//data-driven a-type

DATA-DRIVEN A-TYPE

MASTER THESIS

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Studio FLOW
FA CTU 2024

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"Innovation is the ability to see change as an opportunity – not a threat."

Steve Jobs

/ INTRO

The Anthropocene epoch, marked by significant human impact on the environment, has witnessed a rapid technological revolution and complete digitalization, ushering in profound changes in our lifestyles and interactions. In this unique era, the most pivotal structures for our digital existence, data centers, stand devoid of human presence. The swift integration of artificial intelligence and other technological tools into our lives underscores the pivotal role of facilities like data centers, which have traditionally been designed with a focus on functional and operational efficiency, often at the fringes of human-centric spaces.

As our reliance on digital infrastructure grows, data centers have become central to managing and processing the vast amounts of data necessary for modern urban operations. These facilities, often called the "central nervous systems" of smart cities, support functions ranging from traffic management and public safety to energy distribution and waste management. To create smarter cities, the traditional model of large, remote data centers is becoming obsolete due to latency issues and the demand for real-time data processing. Instead, we are moving towards more decentralized and integrated data center models that can support the immediate needs of urban environments.

A key focus of this thesis is the evolution of a new architectural typology, the urban data center—termed as 'Data-Driven A-Type'—through the innovative use of artificial intelligence, thereby affirming the increasing multimodality and complexity of architecture as a discipline. By harnessing AI, this research strives to design and implement data centers that not only meet current technological demands but also foresee future requirements. The Data-Driven A-Type will embody the principles of sustainability, adaptability, and efficiency, thereby setting a new benchmark for architectural and urban integration in the digital age.

These hubs of computing power are more than just technical spaces; they are emerging as the central cultural landmarks of the digital age. Just as libraries, cathedrals, and other buildings were central to their respective eras' social and cultural fabric, today's emblematic structures are the data centers, symbolizing our shift into a fully digitalized society.

ZADÁNÍ

České vysoké učení technické v Praze, Fakulta architektury
2/ ZADÁNÍ teoretické diplomové práce
Mgr. program navazující

jméno a příjmení: Andrei Kazlouski

datum narození: 04.07.2000

akademický rok / semestr: 2023/2024, letní semestr
obor: Architektura a urbanismus
ústav: 15116 Ústav modelového projektování
vedoucí diplomové práce: doc. Ing. arch. Miloš Florián, Ph.D

téma teoretické diplomové práce:
viz přihláška na DP

zadání teoretické diplomové práce:

1/ popis zadání projektu a očekávaného cíle řešení

Era antropocénu ovlivňuje architekturu a urbanismus. Digitalizace, automatizace a robotizace bude mít zásadní vliv na vznik nových architektonických typologií. Otázka propojení "světa lidí" se "světem strojů" nabývá na relevanci. Rychle prorůstaní nástrojů umělé inteligence do běžného života a práce se promítá i do nároku na technické zázemí v podobě datových center. Integrace těchto zařízeni do městské a příměstské zástavby přináší řadu otázek a problémů, které je třeba podrobně prozkoumat a řešit. Záměrem této teoretické diplomové práce je navrhnout možné varianty integrace datových center do urbánní struktury, s ohledem na efektivní výměnu energie, rozměrovou přizpůsobivost a integrace do komplexní a heterogenní struktury současného města. Návrh bude využívat výstupy z modelů strojového učení. Cílem teoretické diplomové práce bude výzkum, jak bude možně využít metod strojového učení při návrhu typologie budov datových center s ohledem na klimatické a lokální podmínky s důrazem na maximální efektivitu datových center.

2/ Pro AU/ součástí zadání bude konkrétně specifikovaný stavební program
Pro D/ součástí zadání budou konkrétně specifikované jednotlivé fáze projektu, které jsou nezbytnou součástí řešení

Analýza vývoje datových center. Možnosti integraci datových center do urbánních struktur. A v té souvislosti možnosti aplikace různých modelů strojového učení pro architektonické navrhování prototypů datových center v urbánní struktuře.

3/ popis závěrečného výsledku, výstupy a měřítka zpracování

Výstupem teoretické diplomové práce bude publikace, prezentující teorii a metodiku návrhu integrace datových center do urbánních struktur pomoci používaní strojového učení v architektonickém navrhovaní budov. Publikace bude doplněna obrázky, diagramy, tabulkami, ilustracemi a videem o délce cca 2 min. Vše bude doplněno posterem s grafikou vysvětlující obsah práce.

4/ seznam dalších dohodnutých částí projektu (model)

Výstupy variant návrhů datových center bude prezentována modely z 3D tisku.

Datum a podpis studenta 14.2.2024 [signature]

Datum a podpis vedoucího DP 14.2.2024 Miloš Florián

Datum a podpis děkana FA ČVUT [signature]

registrováno studijním oddělením dne 14.2.2024 [signature]

PROHLÁŠENÍ AUTORA

ČESKÉ VYSOKÉ UČENÍ TECHNICKÉ V PRAZE **FAKULTA ARCHITEKTURY**	
AUTOR, DIPLOMANT: Andrei Kazlouski AR 2023/2024, LS **NÁZEV DIPLOMOVÉ PRÁCE:** (ČJ) Atyp řízený daty (AJ) A-type driven by data **JAZYK PRÁCE:** ANGLIČTINA	
Vedoucí práce: **Oponent práce:**	**doc. Ing. arch. Miloš Florián, Ph.D** Ústav: 15116 Ústav modelového projektování **Prof. Ing. arch. Vladimír Šimkovič, Ph.D**
Klíčová slova (česká):	datová centra, umělá inteligence v architektuře, ML , městské datové centrum (UDC), diskrétní architektura, městské zemědělství, post-antropocénní architektura
Anotace (anglická):	This thesis introduces the 'Data-Driven A-Type,' a new architectural typology for urban data centers, leveraging artificial intelligence to enhance sustainability, adaptability, and efficiency. As smart cities evolve, traditional large, remote data centers are becoming obsolete. The focus is on decentralized, integrated models to meet real-time urban needs. Data centers are emerging as central cultural landmarks of our digital age, akin to libraries and cathedrals in the past, symbolizing our shift to a fully digitalized society.
Anotace (česká):	Tato diplomová práce představuje "datově řízený typ A", novou architektonickou typologii pro městská datová centra, která využívá umělou inteligenci ke zvýšení udržitelnosti, přizpůsobivosti a efektivity. S rozvojem smart cities se tradiční velká, vzdálená datová centra stávají zastaralými. Důraz se klade na decentralizované, integrované modely, které uspokojují potřeby měst v reálném čase. Datová centra se stávají ústředními kulturními památkami našeho digitálního věku, podobně jako v minulosti knihovny a katedrály, a symbolizují náš přechod k plně digitalizované společnosti.

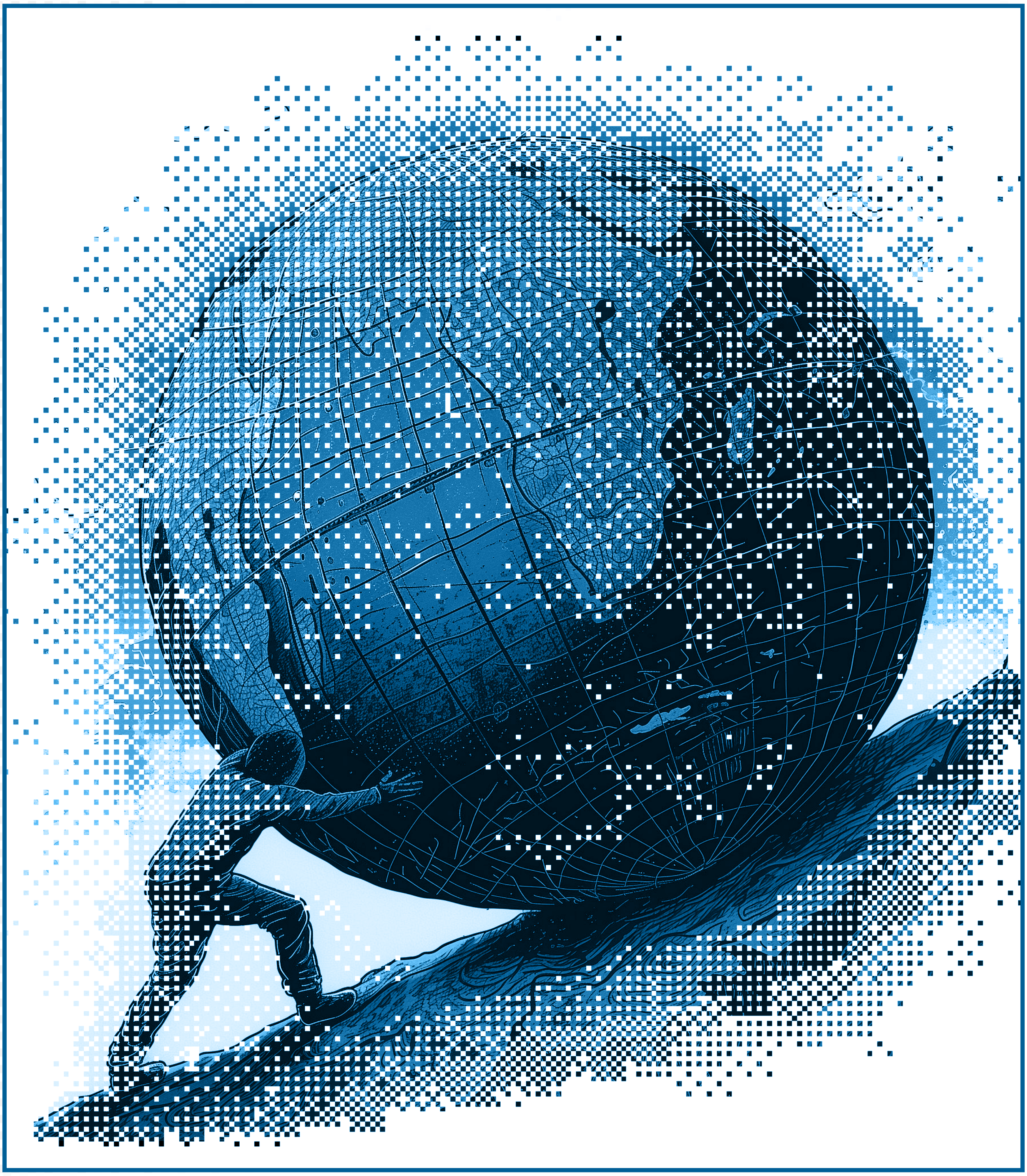
Prohlášení autora

Prohlašuji, že jsem předloženou diplomovou práci vypracoval samostatně a že jsem uvedl veškeré použité informační zdroje v souladu s „Metodickým pokynem o etické přípravě vysokoškolských závěrečných prací."

V Praze dne podpis autora-diplomanta

23.05.2024

Tento dokument je nedílnou a povinnou součástí diplomové práce / portfolia a CD.



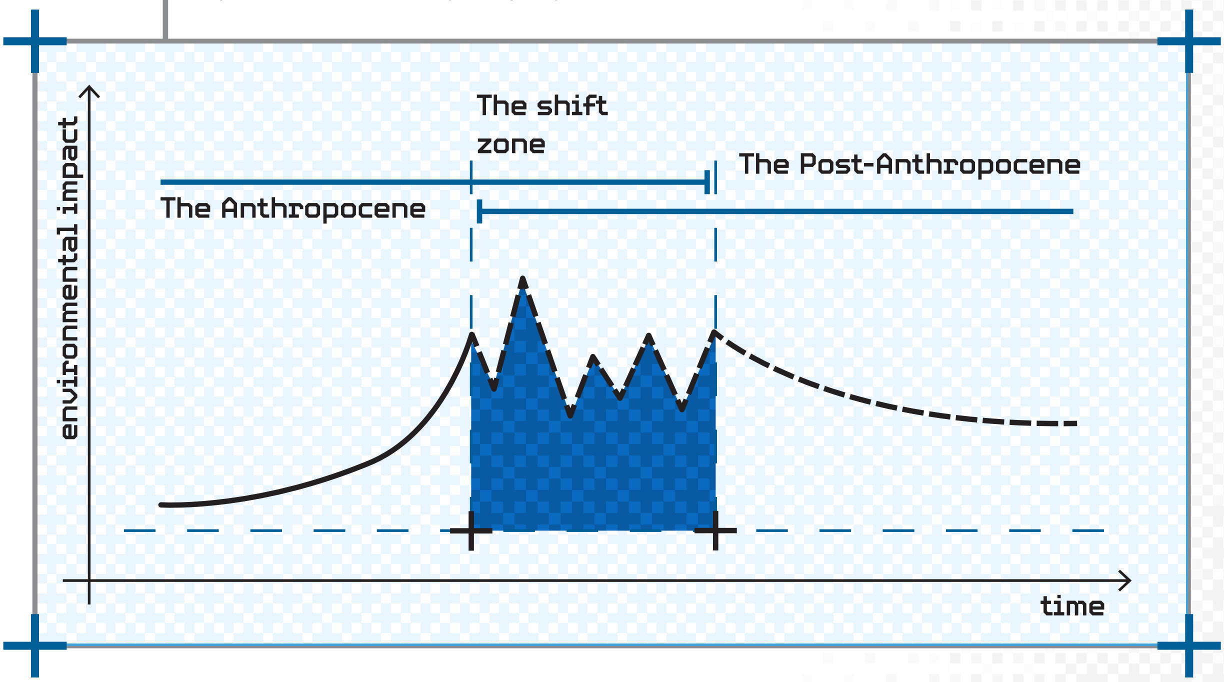
/ Technology and the Post-Anthropocene Shift

The Anthropocene era is defined by human dominance over the environment, which has led to escalating issues with increasingly profound consequences. This necessitates transitioning to a more harmonious relationship with nature, promoting sustainability for a balanced and resilient future.

The term "Anthropocene" gained popularity in the early 2000s to describe the current geological epoch. It is marked by significant changes such as increased carbon dioxide emissions, deforestation, biodiversity loss, and widespread pollution.[1] These impacts highlight the need for sustainable practices to mitigate further environmental degradation, as humanity's footprint on Earth is comparable to natural geological processes. The post-anthropocentric discourse emphasizes shifting focus away from humans as the central subject and rethinking the evolving relationships between humans, the environment, and technology. It explores "What do things do?" rather than "What are things?" understanding the importance of this shift is crucial.

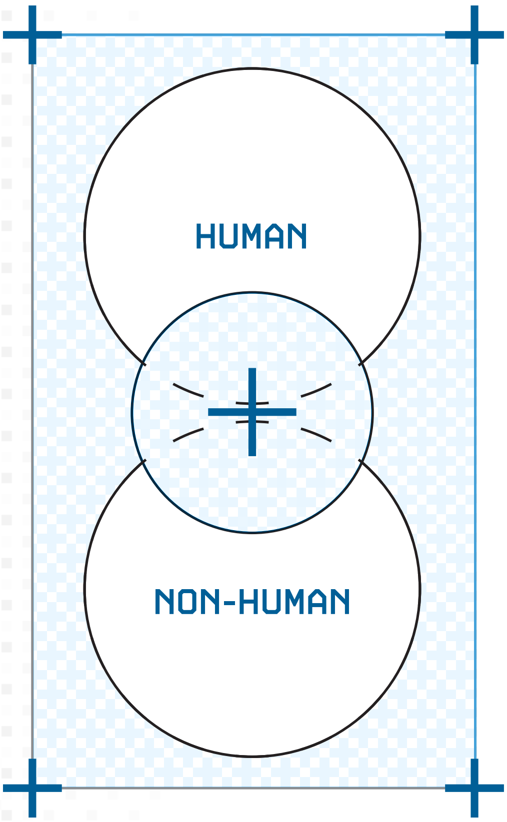
It is not a tipping point after which the planet will be saved from humans, but a gradual process. In this thesis, the shift from the Anthropocene to the post-antropocene will be examined from the perspective of technological progress and its impact on the environment. Leveraging technological advancements is essential to transitioning to the post-Anthropocene era. However, it is important to acknowledge that initial technological implementations may exacerbate environmental impacts. Subsequent technologies designed to mitigate and normalize these effects are necessary. The overall environmental impact can be progressively minimized through a gradual, step-by-step process of continuous technological innovation. Technological advancements, such as innovations in renewable energy, sustainable agriculture, and ecological restoration, are pivotal in facilitating the transition to the Post-Anthropocene. The development of digital technologies and the Internet of Things (IoT) further enables more efficient resource management and monitoring of ecological systems.

While the post-Anthropocene is an intriguing concept, it is essential to note that it remains largely speculative. Its realization and characteristics are not predetermined but depend on humanity's actions and choices in response to the challenges posed by the Anthropocene. Therefore, our focus should primarily be on addressing the pressing issues of the Anthropocene era.



/ Architecture in the age of Anthropocene

The Anthropocene era brings changes in architecture and social structure.For a long time, two distinct bubbles—the world of humans and the world of robots—have coexisted simultaneously but have not yet merged. During the shift from the Anthropocene to the Post-Anthropocene, integrating non-human actors, such as AI and robots, into human lives presents a complex socio-ethical and philosophical problem. This issue revolves around balancing technological advancement with ethical considerations, ensuring that these non-human entities do not perpetuate biases, infringe on privacy, or disrupt social norms and human dignity. Philosophically, it challenges the anthropocentric worldview by questioning the moral and ethical status of non-human actors and their societal roles. Ethically, it necessitates the development of frameworks that address accountability, transparency, and fairness, ensuring that AI and robots enhance human well-being without compromising fundamental human rights or exacerbating social inequalities. These questions can be addressed through architecture, which can provide direction. This will be one of the most critical issues modern architects must address. [2]



Nowadays, non-human actors are confined to closed warehouses and manufactories without any interaction or recognition in the human world. Architecture must reflect the time. The segregation and isolation of production facilities, where all production is based on robots or massive data centers located far from urban environments, create significant barriers to understanding the seamless integration of non-human actors into our lives. There is a need to rethink how architects should approach the physical representation of the world in a way that aligns with progress. As progress accelerates, the speed of innovations integrating into our daily lives becomes almost impossible to foresee. The primary focus of architecture now is the creation of multifunctional spaces, but unforeseen events can disrupt this supposed multifunctionality during the life cycle.

It is time to rethink how architects approach the physical representation of the world around us in a way that aligns with progress. Architecture is no longer solely a human experience, as it was centuries ago. Now, progress and the way of life are gaining momentum, and the speed of innovations integrating into our daily lives is almost unpredictable. The approach to architecture is changing, and its quality is reflected in its ability to adapt to functional use. By reviving the ideas of Metabolist architects, which are based on adaptability in response to changing social and environmental conditions, we can begin to envision architecture for the post-Anthropocene era. Post-Anthropocene architecture should be perceived as capable of constant change in response to conditions, which can be tested for durability over time through various simulations of use, forecasts, and so on.[3]

In this thesis, I will investigate the formation of a new typology that incorporates the qualities of post-Anthropocene architecture using an innovative artificial intelligence method. My research topic is data centers.

/ Data Centers

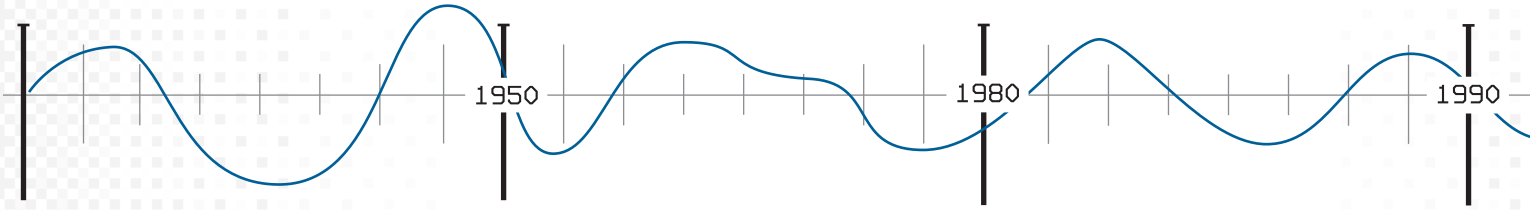
A data center is an excellent example of a type of the building still forming in the context of the Anthropocene era and is already seeking its place in the post-Anthropocene era. In the Anthropocene era, marked by human impact on Earth, we face a unique situation: the most important buildings for our digital life, data centers, exist without any people inside. They are the backbone of our digital world, essential for the flow of information, and integral to our everyday routines. Without them, navigating our day-to-day life would be unimaginable.

The prototype of the data center is the ancient libraries where all the knowledge of the time was stored. Libraries, specifically the compilations of human achievements and works, were indicators of the level of societal development of that era. Since data centers conceptually resemble the prototypes of ancient libraries, data centers have the same significance as libraries in ancient times. Every action we take in the modern world is directly or indirectly connected to the processes occurring in data centers. However, what are data centers, in general? Huge gray boxes, showing no signs of human presence, are reminiscent of the familiar logistics centers that occupy vast spaces on the periphery of our cities or nature. The rapid growth of the data center industry has led to significant environmental concerns, primarily due to its substantial energy consumption and resultant carbon footprint. [4] Data centers require a continuous and vast amount of electricity to power their servers and cooling systems, contributing approximately, According to the International Energy Agency (IEA), 1%-1,3% to global electricity consumption. [5] This high demand for energy often relies on non-renewable sources, leading to considerable greenhouse gas emissions. Additionally, the industry faces challenges related to water usage for cooling purposes, which can strain local water resources, particularly in regions facing water scarcity.

As we delve deeper into digitalization, automation, and robotization, perceiving the present as the transition from the Anthropocene to the post-Anthropocene, the need for new architectural typologies becomes evident. This involves adapting to technological advances and fundamentally rethinking our built environments to accommodate both human and technological entities. The rapid assimilation of artificial intelligence and other technological tools into our lives underscores the importance of facilities such as data centers, which have traditionally been designed with a focus on functional and operational efficiency, often at the periphery of human-centric spaces.

This moment prompts us to rethink how we design and plan our cities. As technology like digital tools, automation, and robots become more significant, we see the need for new buildings. It is not just about keeping up with technology but reimagining how we coexist. Data centers, essential for our digital lives, have usually been built outside our cities. Nevertheless, there is a growing need to promote their integration into our communities, focusing on operational effectiveness, community integration, and environmental sustainability.

These hubs of computing power are more than just technical spaces; they are emerging as the central cultural landmarks of the digital age. Just as libraries, cathedrals, and other buildings were central to their respective eras' social and cultural fabric, today's emblematic structures are the data centers. Throughout history, every era had its defining building types, such as churches, factories, houses, and museums. Data centers are poised to define this era, symbolizing our shift into a fully digitalized society. The thesis will describe the challenges of data centers during the transition from the Anthropocene to the post-Anthropocene era.



Before 1950: Foundations of Digital Computing

Before the 1950s, the computing landscape was dominated by the development of mechanical and analog devices such as the abacus and Charles Babbage's Analytical Engine, which conceptualized the fundamental principles of programmable computing.[6] During the 1940s, significant advancements were achieved by creating the first electronic digital computers. Notably, the Colossus, developed during World War II, was pivotal in cryptographic efforts.[7] At the same time, the ENIAC, which was unveiled in 1945, is credited as one of the earliest electronic general-purpose computers.[8] These developments underscored the transition from mechanical to electronic methodologies in computational technology.

Figure 1.1 ENIAC, U.S. Army Photo

1950-1980: The Mainframe Era

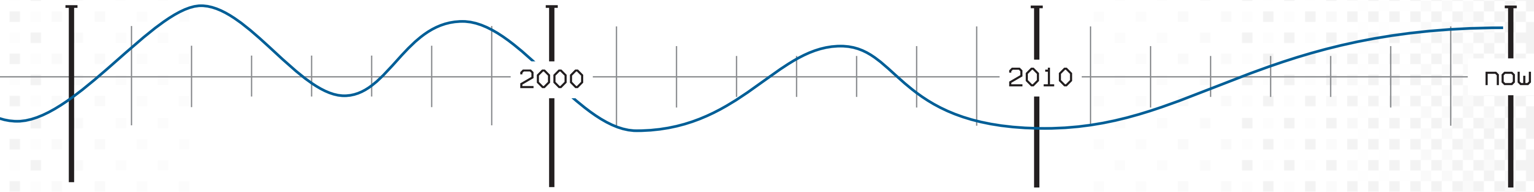
The period between 1950 and 1980 is often called the "Mainframe Era" due to the central role played by large-scale mainframe computers in business and government sectors. The introduction of IBM's 701 and 360 models epitomized this era, offering unprecedented computational power, albeit with significant spatial and financial costs.[9] The era was also marked by technological shifts from vacuum tubes to transistors, leading to more reliable and efficient systems. Furthermore, the advent of operating systems capable of time-sharing significantly enhanced the utility of mainframes by allowing multiple users to interact with the machine simultaneously.

Figure 1.2 IBM 701, IBM

1980-1990: Emergence of Personal Computers and Networking

The 1980s witnessed a pivotal shift with the introduction of personal computers, significantly democratizing computing capabilities beyond large organizations to individuals and small businesses. The launch of the IBM PC in 1981, followed by Apple's Macintosh in 1984, marked the beginning of widespread personal computing. Concurrently, the development of local area networks (LANs) facilitated the networking of multiple computers within a confined area, enabling resource sharing and communication that were previously unfeasible, thereby enhancing operational efficiencies and connectivity.[10]

Figure 1.3 IBM PC, IBM



1990-2000: The Internet and Client/ Server Computing

The 1990s heralded the expansion of the Internet, transitioning computing from a localized to a globally interconnected network. The commercialization of the World Wide Web mid-decade revolutionized information dissemination and connectivity, catalyzing the dot-com boom. This period also saw the rise of the client/ server architecture, where desktop computers (clients) connected to more powerful central computers (servers) to access shared resources. This model became fundamental for business networks, supporting a more distributed computing environment and fostering a new wave of digital applications and services.[11]

Figure 1.4 WWW's "historical" logo, created by Robert Cailliau in 1990.

2000-2010: Expansion of Data Centers and Onset of Cloud Computing

The first decade of the 21st century was characterized by significant growth in data creation, necessitating the development and expansion of data centers to manage, store, and process vast quantities of information. This era also marked the inception of cloud computing, with pioneers such as Amazon Web Services introducing scalable solutions in 2006. Cloud computing offered a transformational shift, providing on-demand computing resources and storage over the Internet, which reduced the need for extensive on-premise hardware and enabled greater scalability and flexibility in data management.[12]

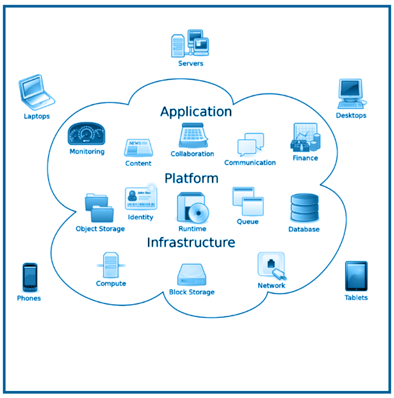


Figure 1.5 Diagram showing overview of cloud computing, Sam Johnston

2010-Present: Dominance of Cloud Computing and Emergence of Edge Computing

From 2010 onwards, cloud computing has become the dominant model, facilitated by significant providers, including Amazon, Google, and Microsoft Azure. This period is characterized by substantial advancements in big data analytics and machine learning, supported by increasingly robust cloud infrastructures.[13] Moreover, the recent trend towards edge computing reflects a shift toward processing data closer to the source of data generation. This is driven by the need for real-time computing within applications such as smart cities and the Internet of Things (IoT), which require rapid processing speeds and reduced latency.[14]

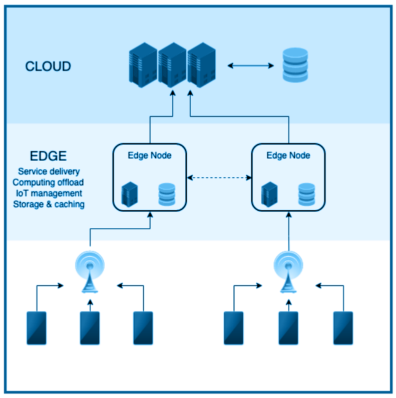
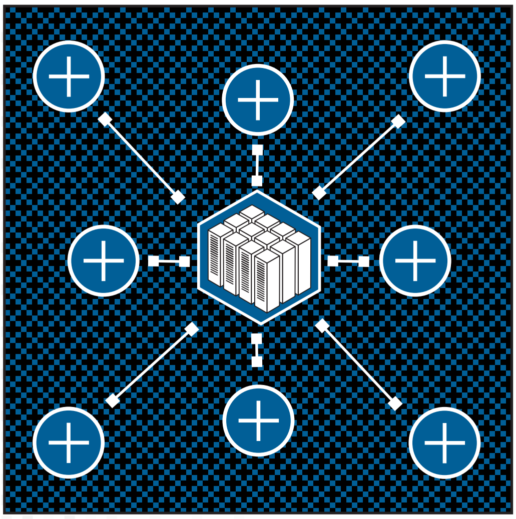


Figure 1.6 The edge computing infrastructure

/ TYPES

/ Colocation

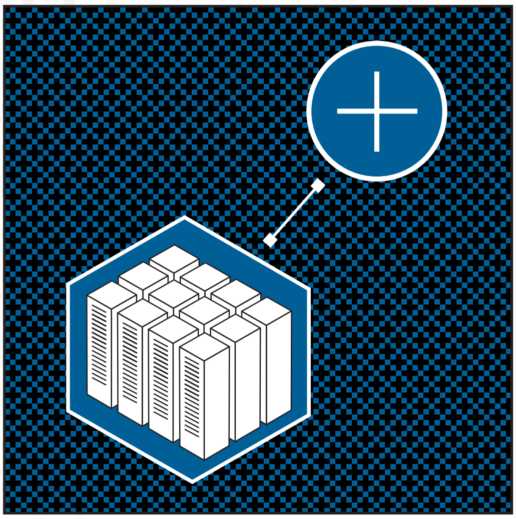


A colocation data center allows businesses to rent space for their servers and other computing hardware. Instead of keeping servers in-house, where they need to manage power, cooling, bandwidth, and security, companies opt for colocation data centers, which provide these services in a shared space. This allows organizations to benefit from economies of scale, higher reliability, better connectivity, and enhanced physical security, which they might not be able to afford independently. Businesses choose colocation to focus more on their core activities while leveraging advanced infrastructure managed by specialized providers.[15]

/ Hyperscale

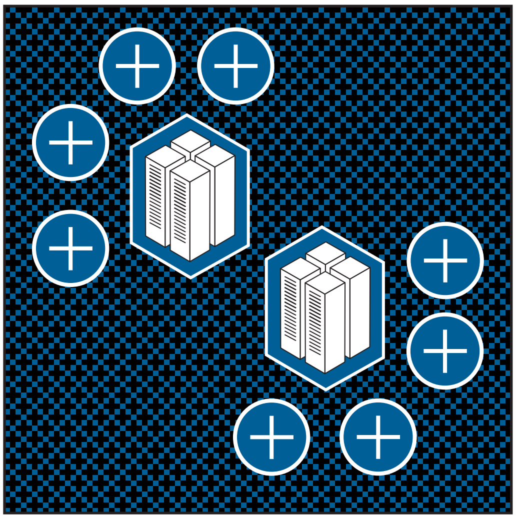
A hyperscale data center is a type of facility designed to support robust and scalable applications by offering significant computing power, storage, and networking resources. These data centers are typically operated by major tech companies like Amazon, Google, Microsoft, Facebook, and Apple, which need to manage vast amounts of data and provide cloud services to millions of users worldwide. Hyperscale data centers are crucial for companies that operate on a global scale and require extensive IT resources to support large-scale consumer services, complex computations, and storage needs. [16]

/ Enterprise



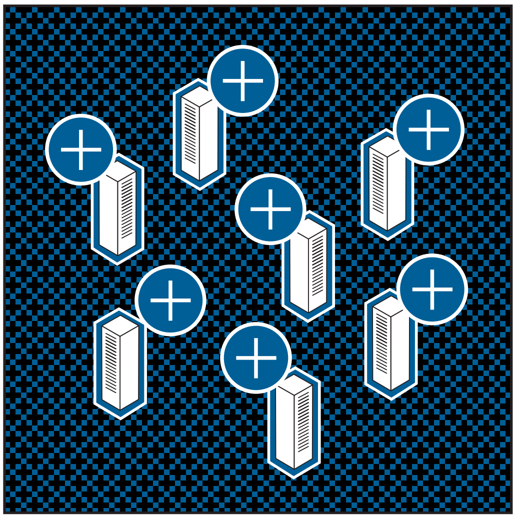
An Enterprise Data Center is a facility used primarily by a single organization to host its internal and business-critical applications. Unlike colocation or cloud data centers that serve multiple tenants, an enterprise data center is dedicated to the needs of one business and is typically owned, managed, and maintained by that business.

/ Edge



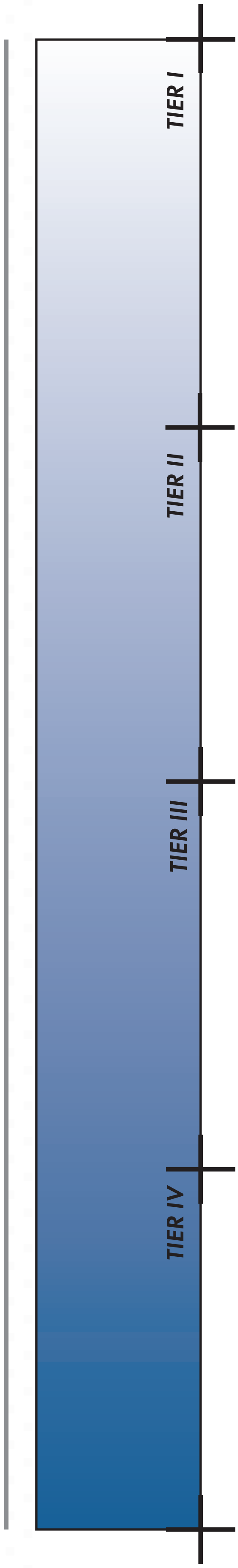
Edge computing processes data close to where it's generated, reducing latency and bandwidth use, and is crucial for real-time applications. Key uses include Internet of Things (IoT) for real-time data processing from sensors in manufacturing, smart homes, and cities; Autonomous Vehicles, enabling rapid sensor data processing for safety and efficiency; Telecommunications, enhancing data processing speed and reducing latency, especially for 5G networks; Content Delivery, improving streaming and gaming speeds by caching content near users; Healthcare, facilitating faster medical responses by processing patient data at the point of care; Retail, supporting real-time. [17]

/ Micro



A Micro Data Center (MDC) is a smaller, modular version of a traditional data center designed to handle specific needs or extend data center networks' reach. These self-contained units include the necessary power, cooling, security, and associated management tools. Micro data centers are often used to process data locally, providing reduced latency and faster processing in locations where constructing a full-scale data center is not feasible or necessary. Micro data centers are a practical solution for businesses that need immediate, localized computing power and data storage, providing flexibility, scalability, and efficiency in a compact form. They support a wide range of applications, particularly in scenarios where speed and local data processing are priorities.[18]

/ TIERS



/

This is the most basic level of data centers that offers 99.671% uptime per year, which amounts to about 28.8 hours of downtime annually. Tier 1 facilities have a single path for power and cooling and no redundant components, making them suitable for small businesses or non-critical applications that can tolerate some downtime. [19, 20]

//

Improving on Tier 1, Tier 2 data centers include redundant capacity components and a single distribution path, achieving 99.741% uptime annually or about 22 hours of downtime. These are used by small to medium-sized businesses that need slightly better reliability but can still afford some downtime. [19,20]

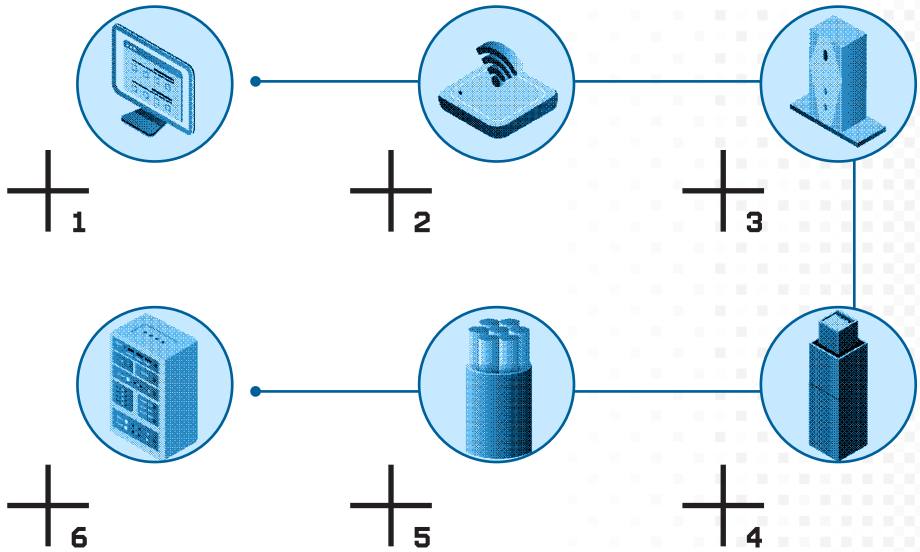
///

These data centers offer even more robust features, including multiple power and cooling distribution paths, with only one path active at a time. They provide 99.982% uptime, translating to roughly 1.6 hours of downtime per year. Tier 3 facilities are ideal for businesses that require high availability and less downtime but do not need the highest level of fault tolerance. [19, 20]

////

The highest level of data centers, Tier 4 facilities, offer 99.995% uptime, or just about 26.3 minutes of downtime per year. They feature full fault tolerance across all critical systems and infrastructure, with multiple independent and physically isolated systems. This tier is best suited for mission-critical operations that demand the utmost in uptime and reliability. [19, 20]

/ WORK - (DATA) - FLOW



DATA FLOW FROM USER DEVICE TO DATA

1. User Device: The process begins with a user device, such as a computer, smartphone, or tablet. This device generates data intended for transmission, which might include a request for a webpage, a file upload, or streaming video.[21]

2. Modem: The modem is a crucial device that connects the user's local network to the external internet service. It converts the digital data from the user device into a format suitable for transmission over telecommunications lines, such as telephone lines or cable systems[21].

3. Router: Connected to the modem via an Ethernet cable, the router directs data traffic both within the user's home network and to the broader internet. It determines the best pathway for the data to reach its intended destination, managing network traffic efficiently to avoid congestion and delays[21].

4. Networking Cables: These cables are essential physical pathways that facilitate the transmission of data. Within home or office settings, Ethernet cables are commonly used to connect devices to the router. For long-distance data transmission, especially between cities or countries, fiber optic cables are used due to their ability to transmit large volumes of data rapidly[21].

5. Internet Service Providers (ISP): The ISP plays a pivotal role in the data transmission process. It manages the movement of data from the user's router to the intended data center servers. This involves routing the data across various interconnected networks, potentially across vast distances depending on the location of the data center [21].

6. Data Center: Upon reaching the data center, the data passes through the data center's specialized network equipment, which directs it to the appropriate server within the facility [21].

/ Traditional modular data centers

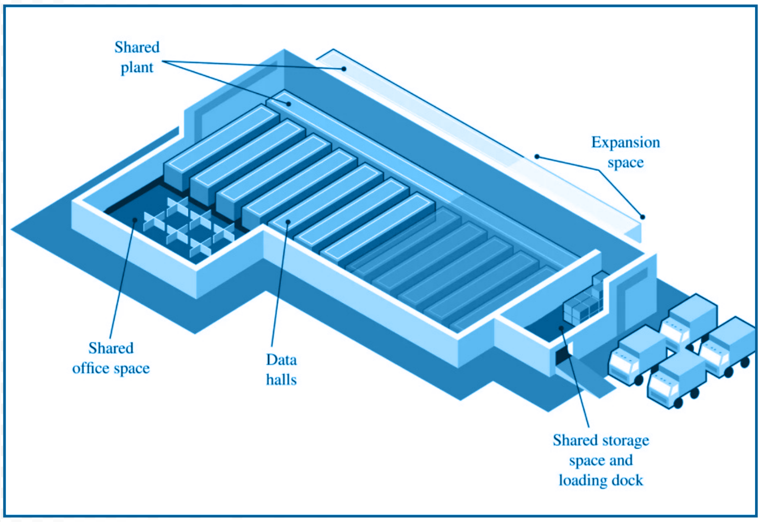


Figure 2.1 Monolithic Modular (Data Halls)

Modular data centers, a type of infrastructure commonly used today, are typically constructed as part of a building and share certain internal and external systems. In the past, these data centers were built all at once, but now they are often expanded gradually by adding more sections for servers, known as data halls. A significant issue with this gradual expansion is that sharing systems between old and new parts can create a risk: if one part fails, it can cause the entire data center to shut down. This is a problem especially when the center keeps operating while new sections are being added. If something goes wrong in the shared systems, it can prevent the successful setup of new, advanced levels of operations because the existing parts are already running and can't be easily upgraded or changed. [22]

/ Monolithic Modular (Data Halls)

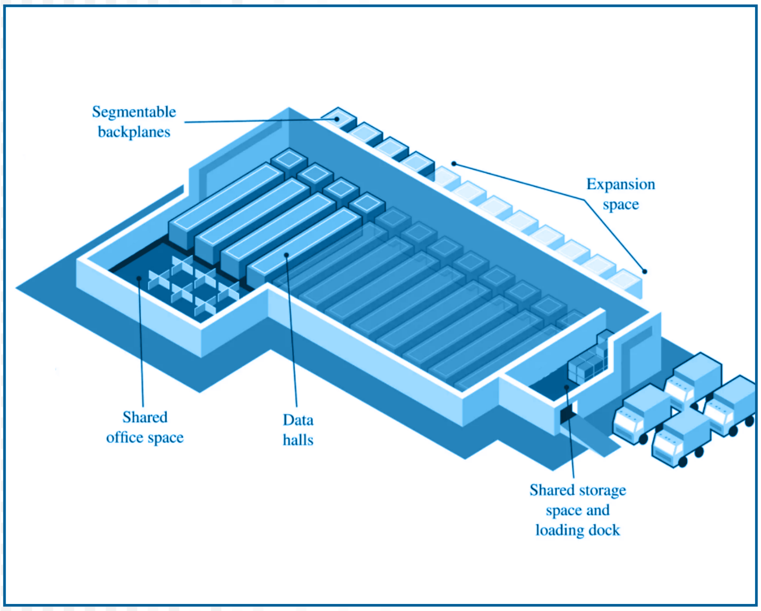


Figure 2.2 Monolithic Modular (Data Halls)

Monolithic modular data centers, as their name suggests, are expansive building-based solutions typically found in large structures, offering over 5 MW of IT power from the outset, with some sites providing up to 20 MW of capacity. Unlike traditional setups, these monolithic facilities employ segmentable backplanes, enhancing reliability by eliminating single points of failure and allowing for each data hall to be independently commissioned to Level 5 before it becomes operational. Commonly, the only shared infrastructure among customers is the medium-voltage utility gear. However, when situated within large buildings that serve multiple customers, users might find their ability to plan and control space limited. Additionally, areas such as offices, storage, and loading docks are often communal. A crucial aspect for customers is the need to prelease shell space to secure room for potential expansion, which involves forecasting future needs and upfront costs. [22]

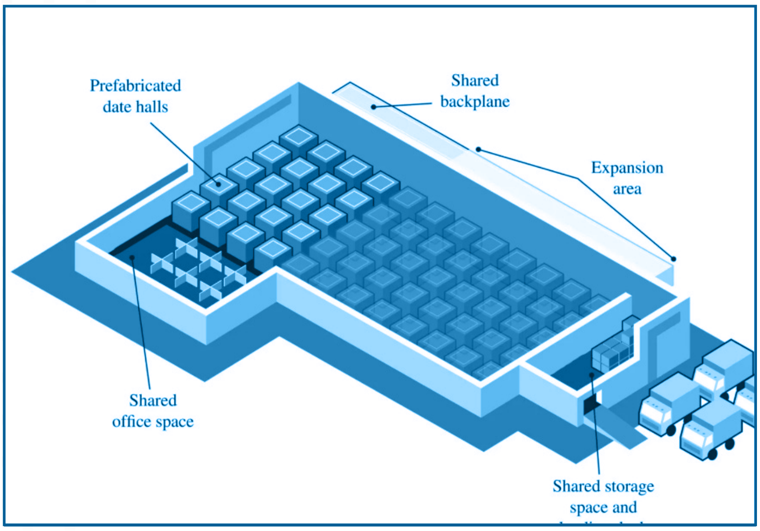


Figure 2.3 Monolithic Modular (Prefabricated)

/ Monolithic Modular (Prefabricated)

These building-based solutions are similar to their data hall counterparts with the exception that they are populated with the provider's prefabricated data halls. The prefabricated data hall necessitates having tight control over the applications of the user. Each application set should drive the limited rack space to its designed load limit to avoid stranding IT capacity. For example, low-load-level groups go in one type of prefabricated data hall, and high-density-load groups go into another. These sites can use shared or segmented backplane architectures to eliminate single points of failure and to enable each unit to be Level 5 commissioned. Like other monolithic solutions, these repositories for containerized data halls require customers to prelease and pay for space in the building to ensure that it is available when needed to support their expanded requirements. [22]

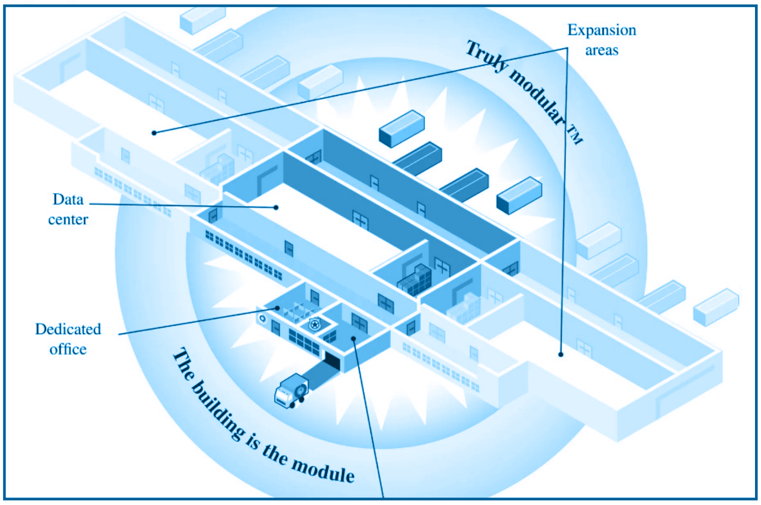


Figure 2.4 Stand-Alone Data Centers

/ Stand-Alone Data Centers

Stand-alone data centers feature modular architectures, incorporating core components within a robust shell that can be easily expanded. These self-contained units meet strict reliability and efficiency standards. Stand-alone facilities offer a distinct solution, providing customers with a dedicated data center located precisely where needed. Encased in a durable shell designed for harsh conditions, they differ from prefabricated or container-based alternatives requiring permanent structures. Stand-alone data centers simplify capacity planning, allowing customers to scale operations with demand without preleasing space. Their modular design includes exclusive operational components such as office space, loading docks, and break rooms, ensuring a private and customizable data management environment. [22]

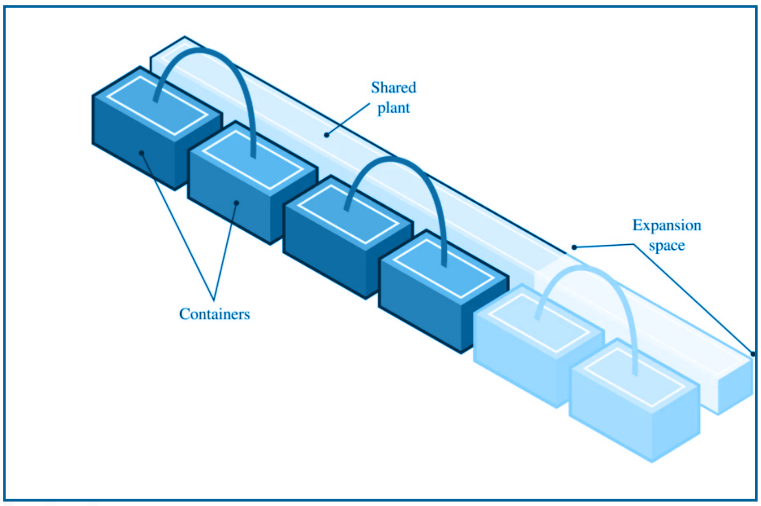


Figure 2.5 Container solutions

/ Container solutions

Often simply called "containers", prefabricated data halls are standardized modules housed within ISO shipping containers designed for rapid deployment to sites with immediate infrastructure requirements. While they are marketed for their swift delivery, the installation of essential shared external components like generators, switchgear, and sometimes chilled water systems can take up to eight months, potentially offsetting the benefits of their rapid deployment capability. For long-term use, these prefabricated containers can be limited by their non-reinforced structures, vulnerable to environmental factors such as wind, corrosion, and moisture intrusion, which also restrict the volume of IT equipment that can be installed. Furthermore, these units typically lack supplementary spaces such as loading docks and security checkpoints, placing the onus on the customer to manage these aspects. [22]

/ Cloud Ring, Naver Data Center
BEHIVE

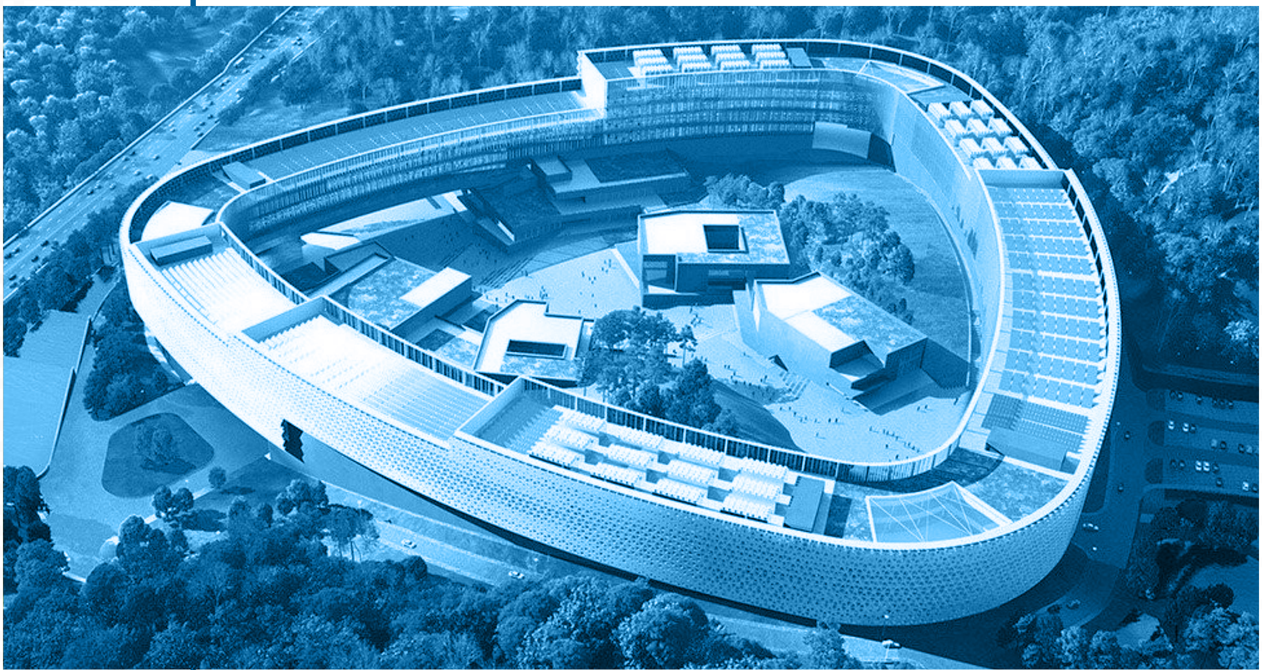


Figure 3.1 BEHIVE DESIGN. Cloud Ring, Naver Data Center.

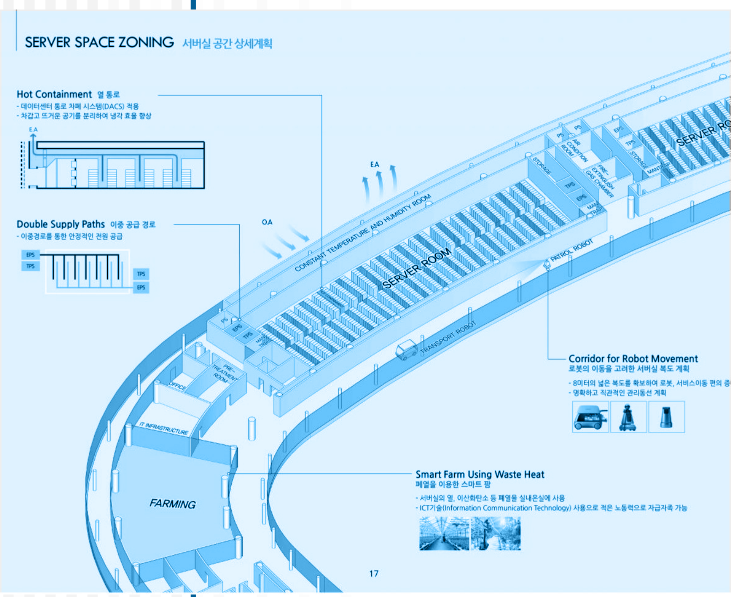


Figure 3.2 BEHIVE DESIGN. Cloud Ring, Naver Data Center.

Naver, Korea's most significant internet enterprise, is expanding its cloud services with a new generation of data centers located in a mountainous site in Sejong City. Drawing inspiration from the World Heritage Site Hahoe Folk Village, the design concept for the data center revolves around a "learning community" safeguarded by the data.[23] The design, named "Cloud Ring," is creatively adapted to the site's challenging topography with a height difference of over 50 meters. It features two main components: an outer ring that hovers like a cloud above the valley, housing server rooms and mechanical spaces, and an inner ring designed like a village with amenity buildings cascading down the valley, including a control center, conference center, learning center, and exhibition space, farming are.

The outer ring's elevated design allows for a straightforward and efficient layout of server rooms. In contrast, the inner ring's buildings blend into the landscape, using tinted concrete to mirror the rustic quality of traditional Korean residences. The materials complement the dual structure and enhance functionality; the outer ring utilizes a multi-layer curtain wall with a perforated screen that acts as a purification mechanism, cooling and purifying air before it enters the server rooms. The project is phased into three curvy parts for construction, integrating vertical biological gardens, office spaces, maintenance, and storage to support the server rooms and facilitate the operation of robotic equipment. The design effectively addresses aesthetic and practical challenges, creating a sustainable and integrated solution for Naver's data center needs.

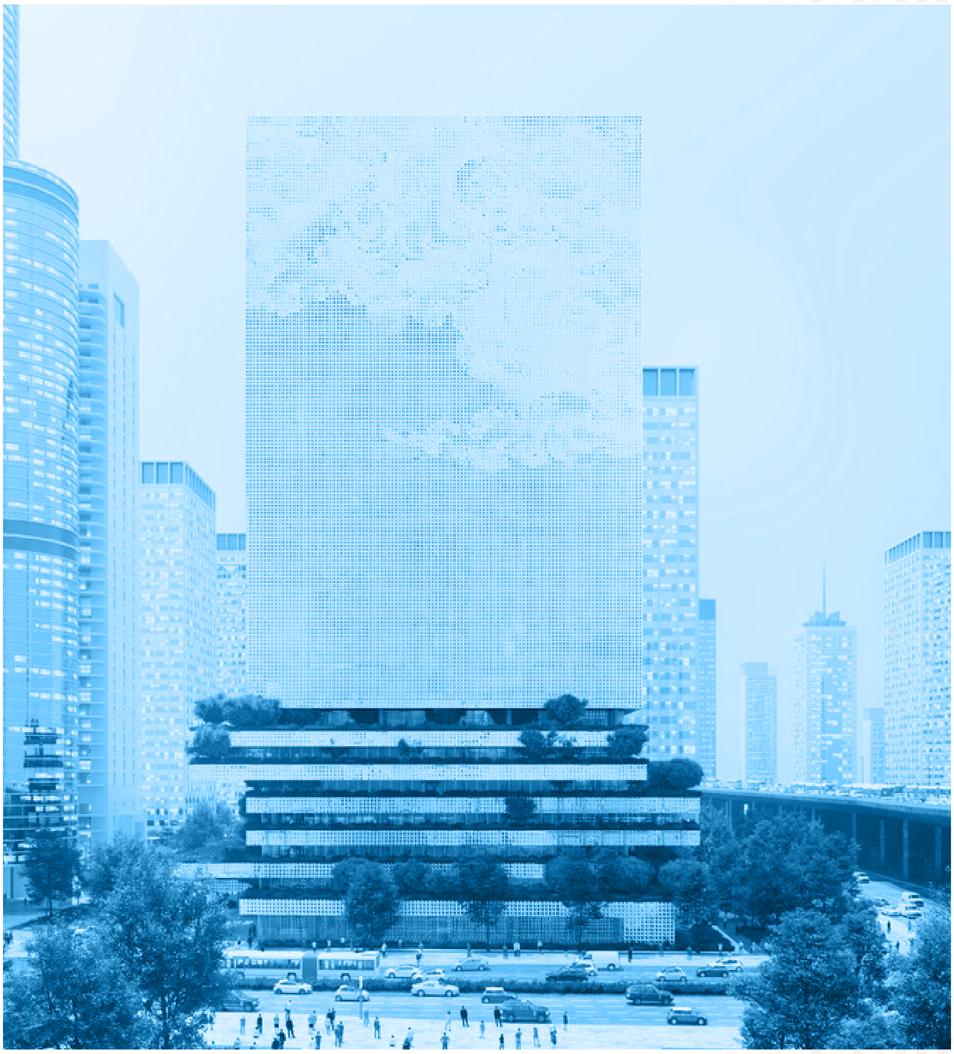
/ Mecanoo's Qianhai Data Center Huasen Architects

Mecanoo has revealed their design for the Qianhai Data Center in Shenzhen, China, [24] which earned them second prize in an international design competition. The design features a 63,000-square-meter structure, envisioned as an urban beacon, consisting of an opaque tower on top of an open base that includes office and support spaces.

Standing at 113 meters, the tower, dubbed the "digital lighthouse," will be a prominent feature within the 15-square-kilometer Qianhai Free Development Zone, symbolizing the district's innovative spirit. Panels display images of clouds reminiscent of traditional Chinese paintings during the day and transform into a dynamic digital display at night, thanks to embedded lighting. The base of the tower, known as the plinth, integrates into its surroundings and is designed to offer a welcoming, green work environment. The office spaces are organized around a double-height operational center and feature large glass facades that open up to terraced landscapes, allowing workers direct views of the shifting outdoor scenery.

The project was developed in collaboration with Huasen Architects, combining Mecanoo's innovative design approach with local architectural expertise to create a landmark data center that blends functionality with aesthetic appeal.

Figure 4.1 Mecanoo. Qianhai Data Center



/ The Spark
Snøhetta

Snøhetta, in partnership with MIRIS, Skanska, Asplan Viak, and Nokia, has developed a sustainable data center concept called The Spark[25], designed to convert excess heat from data centers into a valuable energy resource for powering "Power Cities." This innovative approach aims to transform energy-consuming data centers into energy-producing facilities that support community power generation, enhancing health, recreation, and environmental sustainability.

The Spark sets a new standard for data centers, redefining them as integral parts of smart city infrastructure. It envisions data centers not only as data storage and management hubs but also as central to a city's energy ecosystem, circulating energy like the human circulatory system—dispersing heat to various buildings and then returning it to the data center for efficient cooling. This sustainable cycle is intended to power a variety of urban facilities, including schools and hospitals, thereby contributing to a more human-centric approach amidst our digitalized lives. Snøhetta has extended this concept visually and communicatively through the project's branding, website, and an informational film, making the complex idea accessible to a broader audience.

Figure 5.1 Snøhetta. The Spark

Figure 5.2 Snøhetta. The Spark

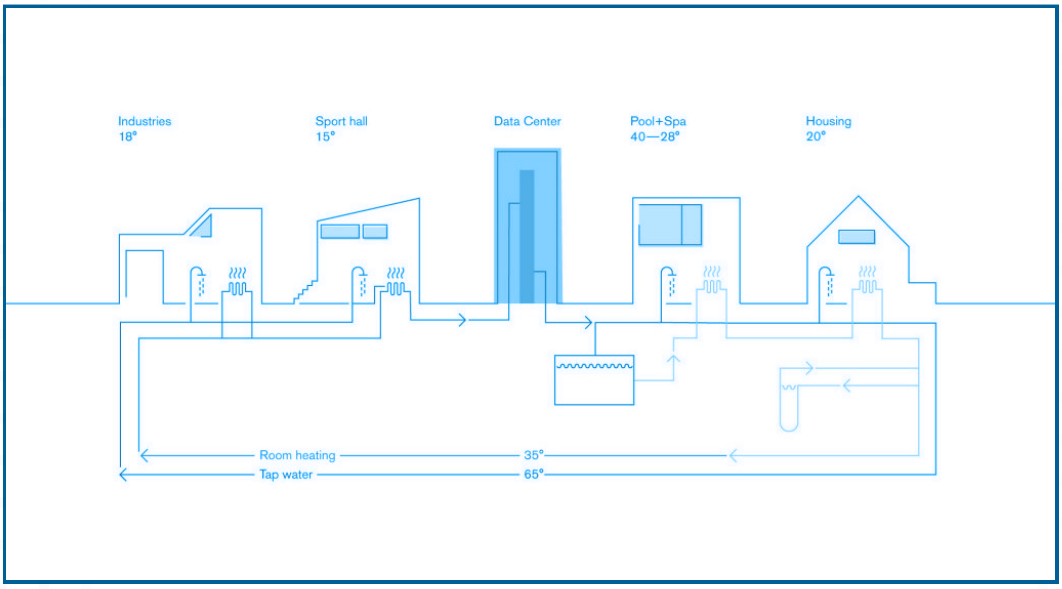


Figure 5.3 Snøhetta. The Spark

/ Datacenter AM4
Benthem Crouwel Architects

Figure 6.1 Jannes Linders. Datacenter AM4 exterior

The AM4, Equinix's new data center in Amsterdam[26] , epitomizes the concept of making the "invisible visible" by housing crucial digital infrastructure within an architecturally striking 72-meter tower. Located in the Science Park, an academic campus, this building prominently displays its function, managing 12 stories of servers that process about 38 percent of all Dutch data traffic, making it a key node in Europe's internet infrastructure.

Designed by Benthem Crouwel Architects, the AM4 reflects a shift in how data centers are perceived and integrated into urban environments. Traditionally, data centers have been nondescript structures located away from city centers. However, with the rise of cloud services and big data, there is a growing need to make these buildings both secure and aesthetically pleasing without making them seem fortress-like. To this end, the AM4 features security measures such as a canal instead of barbed wire fences and an identity checkpoint leading to the servers through a brightly colored bridge, enhancing both security and aesthetic appeal.

The building's design includes a high-rise structure made of triangular aluminum profiles, which create an optical illusion that makes the tower appear slimmer from a distance. This design choice reflects the surrounding environment on its façade, helping the top of the tower blend into the sky. Additionally, the data center is designed for flexibility and sustainability; it is equipped with energy storage systems that not only manage data but also supply heat to nearby buildings. This dual function underscores the data center's role as an integral part of the urban fabric, potentially adaptable to future needs for less server space or different uses like laboratories, offices, or apartments.

/ Ashton Old Baths Manchester MCAU

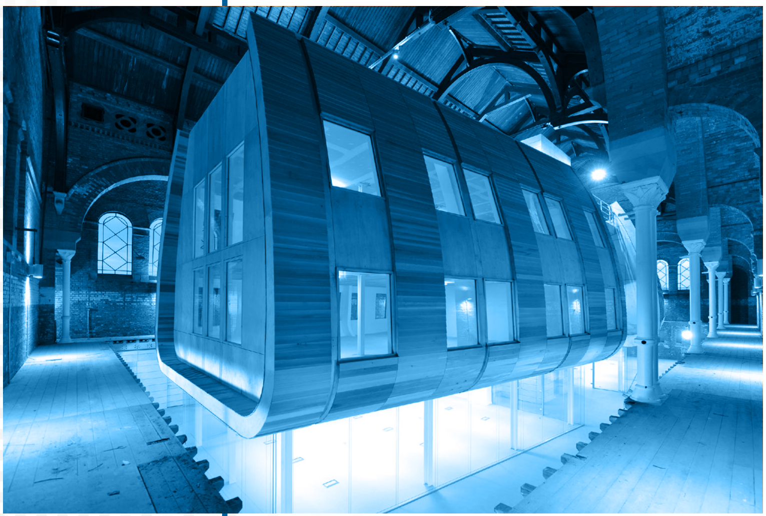


Figure 7.1 MCAU. Rejuvenation Ashton Old Baths Manchester

The Ashton Old Baths in Greater Manchester, UK, a historical building constructed in 1870, has been transformed into a tech hub, merging its rich heritage with modern technology. This Grade II* listed building, akin to London's iconic Battersea Power Station, now houses over 10,000 square feet of office and coworking space, including a new, advanced data center[27].

This data center is a significant addition, supporting local council and NHS infrastructure, with space also available commercially through a cooperative. Designed to Tier III standards, it offers high reliability and is integrated into the building's original spectators' gallery. The design utilizes a 'room within a room' approach with a steel frame and modular panels, ensuring minimal impact on the building's historical structure while providing scalability and efficient power management with two independent UPS systems.

Engineers faced the challenge of fitting modern technological needs into a heritage-listed building, resulting in a facility that not only meets stringent operational standards but also enhances the building's aesthetic. The data center features windows and glass walls with colored lighting, aligning with the historical nature of the building and making the space visually appealing.

This redevelopment revitalizes a historic site and boosts the local digital economy by providing cutting-edge infrastructure. It exemplifies how heritage buildings can be repurposed to accommodate contemporary technological needs, serving as a model for similar projects globally. The Ashton Old Baths data center stands as a testament to the successful integration of architectural heritage and modern digital infrastructure.

Figure 7.2 MCAU. Rejuvenation Ashton Old Baths Manchester

/ Modular solutions

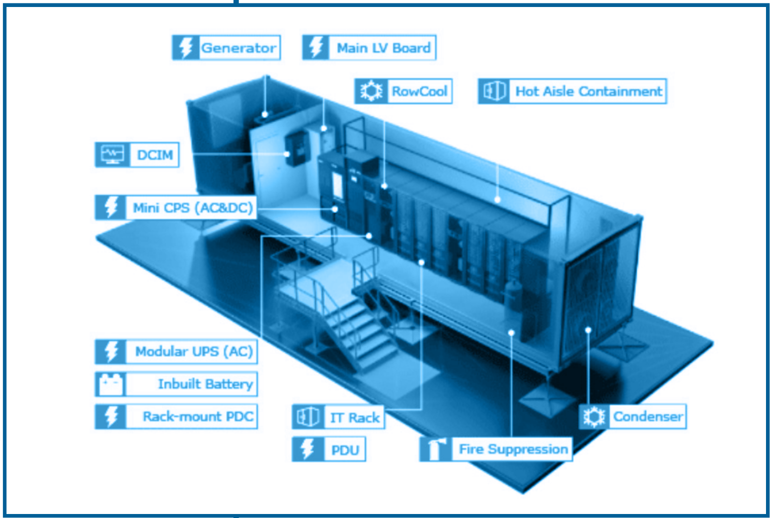


Figure 8.1 MCAU. Modular data center scheme

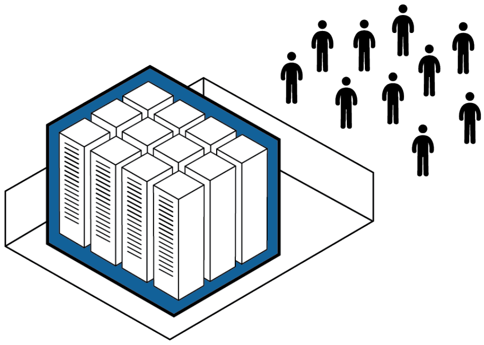
Modular data centers represent a modern approach to data center design and deployment, characterized by their use of prefabricated modules that can be quickly assembled and scaled to meet varying demands. These data centers are composed of standardized components, including power, cooling, and IT equipment, built-in controlled environments, and then transported to the deployment site. Several companies have successfully implemented modular data centers, leveraging flexibility, scalability, and efficiency to meet various business needs.

Notable examples include Huawei Technologies Co. Ltd., which has developed and deployed modular data centers to support its extensive telecommunications and IT infrastructure, emphasizing energy efficiency and rapid deployment.[28] Vertiv Co. has shipped over 1,500 modular data centers worldwide, offering scalable and high-quality solutions designed for rapid deployment, used in industries such as telecommunications and cloud services. Microsoft's Azure Modular Data Center (MDC)[29] revolutionizes IT infrastructure by providing a scalable, flexible, and secure cloud solution tailored for diverse and challenging environments. Prefabricated for rapid deployment, Azure MDC significantly reduces setup time compared to traditional data centers, making it ideal for remote or underserved areas. Its energy-efficient design and advanced cooling solutions minimize operational costs while supporting sustainable practices. With robust security features and compliance with industry regulations, Azure MDC ensures data protection and reliability. This versatile solution seamlessly connects to Azure's global network, enhancing operational capabilities for industries ranging from telecommunications to healthcare, defense, and disaster recovery.

Figure 8.1 Mictosoft Azure MDC

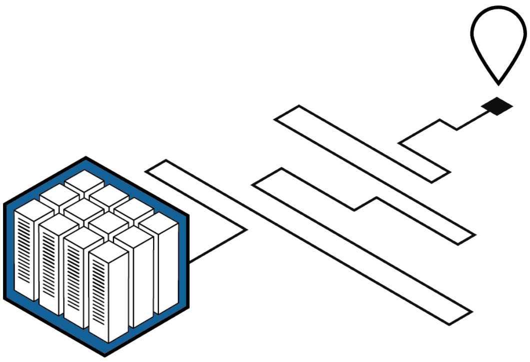
/ Data Centers Common Features

/ HUMAN FREE



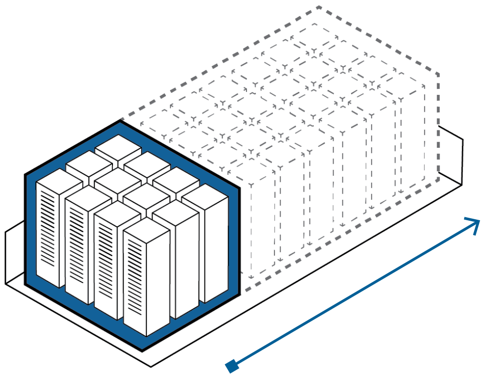
Modern data centers are increasingly designed to be human-free environments. This shift towards automation and remote management reduces the need for on-site personnel, enhancing security and operational efficiency.[30] Advanced robotics and automated systems handle routine maintenance, monitoring, and diagnostics, while sophisticated software enables remote control and troubleshooting. This minimizes human error and unauthorized access, ensuring higher data integrity and physical security. When human intervention is necessary, strict access protocols, such as biometric entry and multi-factor authentication, regulate entry to sensitive areas.

/ FAR FROM THE CITIES



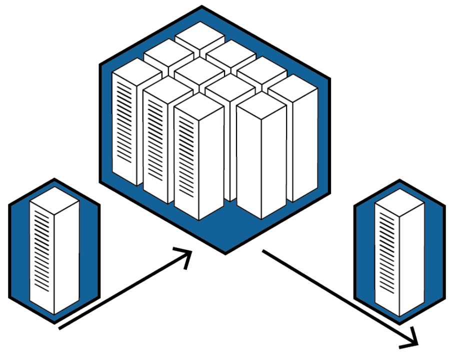
The strategic location of data centers is far away from cities. These remote locations are chosen to provide ample space for expansion and large-scale renewable energy installations like wind turbines and solar panels, along with lower land prices.[31] By situating data centers in less populated areas, they benefit from a more controlled and stable environment, enhancing their operational reliability. However, being far from urban centers also necessitates robust connectivity solutions to ensure seamless data transmission and efficient remote management, reinforcing the importance of advanced networking infrastructure and redundant communication pathways.

/ CONTINUOUS GROWTH



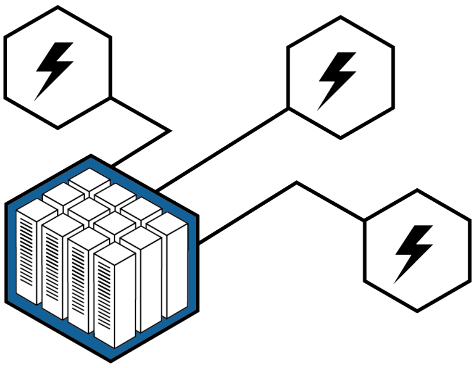
The growing production of data and the consequent need for its storage demand dimensionally adaptive data centers. According to the Observatory of Digital Innovation, 35 zettabytes of data will be generated in the next five years. To accommodate this immense volume, data centers must scale efficiently, requiring expansive physical footprints and advanced infrastructure. This predicted growth will continue contributing to soil consumption as new facilities are built and existing ones are expanded.

/ HARDWARE UPGRADE



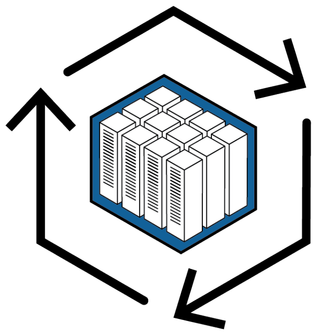
A key feature of modern data centers is regularly updating hardware every few years. This practice is essential for maintaining optimal performance, efficiency, and security. As technology advances rapidly, older hardware can become obsolete, leading to slower processing speeds, increased energy consumption, and higher risks of failure or cyber threats. By updating hardware regularly, data centers can leverage the latest innovations in processors, storage solutions, and networking equipment, ensuring they remain competitive and capable of handling growing data demands.[32]

/ ENERGY CONSUMPTION



A significant feature of data centers is their substantial energy consumption. These facilities house vast computing equipment that requires continuous power to operate servers, storage devices, and networking hardware. Additionally, maintaining optimal operating conditions involves extensive cooling systems to dissipate the heat generated by the equipment, further increasing energy demands. As data centers scale to accommodate the exponential growth in digital data, their energy needs grow correspondingly.[33]

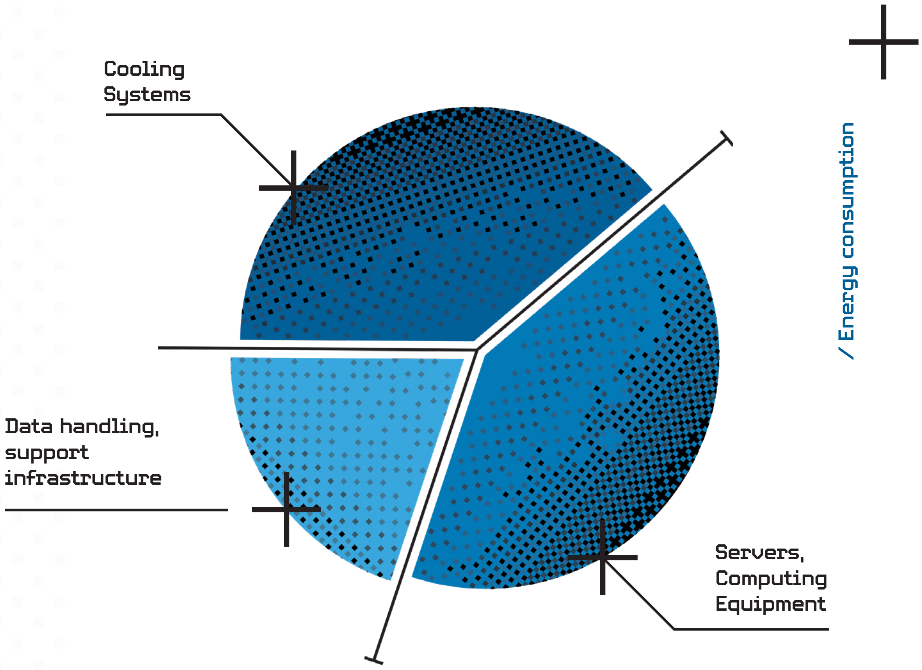
/ SUSTAINABLE DIRECTION



Nowadays, the development of data centers is increasingly guided by a strong emphasis on sustainability. To minimize their environmental impact, today's data centers are increasingly integrating renewable energy sources such as solar and wind power alongside advanced cooling techniques like free cooling and geothermal systems.[34] Energy efficiency is achieved through smart grid integration and modular design for scalability.

MICROSOFT. Data Center Heat Repurposed. 2023. [online] Available at: https://local.microsoft.com/blog/datacenter_heat_repurposed/ [Accessed YYYY-MM-DD].

/ Energy consumption and efficiency of data center components



Servers and Computing Equipment:

Servers are integral to data center operations, executing the core tasks of data processing, storage, and application hosting. These units are perpetually active to ensure the constant availability of digital services, which necessitates a continuous power supply. Servers' power demand is primarily driven by their computational workload. As data throughput and computational needs escalate, the proportion of energy attributed to servers increases correspondingly.

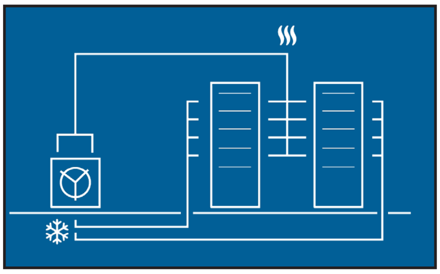
Data handling and support infrastructure:

Infrastructure in data centers includes essential components that manage and support data operations. This group comprises storage devices, networking equipment for data flow management, and the necessary power infrastructure.

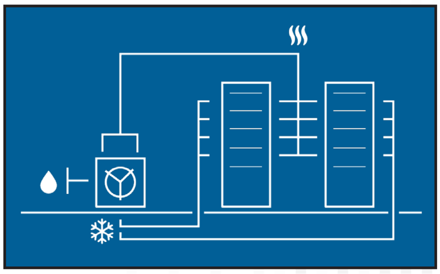
Cooling Systems

Data centers house many servers, storage units, and networking devices that generate considerable heat during operation. This heat must be effectively managed to ensure system reliability. Data centers operate continuously, 24/7, to meet the demands of global digital activities. This non-stop operation generates constant heat, requiring persistent cooling to maintain safe temperature levels. It is estimated that cooling systems can consume 30% to 55% of a data center's total energy usage. Here's a detailed look at the common cooling methods and technologies :

/ Traditional Cooling Methods

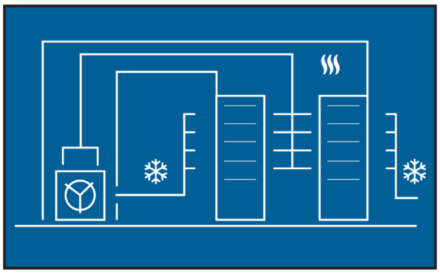


Conventional Air Conditioning (HVAC): Utilizes standard Heating, Ventilation, and Air Conditioning (HVAC)systems similar to those in residential and commercial buildings, characterized by high energy consumption and reliance on chemical refrigerants.[35]

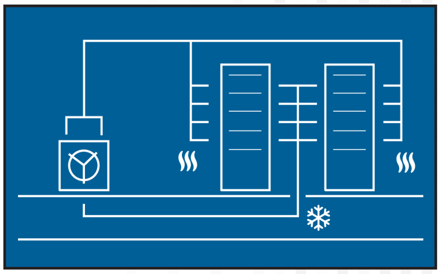


Chilled Water Air Handlers: These systems employ chilled water to cool the air within data centers. Although more efficient than conventional HVAC systems, they require substantial energy to chill and circulate the water.[35]

/ Enhanced Efficiency Cooling Methods

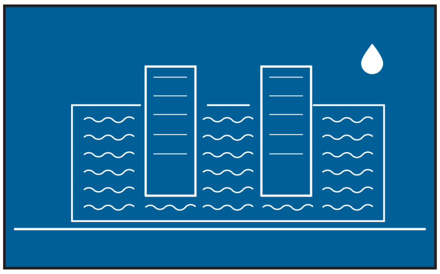


Hot Aisle/Cold Aisle Containment: Organizes servers into hot and cold aisles to allow more precise cooling. This strategy reduces the mixing of hot and cold air, improving efficiency but still depending on powered cooling.[35]

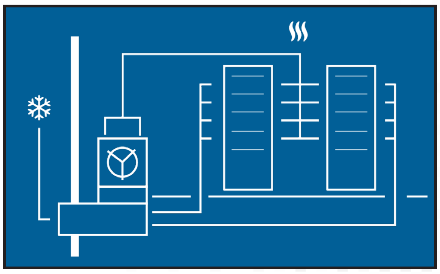


Raised Floor Cooling: Implements a raised floor as a plenum for directing cool air precisely to necessary equipment, enhancing cooling efficiency yet dependent on active cooling units.[35]

/ A+ Cooling Methods



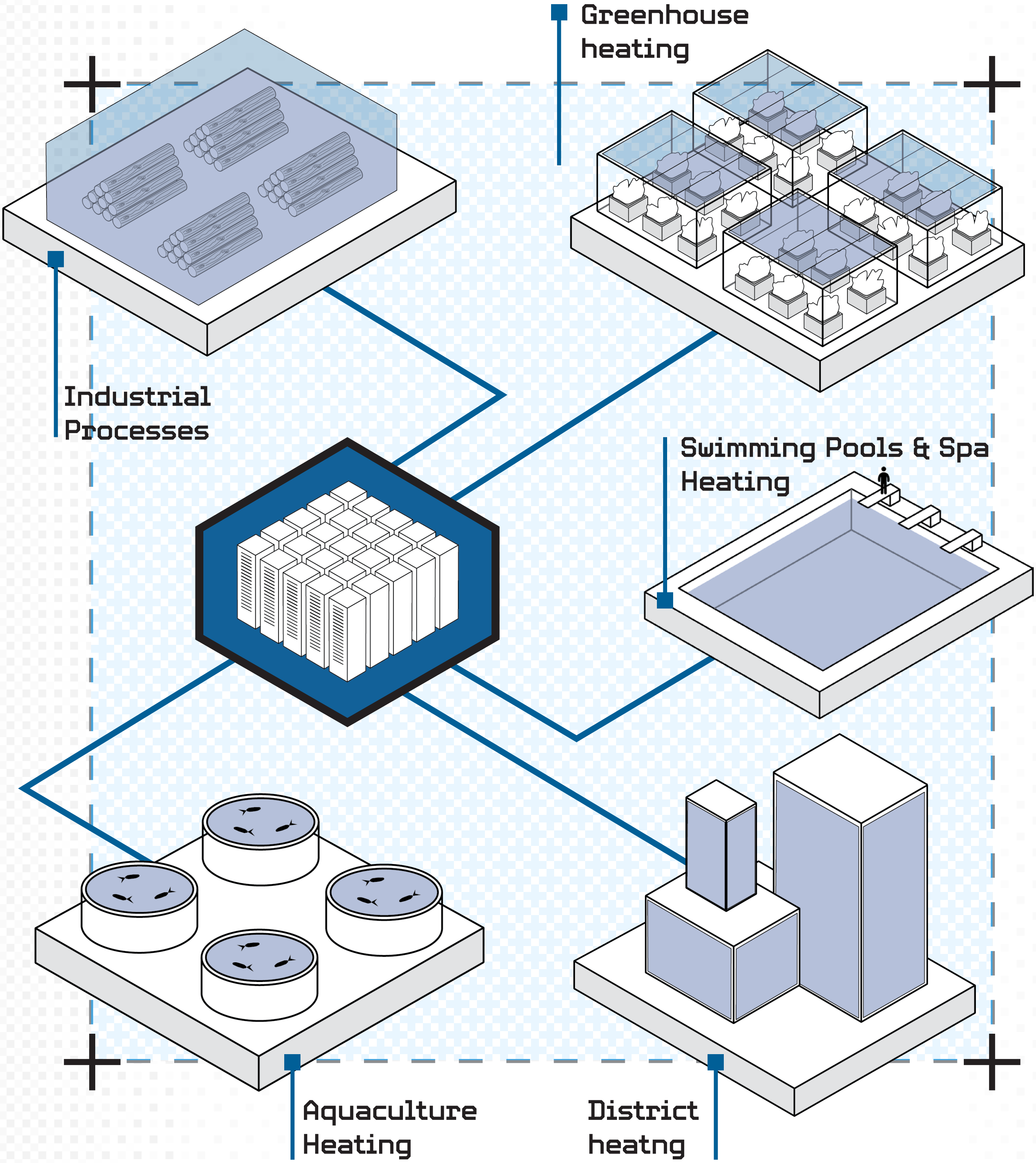
Liquid Cooling : Includes direct liquid cooling and immersion cooling where non-conductive liquids make direct contact with components. These systems are very efficient, directly cooling hardware with minimal energy loss, greatly reducing the need for air cooling.[35]



Free Cooling Using Outside Air: Takes advantage of naturally low external temperatures to effectively cool data centers. This method is highly sustainable in appropriate climates as it minimizes mechanical cooling dependence.[35]

/ HEAT REUSE

Reusing waste heat from data centers is an innovative approach to improving sustainability and energy efficiency. This strategy not only reduces the environmental impact of data centers but also offers economic benefits by providing alternative heating solutions. Here are some specific examples of how this technology is being applied:



/ District Heating

In several cities, data centers are being integrated into urban planning initiatives where excess heat generated by their operation is captured and redirected to heat local homes and public buildings. This approach not only significantly reduces the environmental impact of these facilities but also contributes to the sustainability of urban heating systems.

One notable example is Microsoft and Fortum in Finland. With Fortum Corporation, Microsoft announced plans to build a new data center region in Finland. This project aims to recycle waste heat from the data centers to serve Espoo, Kauniainen, and Kirkkonummi district heating needs. This initiative is expected to be the world's largest scheme to recycle waste heat from data centers, significantly mitigating the region's total CO2 emissions and helping the City of Espoo and neighboring communities reach their emission reduction targets.

Similarly, TU Darmstadt implemented a waste heat utilization project in its high-performance computing data center, "Lichtenberg." The project involved direct hot-water cooling for the high-performance computer, supplying heat at a temperature of 45°C for heating purposes on the university's campus, Lichtwiese. This initiative demonstrated the feasibility and environmental benefits of integrating data center waste heat into district heating networks. [39,40]

By integrating data centers into urban heating systems, cities cannot only leverage the excess heat generated by these facilities but also significantly reduce their carbon footprint. This innovative approach turns a potential waste product into a valuable resource for sustainability and energy efficiency, offering a hopeful solution to the pressing issue of climate change.

/ Greenhouses Heating

Exploring the symbiosis between data centers and greenhouse agriculture by reusing waste heat offers both sustainable and economic benefits. This concept involves using the significant amount of heat generated by data centers to create a greenhouse environment conducive to plant growth, turning energy waste into a valuable resource.

A prime example is found in sub-arctic regions, where most vegetables are imported, prompting the search for local cultivation alternatives. Research by Hampus Markeby Ljungqvist and team shows that a 1 MW data center can offset up to one-third of its energy costs by directing excess heat to an adjacent greenhouse. Such a facility could independently sustain a 2,000 square meter greenhouse or provide two-thirds of the required heating for a 10,000 square meter structure. Using this system for a larger greenhouse could meet almost 8% of the vegetable demand in northern Sweden, where more than 90% of vegetables are imported.[41]

In a study conducted by Sandberg, M., et al., a method to efficiently use waste heat from data centers to heat greenhouses was developed using advanced computer models. These models help predict how greenhouses can maintain adequate temperatures under different weather conditions using waste heat from nearby data centers. If the models show that the greenhouse stays warm in colder weather, the installation can be scaled for larger greenhouses. If not, smaller greenhouses might be more appropriate. Key challenges include developing efficient heat exchangers and modifying greenhouses to efficiently utilize low-temperature heat.[42]

/ Post-processing of agricultural products

Figure 9.1 EcoDataCenter, Pellets

The waste heat from data centers can be utilized to post-process agricultural commodities. Notable examples include drying coffee beans and converting waste wood into fuel. For instance, EcoDataCenter in Falun, Sweden, utilizes waste heat to dry waste wood products, which can then be pelletized and burned for heat. Waste heat from data centers has the potential to dry products in humid environments where other drying methods, like wood burning, are too carbon-intensive. This application could open up new revenue streams in developing countries.

Compact, container-sized data centers, as proposed by Petter Terenius from Uppsala University, could support both agricultural processing and enhance ICT access. Terenius noted, "I suggested deploying container-sized data centers across Costa Rica to not only distribute heat but also improve ICT access." He identified coffee beans, which should not be dried above 140 degrees Fahrenheit to prevent scorching, as an ideal candidate. His research developed an index to measure ICT readiness and potential in coffee-producing countries, finding Costa Rica to be the most suitable for this initiative due to its stable politics and healthy economy.[43]

In Costa Rica, about 50 small data centers could dry the entire coffee harvest. Similarly, in Cyberjaya, Malaysia, excess heat from data centers could be used to dry a range of products from seaweed to fish.

"Data center waste heat can dry various products, including tea leaves, cardboard, and banana flakes," Terenius explained. "In Australia, it could dry fodder, and in Africa, it could help store produce that would otherwise rot or be wasted, improving financial outcomes for farmers."

/ Growing Algae

The next potential use for waste heat from data centers could be to cultivate algae. Algae require minimal resources to thrive—just heat, light, and nutrients—and they do not need soil. Algae are grown for a variety of purposes, including as food additives, fish feed, and biofuel. Additionally, when exposed to the atmosphere, algae have a significant ability to absorb carbon.

In a statement to InformationWeek, Lansbergen and Redding said, "Through our research, we found that the optimal temperature for algae growth matches exactly with the waste heat generated by data centers, making it a suitable solution." A study by Gensler discovered that a 100-cubic-meter pond located next to a large data center could sequester about 14,000 kg of carbon annually across 17 harvests. Installing algae-growing panels on the exterior of the data center could potentially capture an additional 25,000 kg of carbon.

"Waste heat from data centers is typically not very hot and it loses temperature significantly over distance. We estimated a temperature drop of 10 degrees Celsius over just a few hundred meters," explained Lansbergen and Redding. "Any greater distance would necessitate a heat boost, whether for district heating or other uses. Thus, proximity is crucial." [45]

Figure 9.2 the White Data Center

/ Aquaculture approach

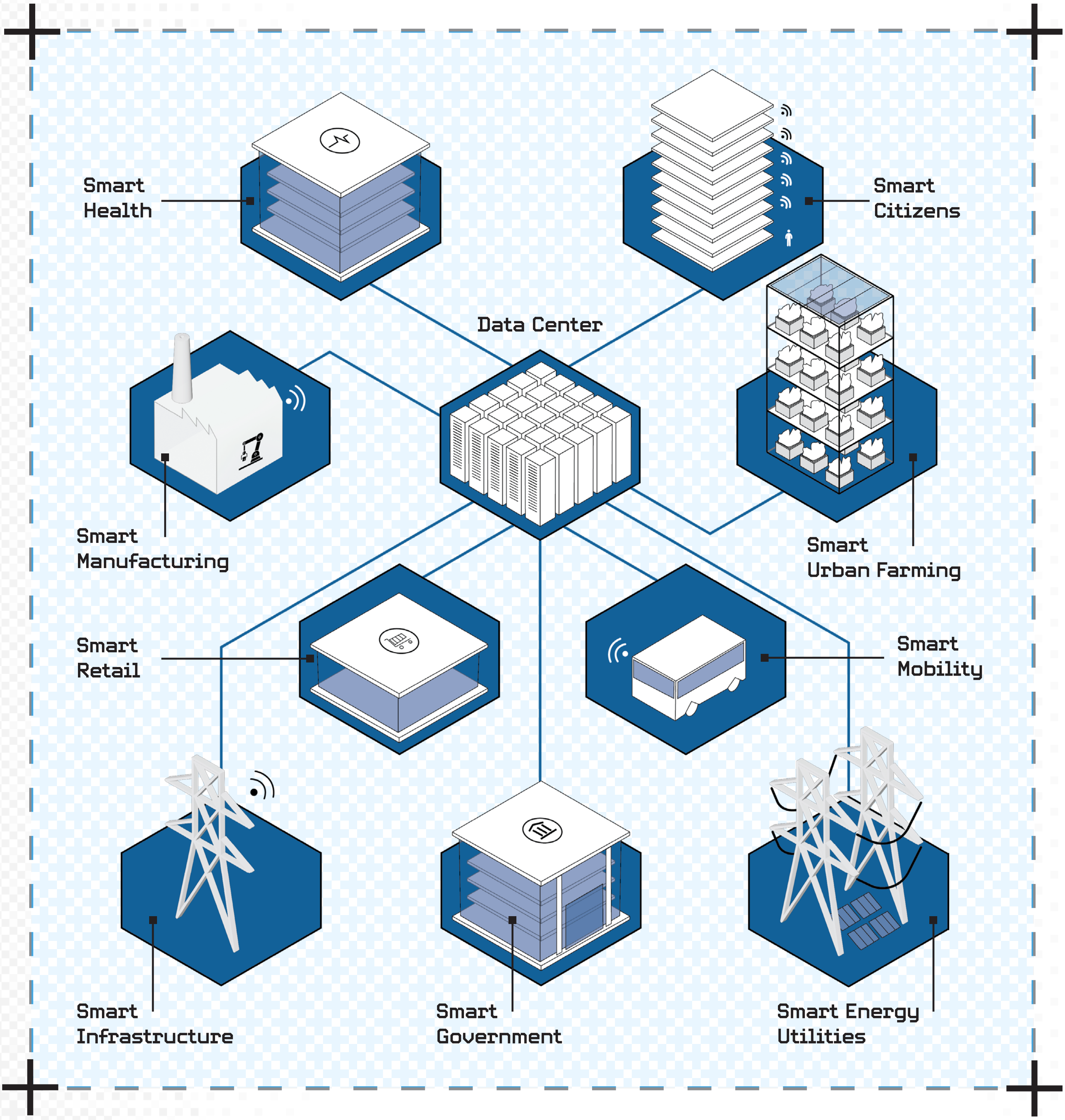
The next potential use for waste heat could be in aquaculture. In Norway, the data center operator Green Mountain is partnering with a lobster farming company to utilize waste heat, enabling the cultivation of lobsters in an innovative land-based facility. The two companies plan to establish a lobster farm adjacent to the data center, using heated seawater to grow these sought-after crustaceans.[46]

Similarly, the White Data Center on Hokkaido Island in Japan employs water heated during the cooling process to raise eels. The water exiting the cooling system maintains a temperature of about 33 degrees Celsius (91.4 degrees Fahrenheit), which is ideal for nurturing these valuable creatures. [47]

Additionally, it is feasible to cultivate fish in aquaponic systems that merge fish farming with plant cultivation. In these systems, water enriched with nitrogen from fish waste serves as a nutrient source for the plants.

/ Urban Integration of Data Centers

At the intersection of rapid urbanization and digitalization, the role of data centers in urban landscapes is becoming a crucial element in architectural and urban planning. Traditionally positioned on the outskirts of cities, these complexes are now envisioned as integral components of the urban fabric. They serve not only their primary functional roles but also enhance urban life in diverse ways. A visionary approach to integrating data centers goes beyond their traditional utilitarian functions, incorporating them into the social, economic, and environmental tapestry of smart cities. [48] This integration promises to transform how these structures interact with and support the evolving dynamics of urban environments.



/ The Role of Data Centers in Smart Cities

In the context of smart cities, data centers emerge as central nervous systems, processing and managing the data necessary for urban operations—from traffic and safety systems to energy and waste management. As cities strive to become smarter, the traditional model of large, remote data centers becomes less viable due to latency issues and the need for real-time processing capabilities. [49]

Healthcare services are improved through better access, monitoring, data management, and resource optimization. For instance, telehealth services enable remote medical consultations, benefiting those in remote or underserved areas. Wearable technology, like smartwatches and fitness trackers, continuously monitors patients' health, allowing for early detection of health issues. IoT devices collect and analyze healthcare data in real-time, optimizing resource use and cutting costs. Electronic Health Records (EHRs) provide healthcare providers with comprehensive patient information, making healthcare delivery more efficient.[50]

Smart citizens are essential in realizing the vision of smart cities. Their participation, feedback, and co-creation are vital for developing citizen-centric smart city solutions. Engaging and empowering citizens through platforms and e-participation tools is crucial for involving them in decision-making, urban planning, and governance processes. Empowering smart citizens involves fostering digital literacy, social inclusion, transparency, and accountability in smart city governance. To enable meaningful participation, challenges such as the digital divide, lack of awareness, and bureaucratic obstacles need to be addressed. Additionally, privacy, security, and the ethical use of citizen data collected by smart city technologies require citizen awareness and robust policies. Transportation services are also enhanced by smart city technologies.

Smart city technologies play a significant role in improving urban mobility and transportation by enhancing efficiency, management, safety, and resilience. Smart Transportation Systems (STS) integrate modern technologies to optimize traffic flow, reduce congestion, and enhance commuter experiences. Key technologies include IoT devices and sensors for real-time data collection, AI and ML algorithms for traffic pattern prediction and route optimization, and big data analytics for decision-making. IoT V2V (Vehicle to Vehicle) and V2I (Vehicle to Infrastructure) solutions provide real-time traffic updates and management, allowing for adaptive traffic signal control, dynamic rerouting, and improved travel safety. Connected vehicles communicate with infrastructure elements such as parking meters and charging docks, optimizing parking availability and charging for electric vehicles. Smart mobility also encompasses various transportation modes, including traditional vehicles, electric vehicles, public transport, car-sharing, ride-hailing, micromobility options like bicycles and e-scooters, autonomous vehicles, and even urban aerial vehicles. The benefits of these advancements include reduced emissions, economic gains, improved quality of life, increased accessibility, and enhanced safety. However, challenges such as high infrastructure costs, legacy system integration, cybersecurity risks, privacy concerns, regulatory hurdles, and the digital divide must be addressed to fully realize the potential of smart mobility.

Smart energy utilities use advanced technologies like IoT devices, sensors, and data analytics to enhance efficiency, reliability, and sustainability. They optimize energy distribution, employ intelligent meters for real-time data on energy usage, and integrate renewable energy sources into the grid. These utilities offer increased efficiency, enhanced reliability, improved customer service, environmental benefits, and cost savings. However, challenges like high initial costs, data security concerns, interoperability, and complex regulatory landscapes must be addressed.[51]

Smart retail [52] integrates advanced technologies and data-driven solutions to enhance the shopping experience, optimize operations, and improve business outcomes. Key technologies include IoT devices and sensors for real-time data on inventory and customer behavior, mobile apps for personalized offers and contactless payments, beacon technology for location-based notifications, AI and ML for analyzing customer behavior and optimizing strategies, and AR and VR for immersive experiences. Benefits include personalized recommendations, seamless checkouts, real-time inventory tracking, targeted marketing, streamlined supply chain management, and enhanced security. Future trends point towards autonomous stores, greater personalization, improved sustainability, and blockchain integration.

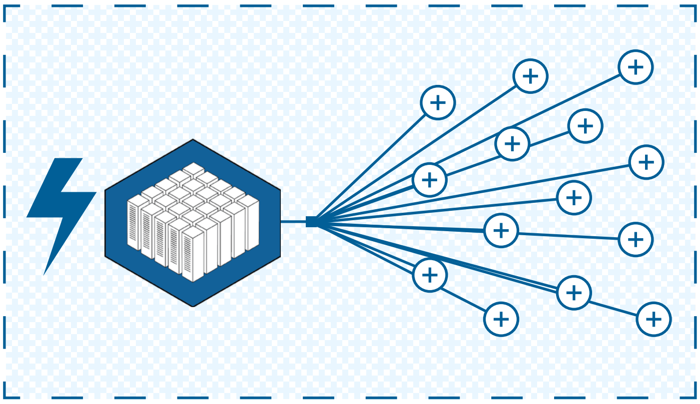
Urban farming [54], also known as urban agriculture or urban gardening, involves growing, processing, and distributing food within urban areas. Techniques [55] such as vertical farming, hydroponics, aquaponics, container farming, and rooftop farming maximize space efficiency and production. Vertical farming uses stacked layers within controlled environments. Hydroponics and aquaponics use soilless cultivation methods and closed-loop systems. Container farming repurposes shipping containers into portable farming units, while rooftop farming transforms underutilized spaces into productive sites. These approaches promote local food production, enhance sustainability, and address critical urban challenges

Smart manufacturing [53] utilizes advanced technologies like AI, cloud computing, IoT, and big data analytics to create intelligent, connected, and self-optimizing systems. These technologies enable integrated and collaborative processes that can respond in real time to changing demands, enhancing efficiency, productivity, and agility. Key components include IIoT for data collection, cloud computing for scalable storage, big data analytics for insights, AI for predictive maintenance and quality control, digital twins for simulation, and robotics for flexible production. Benefits include improved quality control, reduced defects, minimized downtime, optimized supply chains, faster time-to-market, and enhanced sustainability. However, there are challenges such as high upfront costs, cybersecurity risks, integration with legacy systems, workforce re-skilling, and new governance models that must be addressed.

/ Decentralized Data Networks and Edge Computing

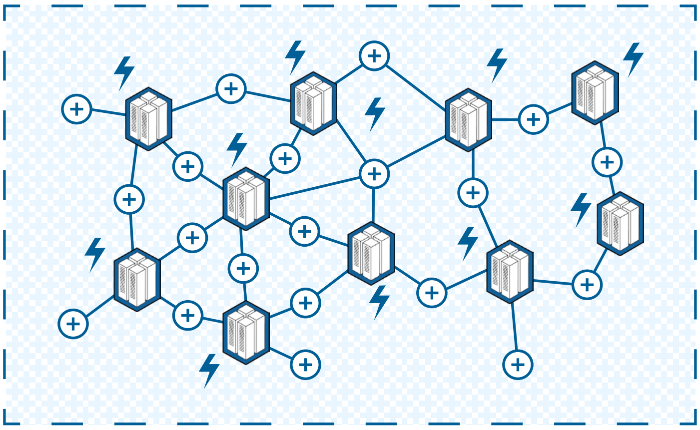
/ Today

Centralised data center infrastructure logic



/ Vision

Decentralised data center infrastructure logic



Decentralized data networks distribute storage and processing across multiple nodes instead of relying on a single, centralized data center. This architecture enhances data accessibility, increases redundancy, and improves security. By eliminating single points of failure, decentralized networks boost system resilience and reliability. They are also scalable, allowing for nodes' dynamic addition or removal to meet changing demands. In urban contexts, deploying local nodes throughout city buildings—commercial, residential, and public—minimizes data transmission distances, reducing latency and improving application performance.

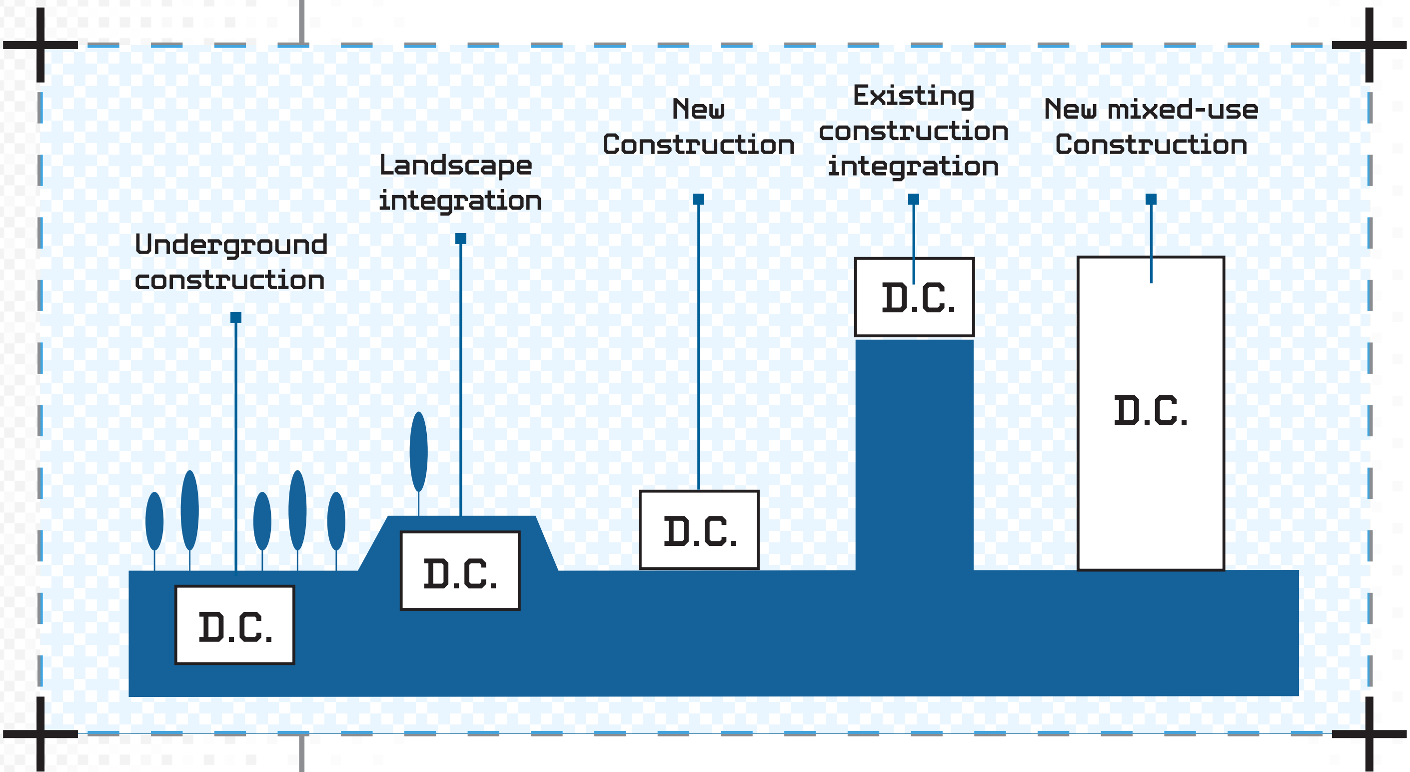
Edge computing processes data closer to its source, reducing latency and bandwidth usage.[57] This benefits real-time applications like autonomous vehicles, smart traffic systems, and IoT devices. By enabling local data processing, edge computing lightens the load on central servers, ensuring faster response times. Strategically placed edge computing nodes in city centers can enhance urban infrastructure performance, from smart streetlights to public transportation systems.

Integrating decentralized data networks [56] and edge computing optimizes data flow and enhances system resilience. Edge computing processes data locally, reducing the need for extensive transfers to central servers, while decentralized networks ensure data is redundantly stored and accessible. This combination minimizes latency and bandwidth usage, providing a more efficient and reliable infrastructure. For example, edge nodes can manage real-time traffic data to prevent congestion, while decentralized networks store historical data for long-term analysis and urban planning. Public safety systems can use edge computing for real-time video analysis and decentralized networks for secure data storage.

By decentralizing network architecture—distributing data processing across multiple points—this approach streamlines data management. [58] It significantly lowers the energy consumption associated with distant data transmission, reducing urban systems' carbon footprint. The integration of edge computing is particularly beneficial for IoT applications and real-time urban management, enhancing operational efficiency and promoting sustainable urban development, paving the way for seamless and rapid Smart City implementation.

/ Urban Data Center - a new A-TYPE

Urban Data Centers (UDCs), new "A-Type" entities, can rapidly transform urban landscapes. These facilities go beyond traditional data storage and processing roles to become multifunctional, integral parts of the urban fabric. They adapt and scale with the city's growth, embodying flexibility and innovation to meet current and future demands. Moreover, as new landmarks of knowledge and technology, they emphasize the significance of data in shaping our urban environments. By harnessing energy-efficient technologies and fostering functional heterogeneity, these A-type entities are not only centers of data but also catalysts for sustainable urban growth and community enrichment.



/ Public Realm

The expansion of Urban Data Centers around the urban environment creates a seamless blend that champions modernization and robotics integration into our lives. Once seen as isolated and utilitarian facilities, UDCs are planned to become pivotal in connecting the technological infrastructure with urban living spaces. This can be understood as the first step in merging the "bubble" of machine-centric architecture with human-centric architecture. By incorporating mixed-use elements such as public spaces, green spaces, and recreational facilities, these buildings serve their primary technological functions and contribute to the urban fabric. This conception promotes a harmonious coexistence, fostering public acceptance and understanding of advanced technologies. Ultimately, this integration signifies a progressive shift towards cities where human and machine environments coalesce, driving forward a future where technology and daily life are inextricably linked.

/ Configurable Spaces

Urban data centers should be conceptualized with flexibility and scalability as fundamental design principles, allowing them to adapt to fluctuating technological demands and spatial requirements. The architectural planning of these centers must incorporate diverse spatial opportunities, recognizing that technological advancements may transform the physical demands for data storage. Such strategic foresight ensures that the centers can efficiently transition spaces to accommodate different functions or expand to meet future technological needs.

/ Heat reuse

Currently, data centers require significant energy for cooling and operational purposes. Reducing their environmental footprint by fostering a sustainable circular economy is a primary challenge. It is essential to repurpose all surplus energy, including heat, by channeling it back to the city and its residents through designated systems. The data center facility operates 24/7, allowing constant heat reuse. Drawing on examples of heat reuse in different conceptual data center projects—such as for district heating, greenhouse heating, and aquaculture—the integration of Urban Data Centers (UDCs) should also be based on heat reuse. However, some challenges affect UDCs. Transporting heat over long distances without significant loss is complex, and seasonal variations mean that 24/7 data centers cannot fully utilize the potential of reused heat during warm seasons. These challenges lead to the conclusion that the most effective way to reuse heat is to place UDCs as close as possible to potential recipients to avoid heat loss. Additionally, the recipients should be capable of utilizing the heat year-round without dependency on the season.

The most suitable co-existor for Urban Data Centers (UDCs) is urban farming infrastructure, allowing for year-round vegetable and greens cultivation. This combination offers numerous benefits in terms of sustainability and urban development. By integrating UDCs with urban farms, we can efficiently repurpose the excess heat generated by data centers to create optimal growing conditions for plants, thus ensuring a continuous supply of fresh produce throughout the year. This synergy maximizes the use of surplus energy and significantly reduces the environmental impact associated with traditional farming and food logistics. When combined with data centers, urban farming infrastructure can help cities move towards self-sufficiency in food production. This reduces the need for long-distance production transportation, lowering carbon emissions and traffic congestion associated with food logistics. From a sustainability perspective, integrating UDCs with urban farms supports the principles of a circular economy. It transforms waste heat into a valuable resource, reducing the overall energy consumption required for agricultural production. Furthermore, urban farms can benefit from the technological advancements and data analytics capabilities of UDCs. Precision agriculture techniques, powered by data from the centers, can optimize growing conditions, monitor plant health, and increase crop yields. This innovative approach not only ensures the efficient use of resources but also pushes

/ Mixed-Functional Use

1. Under The City UDC
Integrating DC underground presents multiple advantages, including reduced cooling costs due to naturally lower temperatures and optimal land use efficiency.

2. UDCs in Parks and City Green Landscapes
DC can be harmoniously integrated into parks and green infrastructure using advanced cooling techniques, such as geothermal energy.

3.UDCs under Sports Facilities
This integration ensures dual land use and contributes to the economic sustainability of the sports venue and the data center.

4.UDCs as Public Space Roofs
Using DC as roofs of public spaces. These structures can provide shelter and energy solutions for the public area below.

5.UDCs Integration into Existing Developments
Integrating DC into existing developments, such as malls or office complexes, optimizes urban space utilization.

6.Rooftop UDCs as Advertisement Spaces
Rooftop DC can serve a dual purpose by functioning as advertising spaces, leveraging the building's height and advertising visibility.

7.UDCs for empty spaces between buildings
Utilizing empty spaces between buildings for DC transforms wasted urban areas into productive sites.

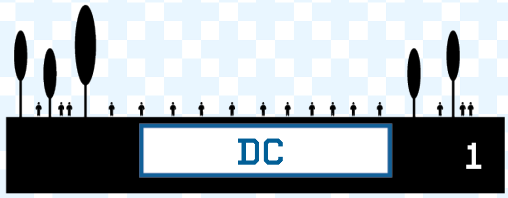
8.Repurposing old telecommunication buildings
Repurposing old telecommunication buildings to house DC equipment preserves and revitalizes underused buildings with a new functional purpose.

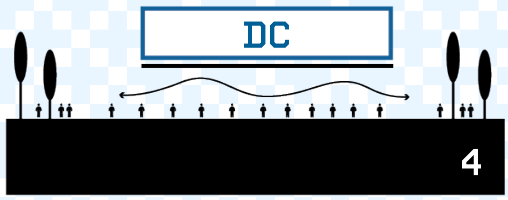
9.UDC under transport facilities
Placing DC within transport facilities, such as beneath bridges, maximizes the use of typically overlooked spaces.

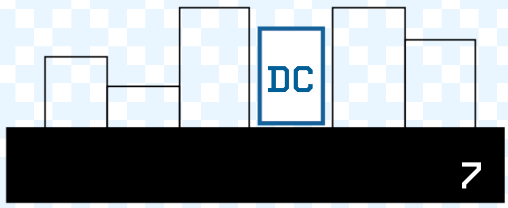
10. Revitalizing Old Industrial Buildings
DC are repurposing old industrial buildings, such as paper mills and factories.

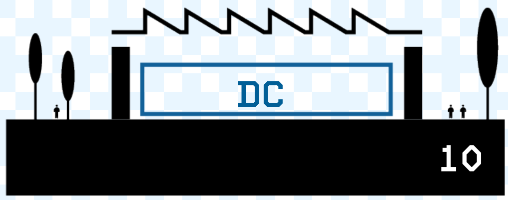
11. Converting Excess Parking Spaces
DC can be established in excess parking spaces, particularly in urban areas where car usage is declining.

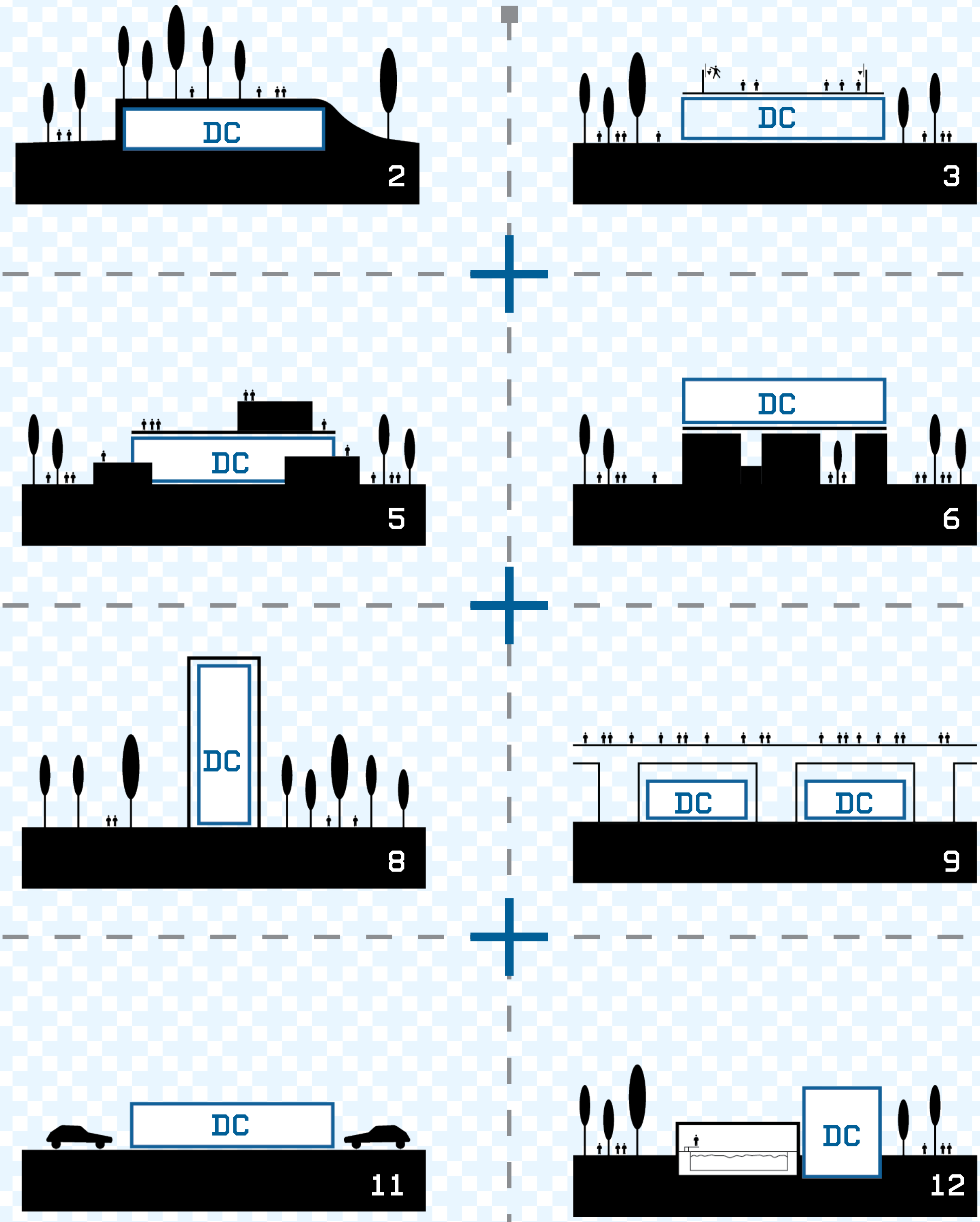
12. Integrating with Spa and Swimming Pool Facilities
Integrating DC with spa and swimming pool facilities allows waste heat utilization for pool heating and other thermal needs.







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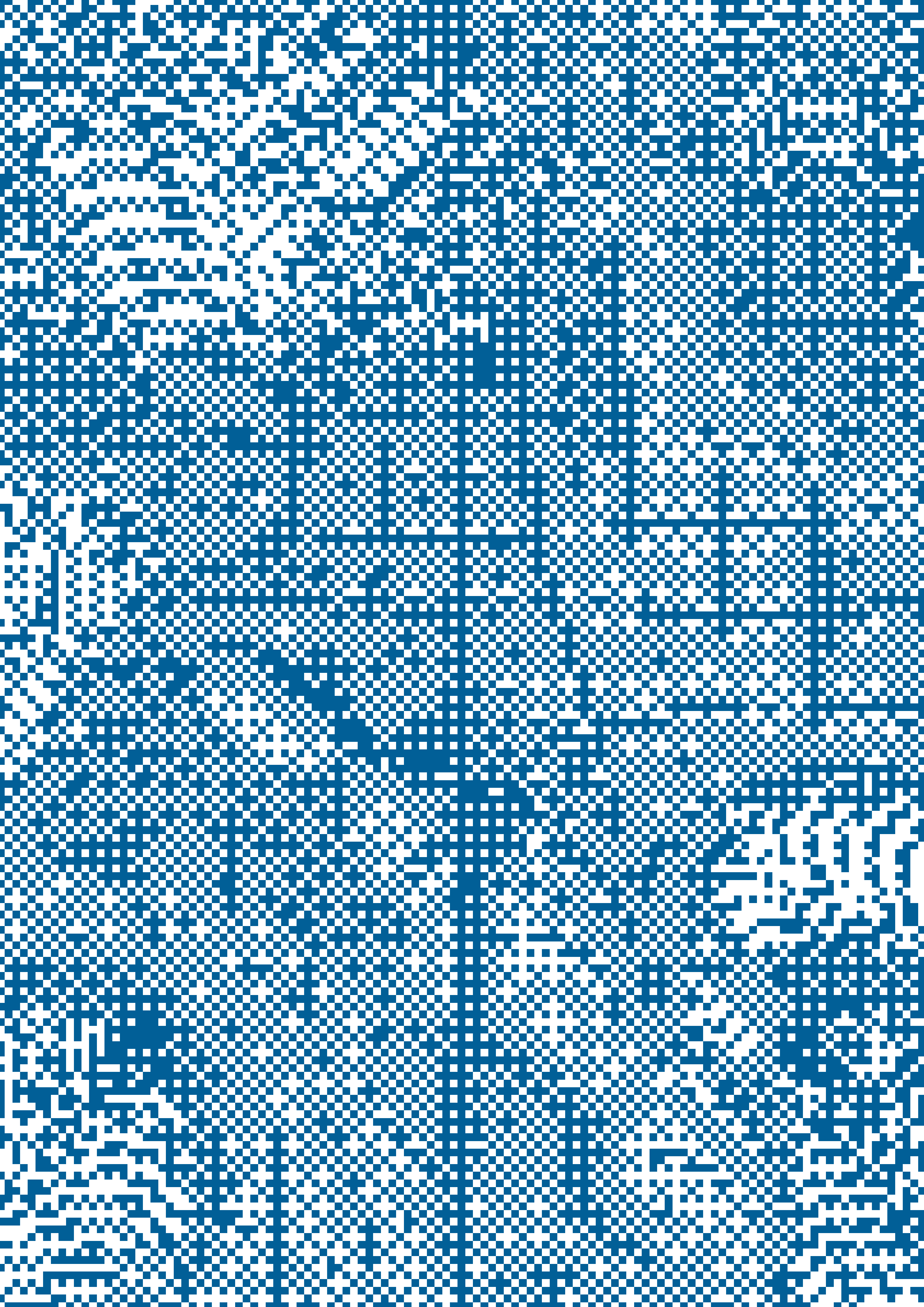


// METHODOLOGY

The methodology of Urban Data Center (UDC) design encompasses a comprehensive approach to dataset creation, machine learning implementation, and the comparison of AI-generated outputs with traditional algorithmic calculations. This section aims to detail the systematic processes and innovative techniques utilized to achieve the research objectives, focusing on the intersection of advanced computational methods and architectural design, specifically within the framework of the Data-driven A-type paradigm.

As part of the Urban Data Center design, I have decided to integrate the data center with an urban farm. Based on the analysis conducted in the previous section, the most optimal solution for heat reuse is the close proximity of the data center with its heat recipient. The units of the urban farm can be placed in close contact with the data center, ensuring efficient heat transfer. Additionally, data centers and urban farms share similar features: both require significant space, do not need windows, can be operated without continuous human presence, and operate 24/7. Furthermore, both data centers and urban farms benefit from being placed in the city; data centers benefit from reduced latency and improved connectivity, while urban farms benefit from accessibility to urban markets and reduced transportation costs. This integration not only maximizes resource efficiency but also promotes sustainable urban development.

Data-Driven A-Type Concept

Central to this research is the Data-driven A-type concept, which emphasizes the construction of urban data centers grounded in extensive data analysis. This approach leverages vast datasets to inform every aspect of design and implementation, ensuring that the resultant structures are innovative and highly optimized for their urban contexts. By integrating data-driven insights into the architectural process, we aim to create urban data centers that are both functional and sustainable, addressing contemporary urban challenges through informed design.

Data Set Creation

The foundation of our research lies in creating an extensive and diverse dataset. Utilizing the Grasshopper plugin for Rhino, we generated various urban structures that reflect the architectural complexities of cities such as London, Paris, Barcelona, Amsterdam, Hong Kong, Singapore, and New York. Each urban model's building footprint was meticulously delineated, and the Solar Envelope concept facilitated by the Ladybug plugin was employed to determine the building's mass based on solar path analysis. This process was further enhanced by integrating various EnergyPlus Weather files (EPWs), ensuring a robust and comprehensive dataset as the bedrock for subsequent analysis and model training.

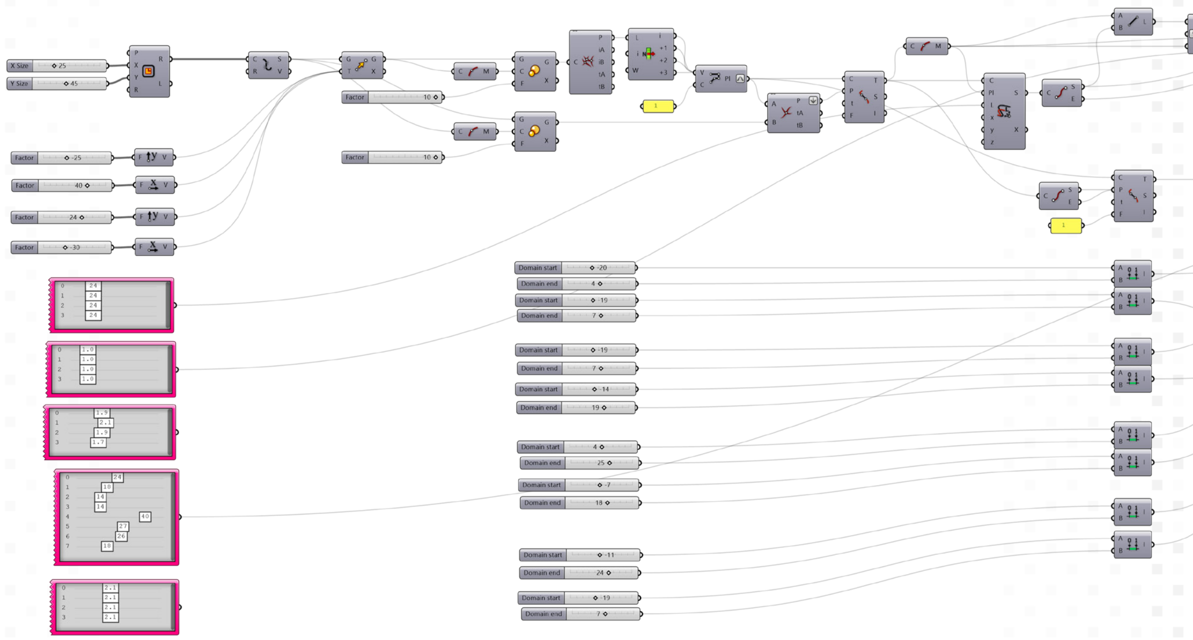
Machine Learning Implementation

The core methodology involves the application of two sequential pix2pix models, a type of Generative Adversarial Network (GAN)[62]. These models were explicitly fine-tuned and trained with the prepared datasets to develop a bespoke architectural tool. The first model processes footprint sketches to generate a height map, while the second model interprets this height map to create a structural representation, detailing the ratio of data modules to green modules. This dual-model approach exemplifies the practical integration of machine learning into architectural design, driving innovation and enhancing design efficiency.

After completing the machine learning training, the model was showcased through a case study to demonstrate its practical application and effectiveness. This case study provided a concrete example of how the trained model can be used to design an integrated urban data center and urban farm, highlighting the benefits and efficiency of the proposed methodology.

/ Synthetic Dataset

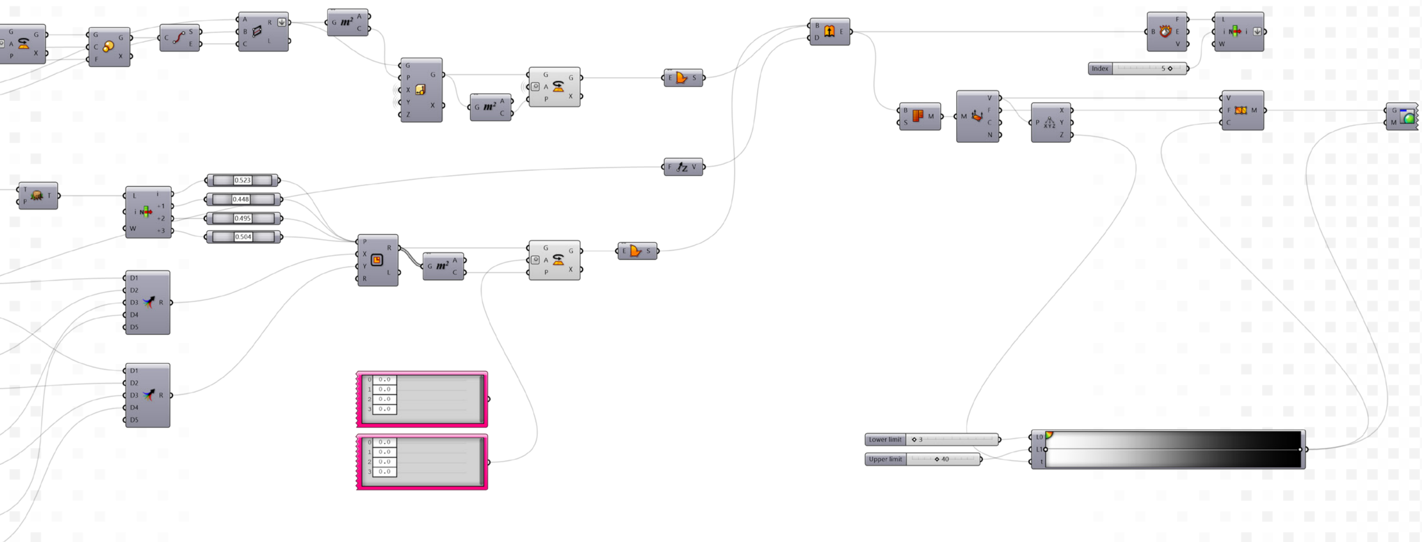
/ GRASSHOPPER definition



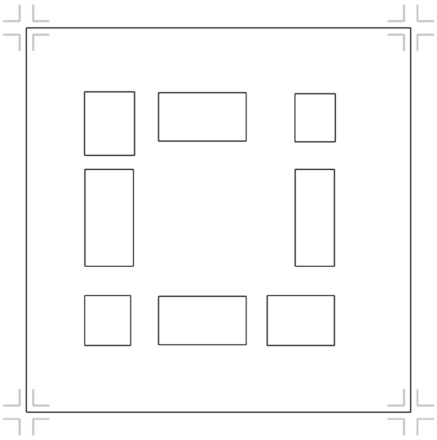
The Grasshopper plugin for Rhino, known for its precision, was harnessed to create a comprehensive dataset. I meticulously developed a script that could generate a diverse array of urban structures, ensuring each one was an accurate representation. This script was instrumental in simulating urban layouts that closely resembled major global cities such as London, Paris, Barcelona, Amsterdam, Hong Kong, Singapore, and New York.

For each urban model, I delineated a building's footprint, which served as the foundational basis for subsequent stages of the project. I utilized the Solar Envelope concept facilitated by the Ladybug plugin. This component was crucial in determining the building's mass by analyzing the sun's path relative to the site.

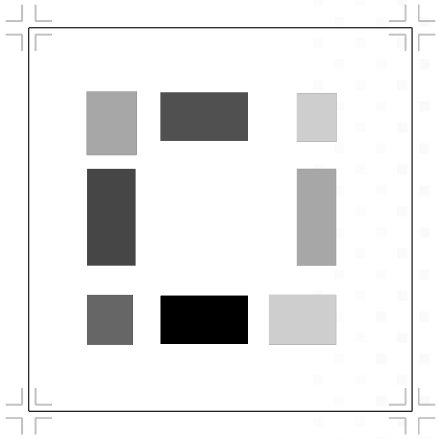
I employed various EnergyPlus Weather files (EPWs) to enrich the dataset and adjusted the north direction to different angles for each urban structure. This methodology not only enhanced the diversity of the data but also proved to be highly efficient, allowing for rapid iteration and exploration of design options. It effectively captured a broad spectrum of urban forms, providing a robust foundation for further detailed calculations and analytical assessments.

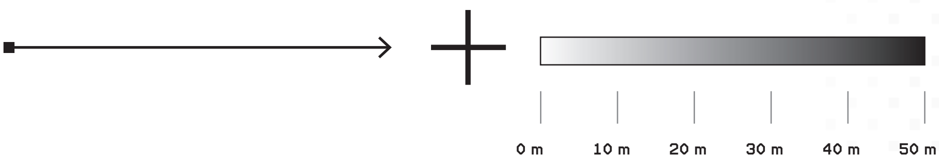


/ Surraundings
buildings footprints



/ Surraundings
buildings Heights

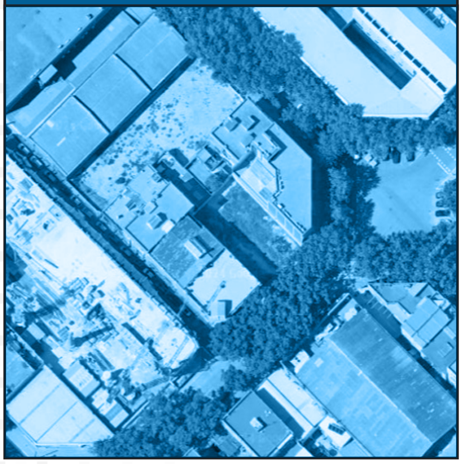




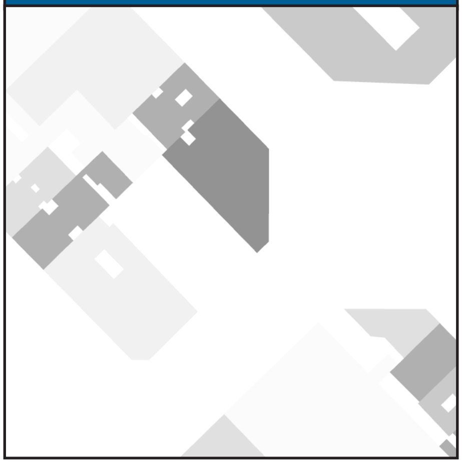
/ Real-world locations

The location dataset consists not only of synthetic locations created using the Grasshopper script described earlier but also of locations that refer to places in the real world. For subsequent iterations, these locations were adjusted and transferred to the same format as the synthetic set.

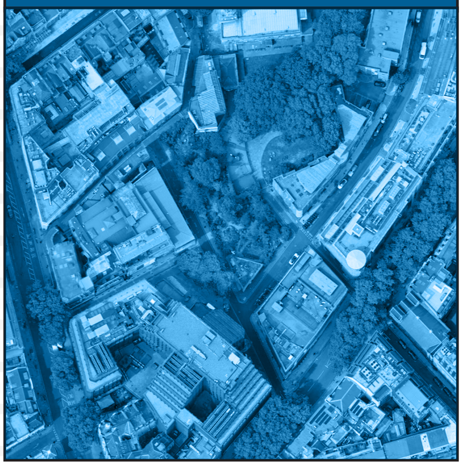
Barselona



Barselona

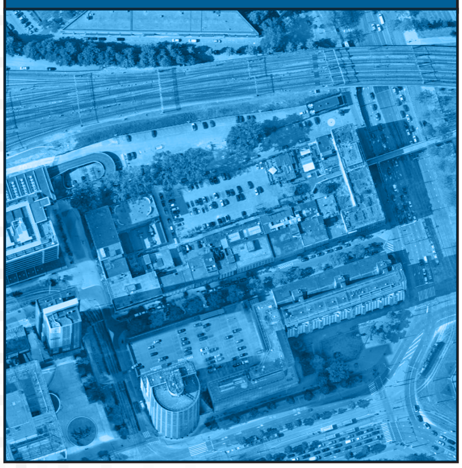


London

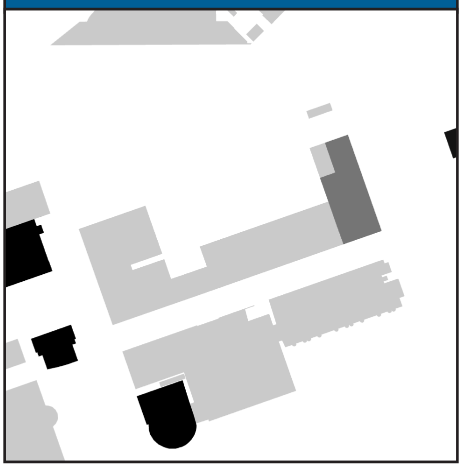


London

Rotterdam



Rotterdam



/ EPW

For the climatic analysis of selected lcoations, I utilized weather data extracted from an EnergyPlus Weather (EPW) file. **Ladybug Tools EPW Map** [63] provides direct access to a vast array of EPW files from a user-friendly interactive map. The EPW files contain detailed hourly weather information for accurate simulation and environmental performance assessment.

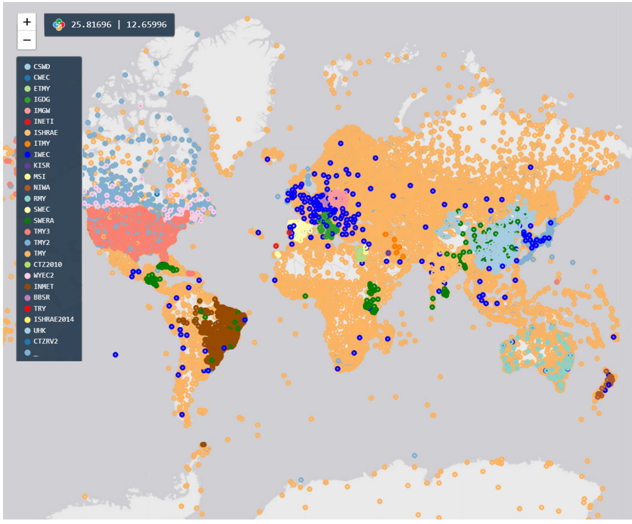


Figure 10.1 Ladybug Tools EPW Map

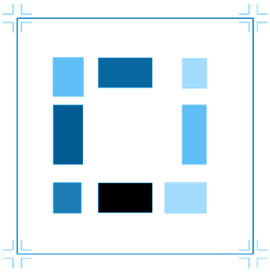
/ The Solar Envelope

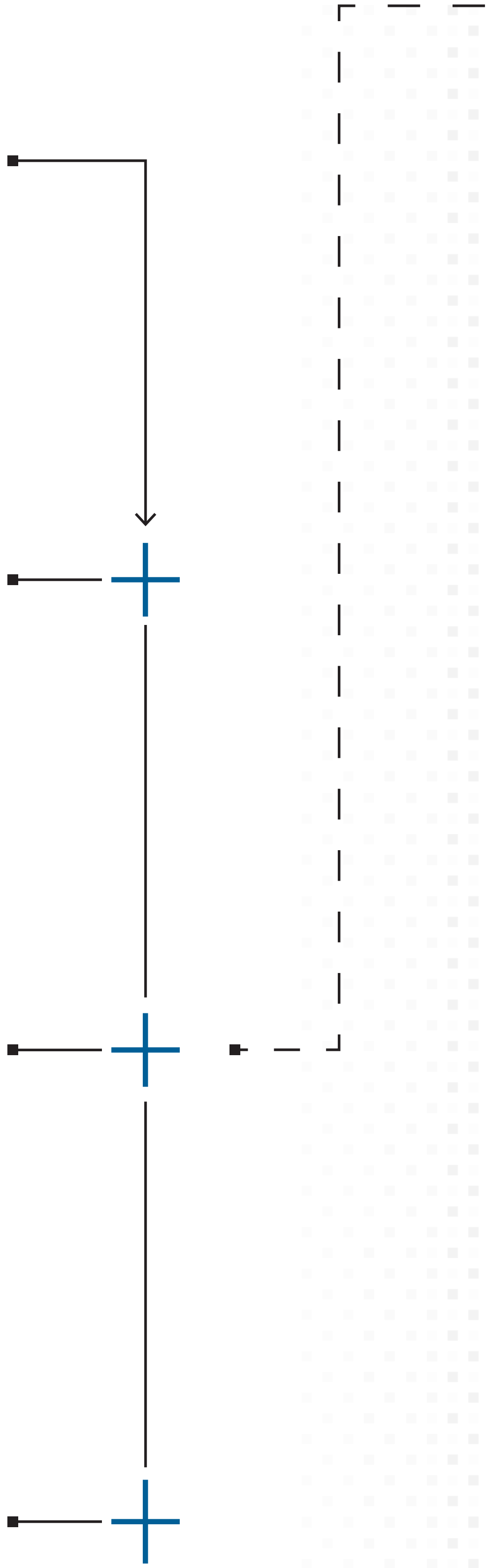
The solar envelope concept is a powerful tool for designing sustainable buildings. It optimizes natural energy flows, passive heating and cooling, and daylighting. It has its roots in ancient civilization, where the alignment of buildings in relation to the sun's path was fundamental to urban planning. The concept was reintroduced and evolved in the 1970s due to the need for sustainable design and the environmental impact of fossil fuel consumption.

The solar envelope is a dynamic integration of the sun's trajectory that maximizes solar exposure and minimizes shadowing in densely populated areas. This concept enables architects to create buildings that adhere to local zoning laws while enhancing energy efficiency and quality of life. By taking into account factors like building height, street width, and orientation, the solar envelope ensures that all buildings have potential access to sunlight.

/ The Solar Envelope Construction

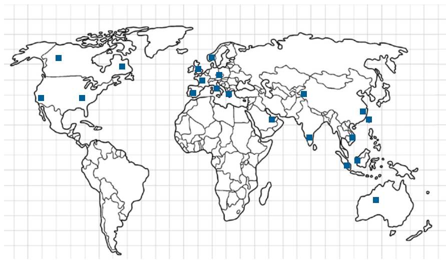
/ Structure





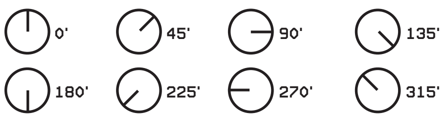
/ EPW

For each generated location, it was decided to use variant EPW data from different parts of the world to enlarge the variety of the samples in the data set.



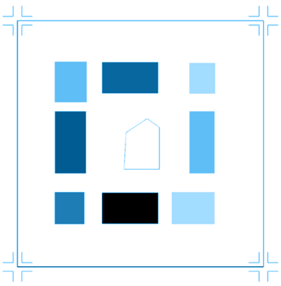
/ North Direction

In order to increase the total amount of samples in the dataset, I decided to calculate the set of north angle values for each location.



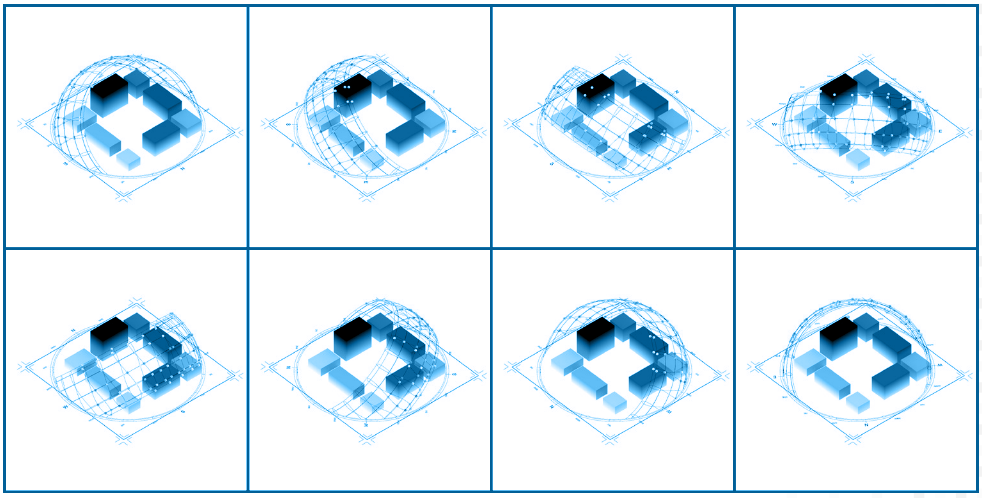
/ Footprint

A footprint of the building was drawn for each structure



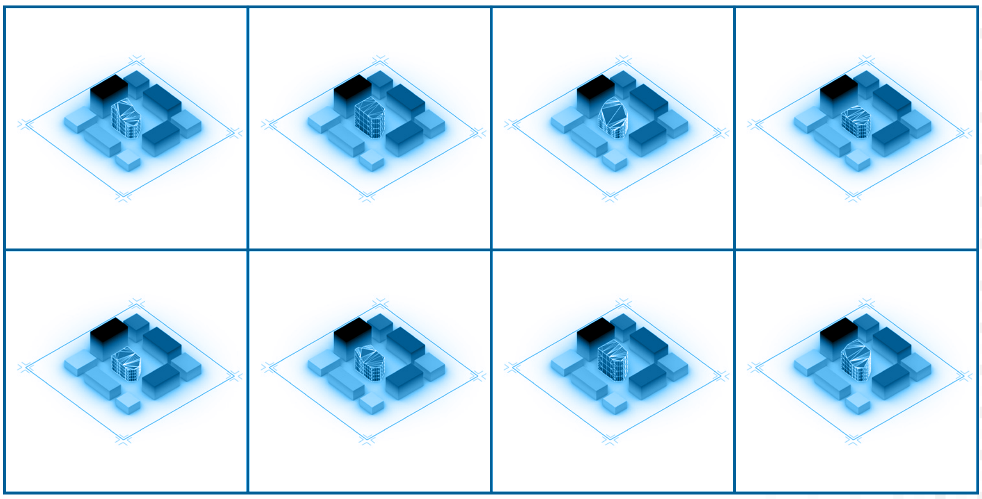
/ Sun Path

The Ladybug Solar Envelope component uses pre-calculated data based on the Ladybug Sunpath component to generate accurate simulations of the sun's path at different times of the year. The sun paths were calculated for eight different north directions. The SunPath construction provided points of sun position during the observed time, which were then used to calculate sun vectors. These sun vectors were used to calculate the solar envelope by determining the angles at which sunlight hit the site.

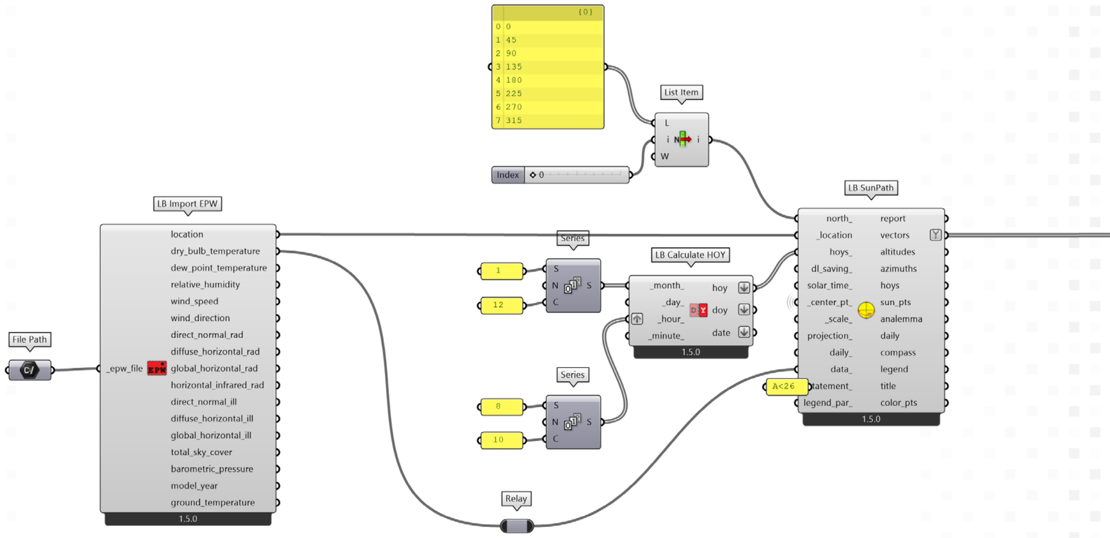


/ Solar Envelope + Building Mass

Using the data from the sun path calculations and the context provided by the surrounding buildings, I engaged the Ladybug's Solar Envelope component. This tool helped define the maximum permissible volumes for new buildings With the solar envelopes defined, I proceeded to create the building masses.



/ BUILDING MASSING GRASSHOPPER DEFINITION



/ EPW

Amsterdam (Netherlands)
Barcelona (Spain)
Berlin (Germany)
Copenhagen (Denmark)
Dublin (Ireland)
Helsinki (Finland)
Istanbul (Turkey)
London (United Kingdom)
Madrid (Spain)
Manchester (United Kingdom)
Milan (Italy)
Munich (Germany)
Oslo (Norway)
Paris (France)
Prague (Czech Republic)
Reykjavik (Iceland)
Stockholm (Sweden)
Warsaw (Poland)
Beijing (China)
Chennai (India)
Delhi (India)
Hong Kong (China)
Jakarta (Indonesia)
Kuala Lumpur (Malaysia)
Mumbai (India)
Osaka (Japan)
Seoul (South Korea)
Shanghai (China)
Singapore (Singapore)
Tokyo (Japan)
Chicago (USA)
Los Angeles (USA)
New York (USA)
Northern Virginia (USA)
Phoenix (USA)
Seattle (USA)
Silicon Valley (USA)
Toronto (Canada)
Santiago (Chile)
São Paulo (Brazil)
Melbourne (Australia)
Sydney (Australia)
Johannesburg (S. Africa)

45 EPWs VARIATIONS

/ Sunpath

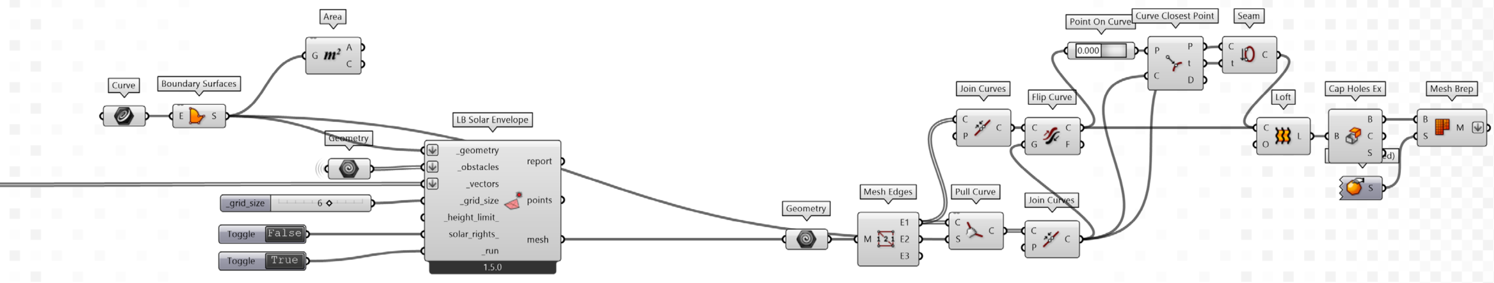
0' 45'

90' 135'

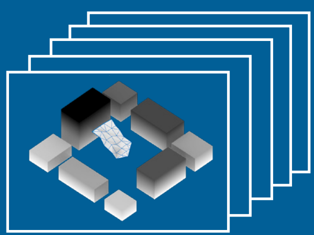
180' 225'

270' 315'

8 NORTH DIRECTIONS VARIATIONS



/ Solar Envelope



100

STRUCTURES VARIATIONS

/ Building Mass

36k

UNIQUE SAMPLES FOR THE NEXT STEP

/ The Impact of Automation on the Construction Industry and Architecture

Automation represents a transformative shift in the construction industry, impacting the methodologies and efficiency of building processes and fundamentally altering the designs and aesthetics of architecture. As industries worldwide leverage technology to enhance productivity and reduce costs, the construction sector has experienced a significant shift toward adopting automated processes. This marks a pronounced departure from traditional building practices, heralding a new era where efficiency and innovation converge.

Automation has been pivotal in enhancing the efficiency of construction processes. The integration of technologies such as Computer Numerical Control (CNC) - a manufacturing method that automates the control, movement, and precision of machine tools through the use of preprogrammed computer software, which is embedded inside the tools machinery and robotic arms, has facilitated a move towards precision and speed that manual processes could seldom match. These technologies enable the rapid cutting, assembly, and installation of building components with minimal error margins. As a result, construction projects benefit from faster completion times and reduced material waste. This revolutionizes how buildings are constructed and influences how architectural aesthetics are conceived, shifting from traditional methods to more dynamic, design-driven approaches.[64]

The exploration of architectural form production reveals a historical dichotomy between the compositional and sculptural approaches, which reflects a profound interaction between analog traditions and digital innovations. The compositional method, exemplified by the architectural assemblies of classical antiquity and neoclassical periods, emphasizes the integrity and distinctiveness of individual elements within a unified structure. In contrast, the sculptural approach, seen in the monolithic carvings of Lalibela and the flowing forms of Gothic architecture, advocates for a seamless, unitary form production. Contemporary advancements in parametric design and digital fabrication technologies complicate this dialogue further, introducing a paradox where designs conceived as continuous forms must be realized through discrete, often non-reusable components.

This necessitates a critical reassessment of architectural practices, urging a shift towards modular and adaptable design strategies that can respond dynamically to changing societal needs. Such a shift reflects a deeper integration of architecture within broader socio-economic frameworks, emphasizing the sustainability of building practices through the reusability and adaptability of components.

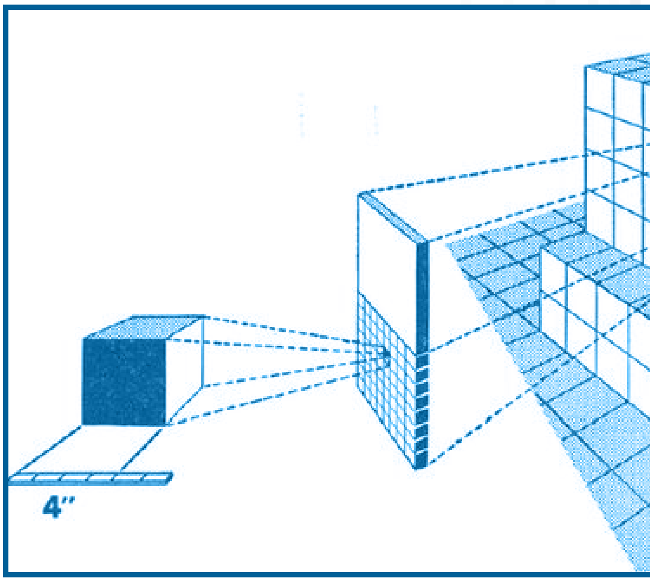
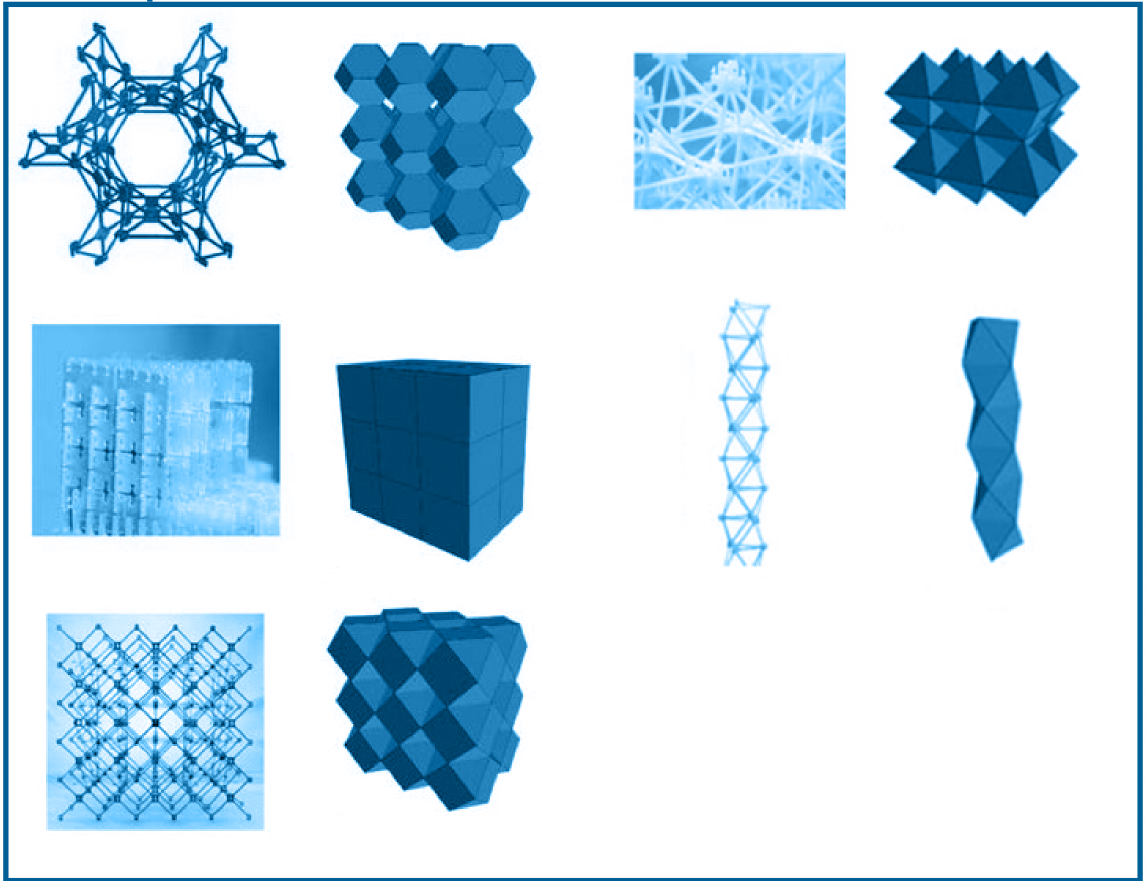


Figure 11.2 Digital materials examples



When looking for concepts that can indirectly be called primary sources of a discrete system, one can cite, for example, the Bemis system. Created by Albert Farwell Bemis in the 1920s and 1930s, it was designed to represent the whole building structure fulfilled with basic cubic 4-inch modules. This example can be a simple prototype system displayed in discrete logic design. [64]

Automation, in fostering the use of discrete architectures, not only challenges traditional methods but also aligns with sustainable practices, highlighting the potential for architecture to adapt and evolve in response to an increasingly automated future. This approach simplifies the translation between design and manufacturing by using these parts as basic elements that encode information in their physical form, as defined by Gershenfeld's concept of digital materials at MIT. These materials are composed of discrete units with finite, discrete connections. Architects and researchers are developing a process where the physical and digital representations of parts are identical, aiming to create a more open, accessible, and adaptive design and production model. This integrated approach views buildings and design products as digital objects composed of discrete parts, bringing the programmability of the digital world to physical objects. [64]

Figure 11.1 The Bemis System, A.F. Bemis

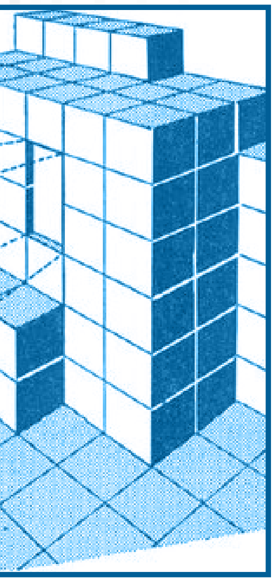
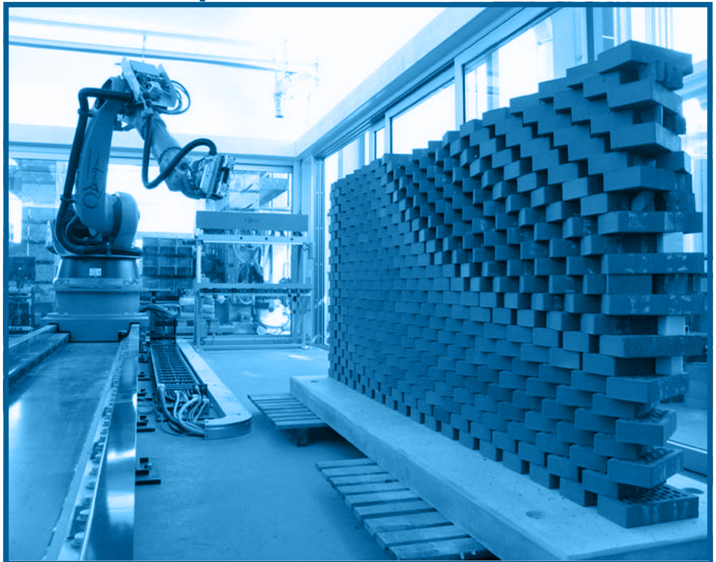
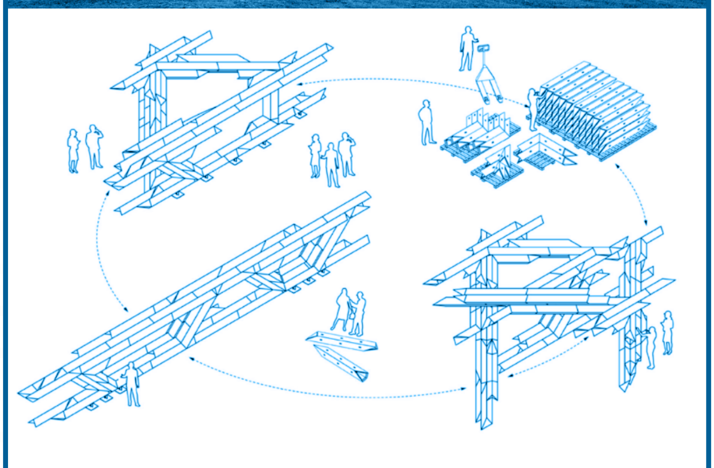


Figure 11.3 Robotic fabrication of non-standardized brick walls, Bonwetsch, Gramazio, and Kohler

Figure 11.4, 11.4a discrete building blocks , Gilles Retsin Architecture



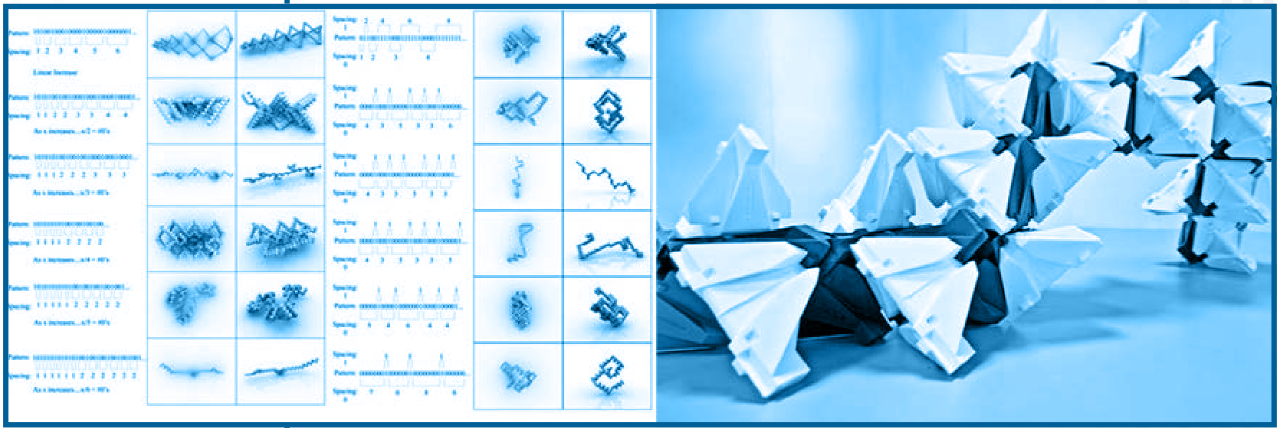


One of the first approaches is the results of proposed robotic fabrication process for non-standardized brick walls, where each element has a unique position defined by the digital model and materialized with a robotic arm. The result of this approach is the creation of highly differentiated assemblies, where the unique location of each element can be fine-tuned to respond to specific aesthetic or performance criteria Indeed, by introducing computationally-controlled positioning and robotic placement, a brick materials system becomes more akin to an amorphous material, where each unit can assume unique placement and orientation within the more significant material mass.

A direct, "engineering" alternative to the paradigm of digital materiality is the concept of digital materials. This approach rejects the idea of materials as inherently analog, requiring computation to bridge the gap between reality and its digital representation. Instead, it reconceptualizes materials themselves, developing methodologies to engineer materials from discrete building blocks, closely mirroring their digital counterparts. This concept stems from alternative models of computation, which aim to eliminate the division between software and the hardware it operates on. The resulting model of materials is one that aligns the discreteness of such materials with the discreteness of the computational structures used to represent them. [64]

Recent methodologies in computational design have combined digital materials with advanced research to propose new ways of designing and manufacturing controllable mechanical metamaterials. Unlike continuous additive manufacturing processes, these methods use discrete, repetitive building parts. This approach eliminates limitations related to scale and production speed, making the production process more efficient. Additionally, the reversibility of assembly allows for easy modification, disassembly, and reuse of components over time, enhancing the adaptability and sustainability of the structures. By integrating robotic functions directly into the materials, the construction process can become more automated and precise. This integration highlights the potential for advanced construction techniques that leverage the inherent properties of these engineered materials.

Figure 11.1 Logic Automata, Skylar Tibbits



Skylar Tibbits' master thesis "Logic Automata" extends the concept of digital materials by embedding computational information directly within the material structure. By designing discrete parts that function as simple logic gates, the assembly process itself becomes a basic digital logic program.

This innovation, known as "computational material," allows the material to guide its own assembly without the need for external information. This self-guiding capability could revolutionize construction, enabling applications such as self-guided assembly and even self-replication of structures, drawing inspiration from biological systems. Self-assembly involves systems that autonomously organize their components into specific patterns and structures. While traditionally applied at micro- and nano-scales, digital materials' ability to embed information and compute assembly sequences opens the possibility of exploring self-assembly at larger scales.

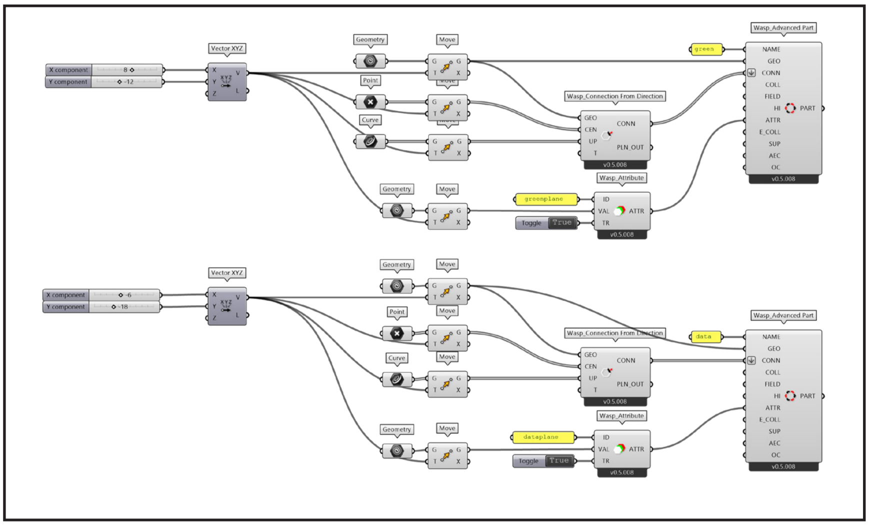
/ WASP : Discrete Modelling Framework [60]

Most tools addressed in modeling with discrete systems are based on the Rhino/Grasshopper ecosystem. The Wasp plugin is a powerful tool for Grasshopper. Wasp offers a specialized framework for combinatorial design using discrete elements, enabling users to create complex models and structures through modular aggregation.

The representation of individual parts in Wasp is composed of two fundamental elements: the part geometry, represented as a 3d mesh, and the connectivity topology, which defines the possible locations of placement of a new part. Connections are represented as oriented planes, allowing the definition of the relative position and orientation of newly placed parts in 3d space. Each connection is tagged by a unique name, allowing assembly rules to be described. Additionally, parts store utility attributes such as their type name, unique ID, collider geometry, and custom additional attributes that the user can freely choose. This lightweight and flexible part description allows us to represent all the required. Once parts are correctly represented, Wasp requires the user to specify assembly rules defining which parts and connections can be attached. Sequentially applying different assembly rules over the already placed parts allows the growth of the aggregated structure. The combination of each part's topological structure and connectivity rules is inspired by graph grammar, a mathematical model used to represent combinatorial possibilities among several discrete units, such as in the case of a self-assembly robotic system.[60]

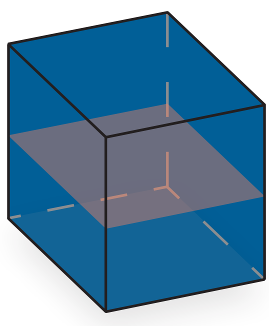
/ Dataset finalisation

/ Modules defenition

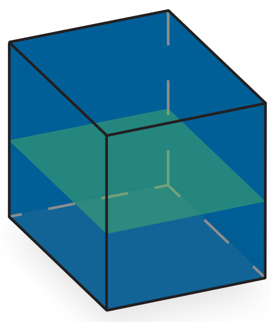


For the discrete aggregation, I used two types of modules: the module that denotes the space for the data center and the module that denotes the space for the urban farm. Each module is a 3x3x3 meter cube. Then, I inserted a plane with assigned materials. The material was red for the data center module with a transparency of 5% and green for the urban farm module with a transparency of 5%. The work with transparency was intended to create a dataset. By working with the material's transparency, it is possible to determine the name of the top view and the quantity distribution of the data center and urban farm modules. The insertion of a plane into a module allows for the avoidance of unnecessary duplication and superimposition of planes with different levels of transparency.

/ DATA module



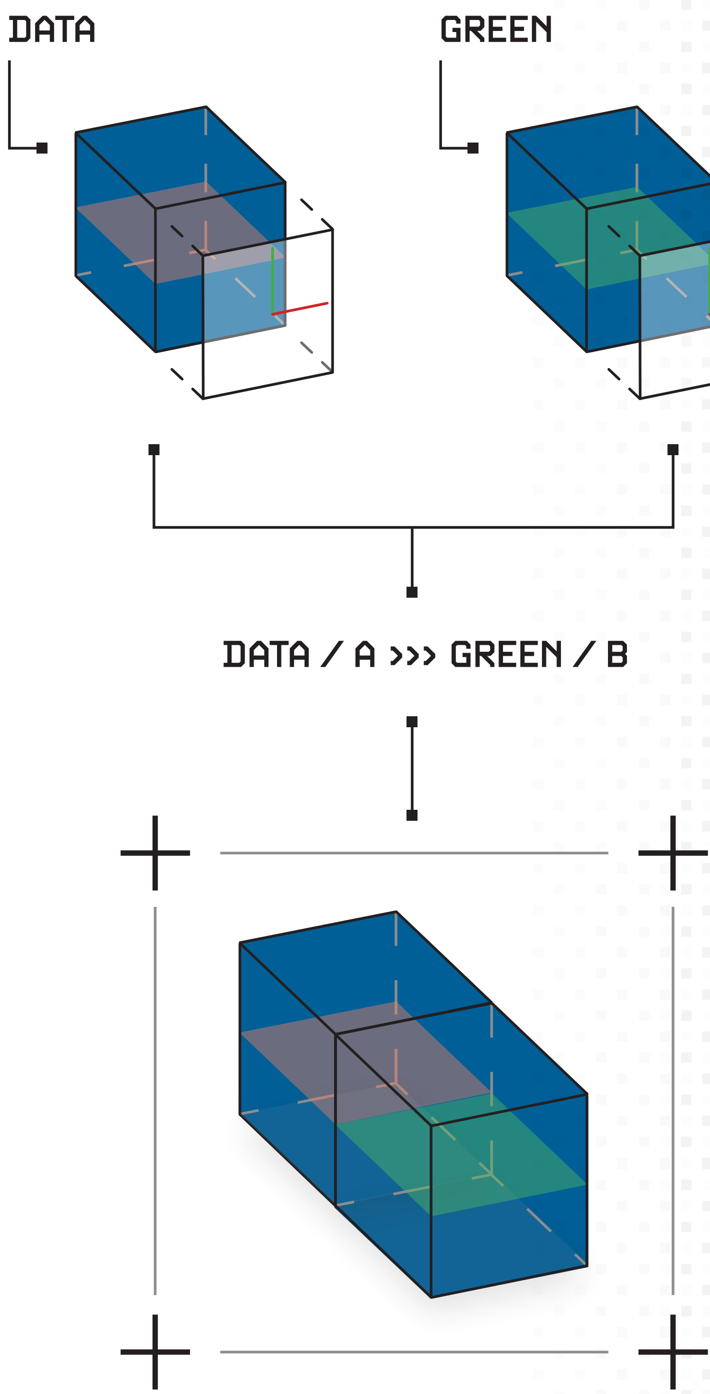
/ GREEN module



/ Discrete Assembly

/ RULES

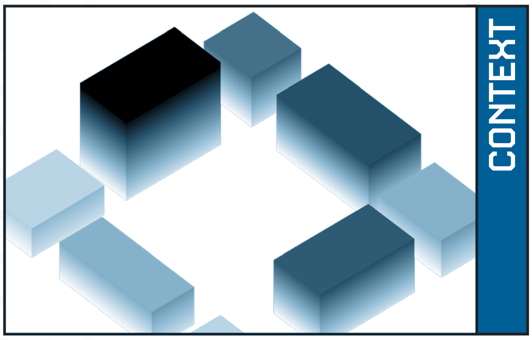
A set of rules was created for assembly processing. Rules connection logic is based on close connection data modules with green modules. Every module's connection was described as a point of connection and direction plane that allowed aggregation to proceed.



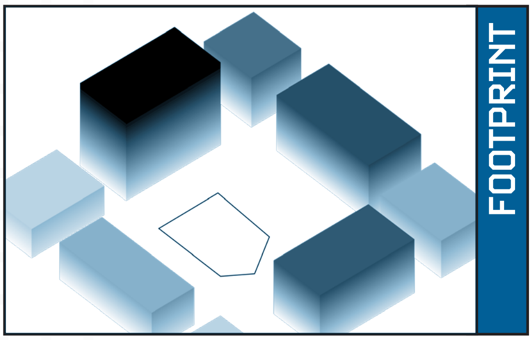
/ Aggregation process

Constructing a building involves a three-phase process. The first phase involves using a previously created dataset of urban environments, including calculating building boundary volume from footprint using solar envelope logic. The second phase is focused on discrete aggregation with the WASP plugin, using precalculated field rules that control the distribution of modules. Finally, the third phase involves the creation of the final representation of the structure, which will be used as a sample in the dataset.

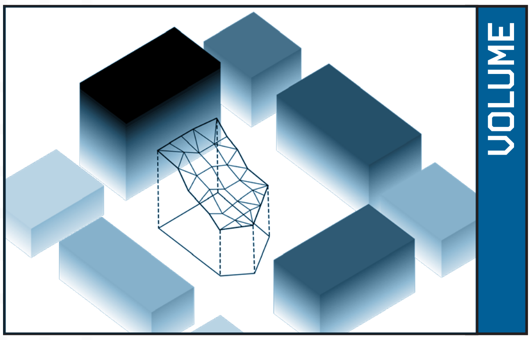
/ PHASE 1



For the step of data set creation, a set of urban structures synthesized with the help of a grasshopper script or copied from real-world locations that were described in detail in previous steps was used. These structures are simulated context for further calculation.

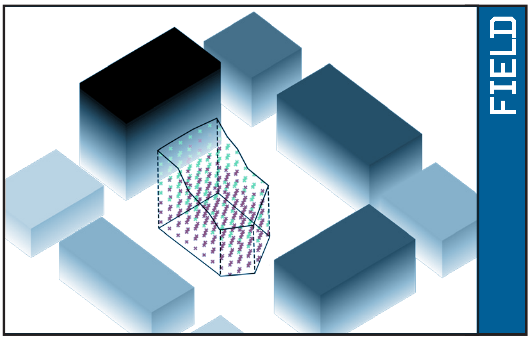


The footprint that described the borders of a data center's building structure was drawn into every structure in a dataset.

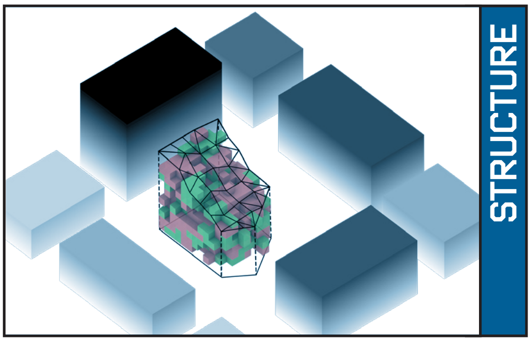


Based on the context and the footprint, the boundary volume for the building was defined using solar envelope analyses completed using the LadyBug plugin.

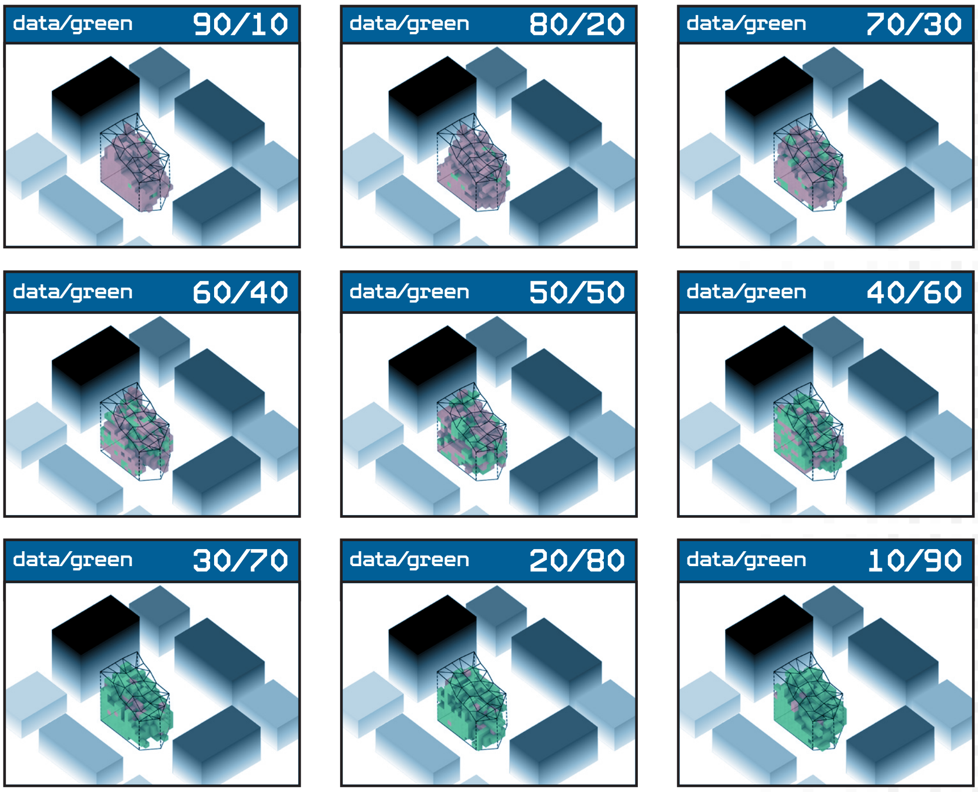
/ PHASE 2



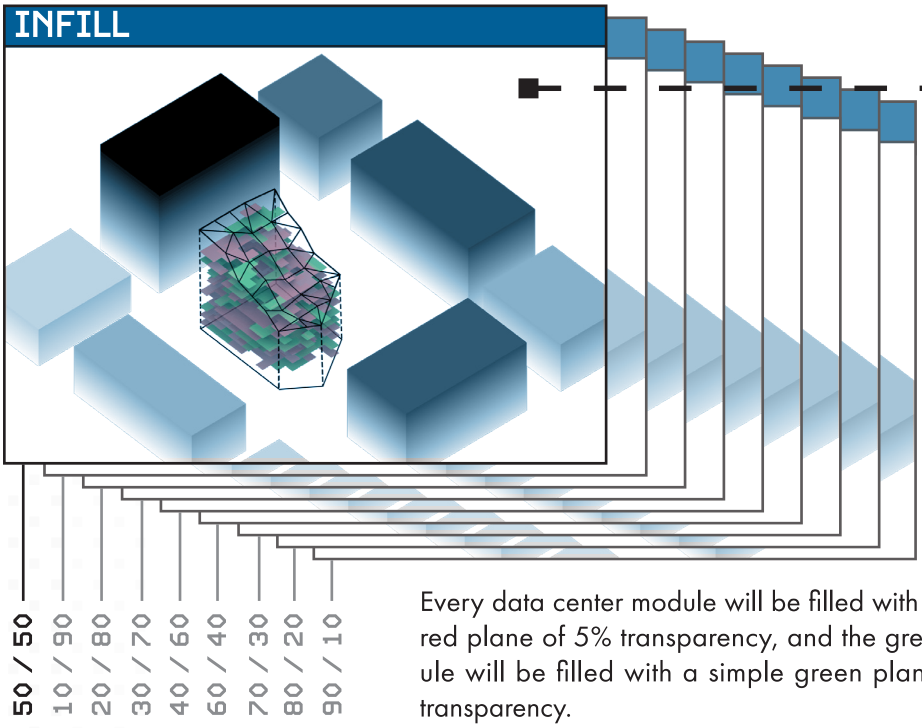
For the structure creation and distribution of data and green modules, the field logic was calculated to increase the distribution chance of green modules to the top border of the solar envelope calculated in the previous step



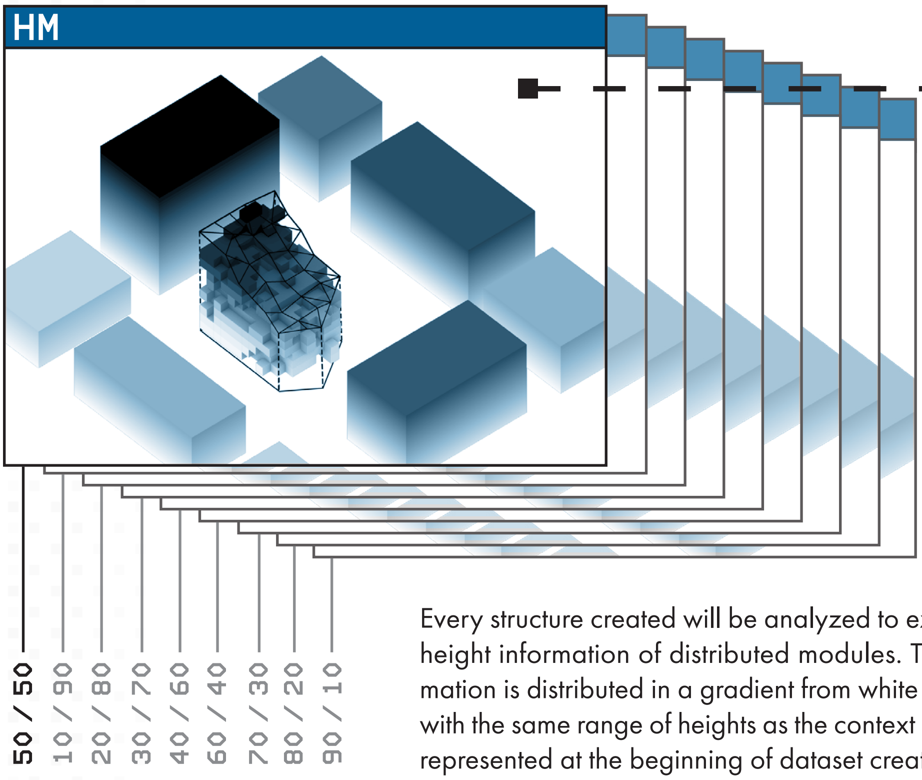
The distribution of data centers and green modules is completed after using precalculated boundary volume and field logic.



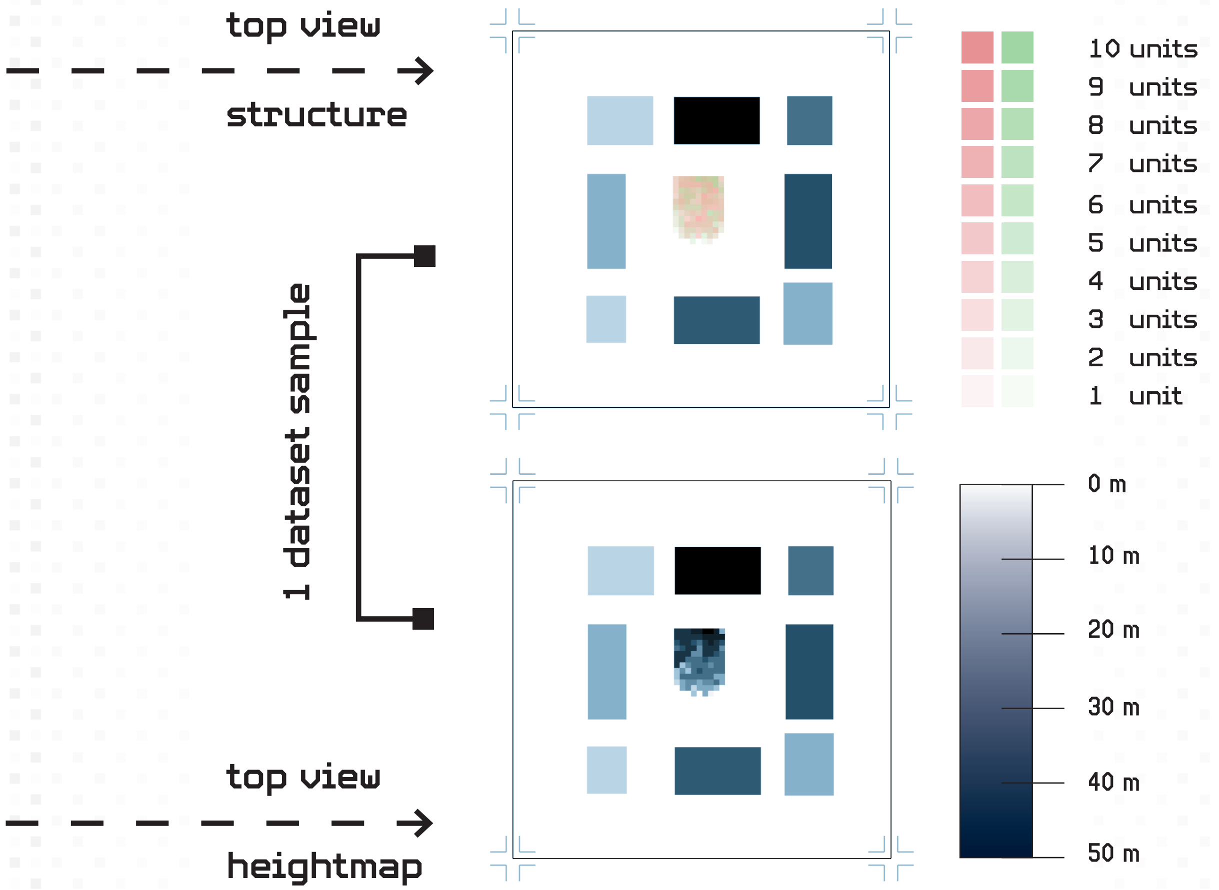
/ PHASE 3



Every data center module will be filled with a simple red plane of 5% transparency, and the green module will be filled with a simple green plane of 5% transparency.



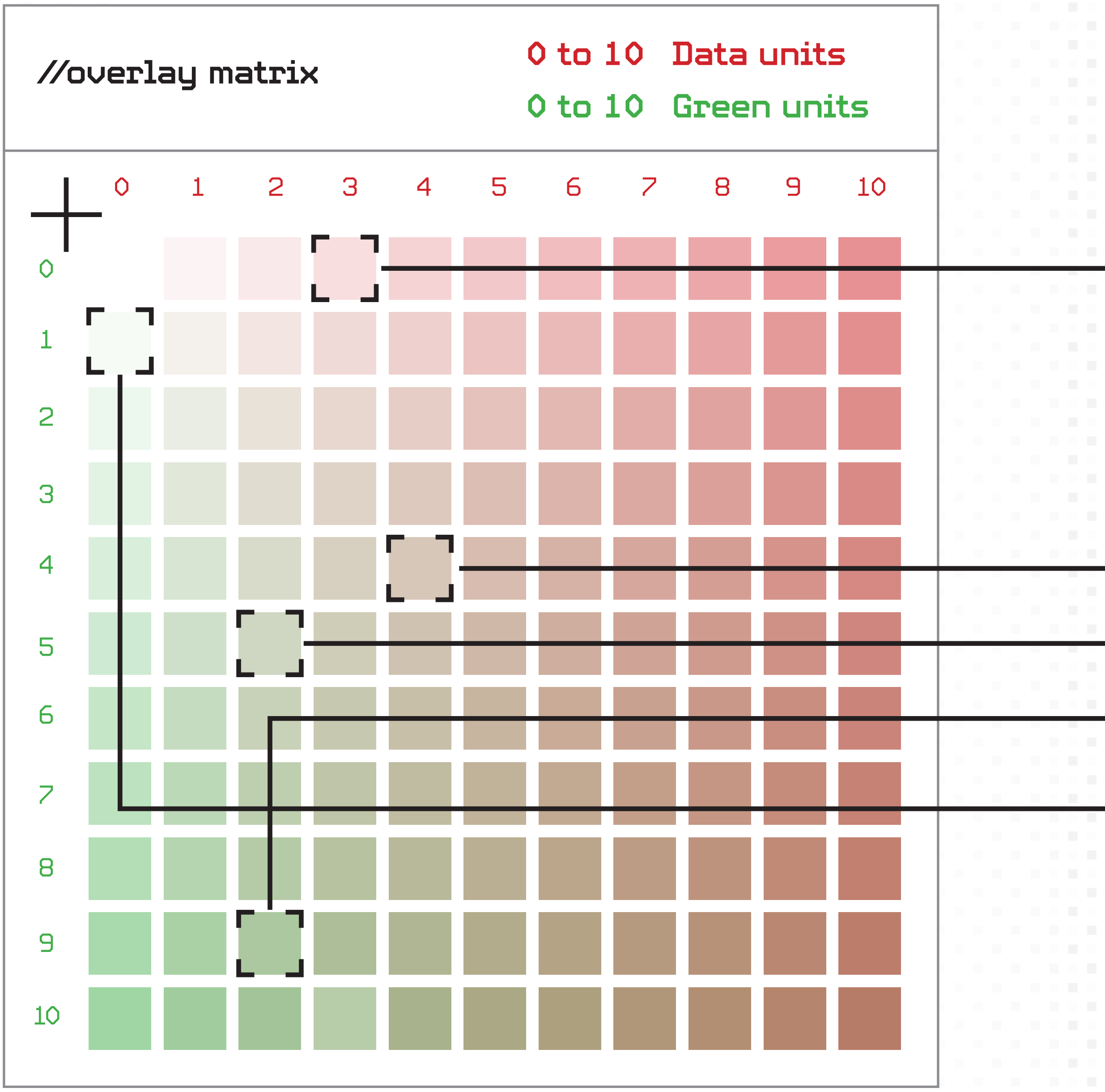
Every structure created will be analyzed to extract the height information of distributed modules. This information is distributed in a gradient from white to black, with the same range of heights as the context buildings represented at the beginning of dataset creation.

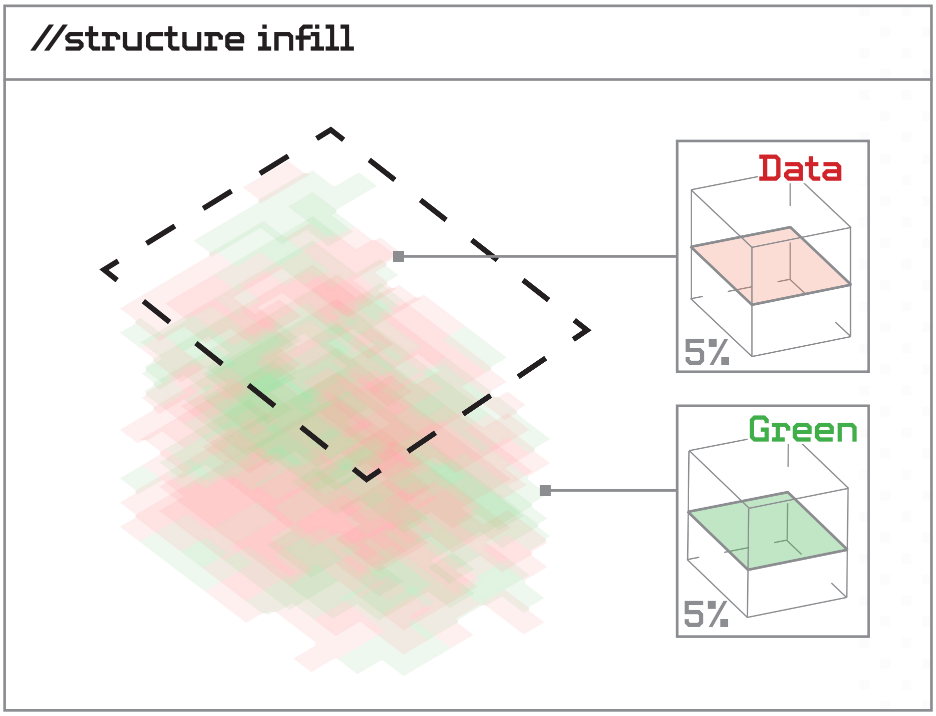


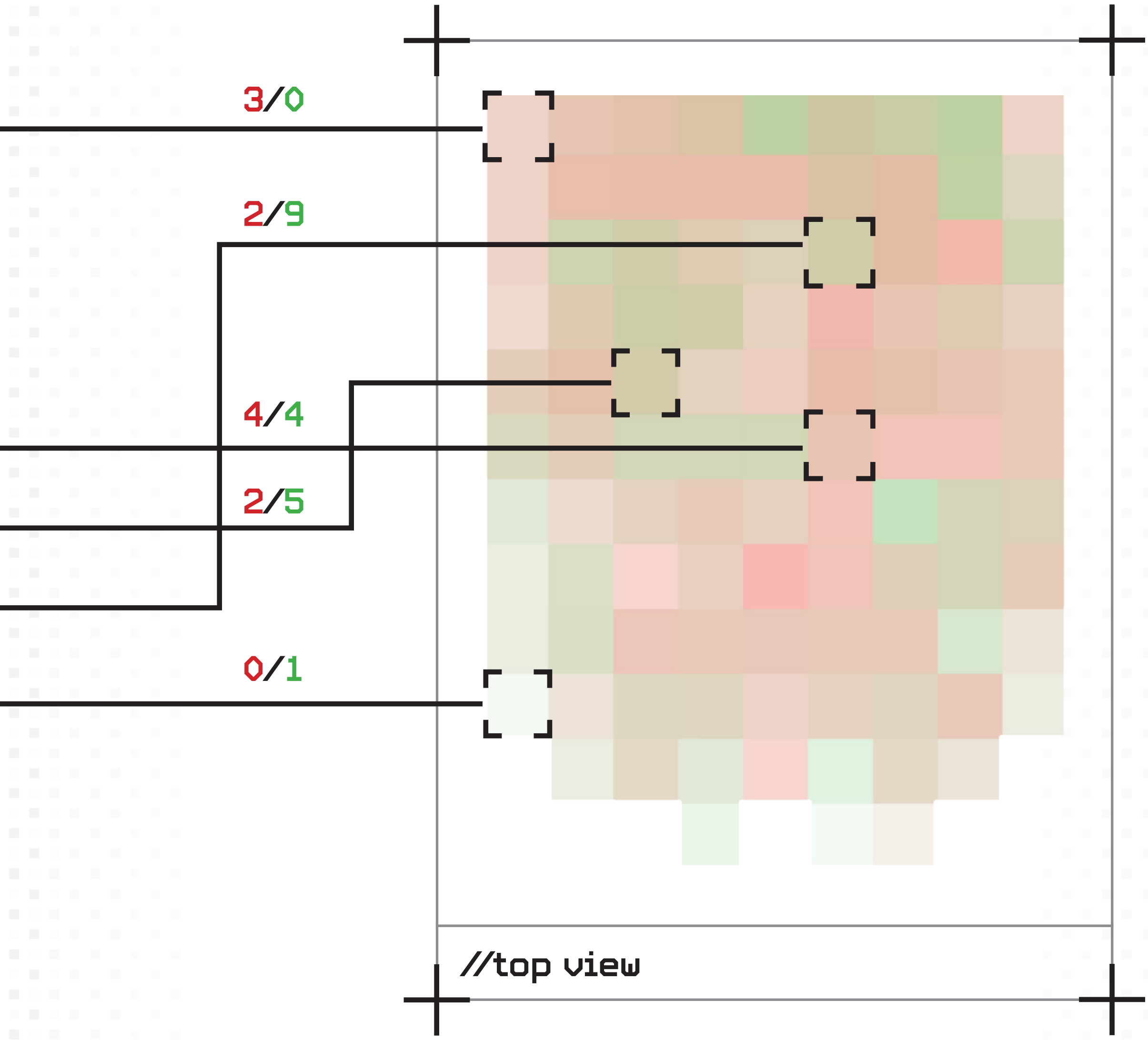
The ultimate depiction of samples intended for utilization within a machine learning framework comprises paired representations: the structure's top view and its corresponding height map top view. The height map encapsulates data indicative of the structure's characteristics contingent upon the surrounding urban context. Conversely, the top view representation delineates the structure's composition, encompassing spatial arrangement and numerical distribution of green and data modules.

/ TRANSPARENCY?

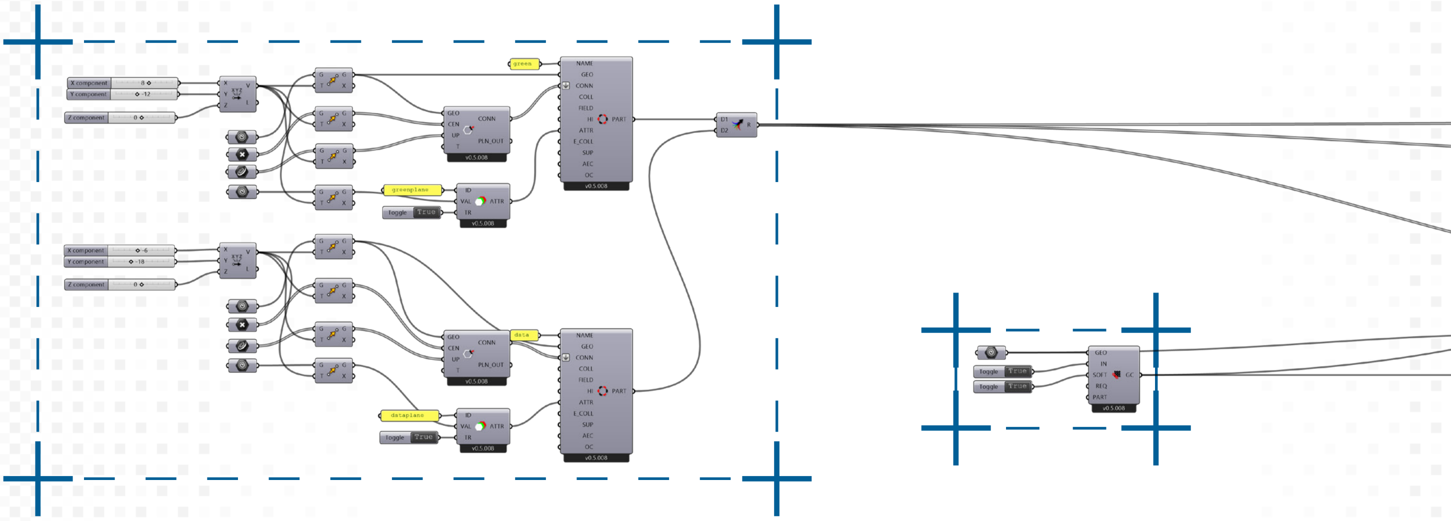
As described in phase three, a plane with a corresponding material in each module of the structure was inserted into every module of the structure to avoid any technical errors in rendering transparency and double overlaps. The data center planes were given a material with a red base color with 5% transparency, while the green planes were given a material with a green base color with 5% transparency. By working with overlapping layers of transparency and transparency of different values of R (Red) and G(Green) channels, it was possible to determine the quantity of every module type in the structure. This approach also enabled us to predict the spatial mapping of the structure without needing knowledge of the aggregation rules themselves.




//structure infill
Data
5%
Green
5%

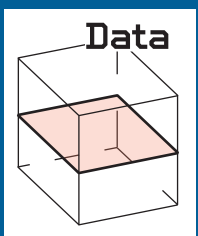

3/0
2/9
4/4
2/5
0/1
//top view

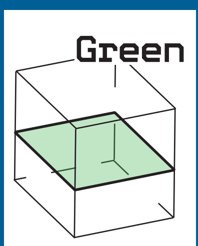
/ DISCRETE ASSEMBLY GRASSHOPPER DEFINITION



/ Discrete Agregation

/ Modules



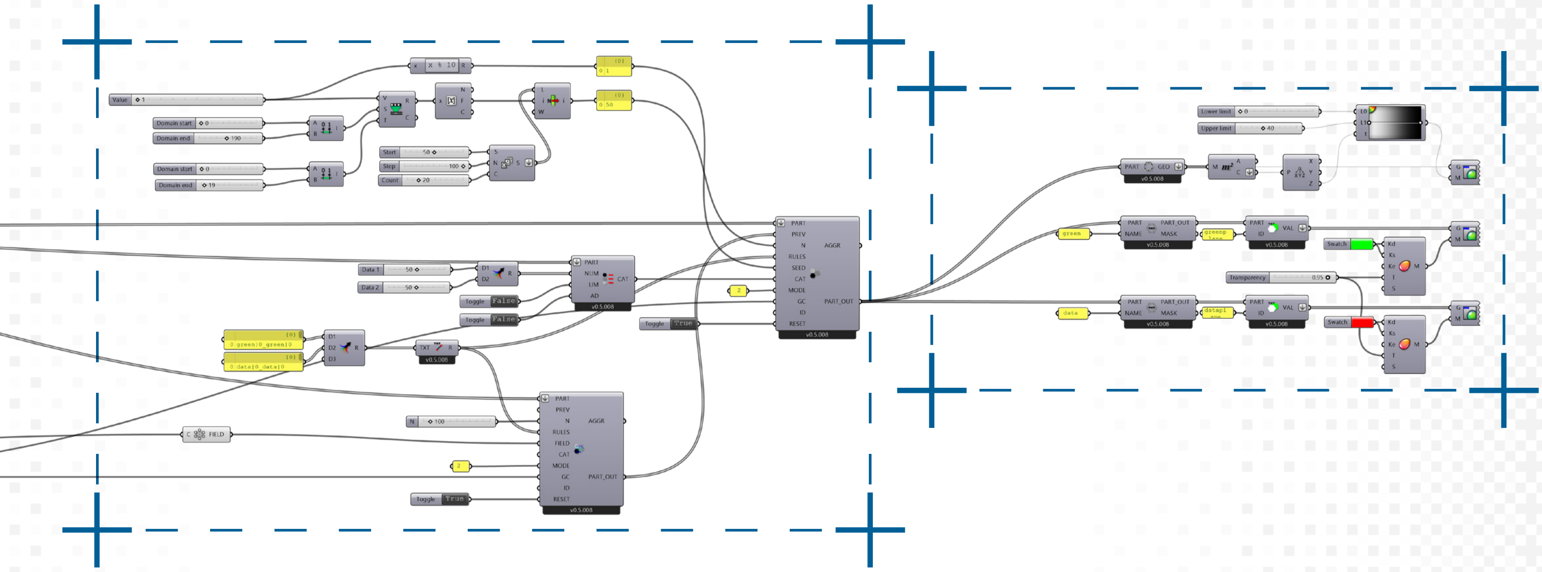


/ Consrtaints & Contexts

36k

BOUNDARY
MESH
CONSTRAINTS

Contexts



/ Data-Green ratio

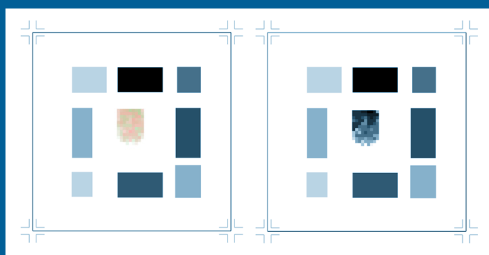
data/green	10/90
data/green	20/80
data/green	30/70
data/green	40/60
data/green	50/50
data/green	60/40
data/green	70/30
data/green	80/20
data/green	90/10

50	800
100	850
150	900
200	950
250	1000
300	1050
350	1100
400	1150
450	1200
500	1250
550	1300
600	1350
650	1400
700	1450
750	1500

9
RATIO OF DATE TO
GREEN MODULES
PER STRUCTURE

10
RATIO OF DATE TO
GREEN MODULES
PER STRUCTURE

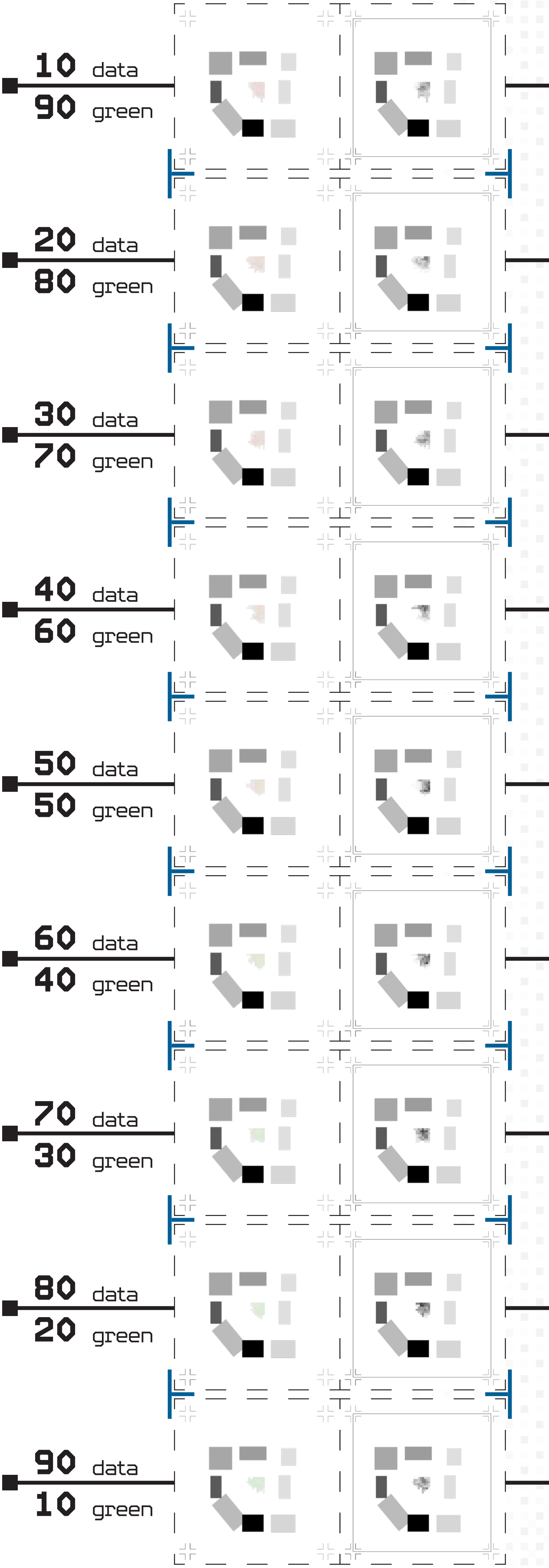
/ Dataset sample

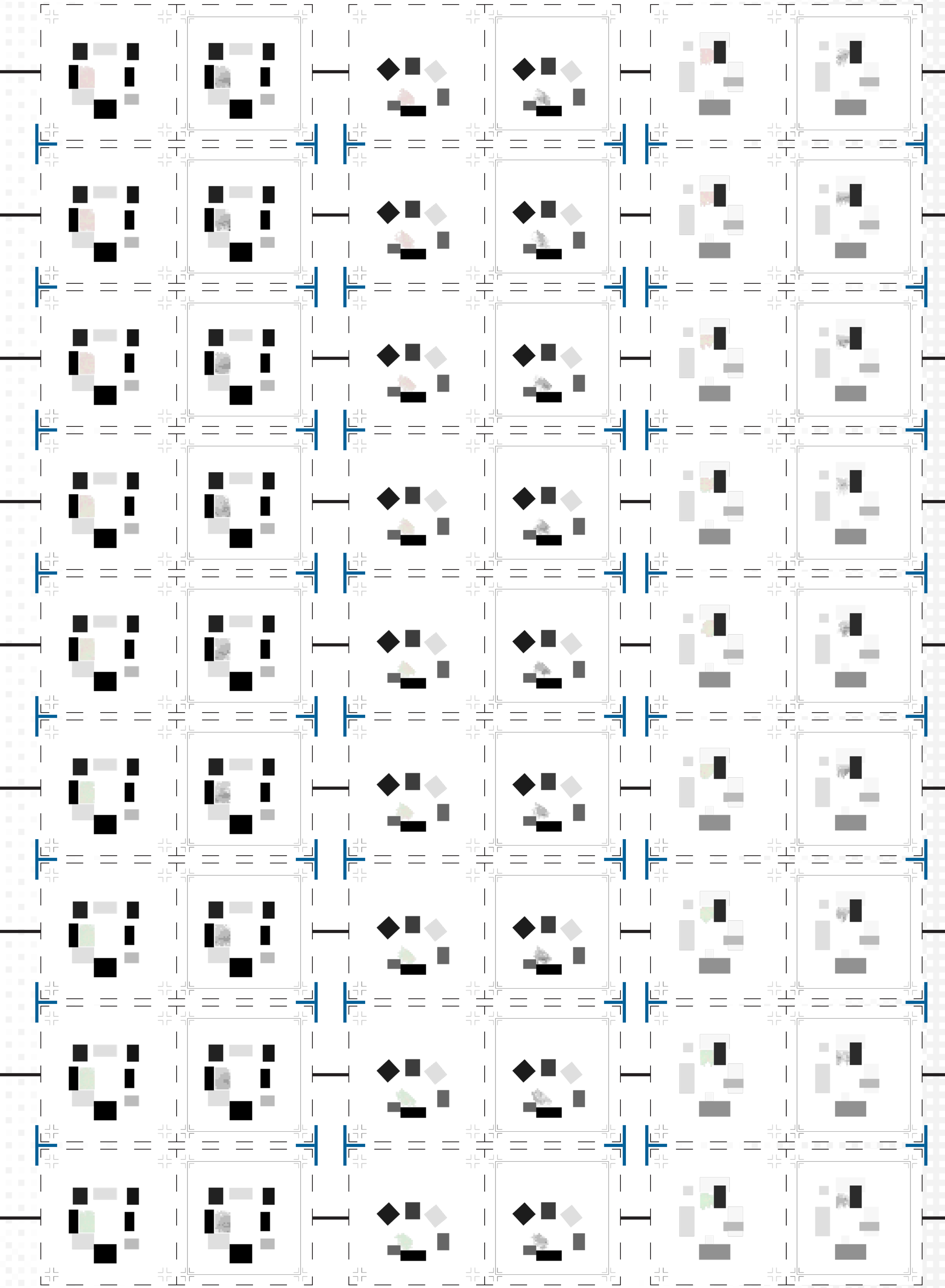


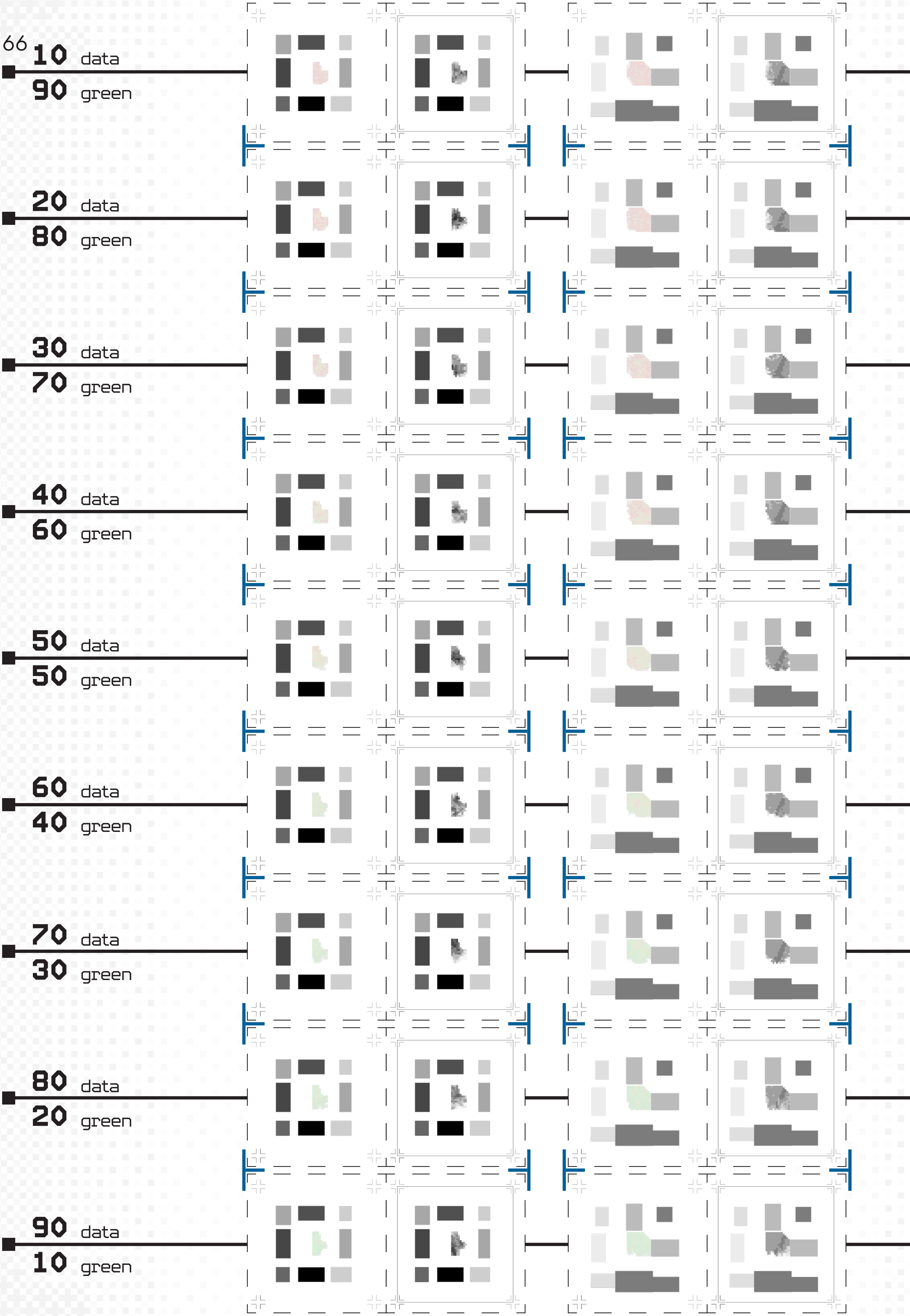
324k
UNIQUE SAMPLES FOR
THE NEXT STEP

+++ DATASET SAMPLES REPRESENTATION

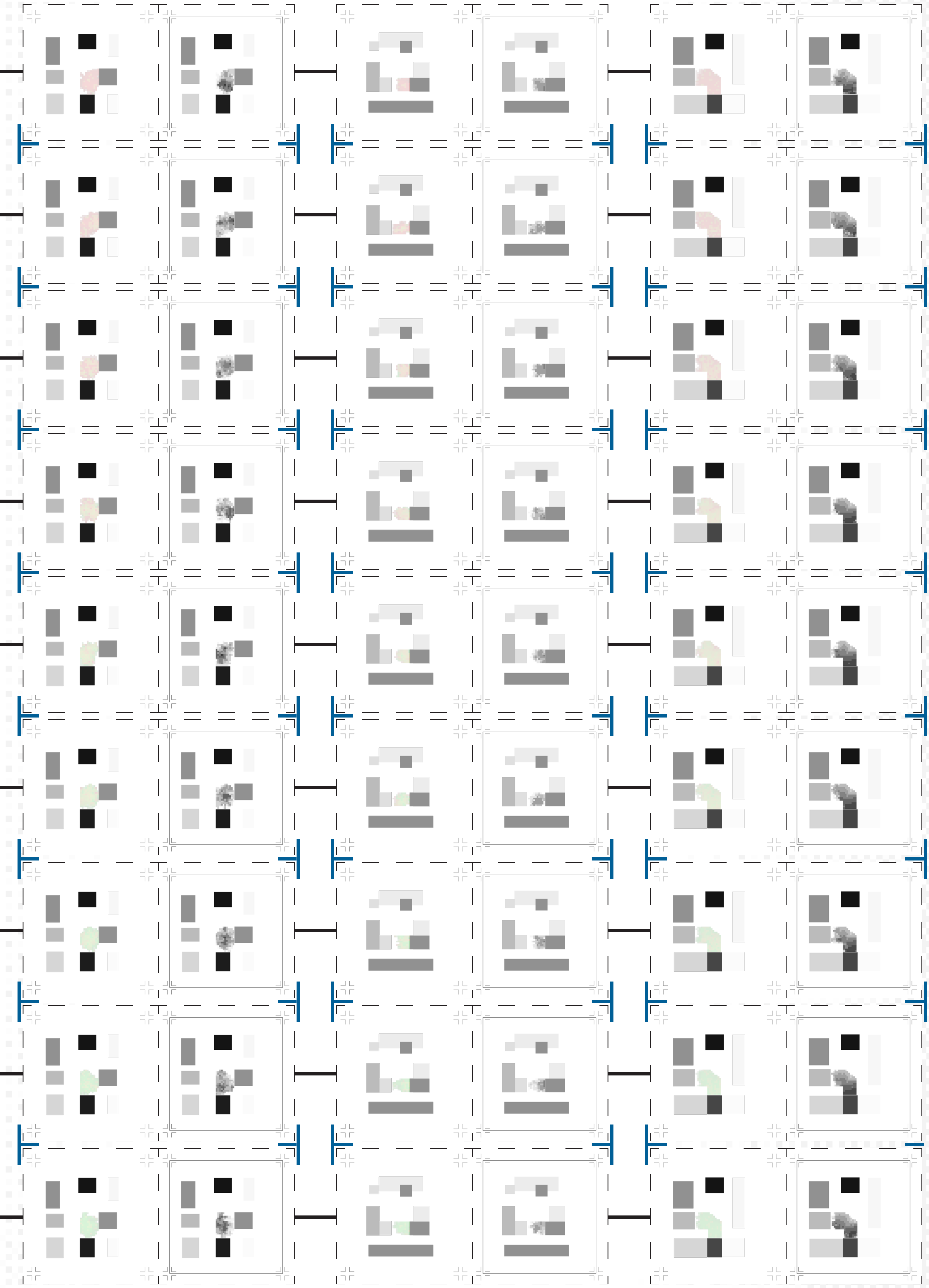
In total, over 100,000 unique samples were generated. To accelerate the generation process, I utilized FA CVUT-based computer classes.







10 data
90 green
20 data
80 green
30 data
70 green
40 data
60 green
50 data
50 green
60 data
40 green
70 data
30 green
80 data
20 green
90 data
10 green



/ Modularity

At the dawn of the 20th century, modularity emerged as a critical architectural milestone, revolutionizing the discipline through systematic organization. In 1923, Walter Gropius, the German architect, introduced the concept of "Baukasten" (a German term for "building block") at the Bauhaus. [61]

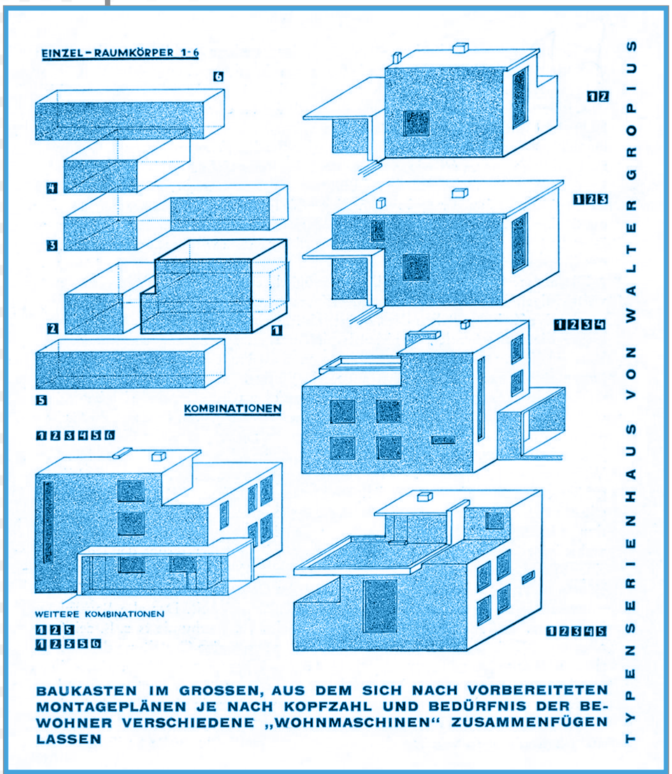


Figure 12.1 "Baukasten", Walter Gropius

Figure 12.2 Tokyo's Nakagin Capsule Tower

This approach emphasized the assembly of standardized modules according to strict rules, aiming to simplify the building process and reduce construction costs.

Other pioneering architects, including Robert W. McLaughlin and Le Corbusier, also embraced modular principles to develop designs that were both accessible and rationally organized. McLaughlin's Winslow Ames house, for instance, exemplified the affordability and practicality of modular housing units. Simultaneously, Le Corbusier's "Modulor" theory sought to humanize these principles by matching building dimensions to human proportions, highlighting the blend of functionality and aesthetics in modular design.

Gradually, modularity inspired a generation of theorists and architects to adapt their work to modular principles, resulting in more reliable and efficient building processes. Iconic projects like Moshe Safdie's Habitat 67 and Archigram's "Plugin City" underscored the lasting influence of modularity on architectural design, showcasing innovative solutions long after World War II.[65]

Notably, the Metabolist movement in Japan during the 1960s embraced modularity with a futuristic vision, seeing it as a means to expand and adapt urban environments continuously. Metabolists like Kisho Kurokawa and Kenzo Tange envisioned cities where modular units could be plugged into existing megastructures, reflecting organic growth and change. This approach highlighted a dynamic, ever-evolving model of urban living, significantly contrasting with the often static nature of earlier modular systems.[65]

Adhering to modular principles had drawbacks; over time, rigidity resulted in monotonous designs, stifling creativity. Modularity impacted architecture, introducing systematic approaches that influenced critical principles. Today, modularity's legacy continues in sustainable and innovative building practices, underscoring its enduring influence in shaping the built environment.

/ CAD

In the early 1980s, the advent of powerful computers and innovative hardware spearheaded the development of computer-aided design (CAD) software, revolutionizing architecture. The roots of CAD trace back to the mid-1950s, with the first prototypes such as PRONTO6 and SketchPad emerging by the 1960s. These pioneering systems facilitated precise 2D architectural drawings and featured user-friendly interfaces, significantly enhancing design accuracy and efficiency. [65]

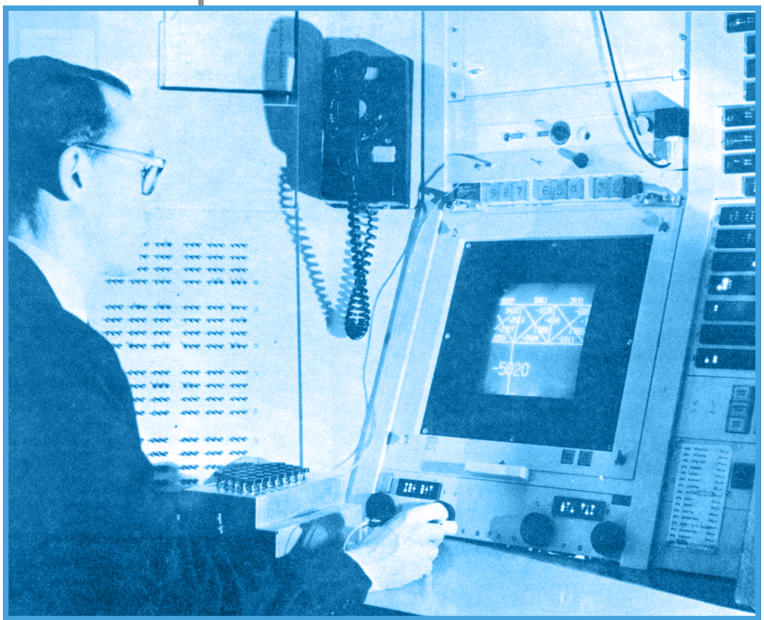


Figure 12.3 Sketchpad , I. Sutherland

The capabilities of CAD software were expanded dramatically by mathematician Pierre Bézier, who introduced the concept of complex curves with his UNISURF software in 1966, enabling the creation of intricate 3D shapes. This innovation found widespread application, notably influencing the automotive and aerospace industries.

CAD pioneers, including Ivan Sutherland, Patrick Hanratty, and Bézier, established CAD as a distinct research discipline. By the late 20th century, CAD had permeated various sectors, including architecture, bringing structured methodologies to the design process. It facilitated precise manipulation of geometric shapes, organization of design elements, and both digital and physical output of models. [65]

Explorations into the potential of CAD extended into speculative realms at institutions like the Architecture Machine Group (AMG) at MIT, led by Nicholas Negroponte. Projects like Urban 2 and Urban 5 examined how computers could further enhance architectural design through advanced user interfaces and program organization.65

Prominent architects, including Frank Gehry, pioneered the use of advanced CAD software, such as Dassault Systèmes' CATIA, to manage complex geometries in iconic projects like the Walt Disney Concert Hall. This application underscored CAD's ability to handle intricate design challenges not feasible with traditional methods.[65]

Figure 12.4 the Walt Disney Concert Hall , Frank Gehry

From its inception through 2010, CAD technology continuously evolved, becoming a foundational tool in architecture. It offered unparalleled control over complex designs, fostered collaboration across disciplines, expanded creative capabilities, and reduced overall project costs. Despite its advantages, architects recognized CAD's limitations, prompting them to integrate complementary technologies that addressed repetitive tasks, controlled intricate shapes, and managed complex design rules.[65]

/ Parametricism

"Parametric modeling" offers an alternative approach to building design by allowing architects to specify explicit rules, complementing traditional geometric modeling tools. This method has historical roots, with architects like Luigi Moretti showcasing its potential in the early 1960s. Moretti's design for Stadion N, which involved nineteen defined parameters transformed into mathematical equations, demonstrated how variations in these parameters could lead to diverse stadium shapes, emphasizing the aesthetic and functional possibilities of parametric modeling.[65]

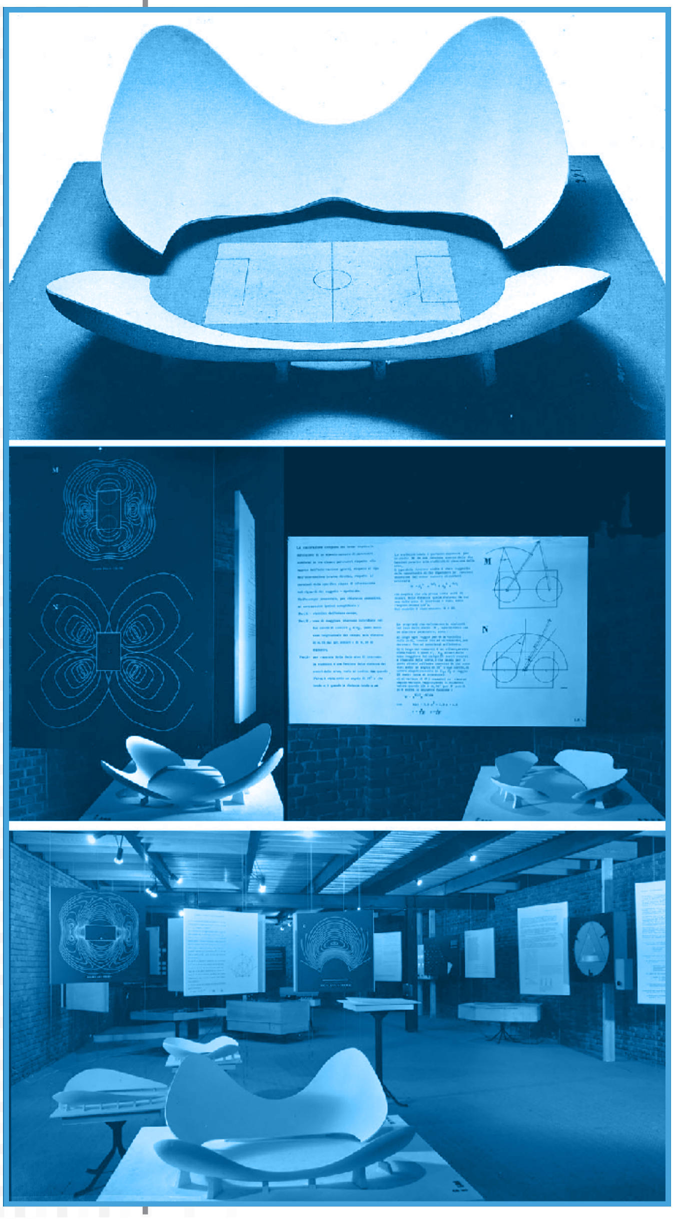


Figure 12.5a,b,c Stadion N, Luigi Moretti

The introduction of visual programming platforms such as Grasshopper has significantly advanced the adoption of parametric modeling. Developed by David Rutten, Grasshopper utilizes a graphical interface that democratizes access to programming logic, enabling architects to conceive designs in a more systematic and rule-based manner. This tool has become crucial for many designers, enhancing the systemization of the design process.[65]

Building Information Modeling (BIM), emerging in the early 2000s, employs parametric principles to manage meta-information associated with building geometries. Tools like Revit and ArchiCAD facilitate the manipulation of parametric objects, offering architects digital replicas of buildings that integrate detailed system behaviors and properties. This capability enriches the semantic depth of BIM models and streamlines complex data management.[65]

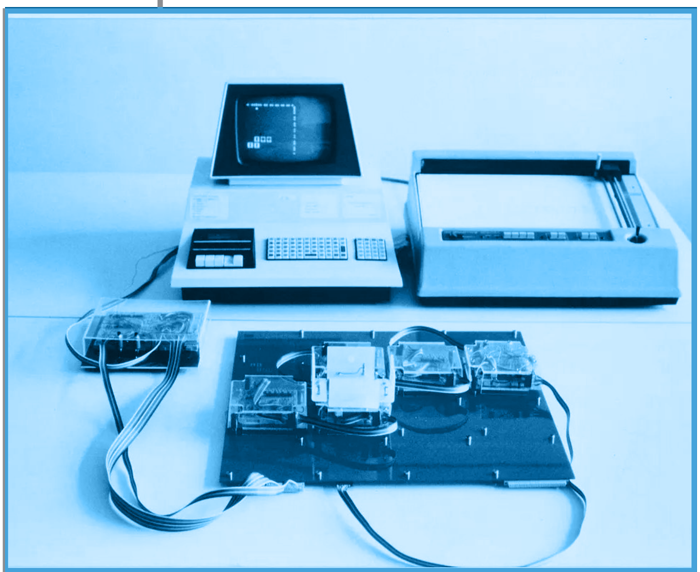
Despite these advancements, parametric modeling is not without its challenges. The focus on efficiency can sometimes overshadow other critical architectural considerations such as spatial organization and style. Additionally, the range of designs produced can be restrictive, and balancing parameters effectively remains computationally demanding. The rigid nature of explicit parameters may also neglect important architectural elements, including sociocultural and stylistic factors.[65]

The integration of artificial intelligence (AI) into architectural design marks a significant evolution, potentially overcoming some of parametric modeling's limitations. Over the past six decades, AI has been poised to enhance architectural design by optimizing parameter use and incorporating broader contextual factors into the design process, signaling a new era in architectural innovation.[65]

/ Artificial Intelligence

Visionaries like Nicholas Negroponte and Cedric Price foresaw the transformative potential of artificial intelligence (AI) in architecture. In the 1970s, Negroponte introduced the concept of the "machine assistant" at MIT, exploring the dynamic interaction between architects and intelligent machines. His projects, Urban 2 and 5, not only optimized architectural floor plans but also illustrated the collaborative potential between humans and AI, showcasing how these tools could enhance the architectural design process. Meanwhile, Cedric Price, in 1976, pioneered the Generator project, which experimented with self-adapting buildings. These structures could reconfigure themselves based on user interactions and environmental conditions, pushing the boundaries of architectural innovation. [65]

Figure 12.6, Urban 2 and 5, MIT



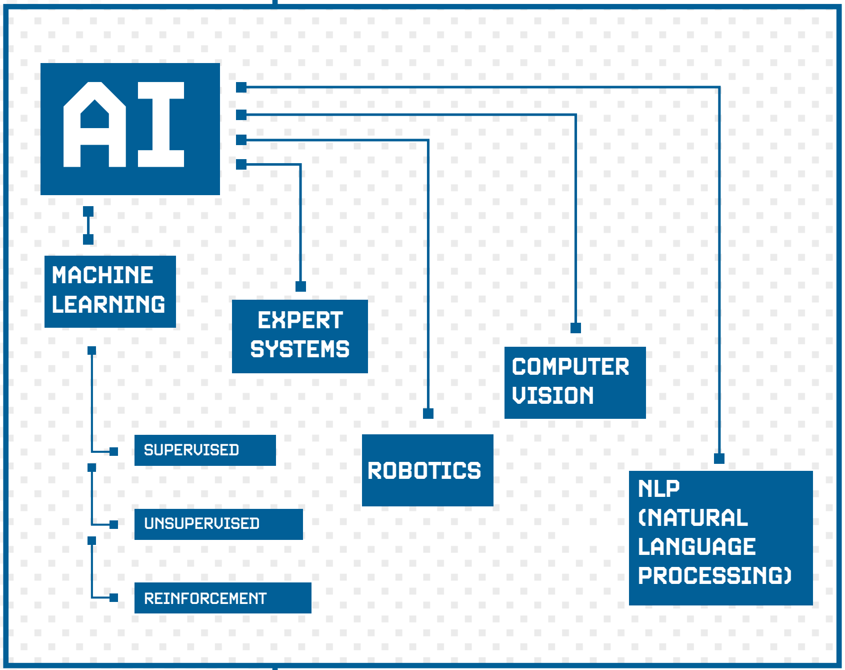
In recent years, the application of AI in architecture has expanded dramatically. AI-driven floor plan generation, for example, represents a significant leap forward in architectural design. Utilizing machine learning algorithms, these systems create and optimize building layouts based on predefined criteria such as space utilization, energy efficiency, and user flow. They can rapidly generate multiple design alternatives, allowing architects to evaluate a variety of configurations quickly and make data-informed decisions.

AI research in urban planning is burgeoning, fueled by an abundance of data capturing the complex layers of urban life, including road networks, the built environment, and topographical details. High-quality data sources such as Google Maps, Open Street Maps, and GIS data collected by governmental and institutional bodies provide a rich foundation for AI applications. These datasets enable researchers to analyze and model urban dynamics more accurately, leading to innovative solutions for city planning and management. By leveraging this extensive data, AI can optimize traffic flow, enhance public transportation systems, predict urban growth, and improve sustainability practices within cities. [65]

Architects play a crucial role as creators of datasets for AI training. By meticulously documenting their design processes and outcomes, they facilitate the development of AI tools that can learn from past projects, anticipate future trends, and suggest optimizations for more sustainable and efficient building practices. This pivotal role positions architects at the forefront of the symbiotic relationship between AI development and architectural innovation, making them key players in shaping future technologies that will redefine the built environment.

Despite these advancements, the architectural community continues to grapple with defining AI's exact role within the discipline. The field is characterized by a variety of applications, theories, and stakeholders, contributing to a dynamic yet fragmented understanding of AI in architecture. Ongoing efforts aim to clarify AI's technical aspects, demonstrate its practical applications across various scales, and foster broad discussions that capture the full spectrum of AI's impact on architecture. The overarching goal is to develop a comprehensive understanding that reflects the complex and varied ways AI reshapes architectural thought and practice.[65]

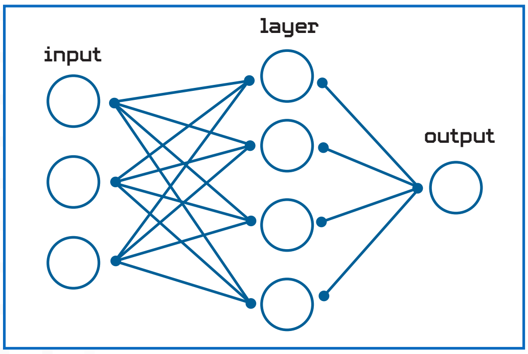
/ AI domains



AI has undergone a significant and transformative evolution since its inception at the Dartmouth Seminar in 1956. This journey, spanning over six decades, has witnessed the emergence of a remarkably diverse and extensive range of innovative technologies and methodologies. The vast field of AI can be broadly categorized into several pivotal areas: machine learning (ML), which enables algorithms to learn from data and make accurate predictions; robotics, involving the design of sophisticated robots for various complex environments; expert systems, which mimic human decision-making in specialized domains; natural language processing (NLP), enabling machines to understand and interact using human language; and computer vision, allowing systems to accurately interpret visual data from their dynamic surroundings.

/ ML

The methodology of this thesis specifically focuses on the practical applications of machine learning (ML), a core AI branch that equips computers to learn from data and make informed decisions. The process begins with data input into an algorithm—a set of rules designed to solve problems. Utilizing statistical techniques, the machine constructs a model from this data. As it receives more data, the machine adjusts its model to improve accuracy over time, thereby 'learning' from its successes and failures.

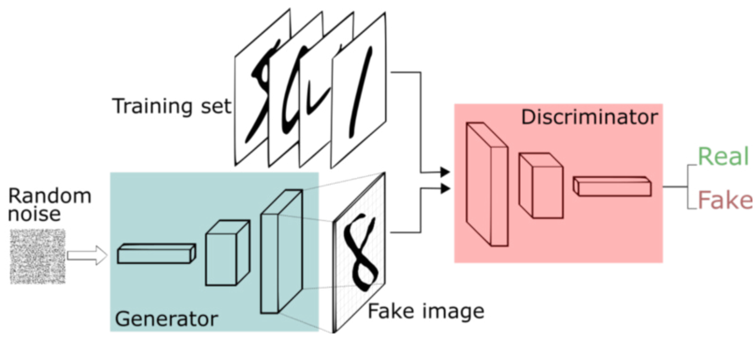


A significant feature of machine learning is the degree of user control over computational processes. In contrast to parametric modeling in architecture, where the user explicitly defines each step and parameter, machine learning permits the model to adjust its parameters within predefined limits. Although users establish the initial architecture of the model, the detailed adjustment of parameters—and occasionally their very definition—is managed internally by the model. Users continue to exert influence through "hyperparameters," which are overarching settings that steer the course of the learning process.

Machine learning is generally divided into three main categories based on the training approach: supervised, unsupervised, and reinforcement learning. Supervised learning utilizes labeled datasets to train algorithms, enabling the model to predict outputs from given inputs by minimizing prediction errors, as commonly seen in image recognition tasks. Unsupervised learning, in contrast, does not rely on labeled data but instead finds patterns or anomalies within the data to understand its structure, useful for clustering and anomaly detection. Reinforcement learning involves an agent that makes decisions to maximize cumulative rewards through trial and error, suitable for applications requiring sequential decision-making, such as in robotics and gaming. These training strategies delineate the broad categories of machine learning, each distinguished by its unique architectural needs.

/ GAN

Figure 13.1, GAN logic,



Generative Adversarial Networks (GANs) represent a transformative advancement in artificial intelligence, particularly in how machines learn and generate data. Conceived by Ian Goodfellow in 2014, GANs consist of two neural network models—the generator and the discriminator—that engage in internal competition. In a typical scenario, such as image generation, the generator creates synthetic images, aiming to replicate the authentic look of a given dataset of images. The discriminator evaluates these images, striving to discern the fake images from the real ones. This interactive dynamic allows the discriminator to guide the generator in improving the realism of its synthetic images. The unique architecture of GANs, which harnesses the tension between the two models, facilitates a continuous refinement of data generation capabilities.

Figure 13.2, pix2pix logic,

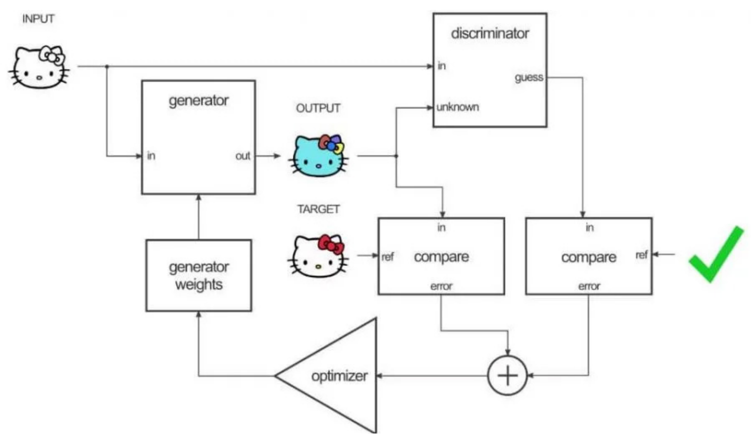
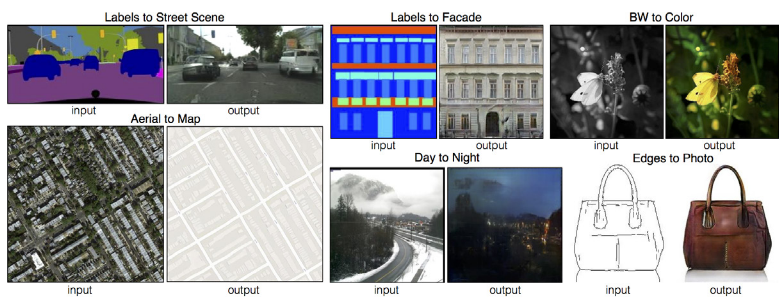


Figure 13.3, pix2pix examples

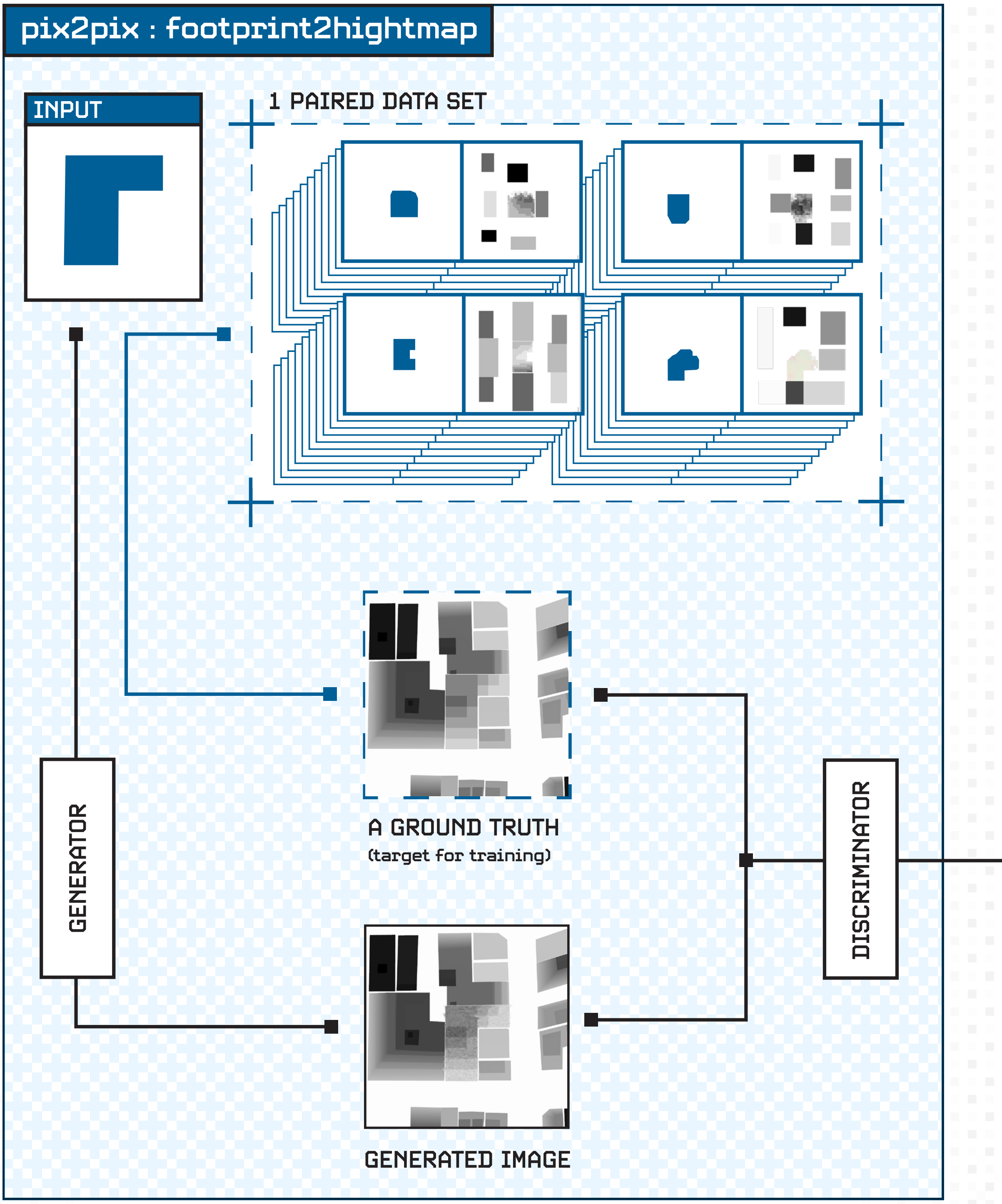


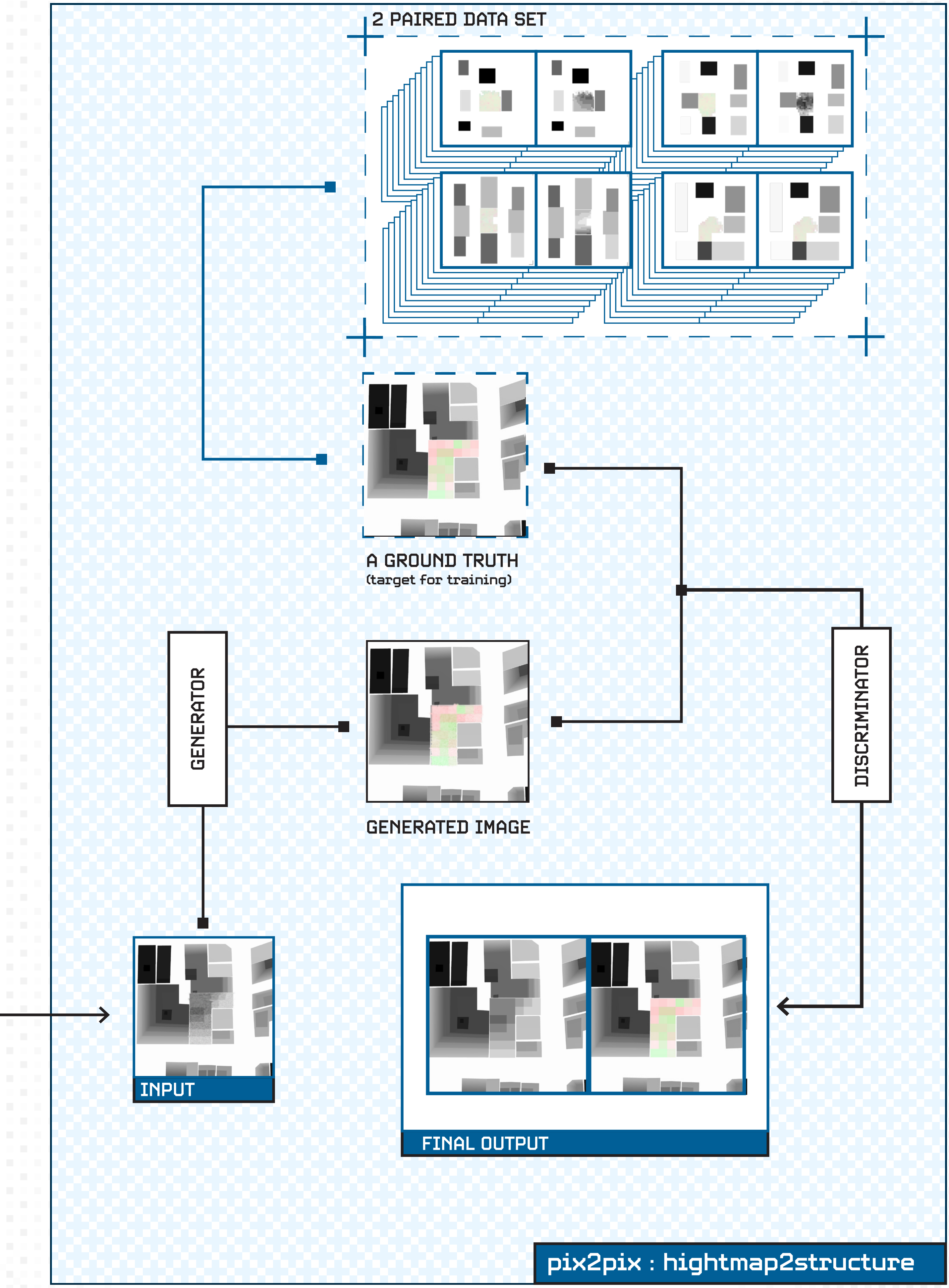
/ pix2pix

In researching the interconnection between AI and architecture, the pix2pix model, a generative adversarial network (GAN)[62] type, was chosen for its proficiency in image-to-image translation tasks. Pix2pix uses paired training data (i.e., corresponding input and target images) to learn how to generate new images from given inputs. This capability makes it particularly suitable for architectural and spatial design applications, where the objective is to create plausible layout dispositions from inputs represented as architectural footprints. For the experiment, a pre-trained pix2pix model from an open-source repository was employed. This model, implemented in PyTorch, provides access to various training checkpoints that have been pre-trained on diverse datasets. The availability of these resources enabled an expedited setup phase, as there was no need to train the model from scratch. Instead, the focus was on fine-tuning the model to better meet the specific requirements of creation new architecture typology . To this end, a dataset created with the help of Grasshopper, which was described in previous pages, was used as the basis for training.

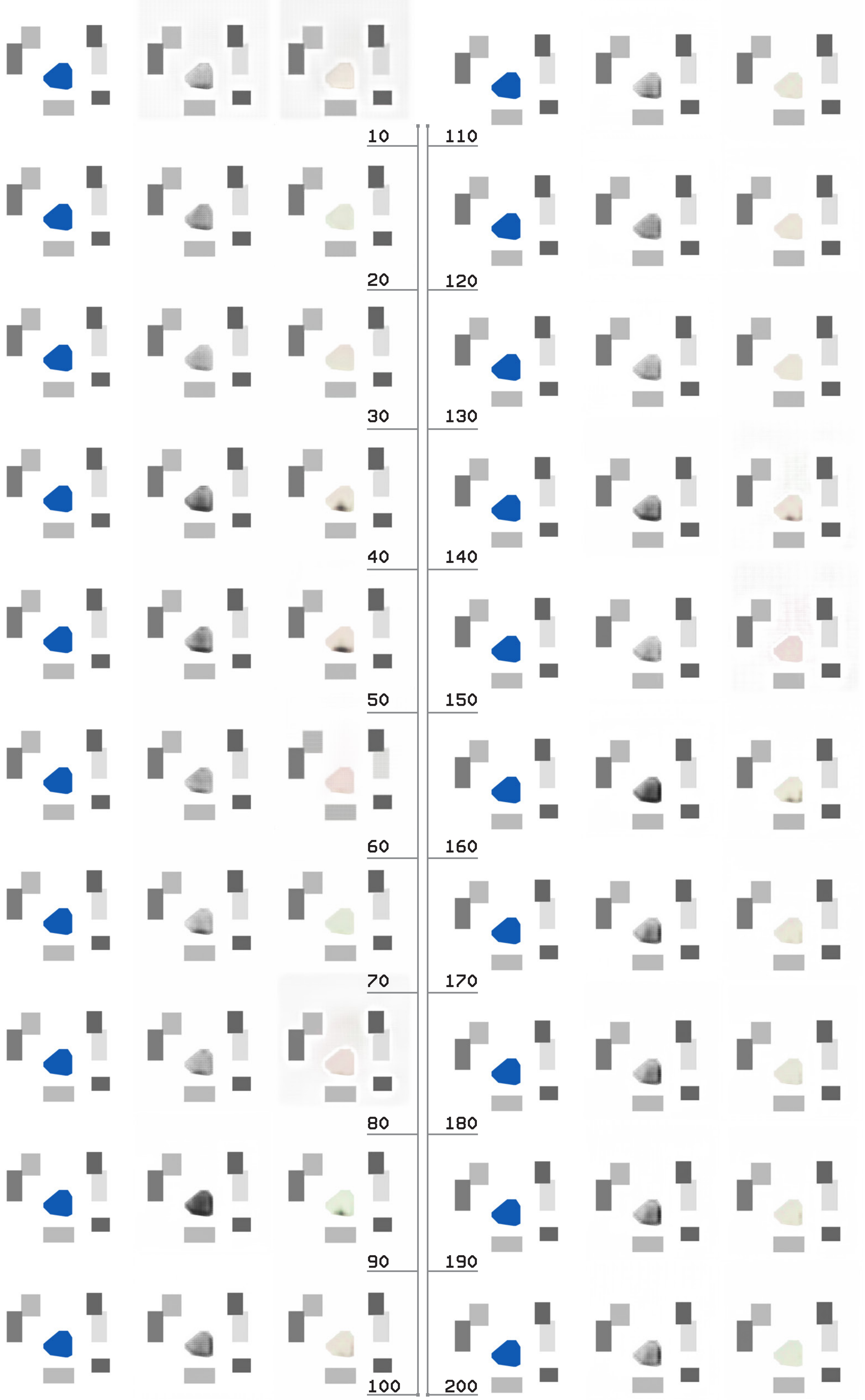
/ Process

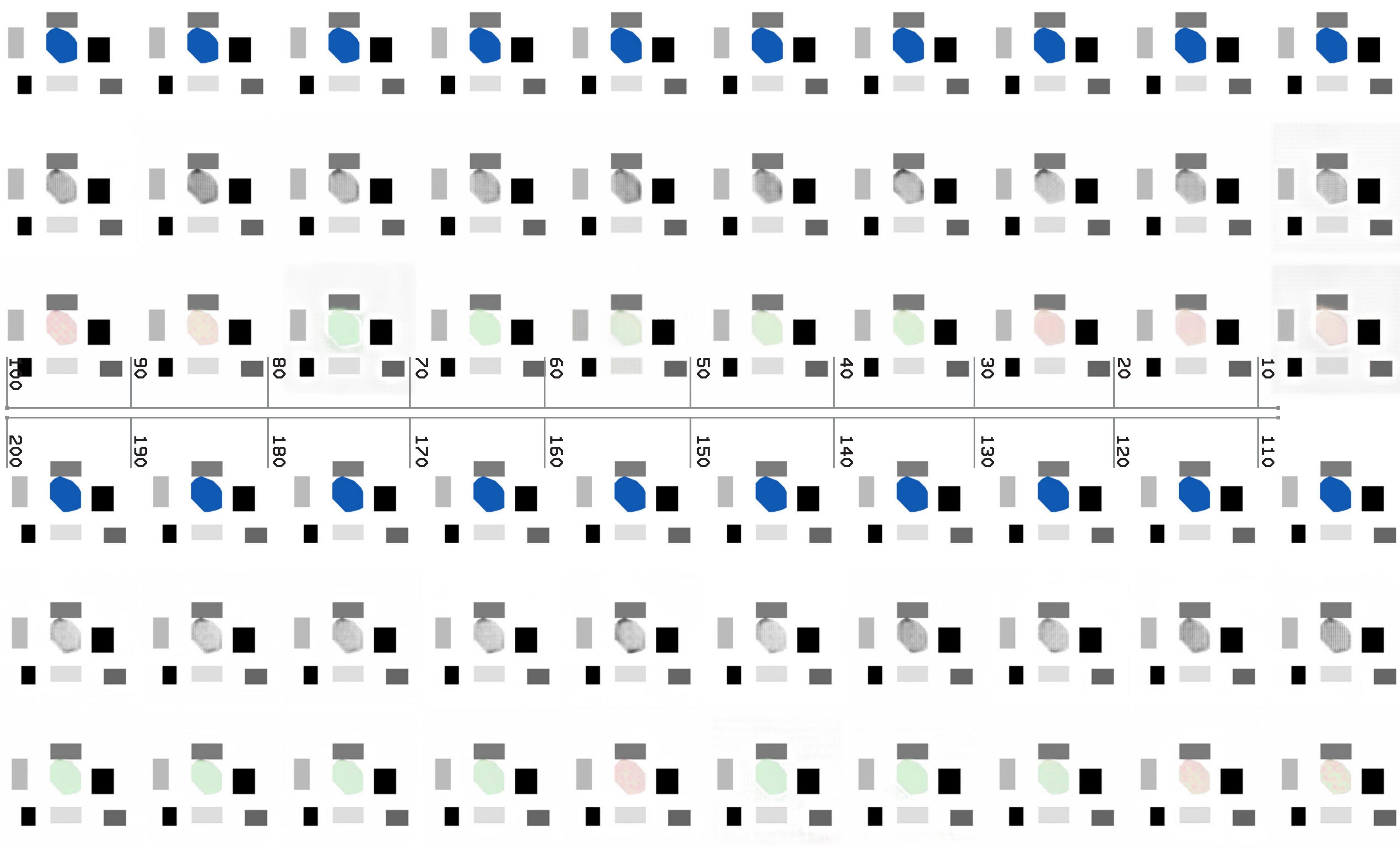
Two pre-trained, open-source models were adapted to explore the interplay between AI and architecture for the thesis methodology. Initially fine-tuned and subsequently trained with prepared datasets, these models were transformed into a bespoke architectural tool. The process involves two sequential pix2pix models: the first model processes the footprint sketches to generate a height map of the proposed structure, while the second model analyzes this height map to determine the building's structural representation, data modules and green modules ratio. This methodology culminates in the development of a tool that enables architects to sketch a building's footprint within a specific context initially; the tool then generates a corresponding map of building heights, which is utilized to define the internal structure. This tool demonstrates the practical application of advanced machine-learning techniques in architectural design, enhancing both creativity and efficiency.




2 PAIRED DATA SET
A GROUND TRUTH
(target for training)
GENERATOR
GENERATED IMAGE
DISCRIMINATOR
INPUT
FINAL OUTPUT
pix2pix : hightmap2structure

// model traing process, EPOCH 0-200, location 3570





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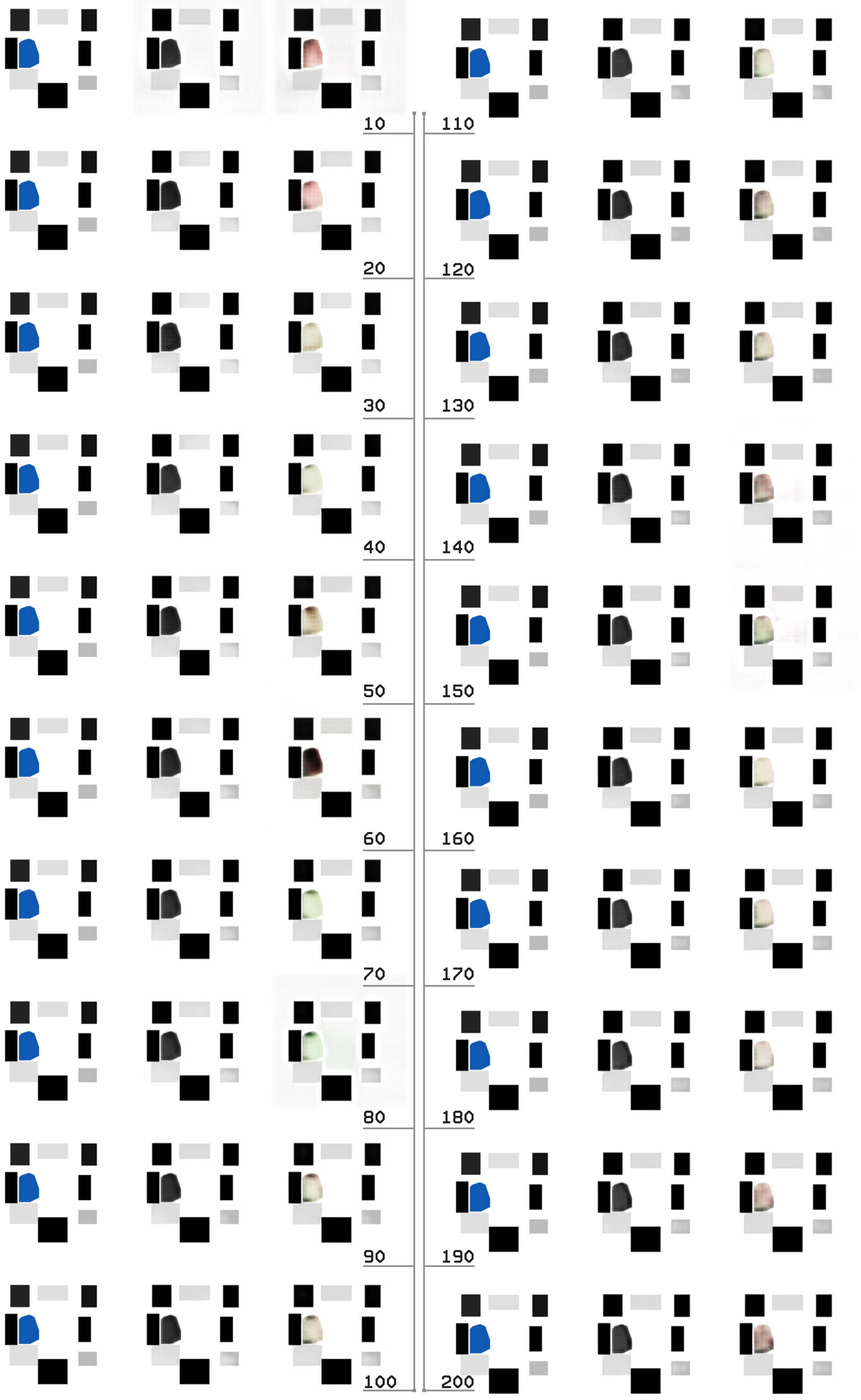

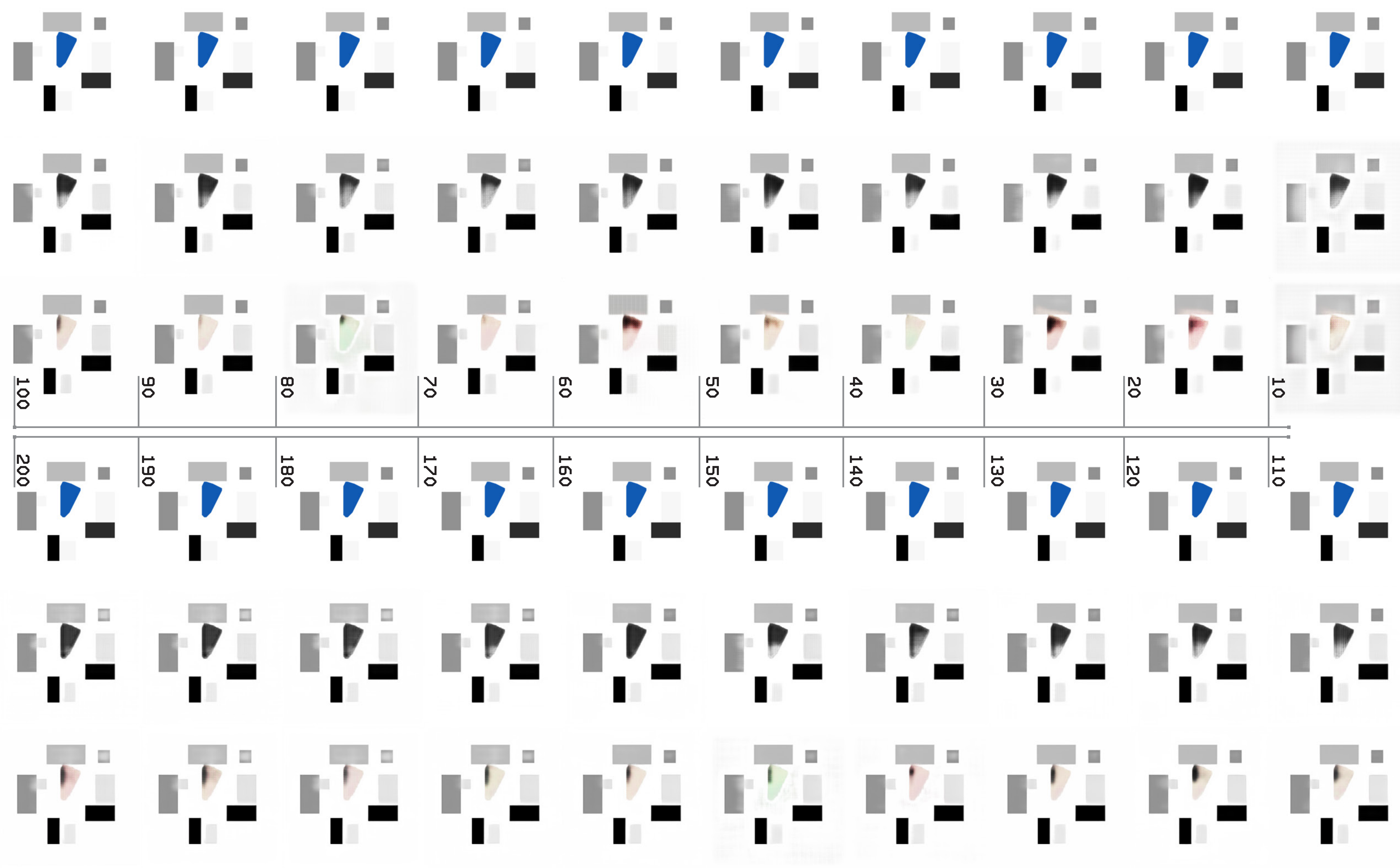

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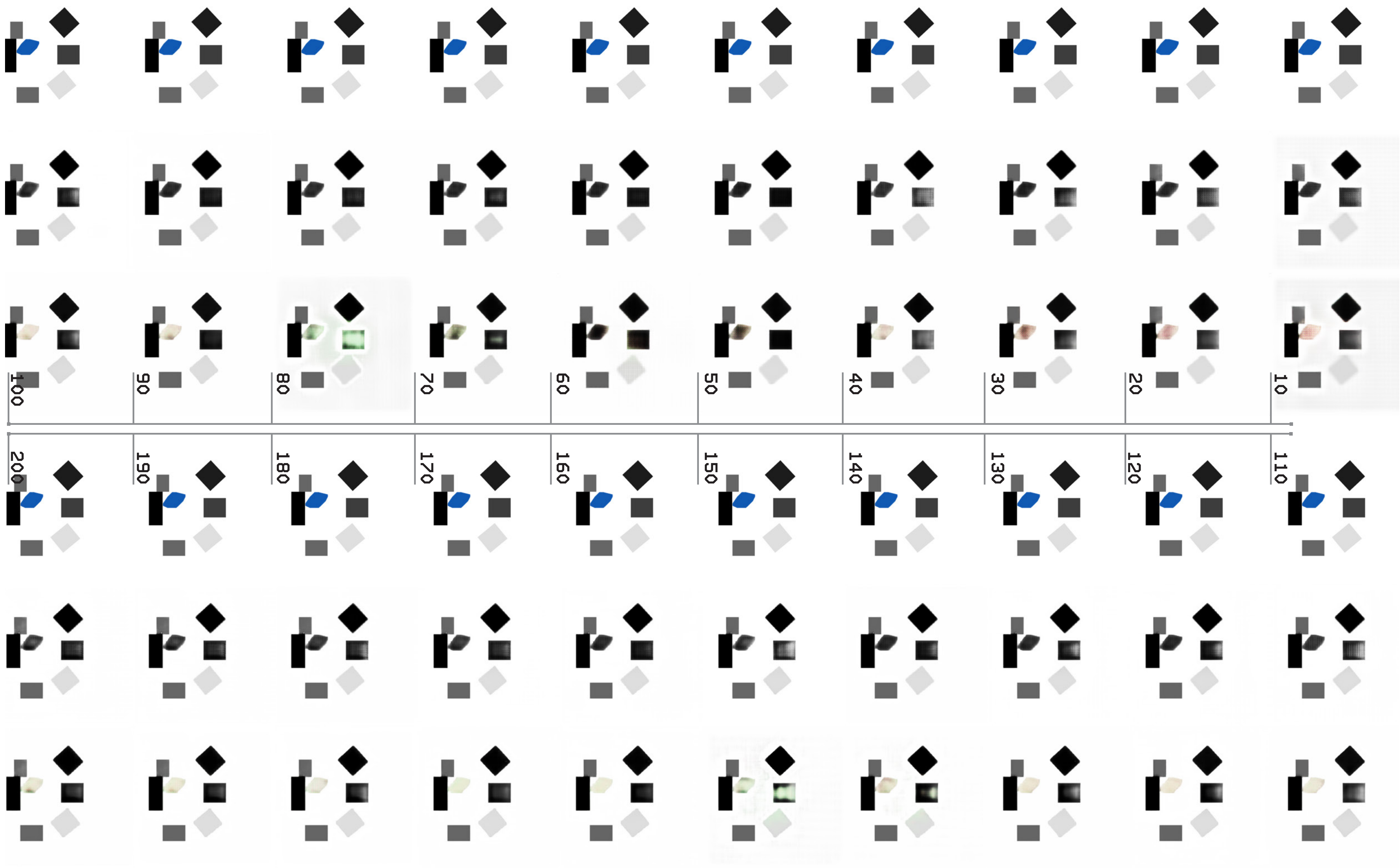

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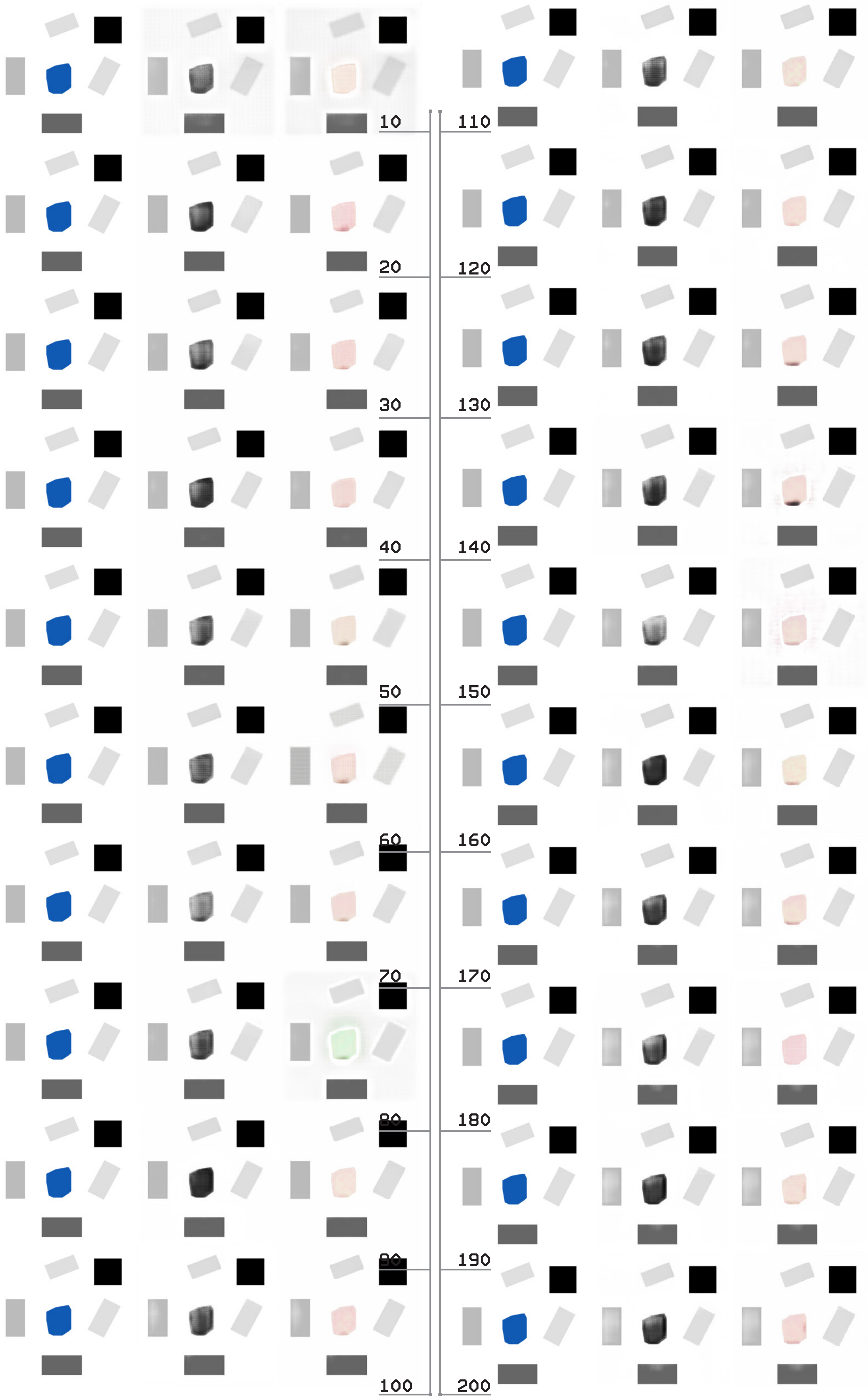

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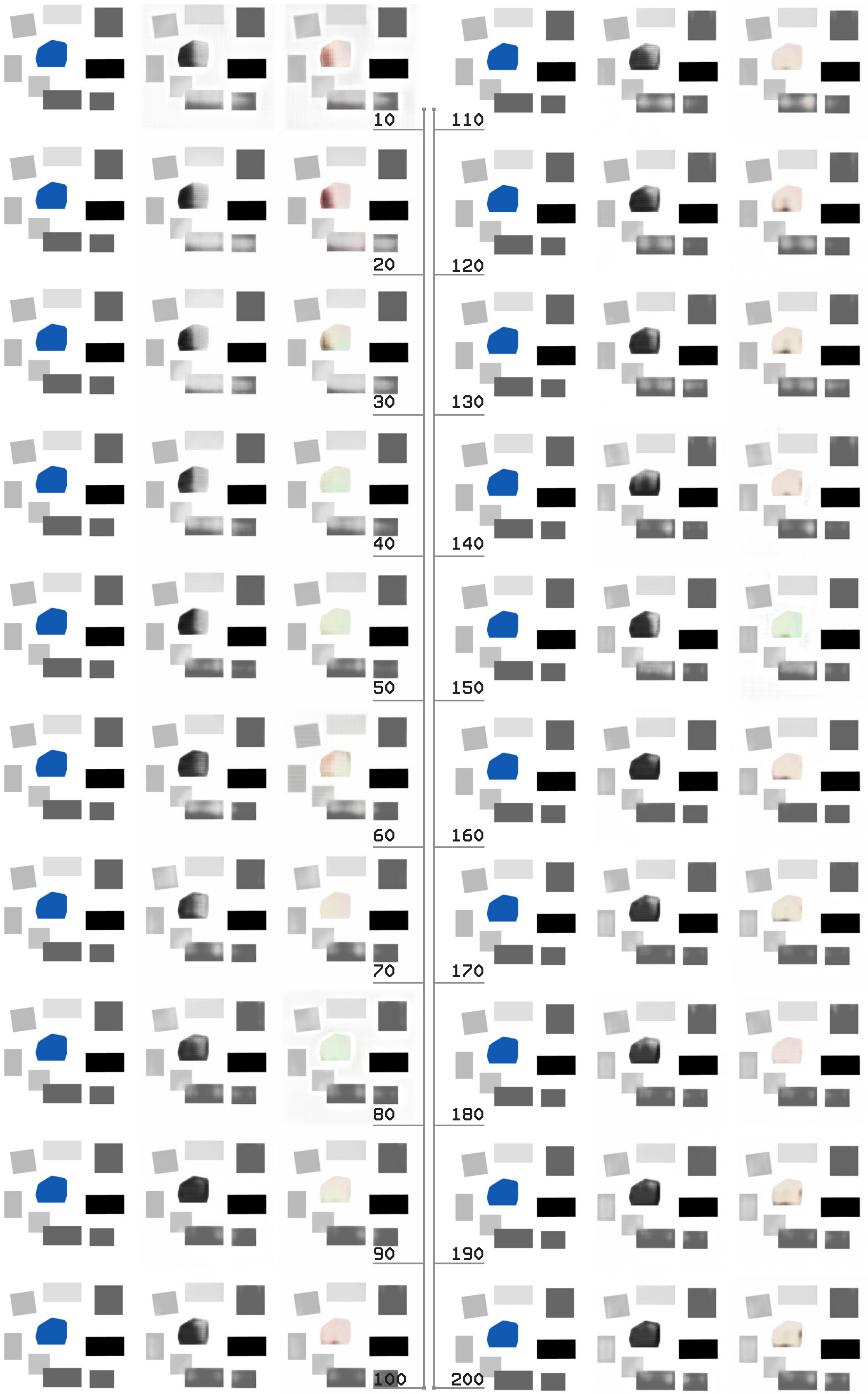
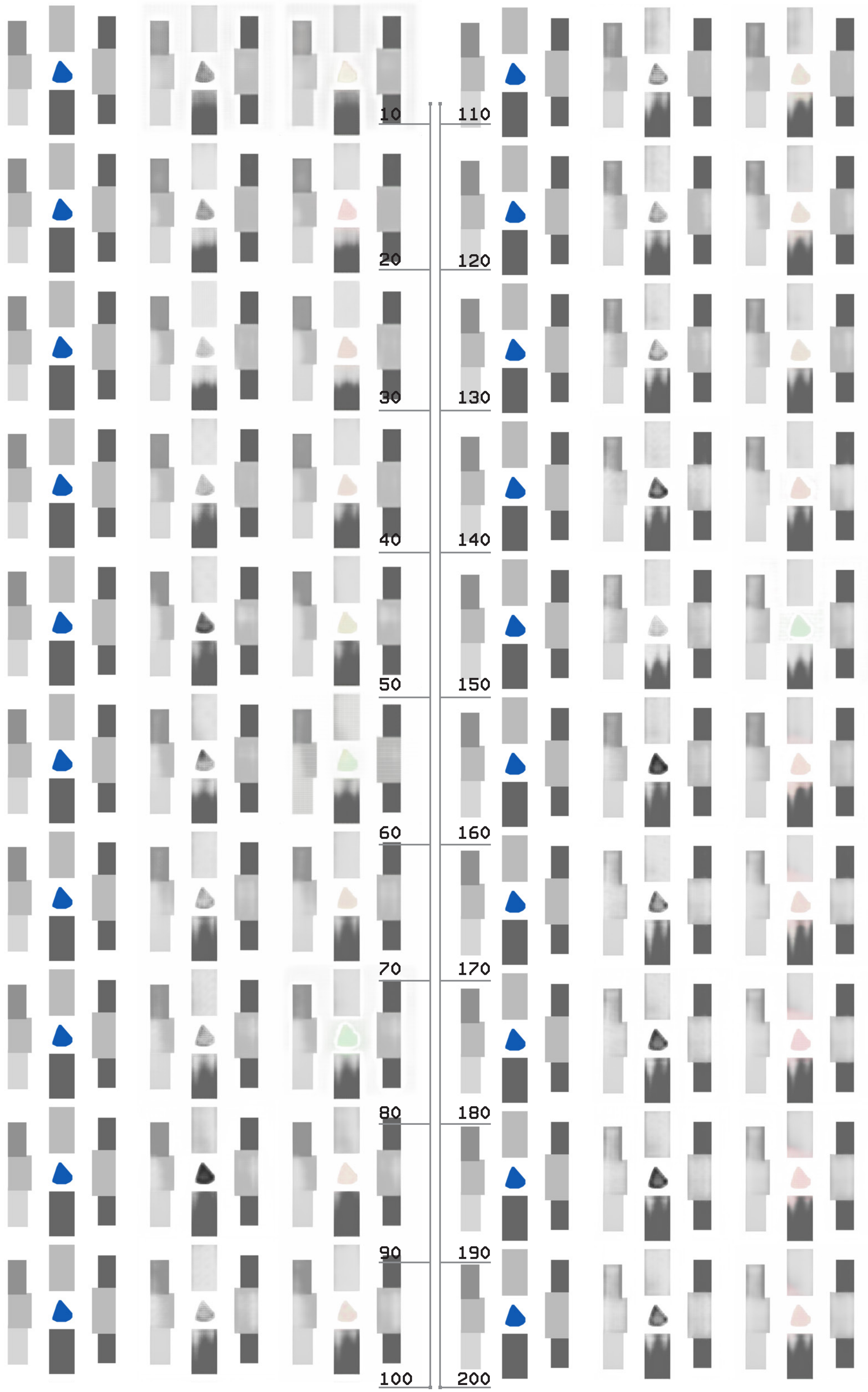
// model traing process, EPOCH 0-200, location 179





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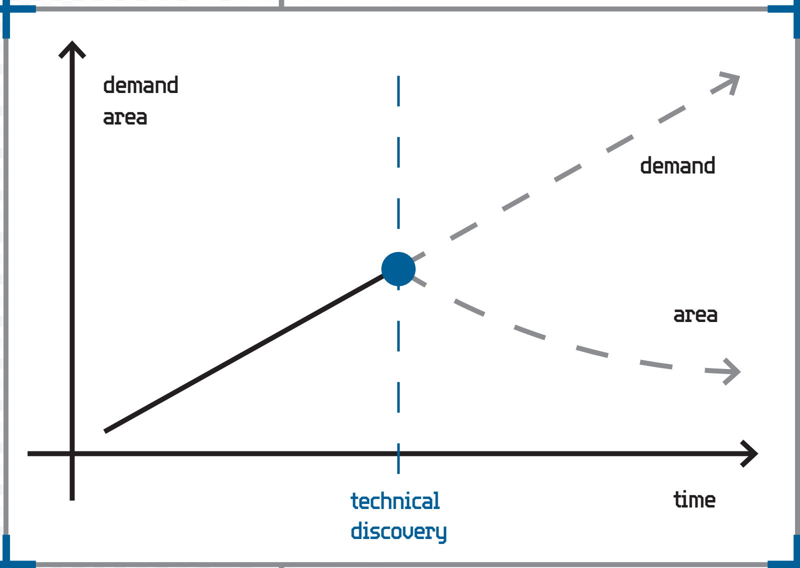
/ Data-driven A-TYPE problematics

The experiment results are presented through an app interface showcasing a case study on an urban data center (UDC) that incorporates algorithmic calculations and machine learning (ML) implementations previously discussed in the thesis. It also includes a structural representation of self-assembly architecture, which will be detailed in subsequent sections.



The APP explores how UDC architecture integrates ML and algorithmic methods in its design process, evolving into a data-driven A-type . The building's operational state hinges on queries related to spatial utilization, highlighting the dynamic nature of its function. Technological progress is relentless and accelerating, making it challenging to forecast long-term industry developments. A significant breakthrough could alter the expected trajectory of technological evolution. An illustrative example of such progress is evident in data storage technologies: We have transitioned from magnetic tapes with limited capacity to compact flash drives capable of storing terabytes of data.

The spatial configuration of the urban data center is intrinsically linked to technological advances, particularly in hardware. Predicting a revolution that might decrease the need for physical space required for data centers is difficult. Therefore, planning for an urban data center must consider two main variables: the steady increase in data center demand driven by widespread digitalization and the consequent growth in spatial requirements. These factors underscore the necessity for architecture that is both adaptable and flexible.[64]

In the context of architecture, analog and digital data are paralleled through traditional and contemporary building techniques. Like analog data, traditional architecture is characterized by a fixed and unchanging composition of parts, such as columns and beams rigidly adhering to a specific design that does not evolve once constructed. The conception of digital architecture with its dynamically changing spatial schemes finds inspiration in recent past projects such as:

The 'SEEK' project, a pivotal work by the Architecture Machine Group in 1970, stands as a compelling early instance of interactive and responsive architecture. It serves as a testament to the transformative journey of architecture from static

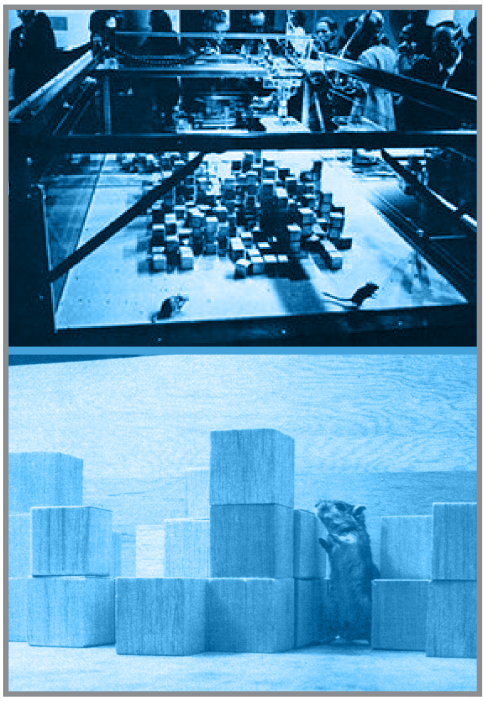


Figure 14.2, SEEK Project, MIT Architecture Machine Group

structures to dynamic environments that adapt in real-time to the needs and actions of their occupants. The project's unique approach, incorporating gerbils as inhabitants whose movements influenced the space's configuration by a robotic arm, underscores its innovative stance on user-responsive environments.

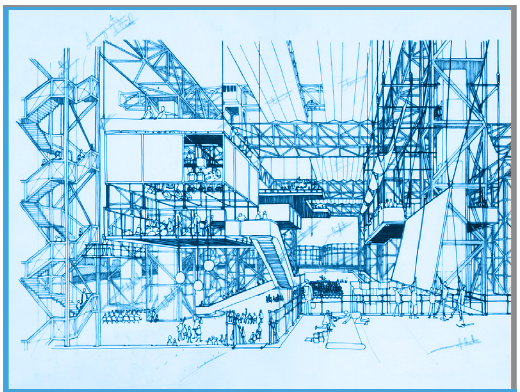


Figure 14.1, Generator, CedricPrice

Figure 14.1, The Universal Constructor, John Frazer

Another bright example of the development of dynamic architecture is Price's works, "Fun Palace," and "Generator," which encapsulates a vision where architecture is not merely a physical structure but a dynamic environment responsive to its inhabitants. By using modular components that could be reconfigured according to the needs of users, Price infused architecture with the ability to change and evolve over time. The incorporation of embedded computation within the structural elements, as seen in the "Generator" project, highlights a forward-thinking integration of technology and architecture. This concept of buildings as "anti-buildings" fundamentally redefines the user's interaction with space, making the architecture an active participant in the experience of those within it. Price's buildings were envisioned as frameworks that encourage continuous interaction and evolution, mirroring the fluid and ever-changing dynamics of human activities and technological advancements.

The collaborative project between John and Julia Frazer, focused on developing computational tools and interfaces for architectural design, foreshadowed certain aspects of contemporary digital design practices. Their work on embedded electronics and the creation of the 'Universal Constructor' project marked a significant departure from traditional design practices. This project's pioneering use of physical coding blocks—small cubic modules embedded with processors and sensors—illustrates a profound shift in design methodology. It moves away from the conventional separation of the conceptual design phase on a two-dimensional plane from the physical construction in three dimensions. The 'Universal Constructor' has emerged as a cornerstone for modern design techniques, using visual scripting languages in architectural software.[64]

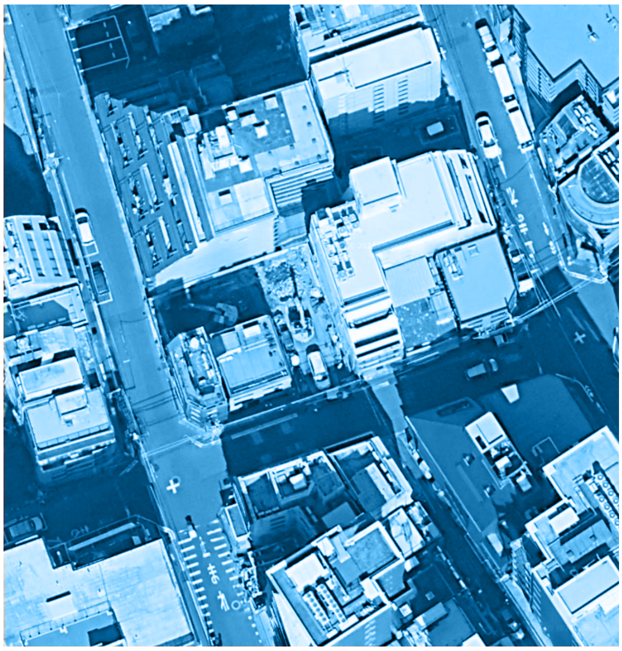
The above-mentioned projects have become an inspiration for the architectural representation of urban data centers, which uses a discrete computational design process and fabrication methods. The demand for a dynamically changing spatial organization of architecture leads to the use of self-assembly modules in the creation process. Characteristic features of self-assembly architecture are as follows:

Automated Construction: These components could autonomously organize and assemble into predetermined structures by embedding computational abilities into building materials.

// Site selection <<1

Tokio

search site loaction



Human processed input

Input transfer to AI

// Footprint and parameters <<2

>> sketch the building footprint

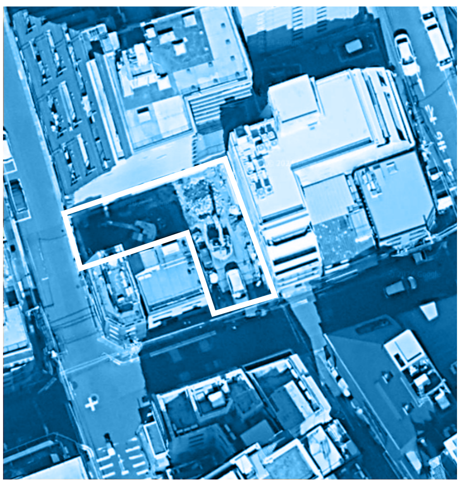
data center
urban farm

>> spatial ratio

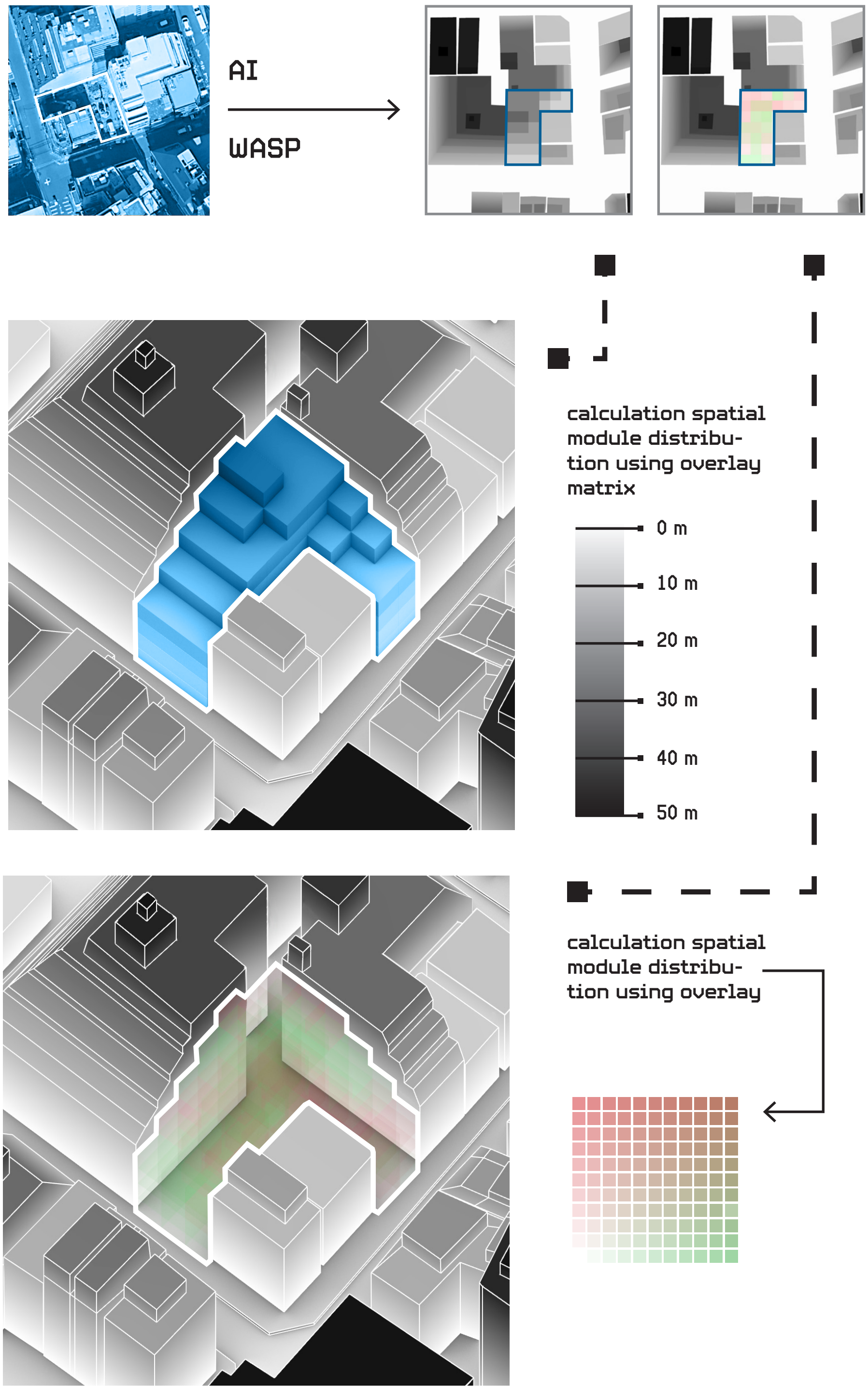
<< drag the slider to change the ratio

data center — urban farm

Pre-trained values

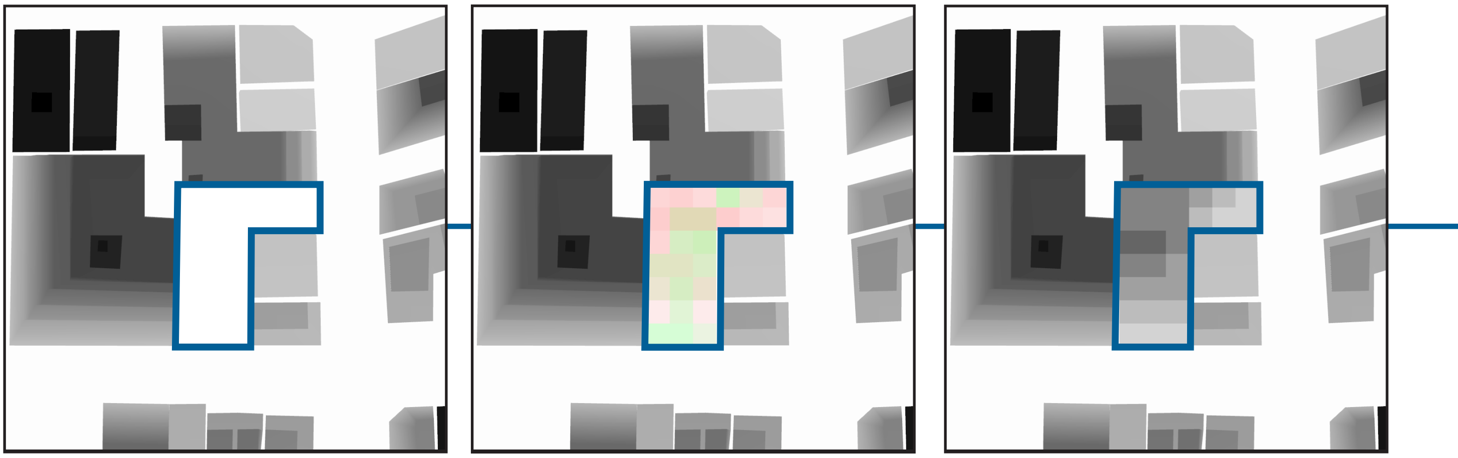


// Heightmap and structure



// WASP X AI output

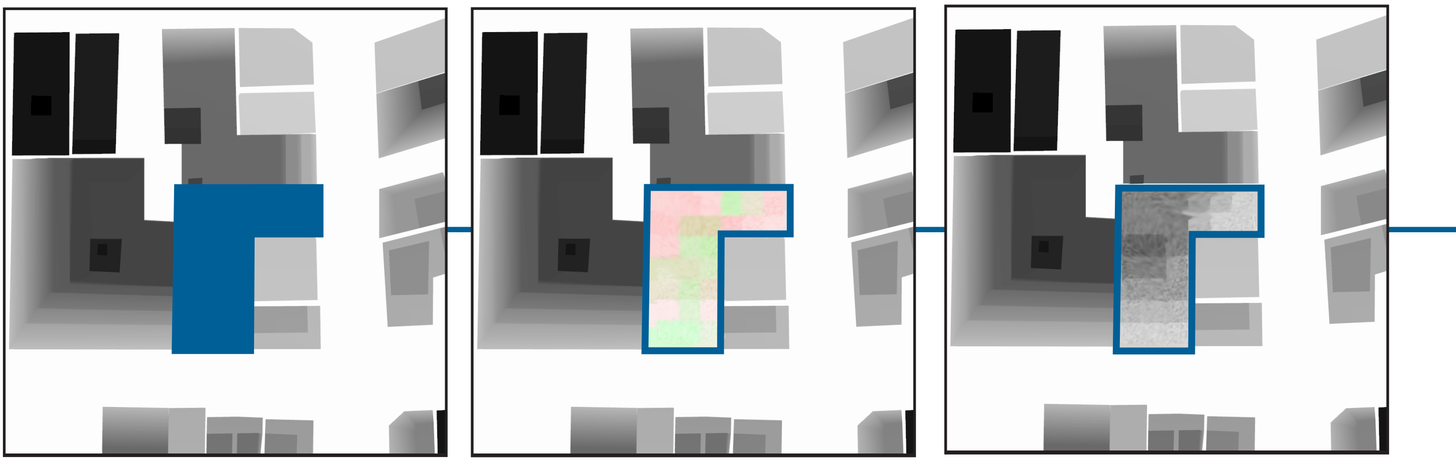
WASP output



The post-processed and optimized model of the Tokyo urban area selected for the experiment is imported as context for calculations and solar envelope.

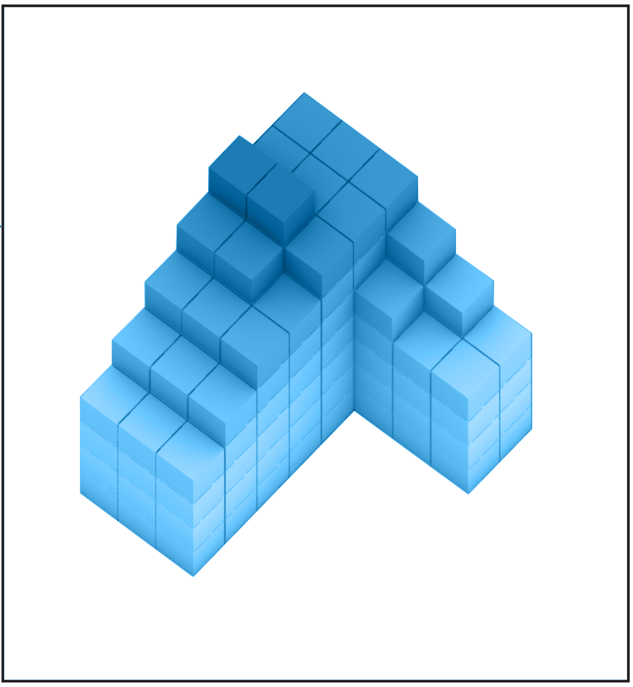
WASP aggregation processing and output extraction are in the form of 3D model representations of building mass and spatial structure organization.

AI output

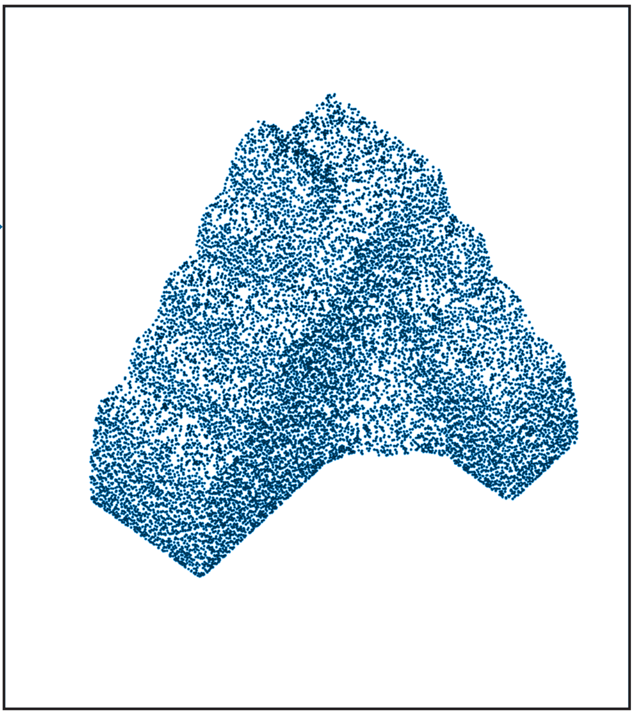


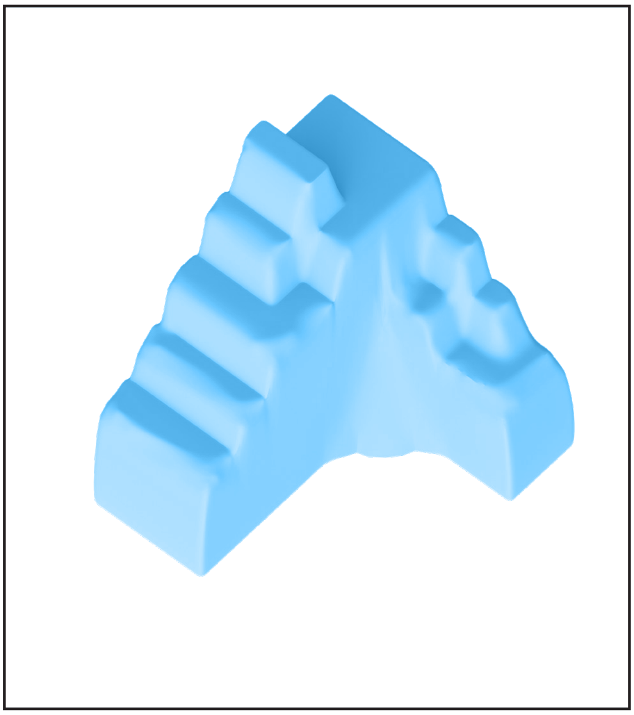
Users input a building footprint sketch, which can be done in any pixel-based graphic program, into a prepared map capture with defined building heights represented in a grayscale gradient based on the height .

AI-based output in the form of two-pixel images of the height map and the structure.



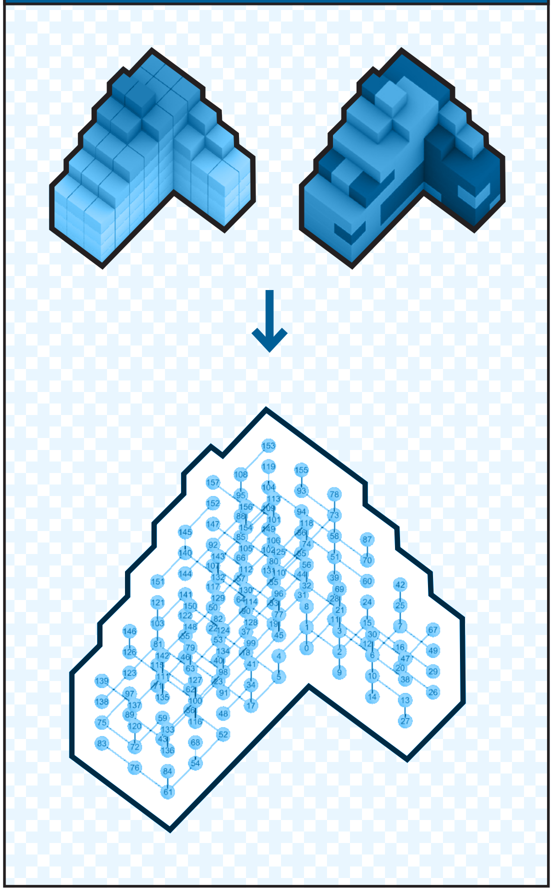
The process of structure generation based on WASP was described in the block devoted to data set creation. Now, let's describe the extraction of AI outputs and compare them with these outputs from WASP. To transfer 2D structure representation, I created a point cloud from an AI-generated height map using an open 3D library that worked in the following way: Firstly, it reads the height values encoded in the image. These height values are then transformed into a 3D point cloud by mapping each pixel's (x, y) coordinates and height value (z) into a three-dimensional space. The resulting point cloud is then post-processed using mesh generation in Rhino. There is a comparison of Point Cloud based on heightmap output from AI with structure output from WASP. As you can see, the volume represented with the point cloud closely approximates the the WASP output. The structural representation based on the overlaying matrix can represent that the overlaying matrix green and data modules correspond to the WASP output with a low margin of error. The WASP result will be used to prototype the UDC for the following iterations for more precise calculation and easier case study showcasing.



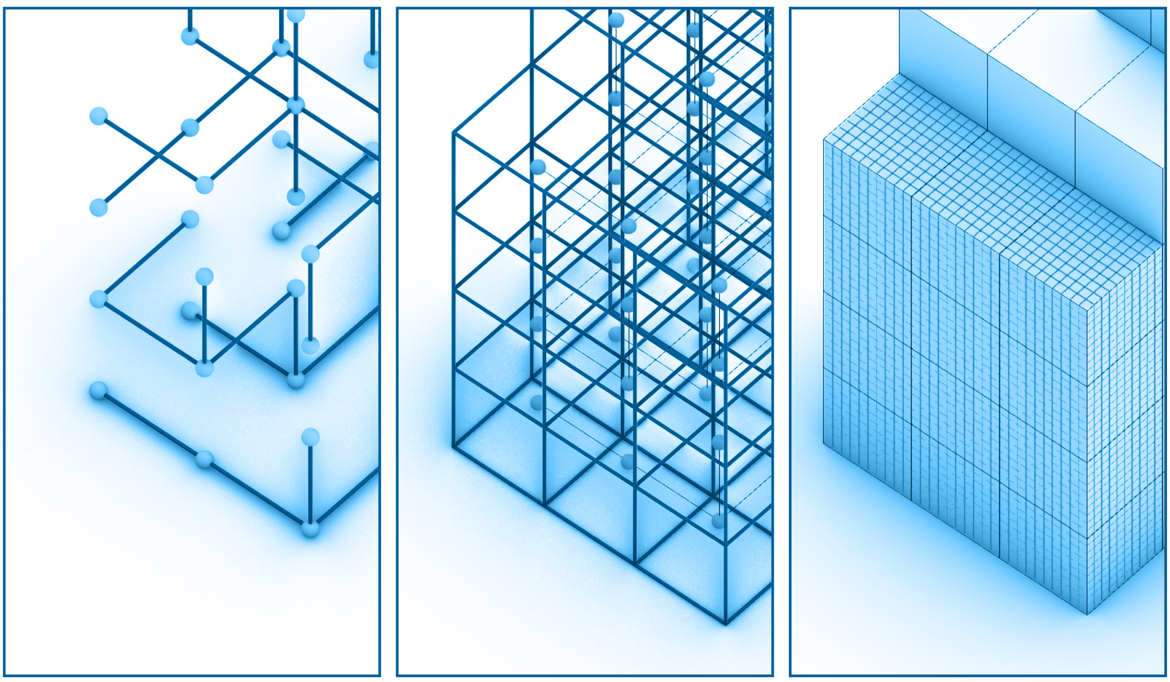


// Configuration theory

/ aggregation graph

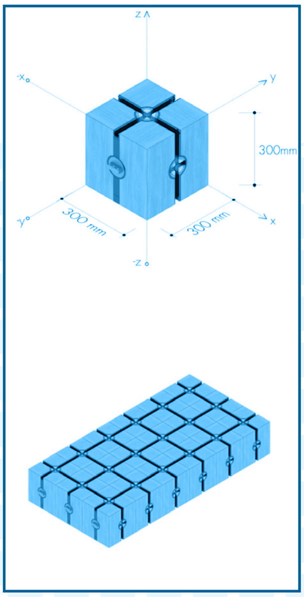


Regardless of how the spatial schemes of the UDC building are obtained, whether using trained ML or calculation from scratch using algorithms presented in the diploma section devoted to dataset generation, the assembly is based on discrete logic. The discrete nature of the assembly, divided into steps, each associated with a unique part, allowed for the creation of a state-based fabrication process. This approach identifies various states of the robotic system, enabling the integration of multiple assemblers, external sensing, actuation equipment, and human-machine collaboration. The state-based model maintains control of each element, allowing instruction modifications based on information from other assemblers. Combined with semi-automatic path planning, this model enhances flexibility and interaction during execution, blurring the line between design and fabrication. The structure is a graph with an exact start and several endpoints. This graph will serve as a guide for the robotic system used to achieve the programmable building result. Every node of the graph represents a type of unit: data unit or green unit. Each unit follows its discrete logic at the level of node space creation. The entire construction is represented as a robotic construction system following the assembly sequence.



+ graph → + unit → + voxel

/ Basic Robotic System



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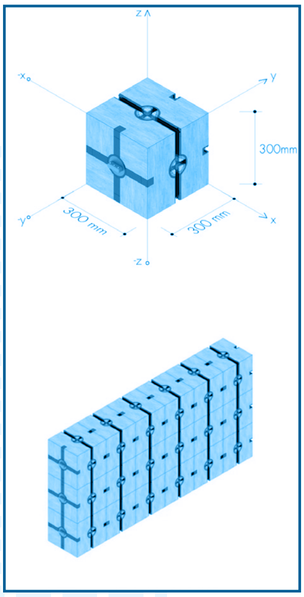

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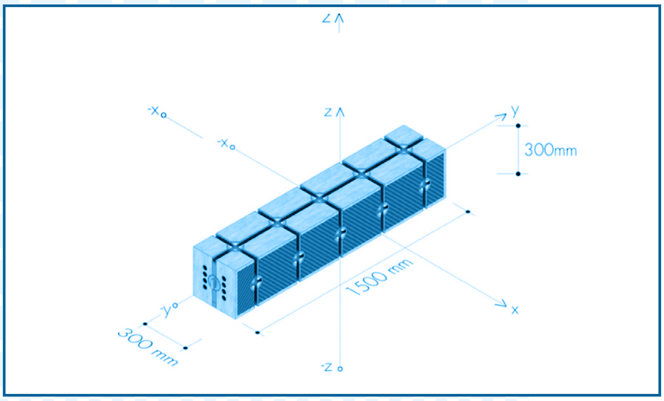

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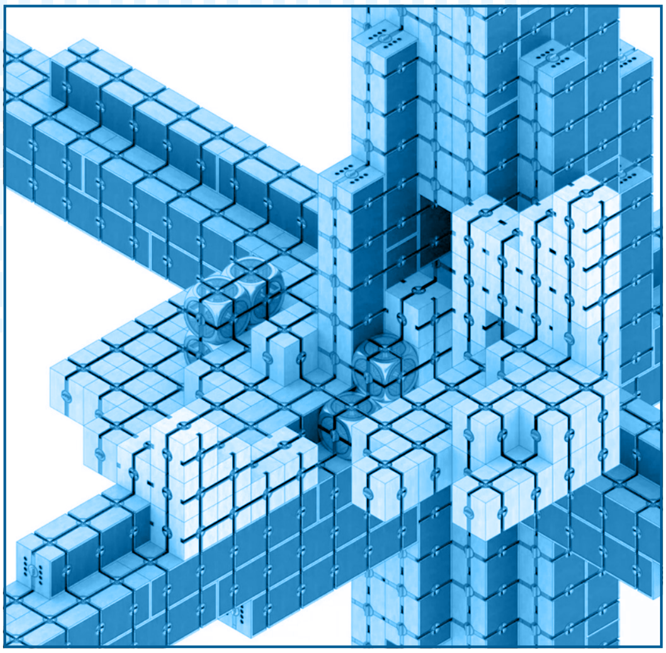
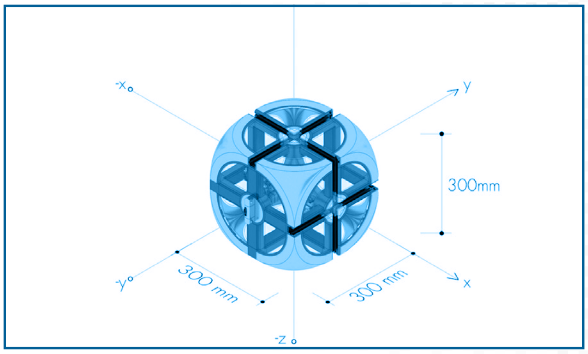


fig

The construction system for the following aggregation step was adapted from an existing robotic system created by iaqi Wang, Wanzhu Jiang, Ying Lin, Zongliang Yu and tailored to meet UDC project-specific needs. The construction system employed uses voxelized static components, which provide a minimum resolution, making it an ultimate discrete system with maximum variability. The vertical partitioning component is a cube with an edge length of 300 mm, equipped with a gear check in the positive direction of each axis and knobs in the negative. With the help of a vertical partitioning component and a particular robot constructor, The Annulata robot, which has an efficient sliding motion mode that does not require additional operating space and, in most cases, only needs to overcome rolling friction, can construct vertical constructions and move inside layers in X and Y directions. A vertical partitioning component uses to connect steel balls in the knob to clap the track, and the cross slot is used to change movement directions. The horizontal partitioning component has the same scale as the vertical, but the track direction is different, making it easy for the floor to flow up and down. The linkage of each side is also different. The slot on the ground is connected to knobs on two sides by bevel gears.

Additionally, larger-scale linear components are used for structural support when necessary. These components are much less active and only change quarterly or annually. They provide an integral part of the construction of water and power supply facilities that can be installed inside them, enhancing the overall functionality and efficiency of the system in a construction project.

Various materials and forms combine to create a versatile library that can adapt to different situations. The interchangeable panels can also be personalized with traditional materials to integrate seamlessly with the surrounding architecture.



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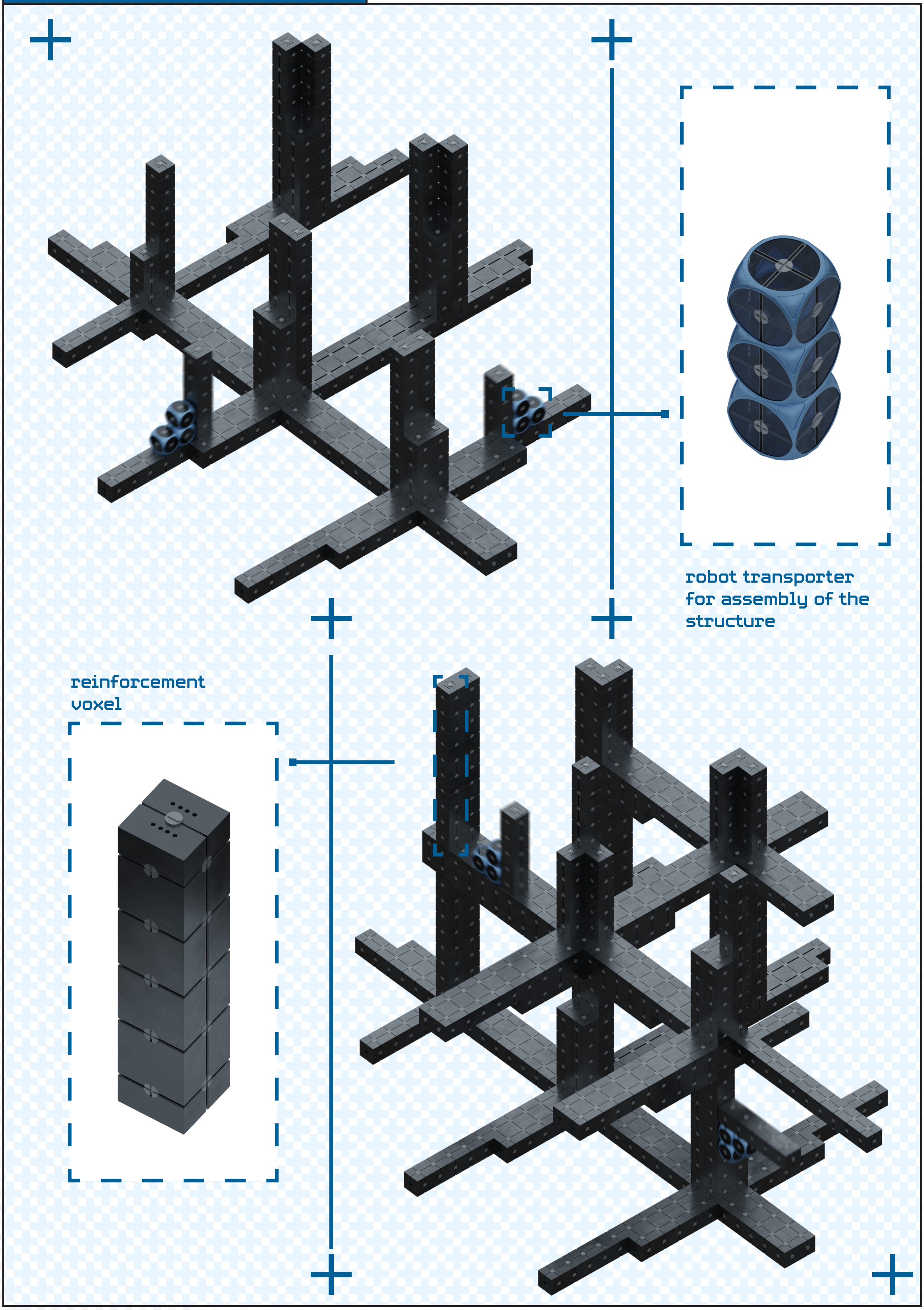
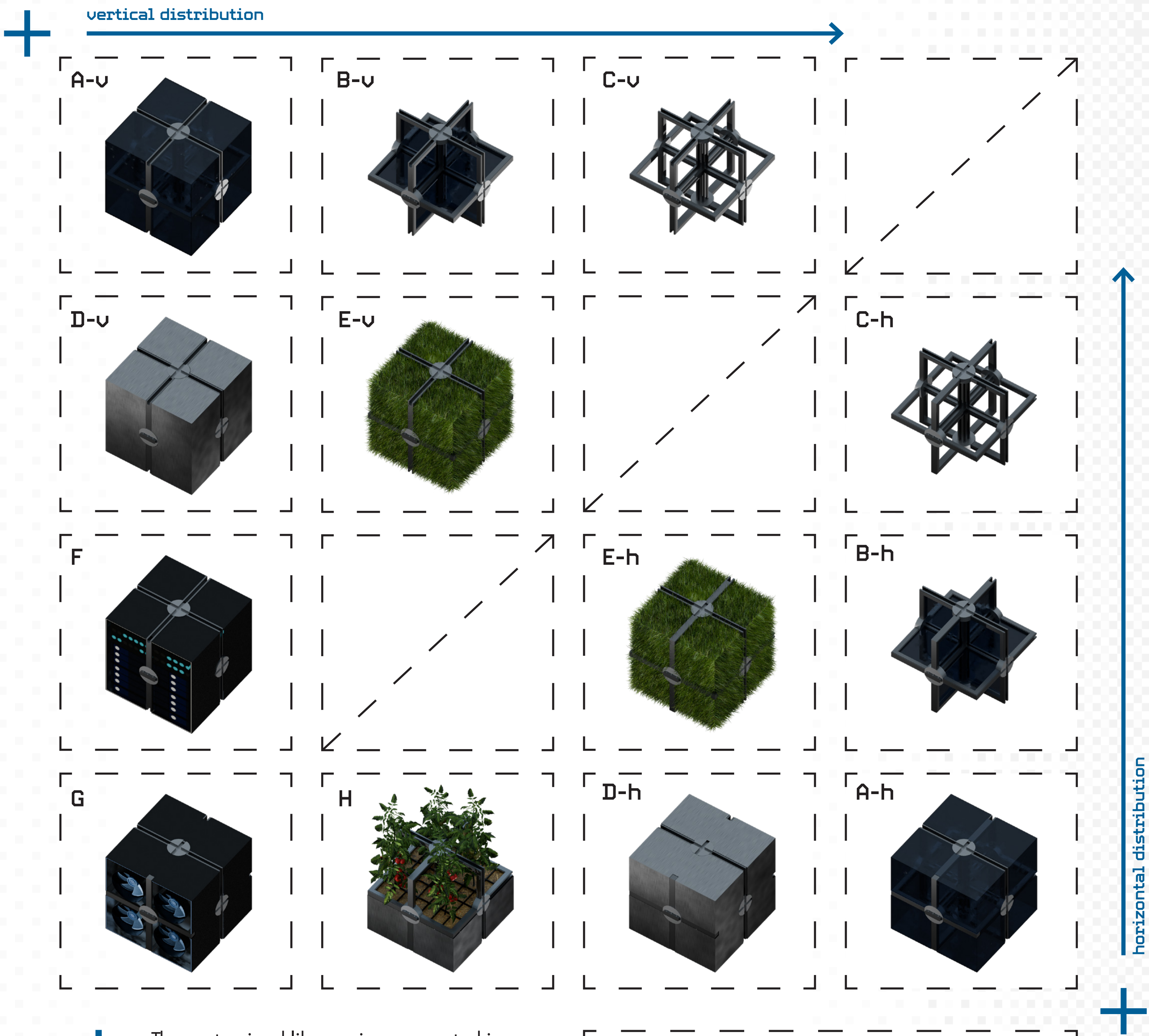
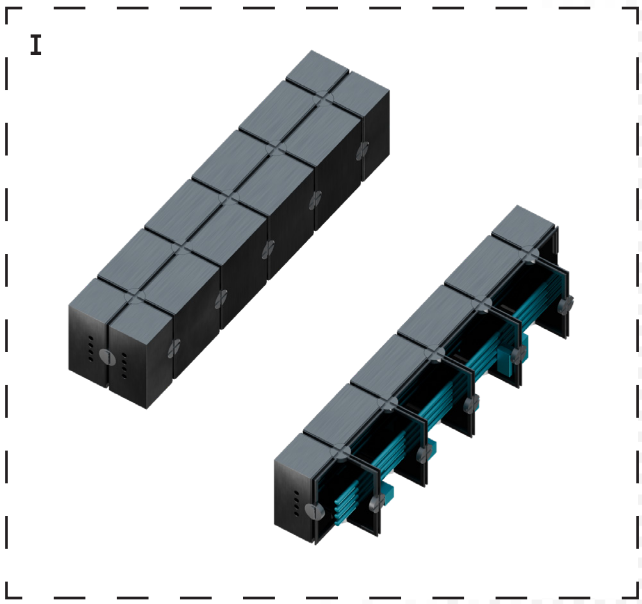
// Configuration practice

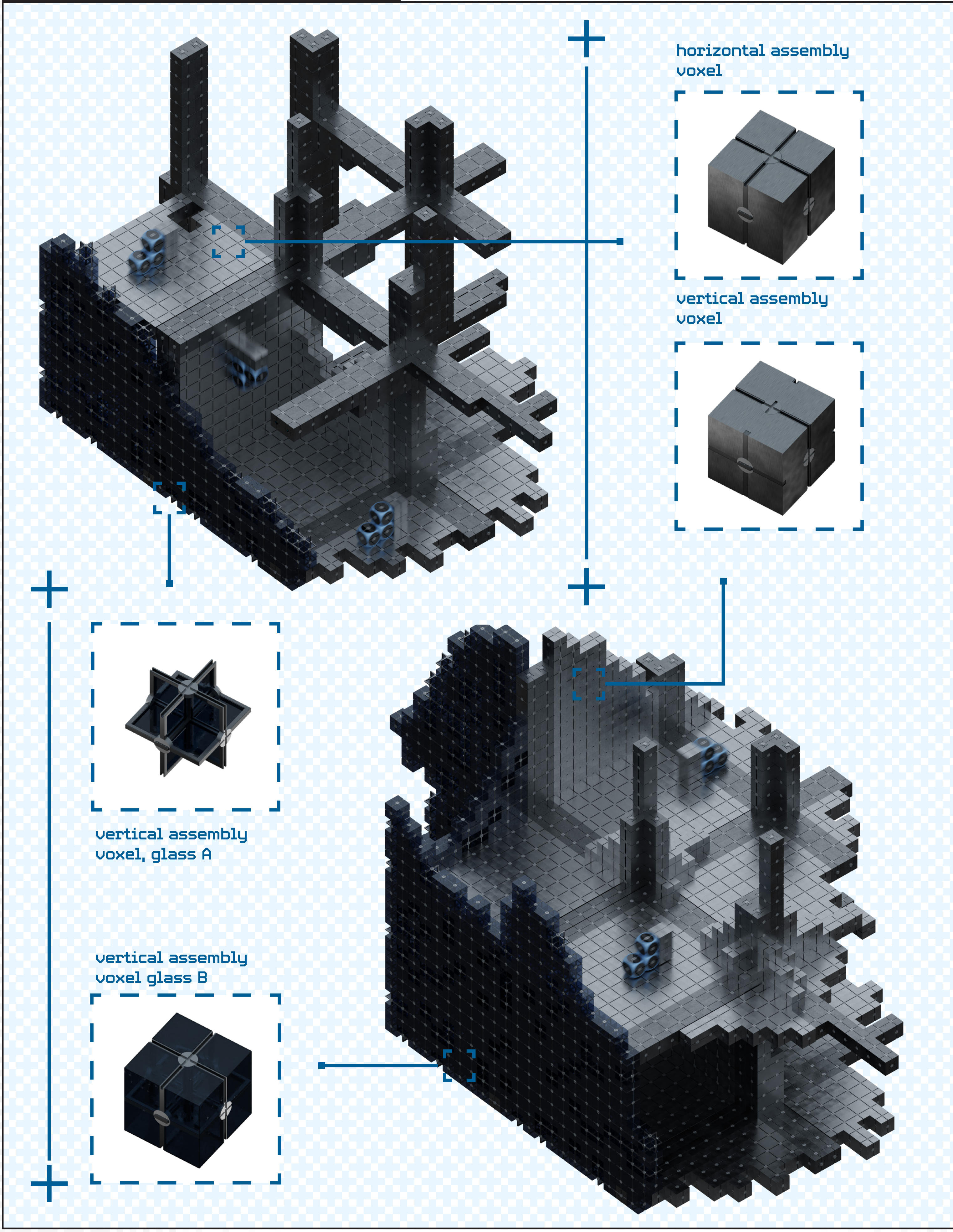


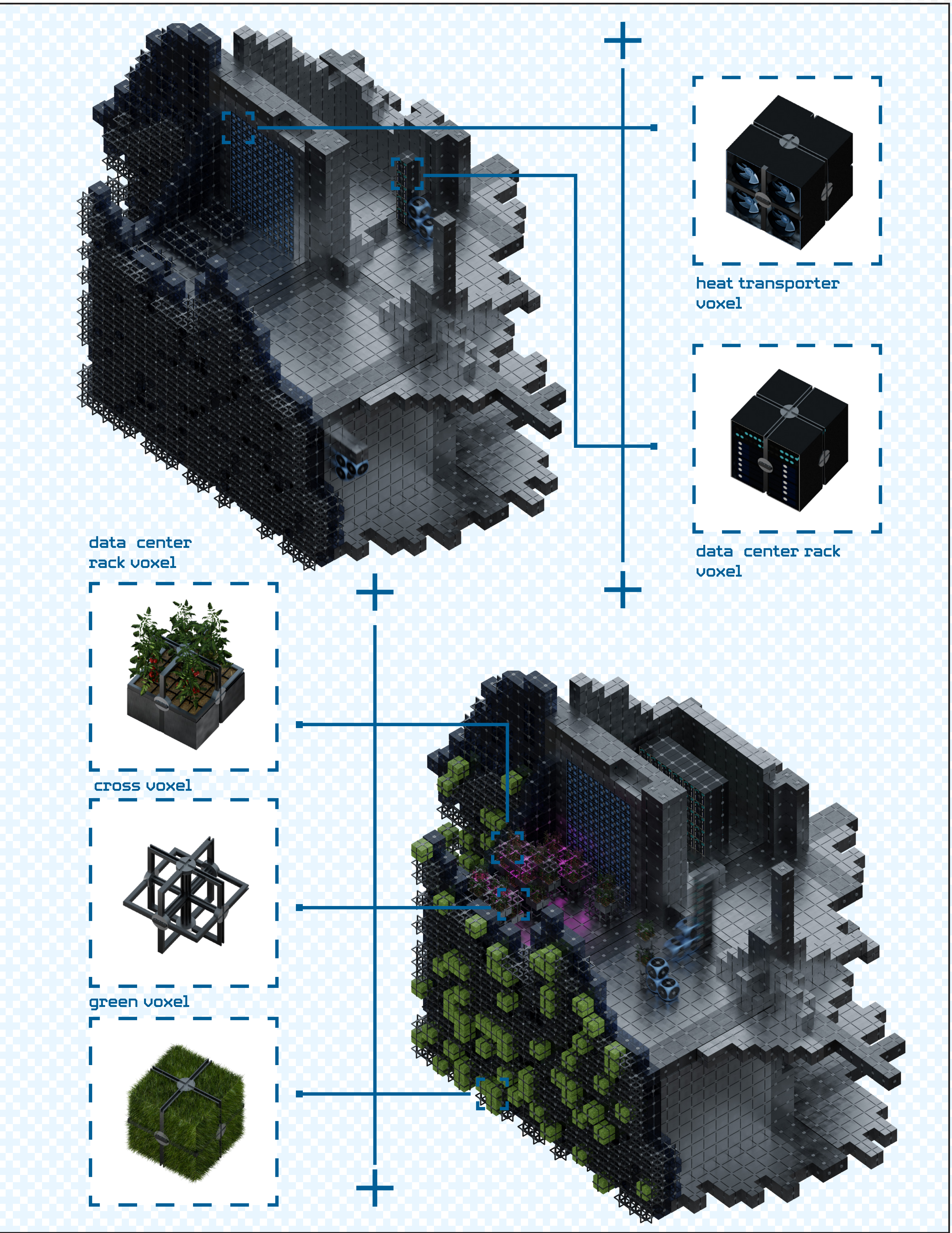


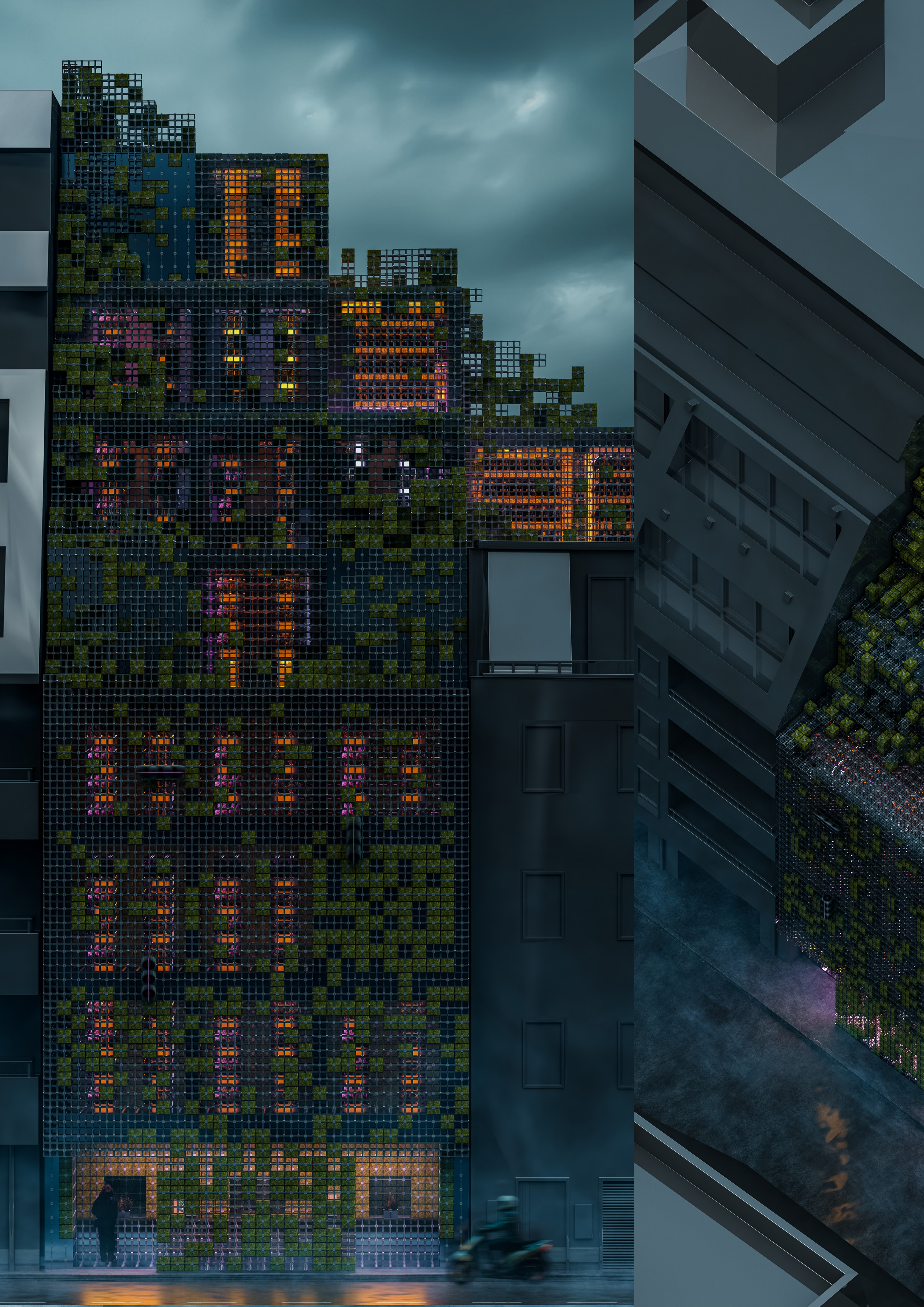
The customized library is represented in various voxels differentiated by functional or spatial usage. Voxels A-v, B-v, C-v, D-v, and E-v are designed for spatial aggregation of the structure in the vertical direction, while voxels A-h, B-h, C-h, D-h, and E-h serve for horizontal assembly. Voxel F represents the data center hardware system. Voxel H is designed for urban farm systems. Voxel G serves as an air transportation unit from the data center to the greenhouse or as a heat-accumulating device for further distribution. Voxel I is a complex unit that functions as the main reinforcing unit of the construction, with integrated pipes for electricity and water distribution.

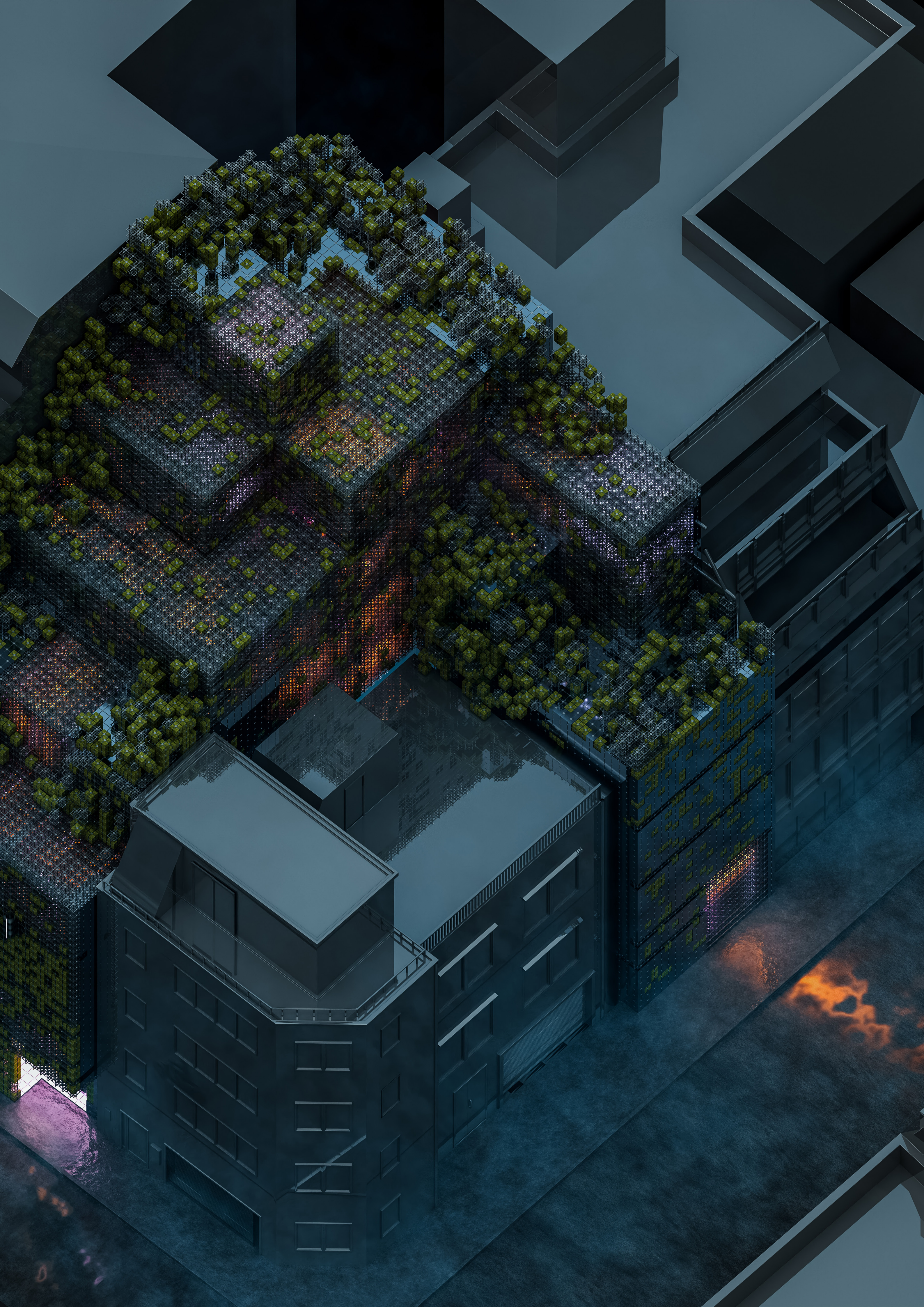


// Configuration practice




heat transporter voxel
data center rack voxel
data center rack voxel
cross voxel
green voxel





// CONCLUSION

The exploration of urban data centers (UDCs) in this thesis has led to developing a new architectural typology, the Data-Driven A-Type. This concept embodies the intersection of advanced computational methods, sustainable design principles, and the practical application of machine learning (ML) in architecture. Integrating artificial intelligence into the design and implementation of UDCs marks a significant shift towards more efficient, adaptable, and sustainable urban infrastructure.

The methodology employed in this research was multifaceted, combining dataset creation, ML implementation, and a comparative analysis of AI-generated outputs with traditional algorithmic calculations. Utilizing the Grasshopper plugin for Rhino, diverse urban structures were generated, reflecting the complexities of cities such as London, Paris, and New York. The Solar Envelope concept and EnergyPlus Weather files further enriched this dataset, providing a robust foundation for subsequent analysis and model training.

The application of sequential pix2pix models, a Generative Adversarial Network (GAN) type, was pivotal in this research. These models were fine-tuned and trained to develop a bespoke tool capable of processing architectural footprints into height maps and structural representations. This dual-model approach exemplifies the practical integration of ML into architectural design, enhancing both innovation and efficiency and transferring architectural paradigm from programmed understanding when the building has unchangeable conditions during the whole life cycle but gains a programmable ability that allows being changeable during the time on the demand of the environment.

A notable application of the trained models was demonstrated through a case study, which showcased the design of an integrated urban data center and urban farm. This case study highlighted the benefits of the proposed methodology, including efficient heat reuse, reduced latency, improved connectivity, and accessibility to urban markets. The integration of UDCs with urban farms not only maximizes resource efficiency but also promotes sustainable urban development.

The evolution of UDCs as central elements of intelligent cities underscores their growing importance in managing and processing the vast amounts of data required for modern urban operations. Traditional large, remote data centers are becoming obsolete due to latency issues and the demand for real-time data processing. Instead, decentralized and integrated data center models are emerging, capable of supporting the immediate needs of urban environments.

The Data-Driven A-Type concept sets a new benchmark for architectural and urban integration in the digital age. By leveraging extensive data analysis and AI, this approach ensures that UDCs are functional, efficient, sustainable, and adaptable to future requirements. The research conducted in this thesis contributes significantly to the field of architecture, offering innovative solutions to contemporary urban challenges.

In conclusion, the Data-Driven A-Type concept represents a paradigm shift in the design and implementation of urban data centers. By integrating advanced computational methods, sustainable design principles, and the practical application of AI, this research provides a comprehensive framework for further developing cooperation between architectural disciplines and artificial intelligence.

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