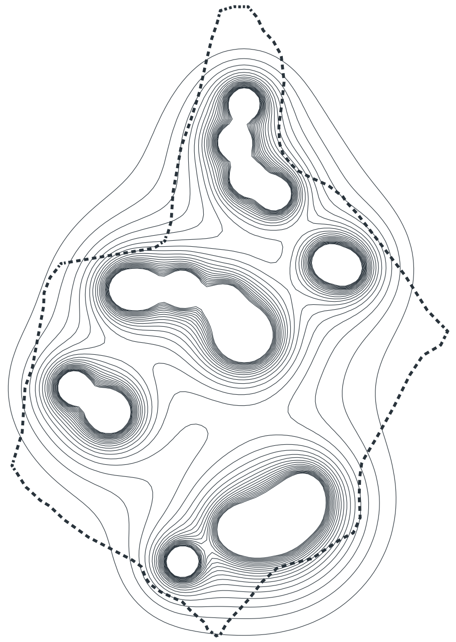
Firstly, points were placed within the site boundary to create the perimeter of the atriums. The points were moved manually in Rhino to create the desired shape of the outside spaces. When the first step was finished, the script generated lines that were offsetted from the atriums. The offsetted lines became the topography of the landscape. Thereafter, the lines were connected to the existing topography to form one unified landscape.



Points placed in Rhino generated the shape of the atriums



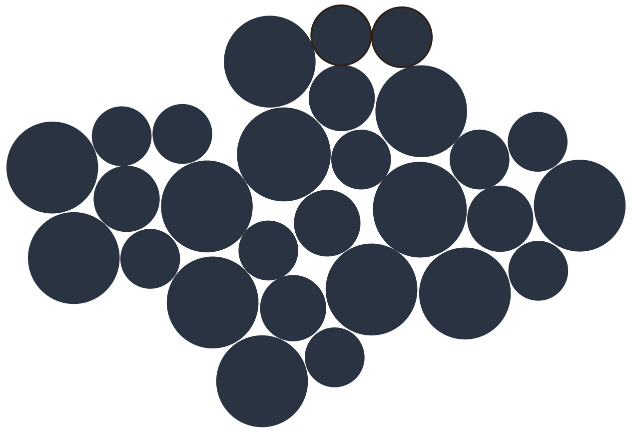
The points were moved manually to create the desired geometries



The script generated topography lines that were offsetted from the atriums

The scripted topography was manually merged with the existing landscape

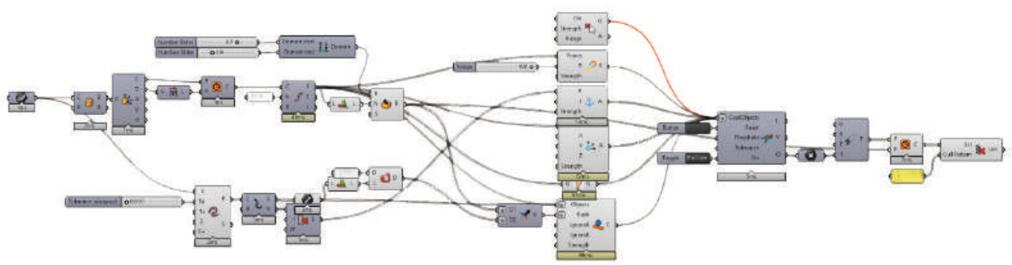
CIRCLE PACKING



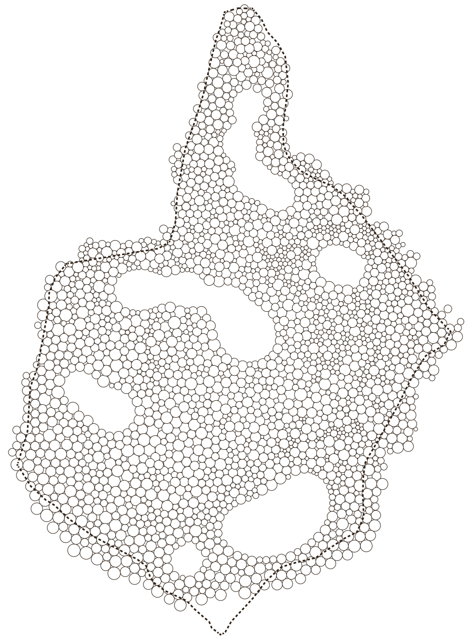
Packed circles

Circle packing is the method of arranging circles in such a way that some or all of them are mutually tangent without any overlapping. The arrangement takes place within a given boundary (Weisstein, n.d).

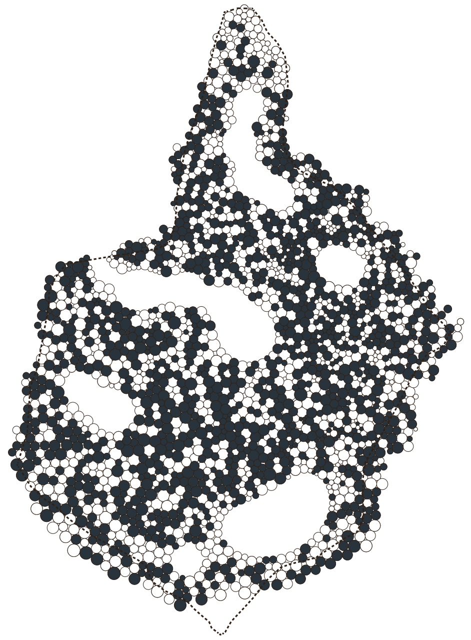
In the design proposal, circle packing was used to populate the site with the aggregated domes. Circles with radii ranging from 2-12 meters were distributed using a script in Grasshopper. Firstly, the script generated circles in varying sizes within the site boundaries. Thereafter, a pattern was used to cull roughly forty percent of the circles. The unculled circles represented the domes while the culled ones illustrated the in-between spaces that were to be filled with C&D waste. Lastly, the script gave the circles a three-dimensional form. Their radii were used as their heights and a plugged-in metaball script gave them their dome shaped geometry. The smaller domes were copied and layered to create levels of aggregated domes.



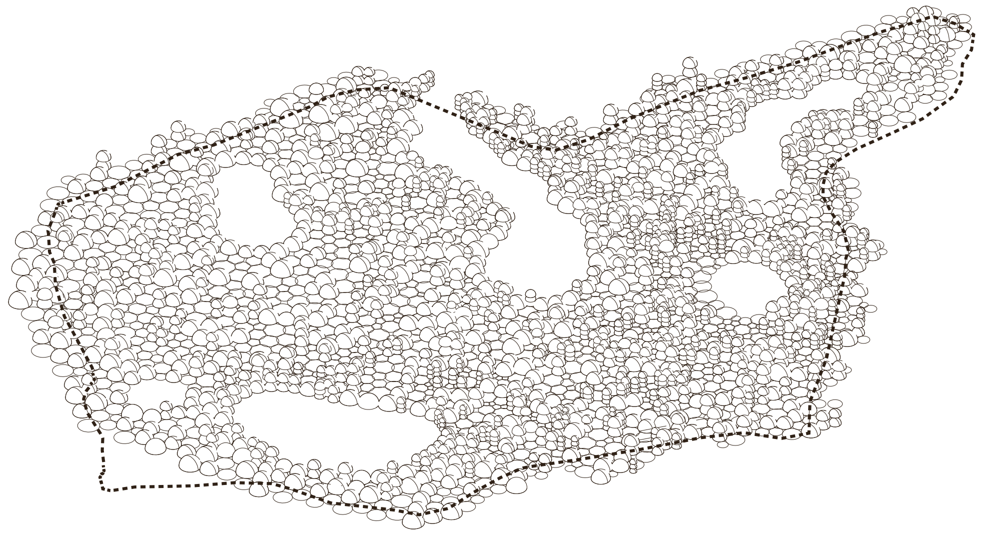
An earlier script that distributed circles within a given boundary



The script distributed circles within the site boundary

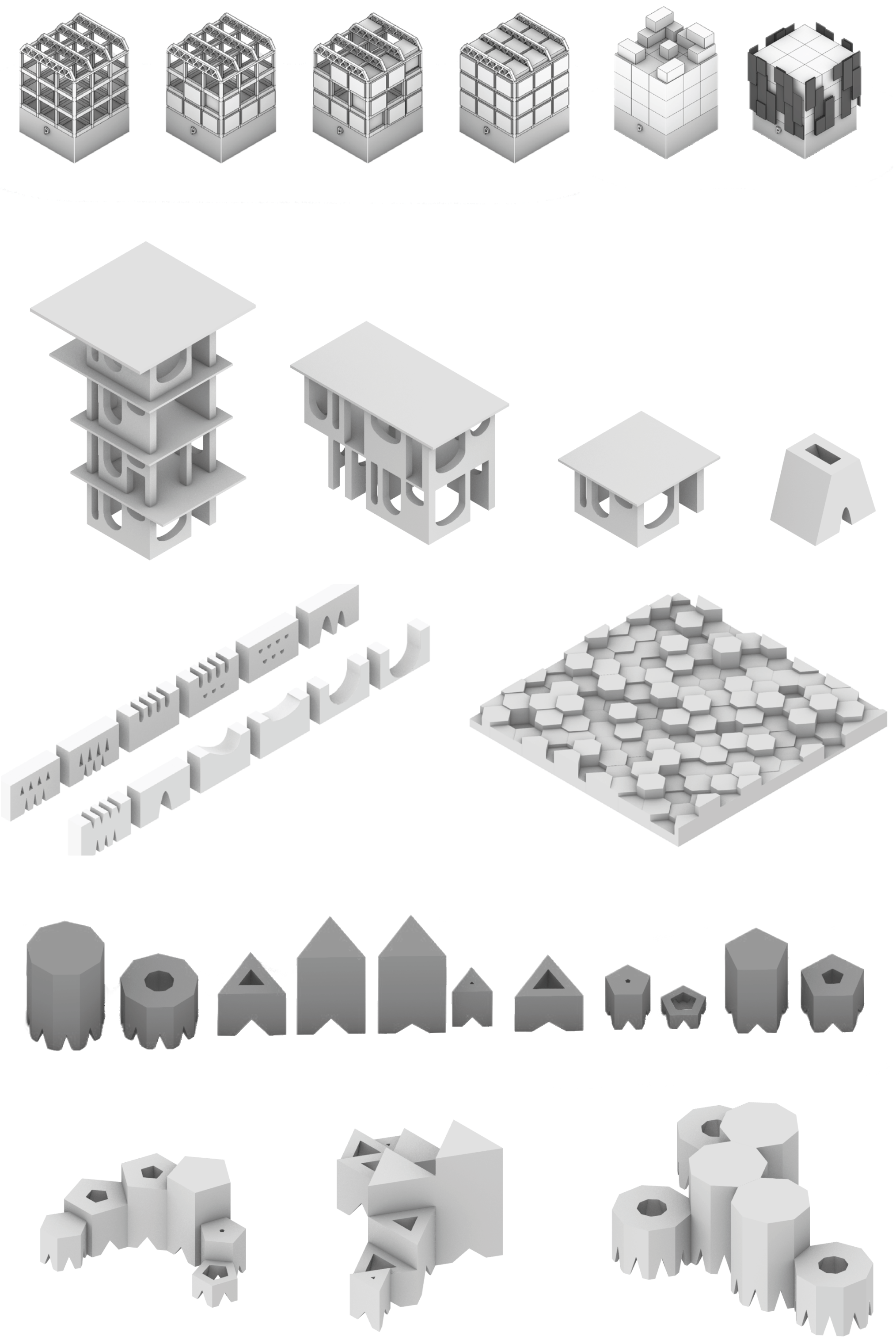


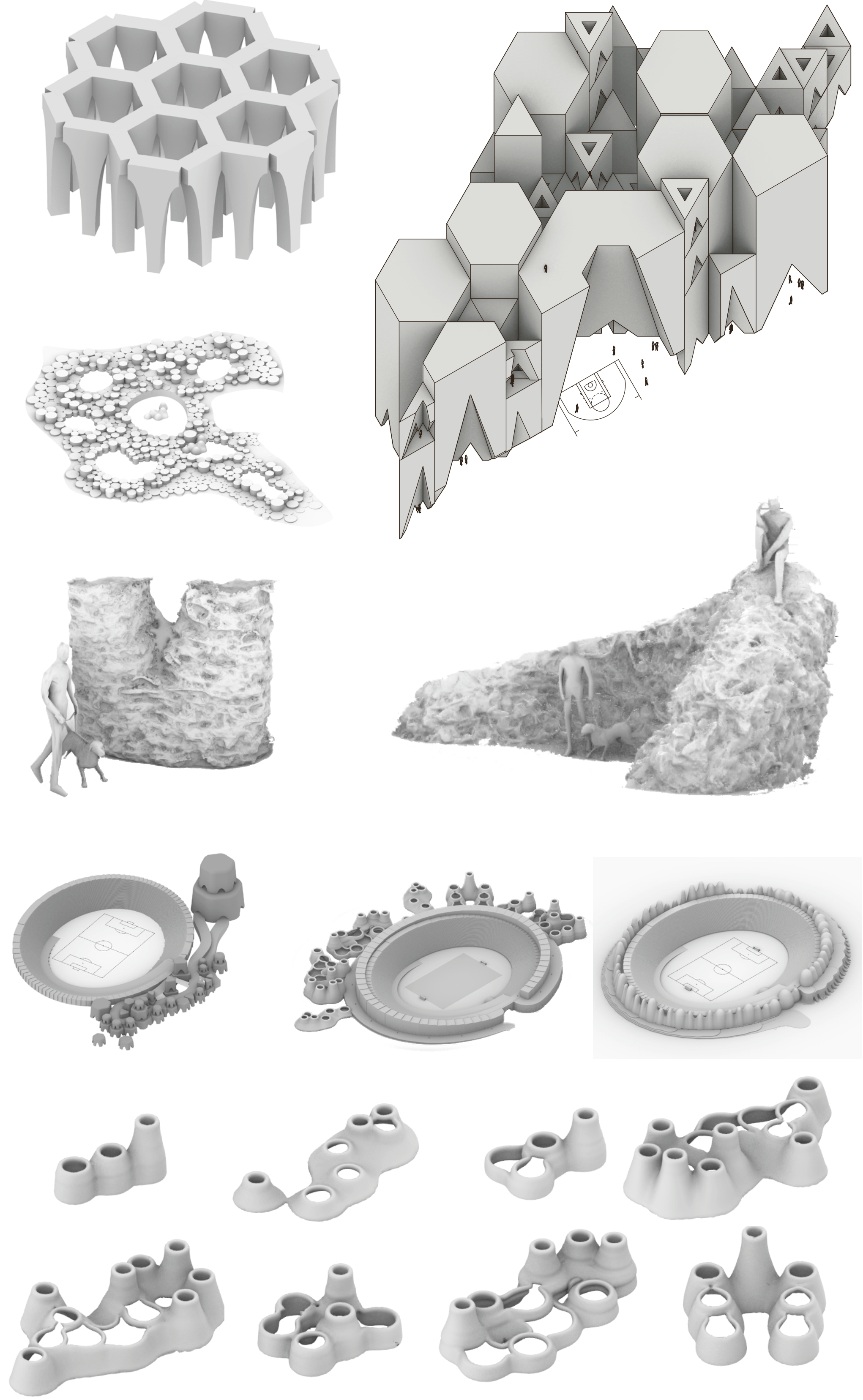
Roughly forty percent of the circles were culled with a pattern



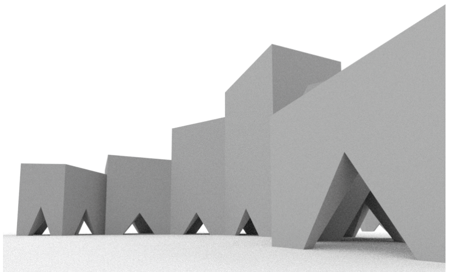
The script formed 3D-dimensional domes from the unculled circles

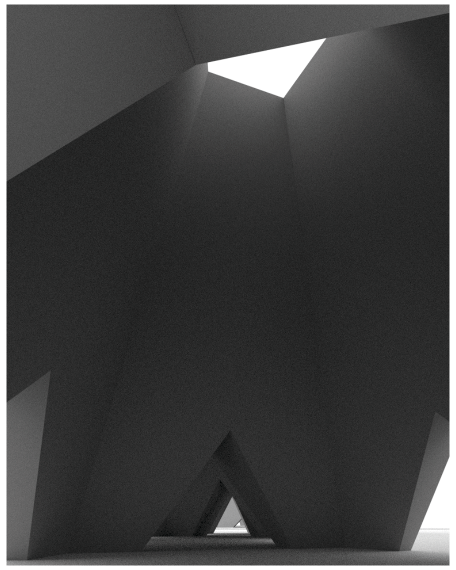
EARLY REPRESENTATIONS

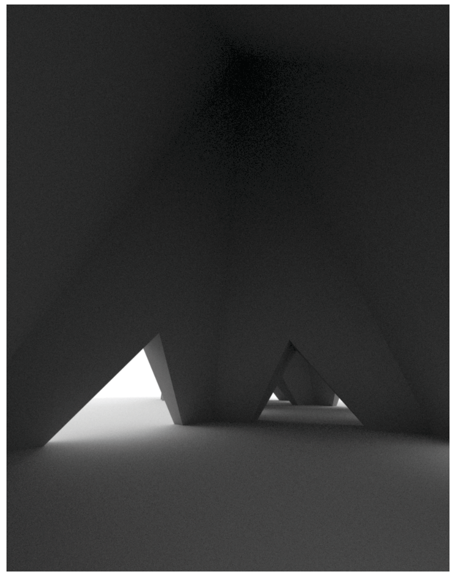


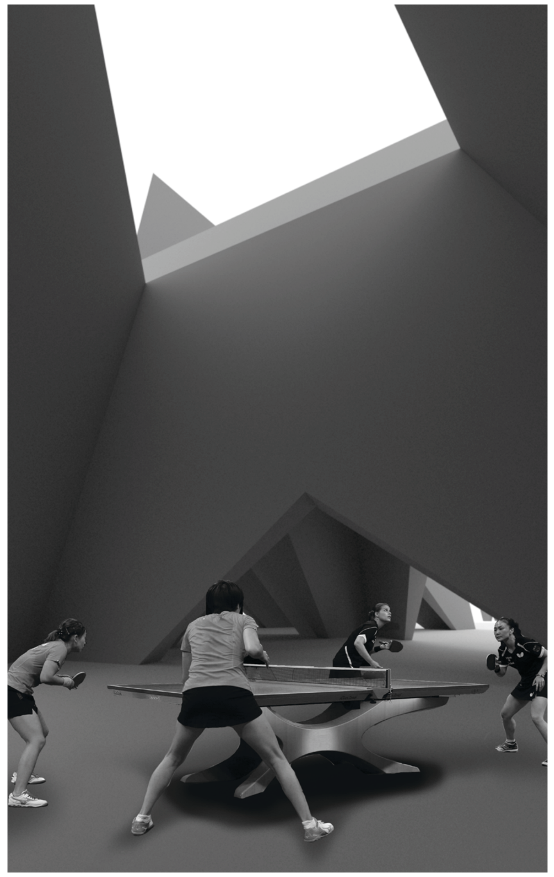


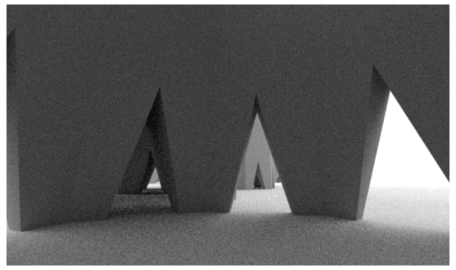
EARLY PERSPECTIVES











SUMMARY

CONCLUSION

This thesis explored the possible opportunities and consequences of aggregated structures in architecture. Working with design speculation made it possible to shift the focus away from giving actual solutions of current problems to creating room for discussion on how things could be. The design proposal was not meant to be looked as an exact blueprint of what future architecture should look like but rather as a design that investigated what constructing with building waste as granular matter could entail.

The topic of building with granular matter posed a challenge as the current research on jamming in architecture is limited to a handful of projects. Additionally, it is a material system that is unlike any traditional construction method we have ever encountered. Material experiments were, therefore, necessary to gain a better understanding of granular jamming. As students we were limited to making the aggregated models by hand. This proved to be challenging as it was difficult and required immense patience, on our part, and time to achieve the geometries that we originally intended for. Given more time and resources, it would have been interesting to investigate further possible geometries in the robot lab. The robot arm can provide a high level of precision that would make apertures and better surface resolutions achievable with JAS. Along with an increased stability of the aggregated model.

As for the question on how aggregated structures change over a long period of time, the structures and aggregates break down when put through natural processes or human intervention. The particles in the aggregated structures can wear down or fall off the structure from being subjected to, for example: rain, impacts to the surface or overall structure. However, unlike traditional building methods, aggregated structures can self-organize to reach structural stability instantly. Depending on the number of particles that fall off, the structure could either collapse or re-stabilize itself. There are possible solutions to make the aggregated structures last longer due to external factors. Gergana Rusenova suggested in her PhD, Jammed Architectural Structures, that a coating could be used to hold the particles in place and protect the structure from rain. For instance, a biodegradable coating could be used to keep the aggregated structure completely reversible. Using a coating to make the aggregated structures keep their form was not part of the scope of this design proposal. It should however be of interest if one were to explore how granular jamming can become a viable building method.

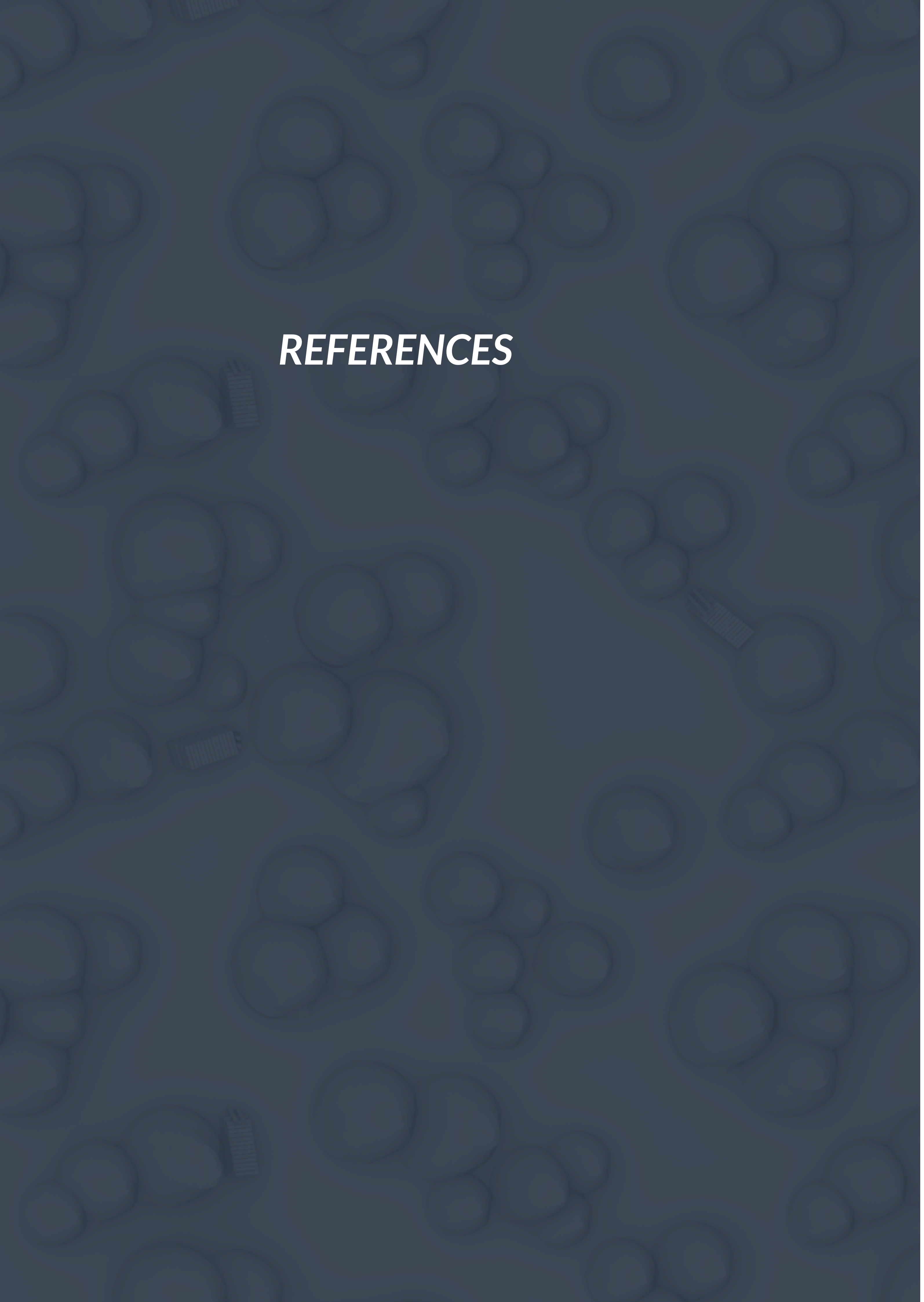
Instead, the aggregated structures were allowed to naturally erode with time, to become a ruin. The aggregated landscape stands as a reminder of the abundance of waste we have generated and will still generate if nothing changes. The parts and bits of architecture that make up the structures, become a testament to the mortality of buildings. Sooner or later, they will all end up in landfills as waste.

In regard to how building waste can be jammed for architectural application, load-bearing and large-scale structures can be constructed by jamming C&D waste. The most optimal aggregates to build with are those that are the hardest and most form stable. This in turn means that not all building waste might be suitable for granular jamming but could instead be used as filler material in the structure.

The reversibility inherent to the material system, makes it possible to construct both temporary and permanent structures. Unlike the traditional building methods, all materials can be reclaimed and repurposed elsewhere.

Advancements in material technology have made it possible to create new and sustainable materials from various resources such as waste. The aggregated structure can be seen as a repository or a material bank in which every waste particle can be reused over and over again. Currently, there are types of building waste that are difficult or cannot be recycled, but someday there might be ways to do so. In the meanwhile, instead of ending up in landfills, the waste particles could be stored as a public pavilion or as any other type of architectural structure.

With this design proposal, we also wanted to show one of the many possibilities of constructing with building waste. Building with waste is not an uncommon notion. In many countries in the Global South, the cost of manufacturing and purchasing cement-based construction materials is expensive due to the shortage of raw materials. This has led to many being unable to afford housing. Some have, therefore, turned to waste as a resource for affordable construction. In Uganda, the abundance of plastic bottles has been used to alleviate the country's housing shortage. Building aggregated structures from waste could be one possibility of exploring affordable construction opportunities. Waste is after all, an abundant resource that can be found in every country. Instead of viewing waste as a problem and a burden for the environment, we should see it as the untapped resource that it is.



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