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# SPATIAL AUTONOMY: Exploring Industry 4.0/5.0 Trends on Architectural Design

Diana Salamaga

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## EXPLORING INDUSTRY 4.0 TRENDS ON ARCHITECTURAL DESIGN

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## Exploring Industry 4.0/5.0 Trends on Architectural Design

Thesis Research Project Book is Presented
to:

***Jade Yang***
***Razvan Voicu***

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by

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# ABSTRACT

*The rise of Industry 4.0 and 5.0 presents significant opportunities for the architecture industry to incorporate advanced technologies into its design and construction processes. However, the full potential of these technologies in architectural design has yet to be fully explored. This thesis, titled 'Spatial Autonomy: Exploring Industry 4.0 and 5.0 Trends in Architectural Design,' aims to investigate the ability of buildings to function autonomously through the integration of smart technologies. This exploration focuses on how Industry 4.0 and 5.0 trends can optimize building performance, creating more comfortable and enjoyable experiences for users, while also enhancing efficiency and sustainability. It examines the emerging questions: How to design in response to these technologies? What constitutes a design framework for integrating Industry 4.0 and 5.0 into architectural design, and how can this framework be applied to future projects?*

*As digital, cloud, and AI computing demands increase globally, current data centers, which contribute to 0.3% of global CO2 emissions, are primarily designed to meet existing demands rather than anticipating and creating a more balanced relationship between demand and environmental sustainability. This thesis challenges this norm by proposing the design of a data center integrated within a mixed-use complex that adheres to the principles of Industry 5.0, emphasizing environmental and social health. This approach advocates for the integration of systems at the onset of the design process, proposing that early incorporation can significantly enhance the benefits of these advanced technologies. The research seeks to redefine the data center not just as a static structure but as a dynamic, responsive, and sustainable architectural form that functions as a closed feedback loop with its urban environment, dynamically interacting with and adapting to its human and ecological context.*

*In conclusion, 'Spatial Autonomy' not only explores but also aims to redefine the process of designing in the digital age, setting a precedent for a more harmonious integration of cutting-edge technologies into architectural design. This thesis illustrates the potential for buildings to be not merely static structures but dynamic environments that intelligently respond to user needs and contribute actively to environmental sustainability.*

# RESEARCH OBJECTIVES

- ***To explore and define the integration of smart technologies within the architectural design process, enhancing building autonomy and user interaction.***

- ***To develop a speculative design for a data center that functions as a dynamic, responsive, and sustainable part of a mixed-use complex and as integrated component of urban infrastructure. The design uses advanced IoT technologies and the principles of Industry 4.0 and 5.0 to enhance operational efficiency and interconnectivity.***

# KEY WORDS AND LITERATURE FINDINGS

## HUMAN-CENTRIC DESIGN

Industry 5.0 emphasizes human-centric design, aiming to enhance user comfort and accessibility within technological advancements. This principle, as outlined by the European Commission (2021), shows the transition from shareholder to stakeholder value in industry, placing the wellbeing of the individual at the center of production processes. Incorporating human-centric design principles into the architectural framework of a data center within a mixed-use complex ensures that the facility is not just a hub of technological activity but also a space that enhances the daily experiences of its users and not only meets functional requirements. This approach encourages **the creation of spaces that are dynamically responsive and adaptive to humans**, thereby showing the essence of Industry 5.0 within an architectural context (Alves, 2021).

## AUTONOMOUS BUILDING

An autonomous building is one that uses a variety of technologies, including sensors and actuators, to collect activity data on various building-related features so that it can be evaluated and used to determine which processes can operate more effectively. Once the operations that need to be improved are identified, the smart building technology links systems together to optimize them through automation to make the building more efficient, decreasing expenses and reducing its environmental effect. While technology **optimizes** a smart building, the same technology may also be utilized to enhance occupant conditions to promote their safety, comfort, and productivity. Therefore, smart buildings put an emphasis on three key features: lowering the expense of building operation cost, improvement of building users' wellbeing, pleasure, and health, and reducing the impact of buildings on the environment. Building Automation System is each smart building's primary component (BAS). It manages mechanical and electrical components of the building, including the ventilation, lighting, electricity, and security systems. **These subsystems function independently and have minimal connectivity in conventional buildings.** Information technology is used in smart buildings to connect a range of subsystems so that they may share information and improve overall building efficiency. Autonomous buildings are an improved version of intelligent buildings that offer wider integration with utilities and city infrastructure and may use sophisticated algorithms like machine learning or AI for advanced control and diagnostics. The Internet of Things (IoT) is used in conjunction with smart buildings, and a larger variety of equipment, such as consumer electronics, mobile devices, and multimedia, are utilized. Main components of smart building technologies are IoT, connectivity, cloud, analytics, and integration. They offer a range of advantages in comparison with conventional building systems, such as opportunities for automation, motion-activated lighting, occupancy sensors on the floor, beacons to monitor workspace usage, etc.

## FLEXIBLE SPACES

Integrating flexible spaces within IoT building systems significantly enhances building functionality and adaptability. These flexible spaces, characterized by movable walls and modular components, seamlessly align with IoT technology, which allows for real-time adjustments to the **space configurations based on user needs and environmental data**. IoT systems can dynamically manage resources such as lighting, HVAC, and security in response to these changes, optimizing energy use and improving user comfort (Fernández, Zalba, & Casas, 2023). This synergy between flexible design and IoT not only supports sustainable building practices by minimizing energy consumption but also enhances space utilization, ensuring that buildings can adapt to different functional needs without requiring extensive physical modifications.

## DATA CENTERS CHALLENGES

Data centers face significant challenges regarding energy consumption and sustainability. They are responsible for approximately 1% of global energy-related greenhouse gas (GHG) emissions and consume a significant amount of the world's electricity. Innovations in IoT and AI are critical in addressing these issues by **enhancing energy management and operational efficiency**. One major aspect of sustainable data center operation involves optimizing power distribution and utilizing advanced cooling techniques. These strategies not only reduce the environmental impact but also lower operating costs. For example, it's estimated that data centers connected to electricity grids with a lower share of generation based on fossil fuels produce fewer associated emissions, highlighting the importance of renewable energy sources (IEA, 2023). Moreover, the rapid growth in data center energy demands, particularly from large and hyperscale centers, has been substantial, though slightly offset by strong efficiency improvements. For example, data center energy use, not taking into account cryptocurrency mining, grew moderately from 240-340 TWh in 2022, representing about 1-1.3% of global final electricity demand (IEA, 2023).

## IOT-ENABLED KINETIC FACADES

Kinetic facades, when integrated with IoT technologies, provide a dynamic solution to optimize building energy efficiency by adapting to environmental conditions such as sunlight and temperature. These systems use movable shading elements that adjust in real-time to enhance indoor environmental quality and reduce energy consumption, which could greatly benefit data centers where energy management is crucial (Kim et al., 2024). The integration of IoT enables **real-time data collection and automated adjustments** of the facade elements, optimizing incoming natural light and minimizing heat gains. This intelligent adaptation not only improves the comfort levels within the building but also significantly cuts down on the energy required for heating, cooling, and artificial lighting. Research shows that such systems can lead to substantial energy savings and even exceed certain sustainability standards like LEED, by ensuring optimal lighting and thermal conditions (Kim et al., 2024).

**Smart Building Automation:** Buildings is equipped with sensors, cameras, and automation systems that can detect and adjust lighting, temperature, and other environmental factors, resulting in energy savings and improved occupant comfort.

**Personalized Services:** Personalized services such as concierge services, package delivery, and food delivery enhance the convenience and comfort.

**Mobility Services:** Mobility services such as car sharing, bike sharing, and electric vehicle charging stations enhance accessibility and reduce the need for private vehicle ownership.

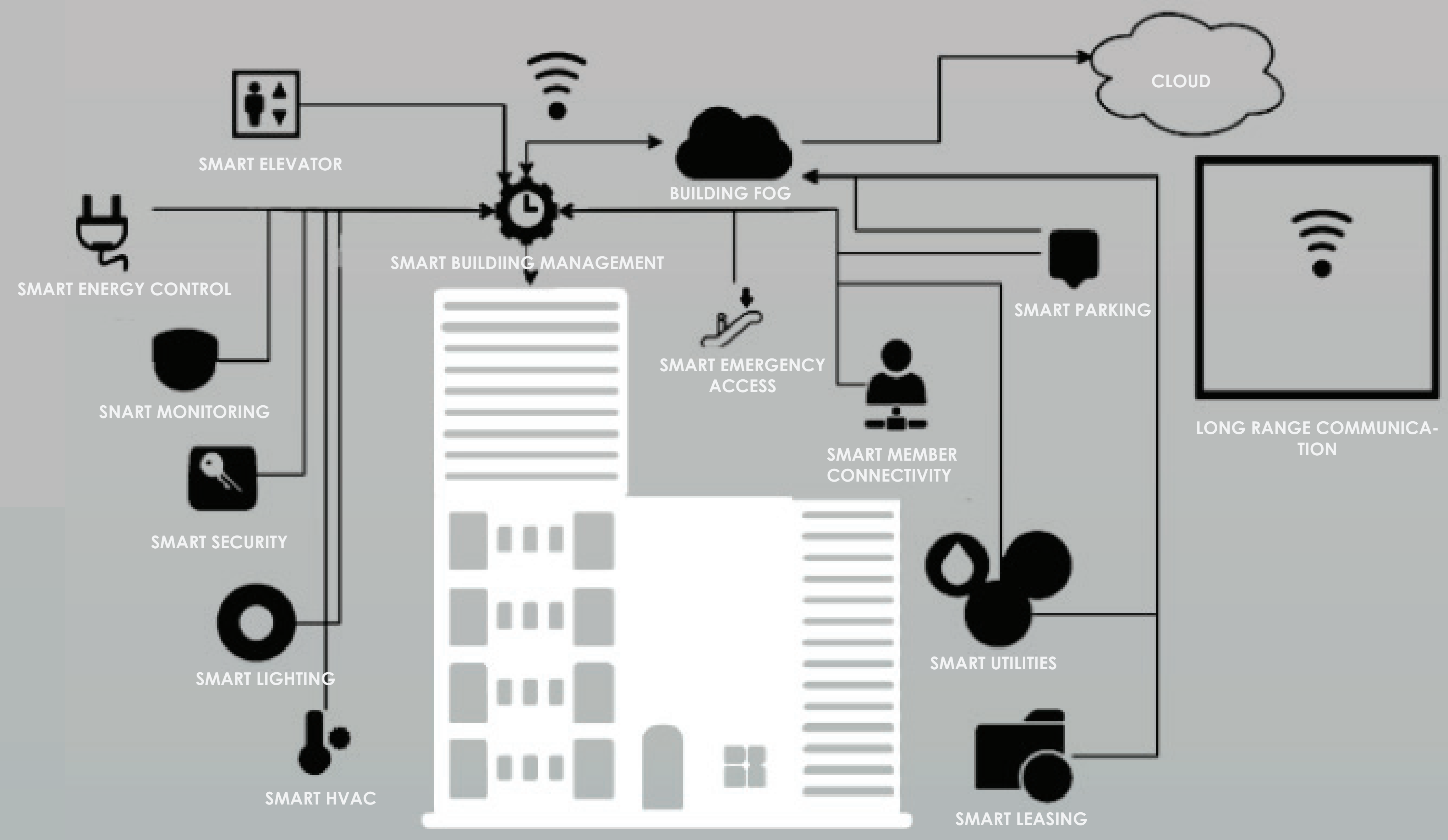
**Building Management Systems (BMS):** BMS monitors and controls various building systems, such as heating, ventilation, and air conditioning (HVAC), lighting, and security, from a central location, allowing for more efficient operation and maintenance.

**Cloud Computing and Big Data Analytics:** Cloud computing and big data analytics is used to analyze building performance data, optimize building systems, and improve energy efficiency.

**Collaborative Workspaces:** Collaborative space incorporate flexible furniture and advanced communication technologies that enhance collaboration and productivity.

**Mixed-Use Spaces:** Mixed-use spaces that combine commercial, residential, and recreational activities create vibrant communities and reduce the need for long commutes.

**Augmented Reality (AR) and Virtual Reality (VR) Features:** AR and VR are used to provide interactive experiences for visitors and tenants, such as virtual tours, interactive maps, and other immersive experiences.




SMART BUILDING IOT

## INTEGRATING INTO SMART CITY GRIDS

Integrating data centers into smart city grids with IoT technologies offers substantial benefits, particularly in optimizing energy management and operational efficiency across urban environments. Data centers equipped with IoT can actively **interact with smart grids to manage energy loads more dynamically.** This interaction allows for real-time energy optimization, using IoT for enhanced communication between the data center and the energy grid, which can lead to significant improvements in energy efficiency and reduction in operational costs. For example, IoT enables real-time data collection and processing, allowing data centers to adjust their energy consumption based on immediate energy supply and demand conditions within the smart grid. This can include reducing power usage during peak grid loads to alleviate grid stress or increasing it when excess renewable energy is available, as a result contributing to a more balanced and resilient urban energy infrastructure. Furthermore, this integration supports the **broader goals of smart cities** by enhancing sustainability using improved resource management and reduced environmental impact. The use of IoT in smart cities, including data centers, involves complex systems where various technologies are integrated to manage and optimize infrastructure and services efficiently, including the use of advanced data analytics to predict and respond to city-wide energy needs effectively.

# CHAPTER II

- Precedent Analysis
- Project within an initiative “Mariupol Reborn”

  Viktor Zotov’s Vision
- Selected Site and Program Analysis

*PRECEDENT 1*

## The Spark (Lyseparken, Os, Norway)

**Relevance**

Shows the transition from energy-consuming infrastructures to energy-producing resources within urban settings. It's designed to transform high energy-consuming data centers into structures that can supply energy back to the community, effectively making cities more self-sustaining, which aligns with the thesis's focus. (ArchDaily) (Snøhetta).

**Space**

The data center utilizes its architectural layout to optimize both its core functional roles and its interaction with the surrounding community. It is designed to efficiently manage the flow of energy and data while ensuring the space remains adaptable to future technological and functional requirements (Snøhetta).

**Usage/Program**

Beyond its primary function as a data center, "The Spark" is intended to serve as a communal energy source. Its design incorporates the capability to redistribute generated excess heat to nearby buildings, contributing to the heating of homes, schools, and other facilities. This not only optimizes energy use but also embeds the structure into the daily lives of the city's residents, making it a crucial part of the urban infrastructure (ArchDaily) (Snøhetta).

**Structure and Materials**

Wood and locally sourced stone are used, reducing the carbon footprint and enhancing the building's thermal properties. This choice of materials supports the building's sustainability goals and complements its role in energy-efficient design (Snøhetta).

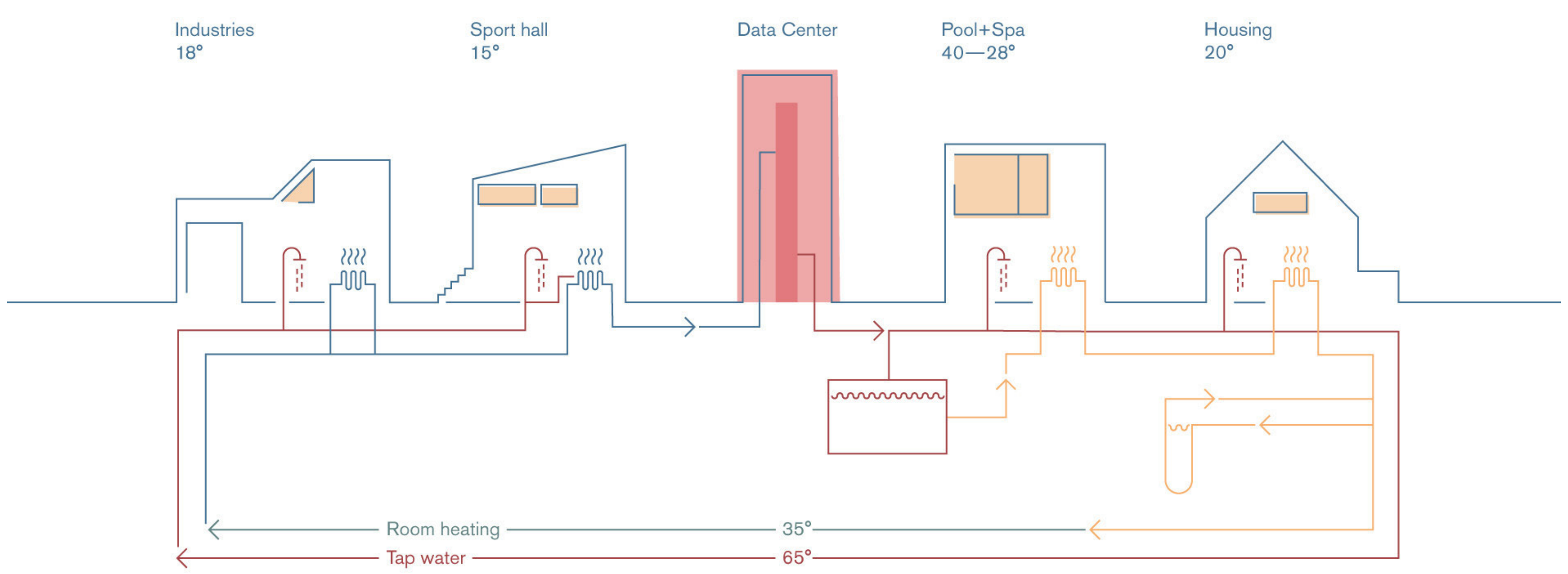



Figure 1. Energy flow diagram for a sustainable data center integrated into a mixed-use urban setting

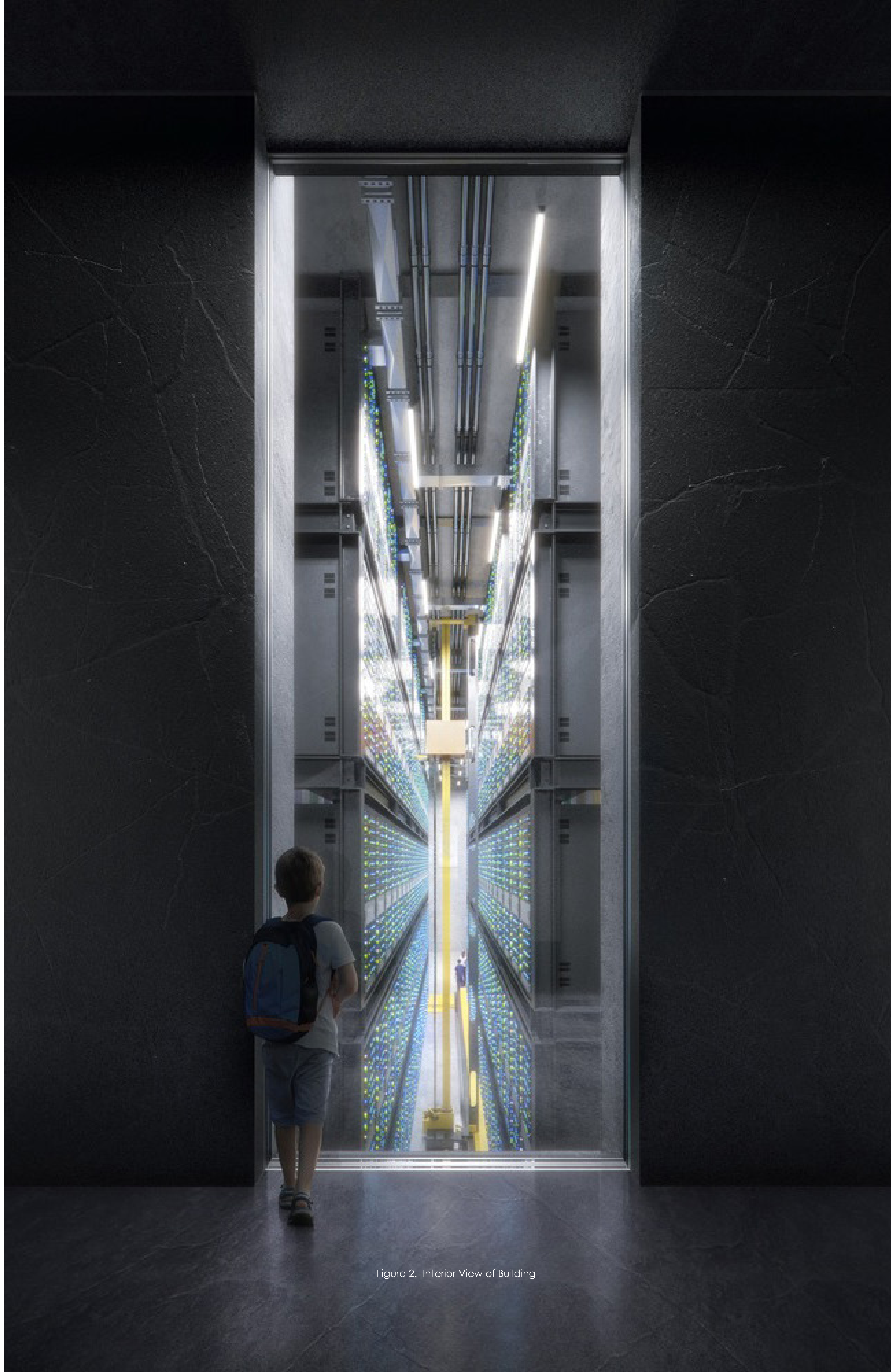


Figure 2.  Interior View of Building

*PRECEDENT 2*

## The Edge Building (Amsterdam, Holland)

**Relevance:**

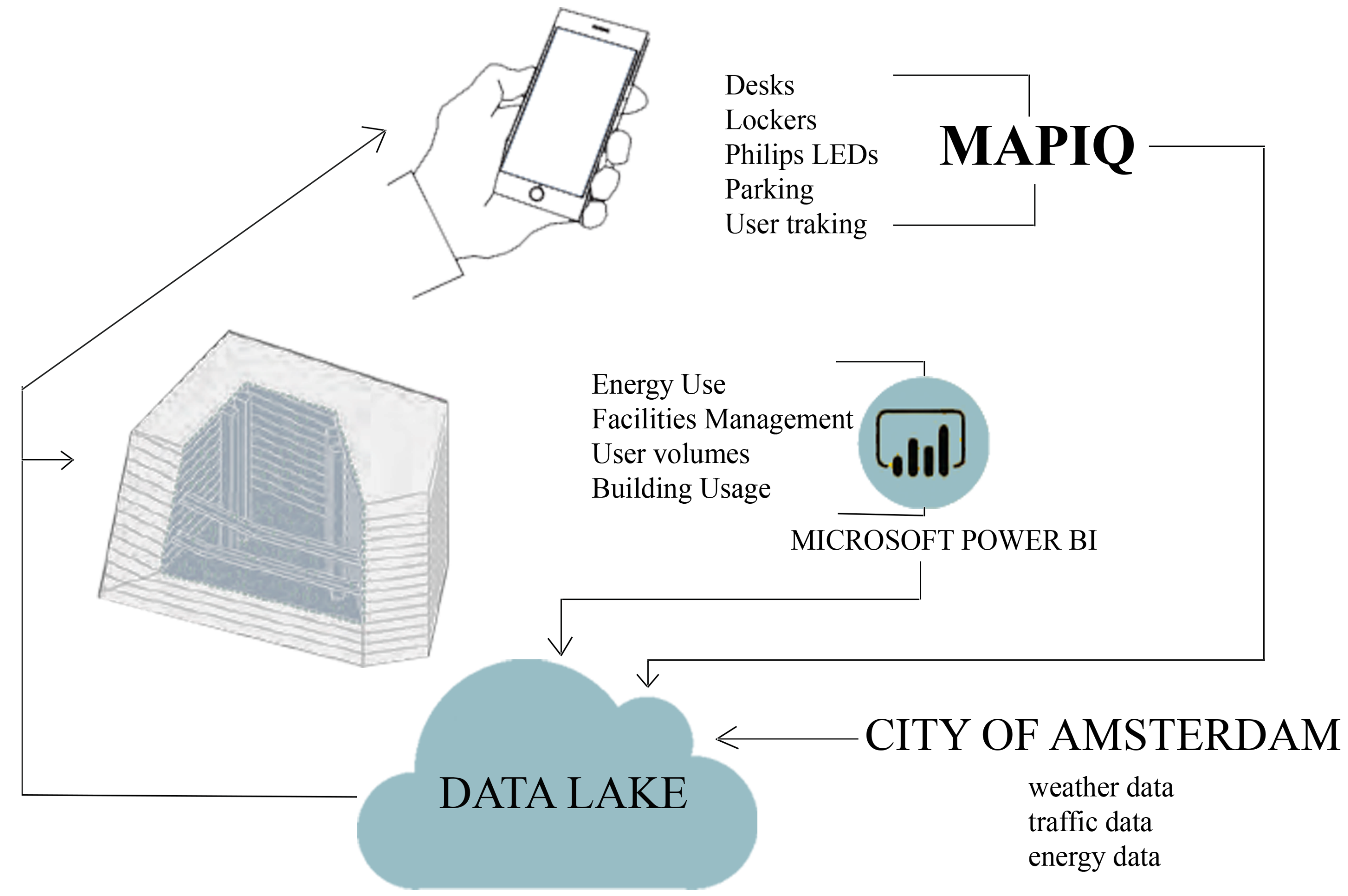
- The Edge is one of the greenest buildings globally, achieving a BREEAM (Building Research Establishment Environmental Assessment Method) score of 98.36%.
- Features include over 5,000 square meters of solar panels on the roof, energy-efficient LED lighting, and a sophisticated climate control system.
- The building employs advanced IoT (Internet of Things) technology, with over 28,000 sensors to monitor and optimize various aspects of building operations. The intelligent lighting system adjusts based on natural light and occupancy, reducing energy consumption.

**Space:** The building features open, flexible floor plans that allow for a variety of uses and configurations, and are adaptable to the changing needs of its occupants. The building's use of smart building systems and IoT sensors also allows for real-time adjustments to the building's systems and spaces, improving user comfort and productivity. Additionally, the building features a large atrium space at its center, which serves as a communal area for occupants to gather and interact, promoting collaboration and community. The Edge Building's use of open and adaptable spaces is a reflection of the current trend in architectural design towards creating spaces that are user-centered, flexible, and responsive to the changing needs of their occupants.

**Form:** The Edge Building's form showcases the use of Industry 4.0 technologies such as parametric design and BIM. Features a range of advanced building systems, such as an on-site water treatment plant and a rooftop solar panel array, which contribute to its sustainability and energy efficiency.

**Program/Usage:** multi-tenant office building that houses a range of companies and organizations, including Deloitte, AKD, and Ahold Delhaize  use of smart building systems and IoT sensors also allows for real-time adjustments to the building's systems and spaces, improving user comfort and productivity.

**Structure and materials:** steel and concrete frame that is clad in a high-performance glass facade, which allows for maximum transparency and natural light penetration. The building's structure is optimized for energy efficiency, with a focus on reducing the building's carbon footprint and minimizing its environmental impact.



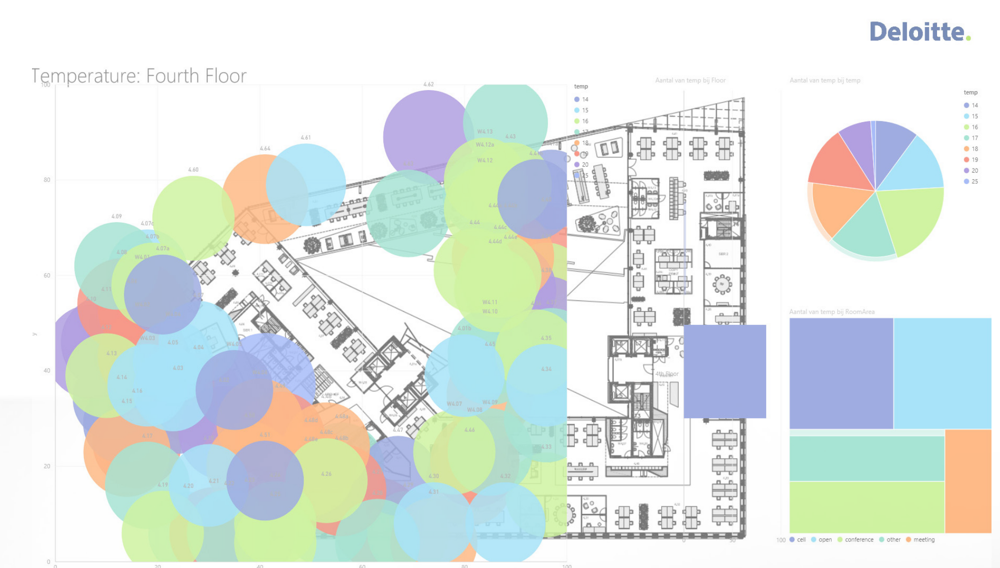




Figure 3. Heat Map of The Edge, Amsterdam

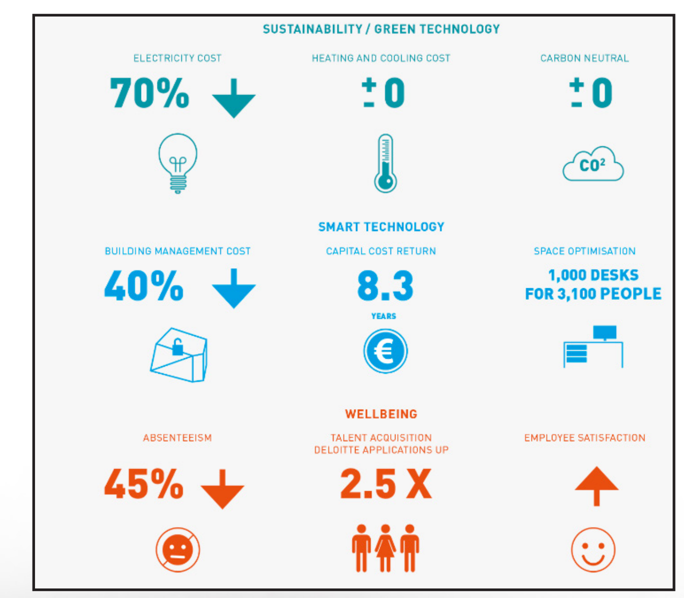



Figure 4. PLP Architecture. "Positioning."

Figure 5. The Edge

*PRECEDENT 3*

## FutureHAUS, Dubai

**Relevance:**

- Implemented Direct Current (DC) powered rails allow efficient energy distribution to the moving walls, reducing overall energy consumption.
- The integration of smart technologies enables centralized control of energy, HVAC, entertainment, and lighting systems, ensuring a seamless and energy-efficient operation of the entire house.

Internet of Things (IoT) Integration:

- The FutureHAUS Dubai serves as a pioneering example of an IoT-enabled Smart Built Environment (SBE), with sensors and actuators enhancing various functionalities within the living space.
- Multi-modal user interfaces and interaction techniques are being developed to effectively communicate information and provide user feedback, ensuring an optimal living experience in the smart home.

Seamless User Experience:

- A prototype app is in development to enable comprehensive control of the entire home, allowing residents to manage various systems, including energy, HVAC, entertainment, and more, with ease and convenience.
- Interactive wall displays implemented by computer scientists contribute to a user-friendly and intuitive living experience, supporting accessibility and healthy living for all residents, including aging in place.

**Space:**

- FutureHAUS Dubai draws inspiration from automotive and airplane production techniques, incorporating modular structures that adapt to different functional needs throughout the day.
- Utilizing automated wall cartridges, the house transforms from an office during the day to an expanded living room at dusk and a full bedroom at night, optimizing space usage and minimizing energy costs.

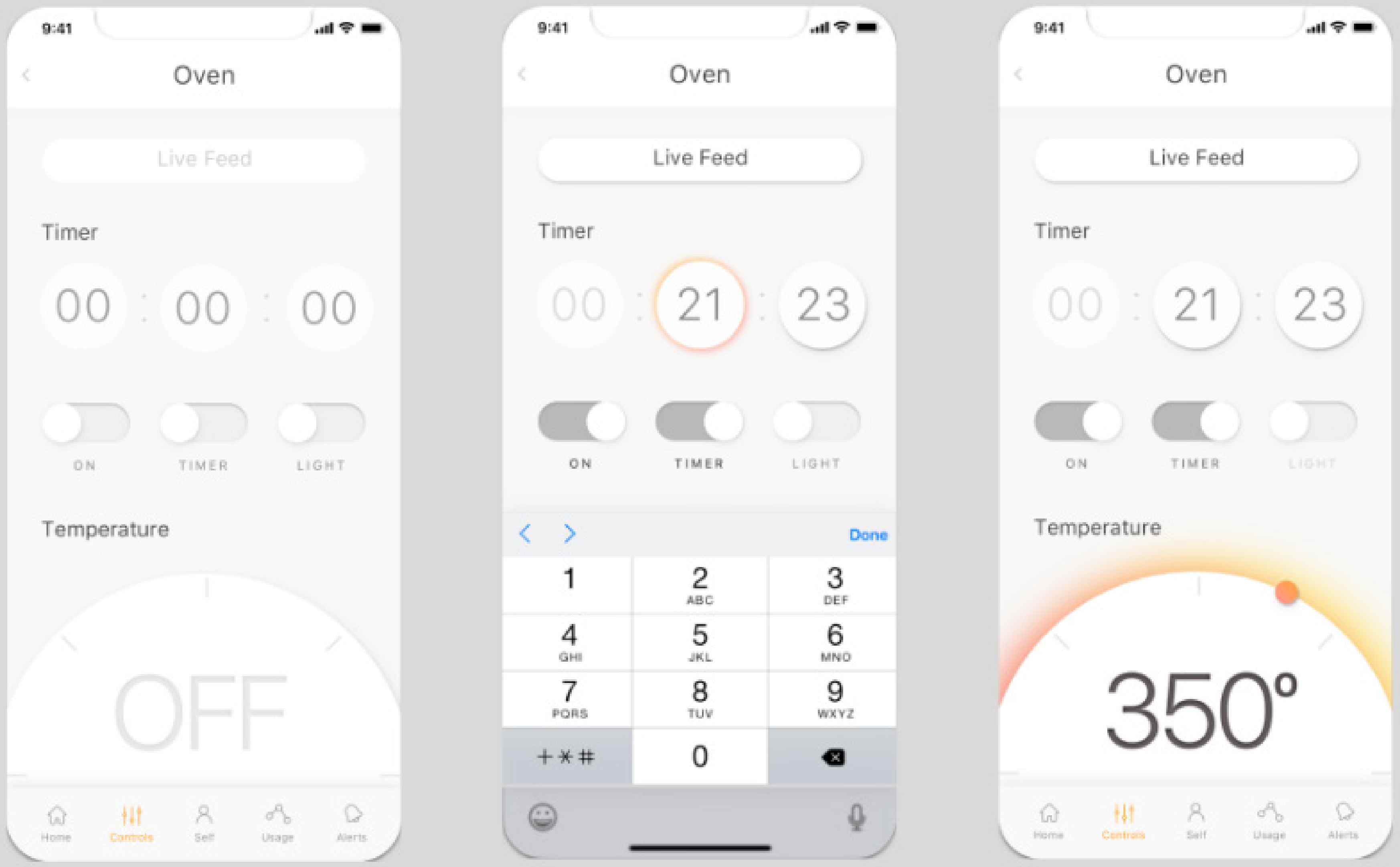



Figure 6. Human-Computer Interaction

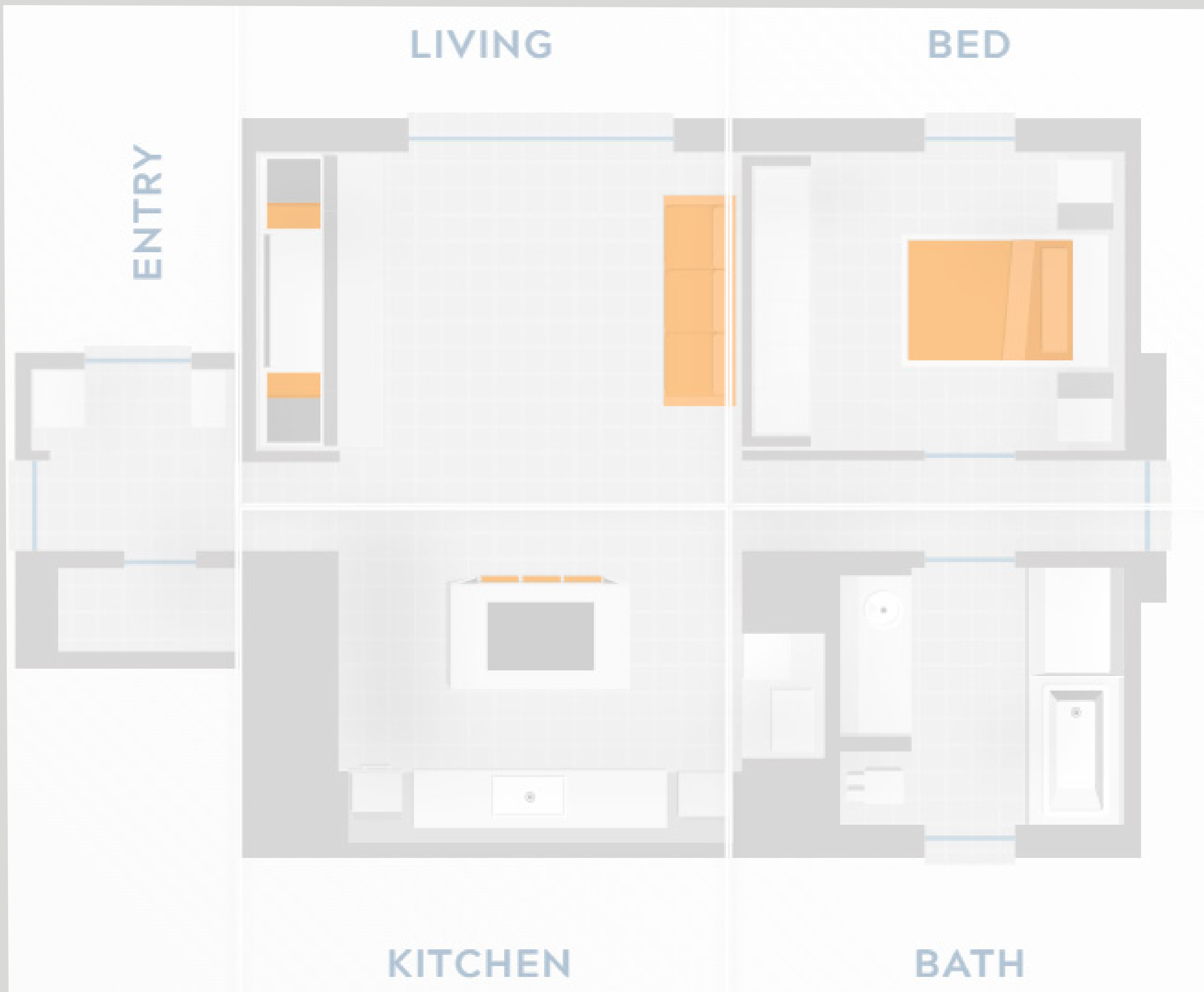



Figure 7. FutureHAUS Hover Animation.

*PRECEDENT 4*

## RTPIS Labalatory (Clemson, South Carolina)

**Relevance:** research facility that focuses on the development and integration of advanced sensing, communication, and computing technologies into the built environment. The laboratory's research encompasses a range of applications, from smart buildings and intelligent transportation systems to resilient infrastructure and disaster response. The laboratory's work is driven by the use of Industry 4.0 technologies such as the Internet of Things (IoT), big data analytics, and machine learning, which allow for real-time monitoring and optimization of building systems and infrastructure.

**Instruments and controls:** equipped with a range of advanced instruments and controls that allow for the real-time monitoring and optimization of building systems and infrastructure. These instruments and controls are an essential part of the laboratory's research, which focuses on the development and integration of advanced sensing, communication, and computing technologies into the built environment. Some of the key instruments and controls in the laboratory include high-resolution cameras, wireless sensor networks, smart building automation systems, and data analytics software. These technologies allow researchers to collect and analyze data on building performance, energy consumption, and user behavior, and to use this data to optimize building systems for efficiency and sustainability.

**Space:** The building's form reflects its function, with a design that emphasizes flexibility and adaptability to accommodate a wide range of research needs. The laboratory features an open and collaborative floor plan that encourages interaction and communication between researchers, and includes a range of specialized spaces such as simulation labs, data analysis labs, and control rooms.

Zone 1 IoT Devices
1 x Power Meter
2 x Occupancy Sensors
1 x Thermostat
4 x Luminaire Controllers
1 x Scene Switch
1 x HVAC Unit
4 x Light Panels
1 x Workstation with IoT Software Platforms

Zone 2 IoT Devices
2 x Power Meters
4 x Occupancy Sensors
2 x Thermostats
8 x Luminaire Controllers
2 x Scene Switches
2 x HVAC units
8 x Light Panels

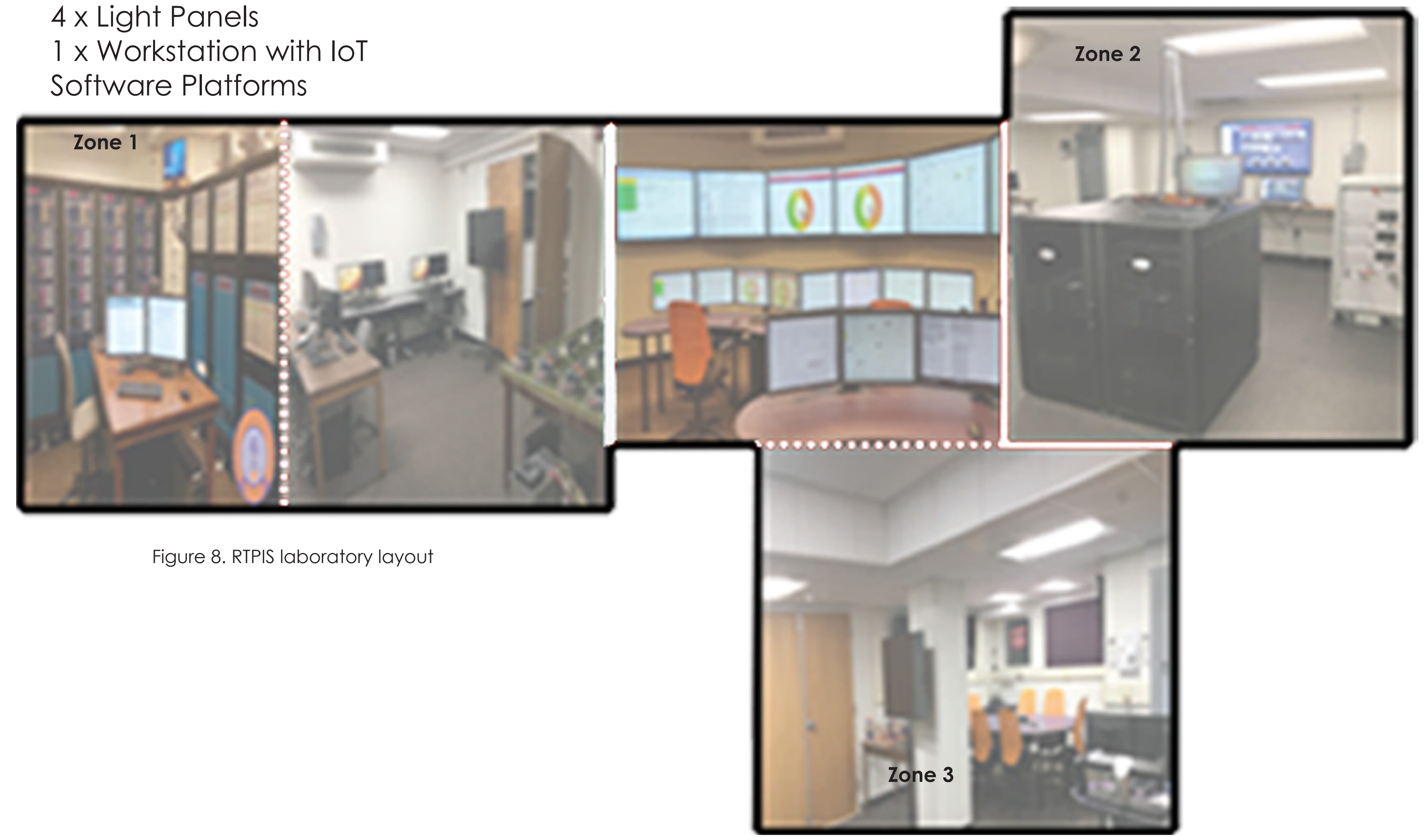



Figure 8. RTPIS laboratory layout

Zone 3 IoT Devices
1x Power Meter
2 x Occupancy Sensors
1 x Thermostat
4 x Luminaire Controllers
1 x Scene Switch
1 x HVAC Unit
4 x Light Panels
1 x Workstations with IoT

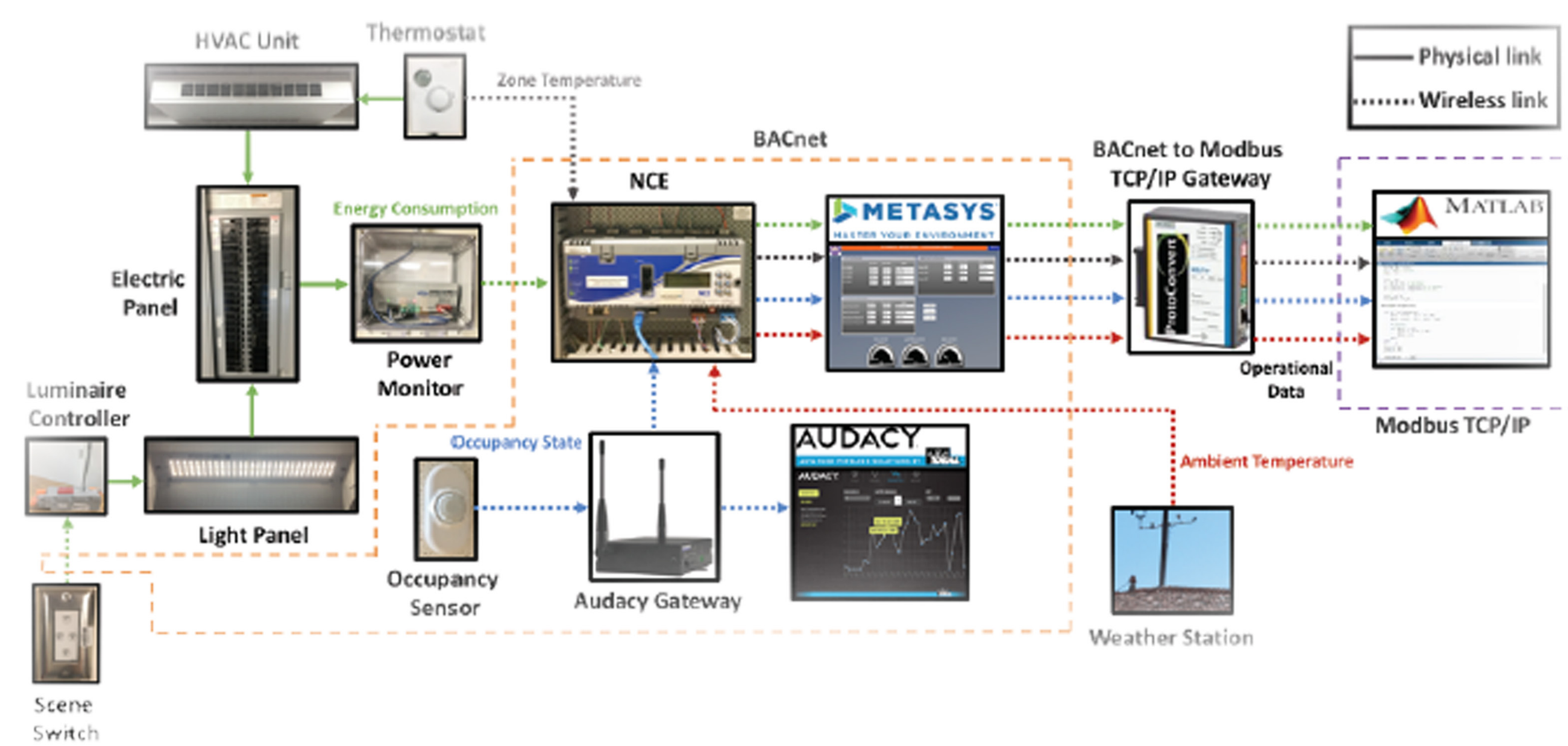



Figure 9. Integration of all the IoT devices and technologies and software platforms using BACnet protocol for data measurement in RTPIS laboratory

# MARIUPOL REBORN

*VIKTOR ZOTOV VISION*

COMPACT CITY BY THE SEA

INDUSTRIAL CITY WITH MODERN TECH-NOLOGIES


1 HISTOTICAL CENTER
2 NEW CENTER

CONTINUOUS SEA PROMENADE

TOURIST TRAM

HIGH DENSITY OF BUILDINGS

HIGH-SPEED TRAM

DENSIFICATION OF THE CITY

A CONTINUOUS SYSTEM OF GREEN SPACES

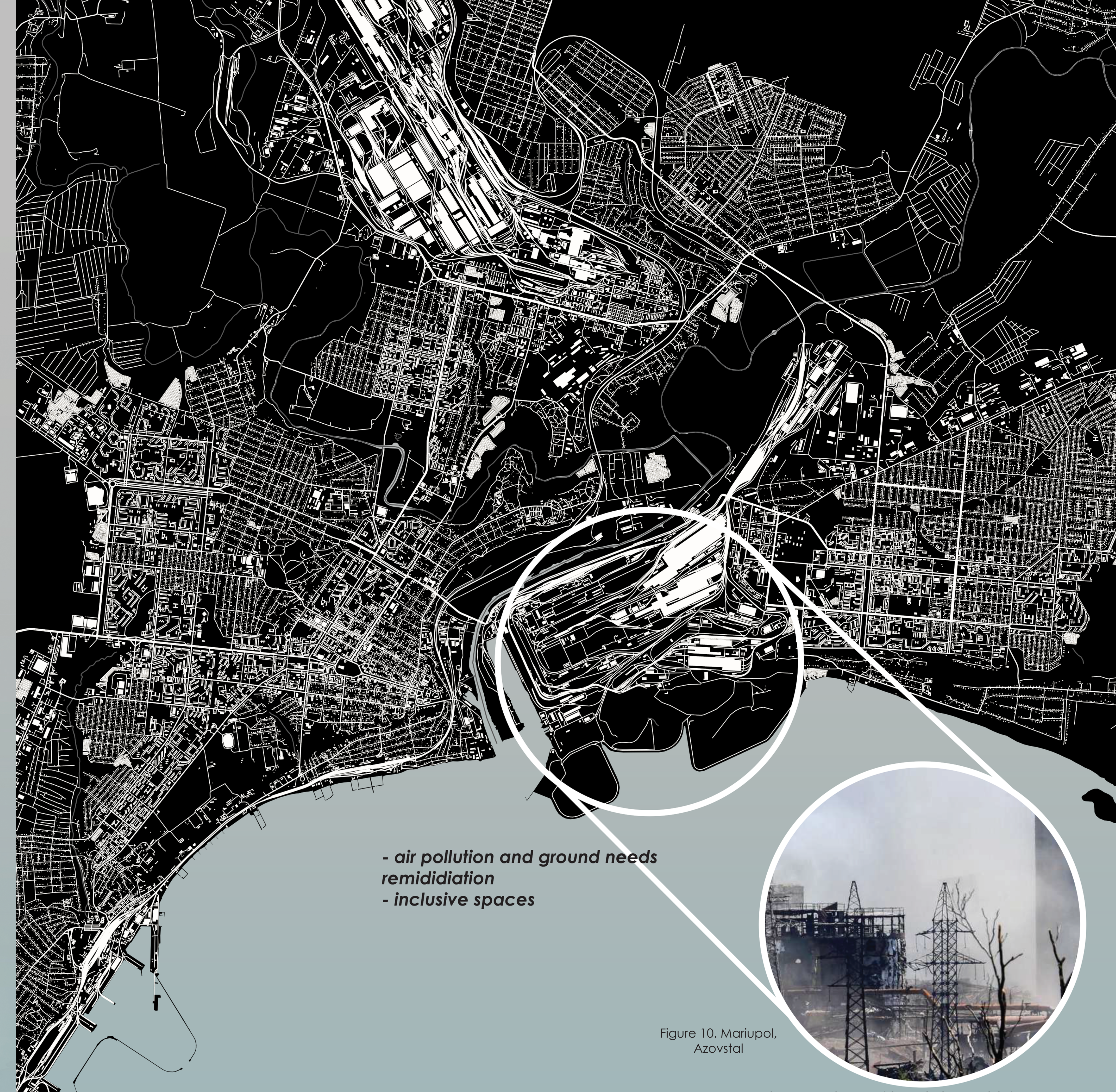
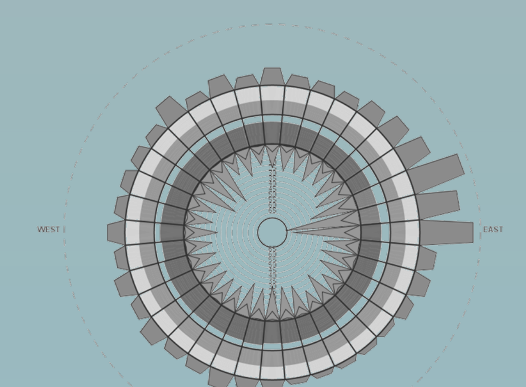
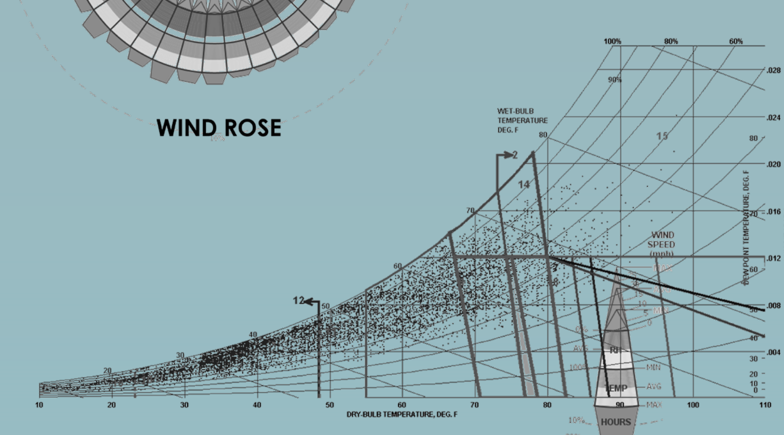



Figure 10. Mariupol, Azovstal

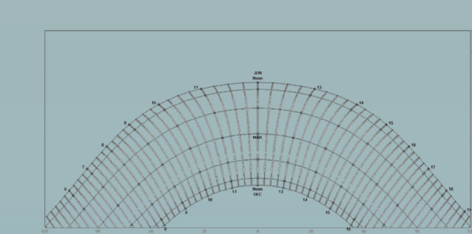
MARIUPOL MASTERPLAN
LATITUDE/LONGITUDE: 47.0425 NORTH, 37.4844 EAST



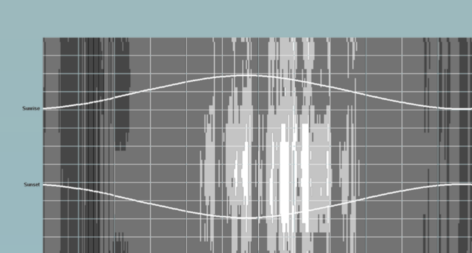
WIND ROSE



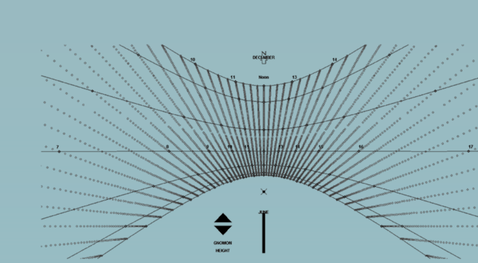
PSYCHROMETRIC CHART



SUN SHADING CHART



TIMETABLE PLOT



SUN CHART

- BIOREMEDIATION LANDSCAPING, GREEN ROOFS, VERTICAL GARDENS, FARMING - DRONES MAINT-ANIED
- BIOPHILIC DESIGN ELEMENTS
- SMART AIR QUALITY MONITORING
- AUTOMATED NATURAL VENTILATION
- PERSONAL HEALTH DASHBOARD
- SMART ENVIRONMENTAL MONITORING
- AIR FILTRATION
- POSITIVE PRESSURE ENVIRONMENTS
- SMART ELEVATOR
- SMART ENERGY CONTROL
- SMART MONITORING
- SMART SECURITY
- SMART LIGHTING
- SMART HVAC
- SMART BUILDING MANAGEMENT
- SMART EMERGENCY ACCESS
- SMART MEMBER CONNECTIVITY
- SMART PARKING
- SMART UTILITIES
- SMART LEASING


**Why in the center of a new city center?**

- **Optimal Connectivity:** Central location ensures efficient data management and connectivity for the entire city, reducing latency for all urban services.
- **Symbol of Innovation:** Demonstrates the city's commitment to technology and progress, serving as a physical embodiment of modern urban development.

*The site location is in Mariupol, Ukraine, which currently has 80% destroyed infrastructure. This thesis is also a project within a project of Viktor Zotov's new vision of the city in the place of a new city center.*

**Why Start with a Data Center?**

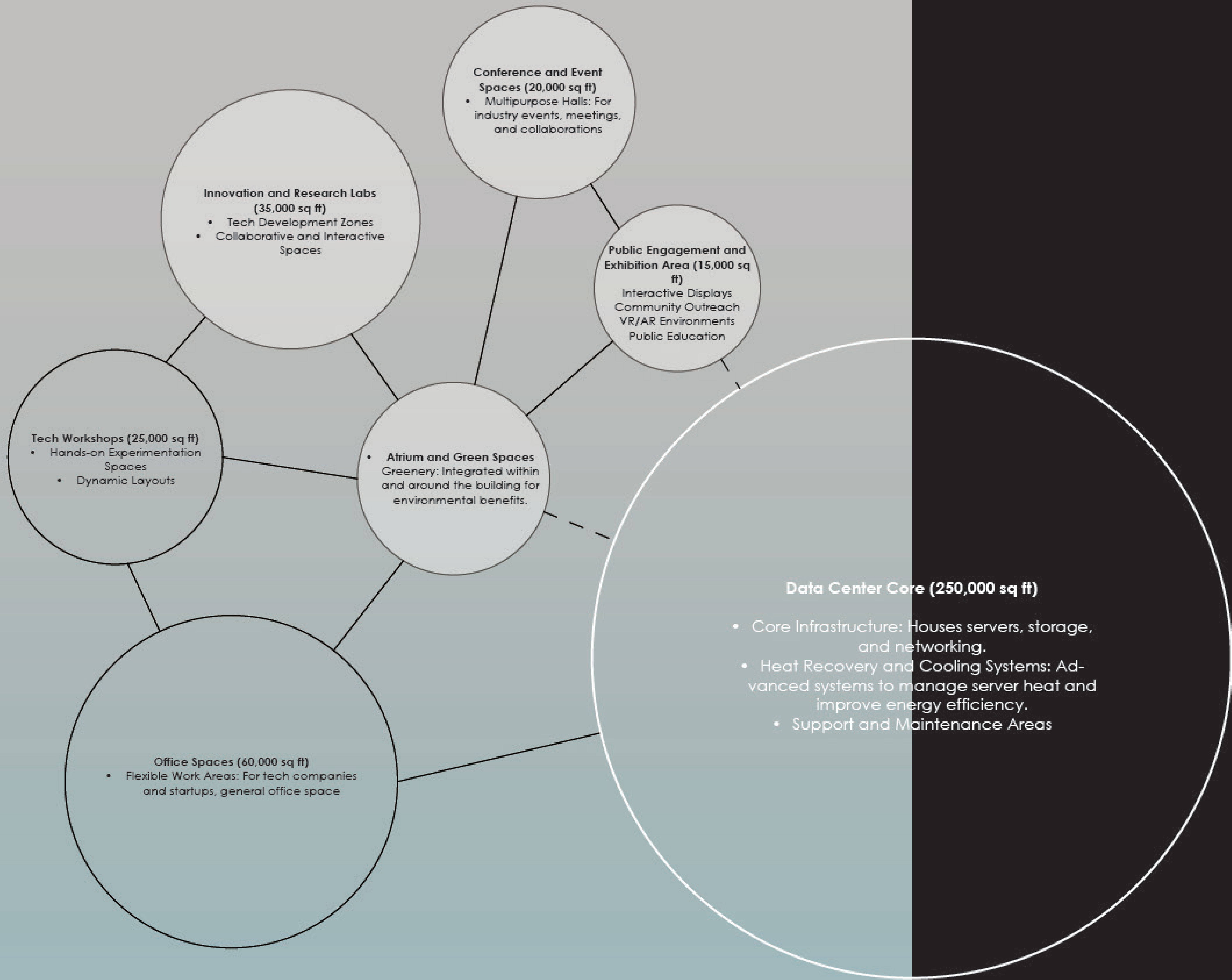
- **Digital Infrastructure Foundation** (backbone of modern urban development)
- **Attracting Investment**
- **Post-conflict:** having a secure and reliable data infrastructure is important for urban resilience, helping ensure continuity of services in emergencies.
- **Supports Smart City Initiatives**
- **Symbolic Significance:** future-forward vision of the city, aligning with goals of the 'MARIUPOL REBORN'.
- Modern data center with one of main focuses on sustainability

**Uses of the Data Center**

- **Smart City Infrastructure:** Supports IoT devices for traffic management, public utilities monitoring, environmental sensors, and public safety systems.
- **Public Administration Data Management:** Hosts servers and storage for city government data, records, city planning information, public services data, and administrative communication networks.
- **Commercial and Business Data Services:** Provides data storage, cloud computing, and processing capabilities for local businesses, supporting everything from small startups to large enterprises.
- **Community and Residential Connectivity:** Facilitates internet and telecommunication services for residents, including support for smart home technologies and community networks.
- **Healthcare and Educational Data:** Manages data for local healthcare systems (like electronic medical records) and educational institutions (such as research data and virtual learning platforms).
- **Security and Surveillance:** Stores and processes data from city-wide security cameras and emergency response systems, contributing to public safety and security.
- **Data Backup and Disaster Recovery:** Serves as a central point for data backup and recovery, crucial for maintaining data integrity and availability in case of emergencies.

# CHAPTER III

- Site and Context
- Design Process
- Formal design approaches
- Structure and materials
- Programmatic approaches
- Building performances
- IoT Infrastructure




**Data Center Core: 250,000 sq ft (core infrastructure, heat recovery, support areas)**

**Extended Office Spaces: 60,000 sq ft (flexible work areas, smart management systems)**

**Innovation and Research Labs: 35,000 sq ft (tech development zones, collaborative spaces)**

**Tech Workshops: 25,000 sq ft (hands-on experimentation areas, dynamic layouts)**

**Public Engagement Area: 15,000 sq ft (interactive displays, community outreach)**

**Green Spaces: 20,000 sq ft (vertical gardens)**

**Conference and Event Spaces: 20,000 sq ft (multipurpose halls)**

**TOTAL PROGRAM SPACE: 425,000 sq ft**

Data Center Square Footage Calculations Estimations

To estimate the square footage for a data center that supports an 8 square kilometer dense urban development near the sea, with buildings ranging from 3 to 20 stories:

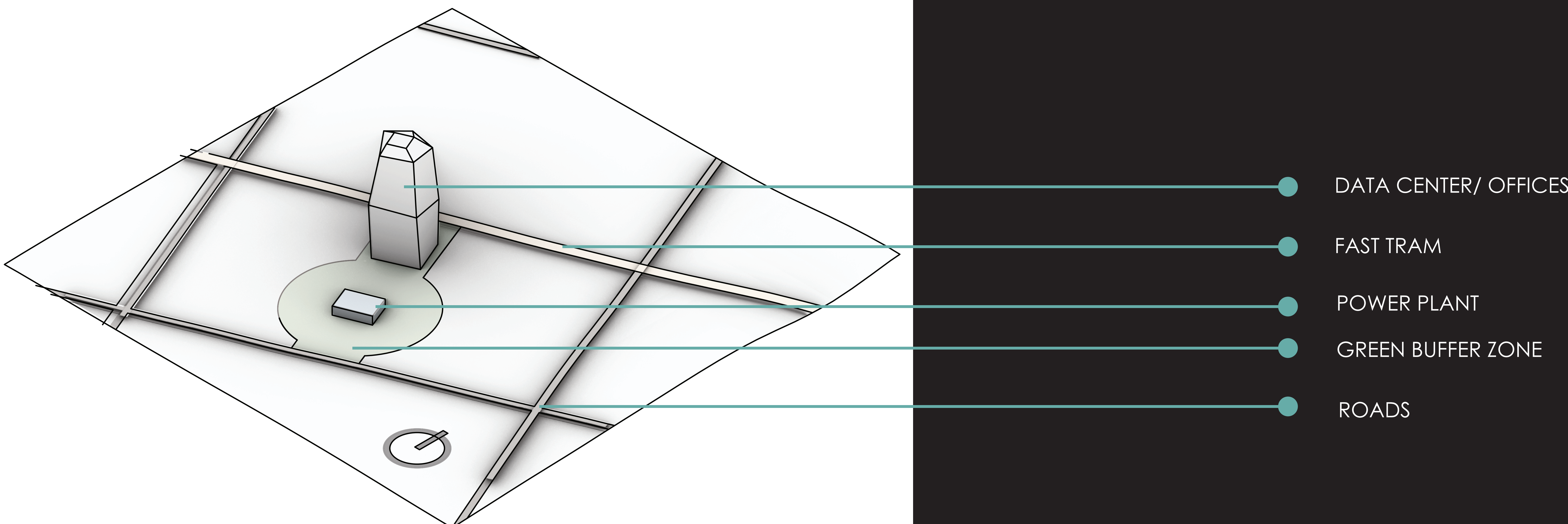
Assuming a dense urban area with approximately 15,000 people per square kilometer, this means a total population of around 120,000 for the 8 square kilometers. Considering the mixed-use nature of the area, there are approximately 5,000 businesses and public service entities. The development will include modern urban services like smart traffic systems, public safety networks, IoT implementations for utilities, etc.

Assuming each household (around 50 000 households) requires server capacity equivalent to one rack unit for personal data, streaming, IoT devices, etc., this totals to 50,000 U (rack unit).
Commercial and Public Services: Estimating 5 rack units per entity for businesses and services, the requirement would be 20000 U.
Smart City Infrastructure: 10,000 U for smart city infrastructure management.
Redundancy and Scalability: Adding 30% more capacity to account for future growth and redundancy.

Total Rack Units (U):
- Residential: 50,000 U
- Commercial/Public: 20 000 U
- Smart City Infrastructure: 10 000 U
- Total: 80 000 U
- With Redundancy and Growth: 104 000 U

Conversion to Racks and Space:
Assuming an average server rack can hold 42 U, the total number of racks needed would be approximately 104,000 U / 42 ≈ 2,476 racks [1].
Each rack, including aisles, cooling, and power infrastructure, requires about 100 square feet [2].
Therefore, the total space required is roughly 2,476 racks * 100 square feet per rack ≈ 247,600 square feet.

Used Sources for this calculations:
[1] https://blog.enconnex.com/exploring-server-rack-sizes-and-dimensions-depth-width-height
[2]
https://www.datacate.net/determining-data-center-space-requirements/




*SITE AXONOMETRY DIAGRAM*

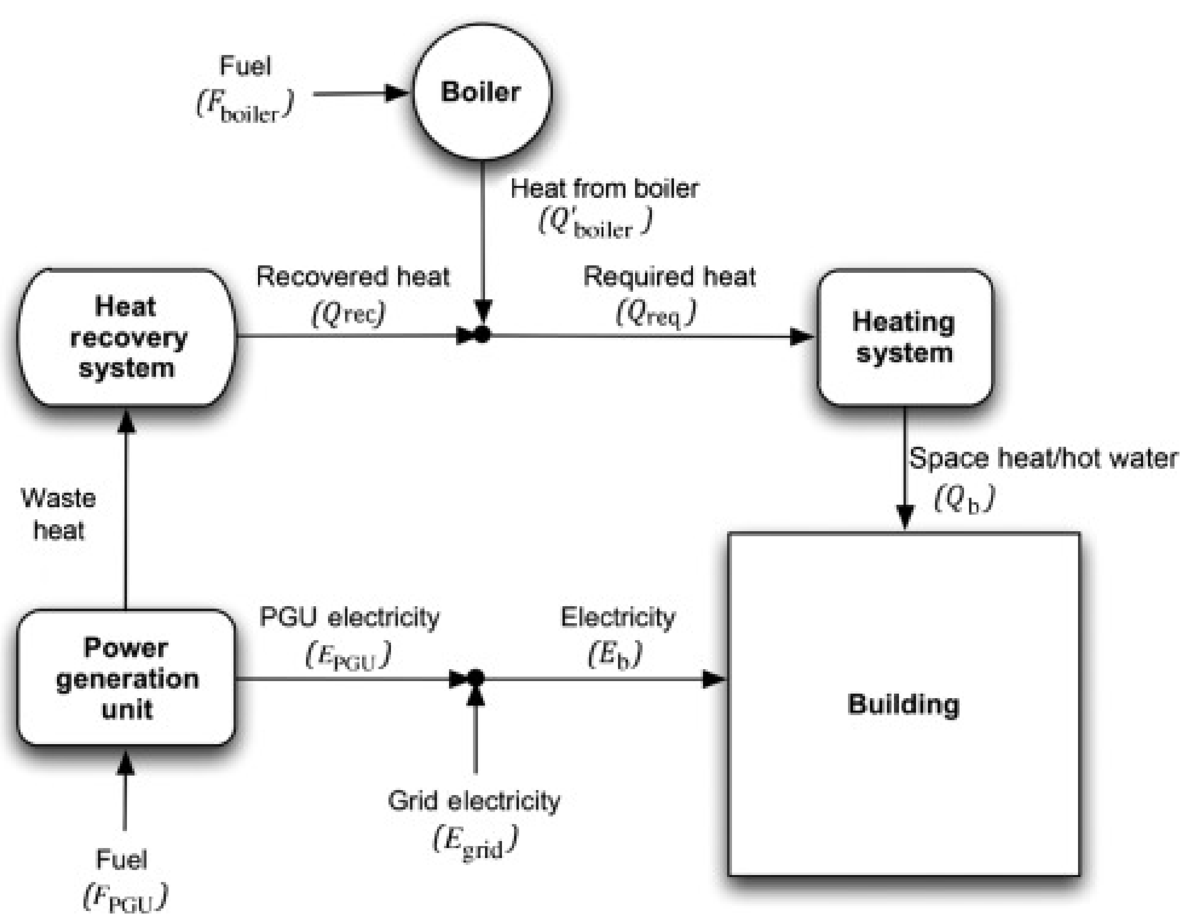



Figure 12. Schematic showing heat flow in a building CHP unit.

*Choosing a hydrogen fuel cell CHP (Combined Heat and Power) plant offers a clean and efficient energy solution that aligns with site sustainability goals. Hydrogen fuel cells produce electricity through a chemical reaction rather than combustion, resulting in zero emissions at the point of use—only water vapor and heat as byproducts that will be reused as offices grey water. It operates at high efficiencies and provide consistent power independent of weather conditions, unlike solar or wind energy, which is crucial for data centers. Integrating CHP systems maximizes the energy utilization by capturing and repurposing the waste heat for heating or cooling, enhancing overall energy efficiency.*

**Power Plant Electrical Load Calculation (Estimate)**
Data Center Load: For a 225,000 sq ft data center, with an average power density of 30 watts per square foot (typical for data centers), the electrical load is:
*225000*30=6750000 Watts or 6.75 MW.*

Additional Load for Offices and Other Areas: Assuming additional spaces like offices and labs contribute an extra 25% load:
*6.75 *25 = 1.6875 MW*

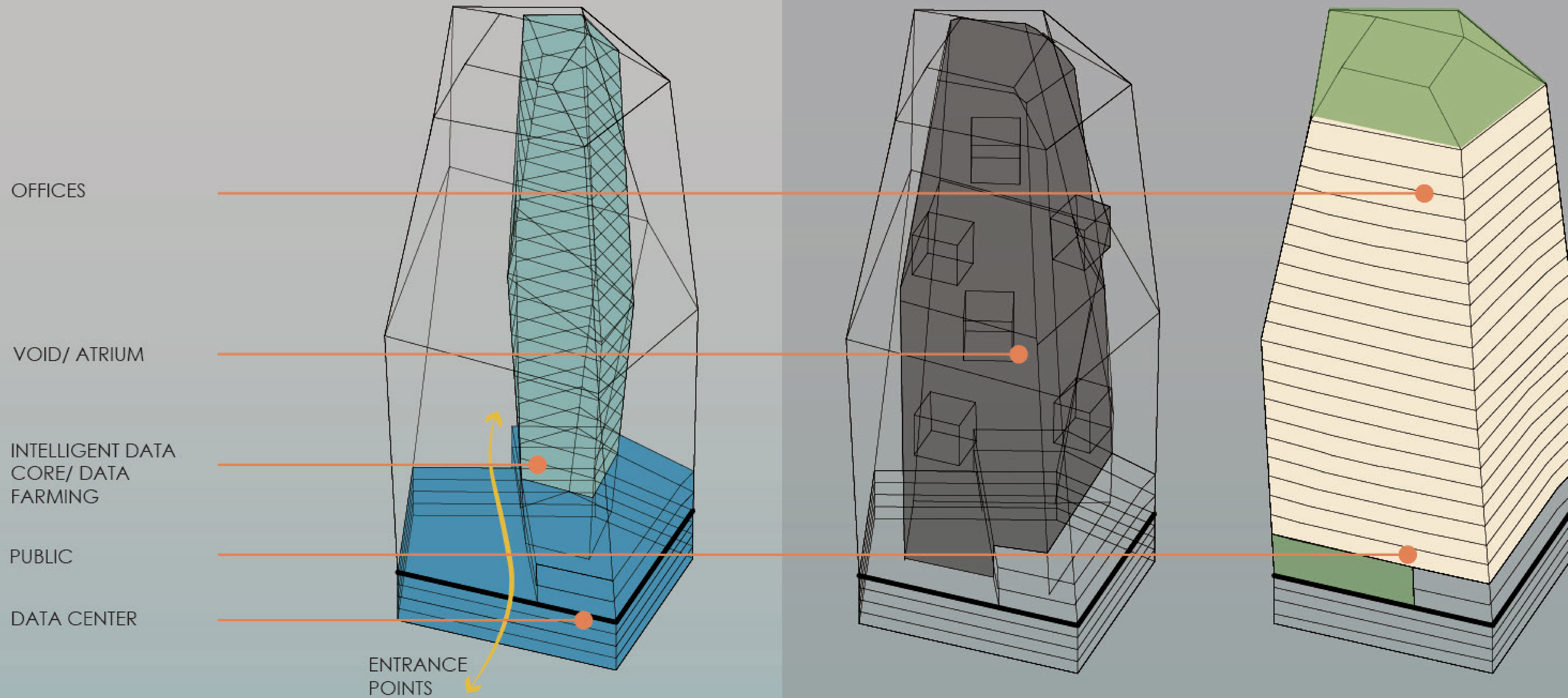
Total Electrical Load:
*6.75 MW+ 1.6875 = 8.44=MW*

Thermal Load Consideration
1.Heating and Cooling Needs: The thermal load for heating office spaces or driving absorption chillers for the data center's cooling systems also needs to be considered.
2. Estimating Thermal Load: This can be roughly estimated at 20-30% of the electrical load.

**CHP Plant Sizing with Efficiency Consideration**
Efficiency of CHP Plan: CHP plants are efficient in converting fuel to energy, with average efficiencies around 80%.

Calculating Capacity Based on Efficiency:
To meet the 8.44 MW electrical demand, considering an efficiency of 80%, the required CHP plant size would be: *8.44 / 0.80 = 10.55 MW*

Additional Capacity for Thermal Energy: Including the capacity for thermal energy generation, the CHP plant size might increase to:
*10.55 MW + 20-30%= 11 to 13 MW.* - **would require approximately 10000 square feet ~**




**Data Farming for Offices**

**Function:** Dedicated zones on each floor for data-related activities supporting office functions like cloud computing services, data storage, or business analytics.

**Integration:** Seamlessly blended into the office layout, ensuring that office workers have convenient access to these facilities.

**Design:** Equipped with the necessary technical infrastructure while maintaining a conducive environment for office productivity.

**Intelligent Data Core**

**Function:** acts as the nerve center for advanced data processing and management, equipped with AI, machine learning, and big data analytics.

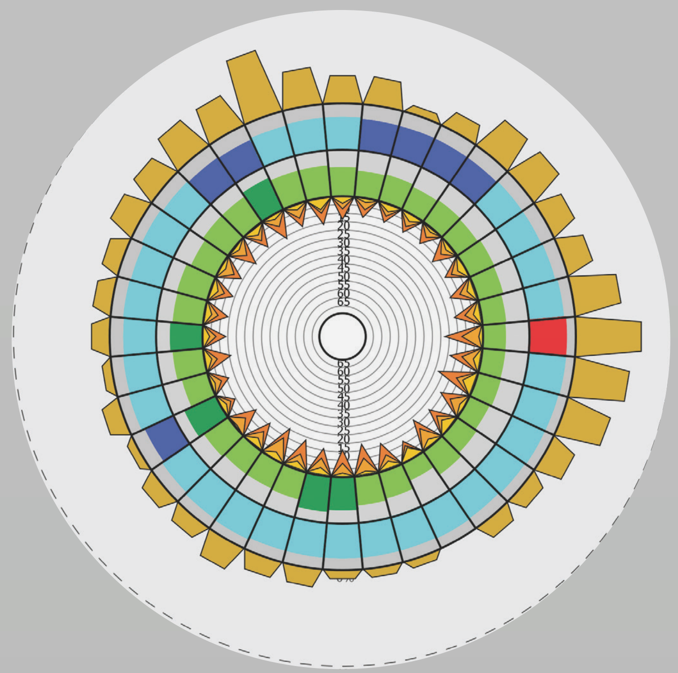
**Integration:** Distributed on each floor in a centralized area easily accessible from office spaces and other functional areas.

**Design:** Visible and interactive areas on certain floors for demonstrations or public engagement, while maintaining high-security zones for sensitive operations.

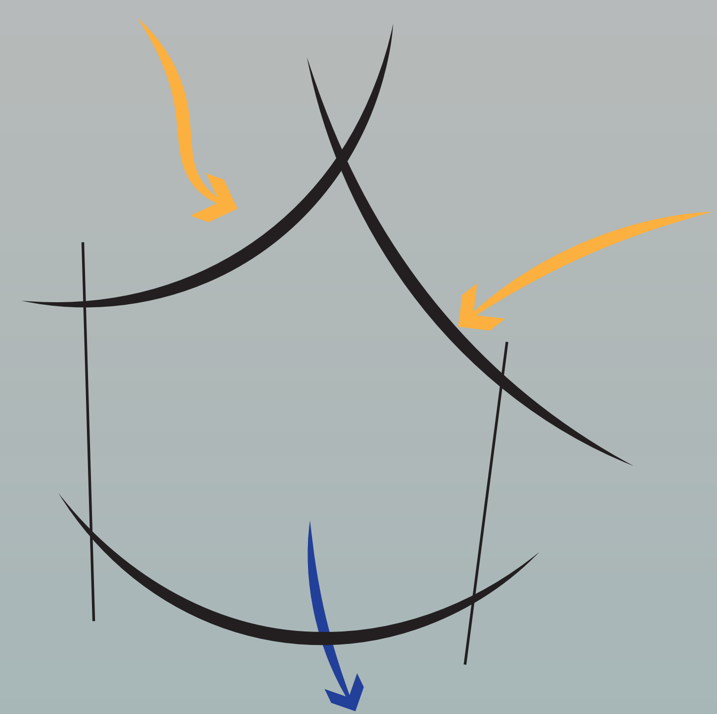
**FORM CONCEPT**

*The building's form is informed by analysis of local wind patterns, focusing on the most prevalent wind directions and speeds to optimize natural cross ventilation enabled by kinetic facade. Two pairs of large kinetic facade modules are placed on three opposite sides of the building (east and north-west for positive pressure as it has the most wind speed in summer from wind diagrams and south for negative pressure), enabling them to harness wind pressure effectively for cross ventilation. The kinetic modules in this 6 points can adjust in real-time, opening or closing to create more positive or negative pressure as needed, enhancing airflow control and efficiency. The building uses the differential pressure created by the wind on various sides to facilitate natural cross ventilation, reducing the need for mechanical cooling.*

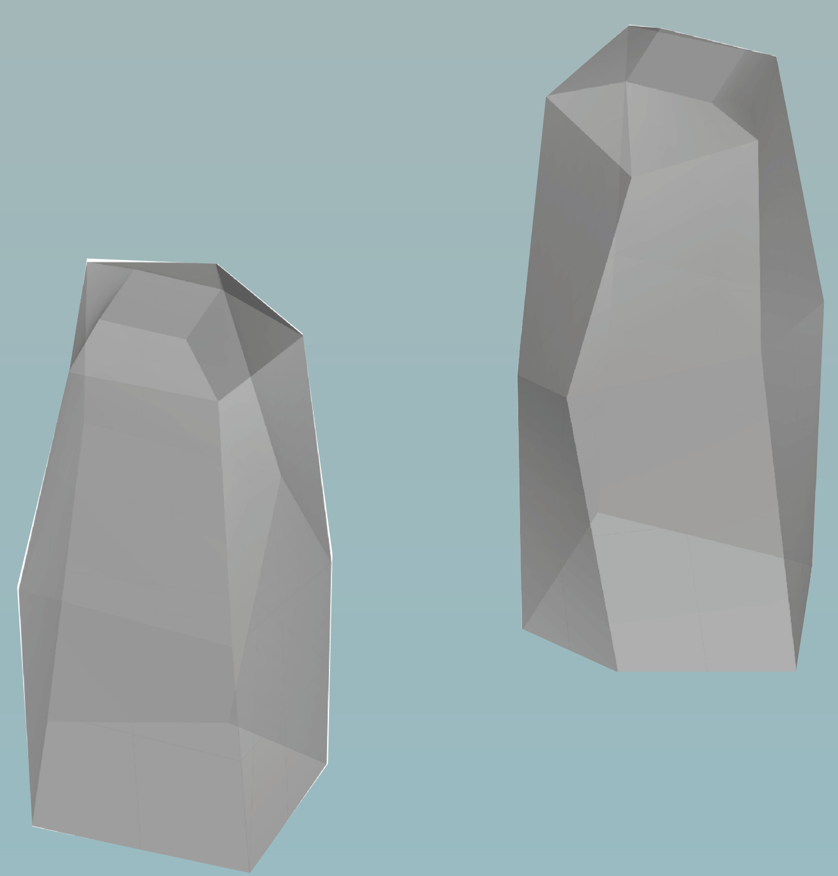
*Utilizing just two pairs of two-floor height openings in a kinetic facade can efficiently facilitate natural ventilation in tall building, primarily due to the enhanced chimney effect and effective cross-ventilation they offer. These large openings, strategically placed to harness differential wind pressures and varying wind directions at different building heights, can significantly improve air exchange. This setup maximizes airflow throughout the building, effectively reducing the need for mechanical ventilation and contributing to overall energy efficiency, making two pairs a sufficient and sustainable choice for the building's design.*



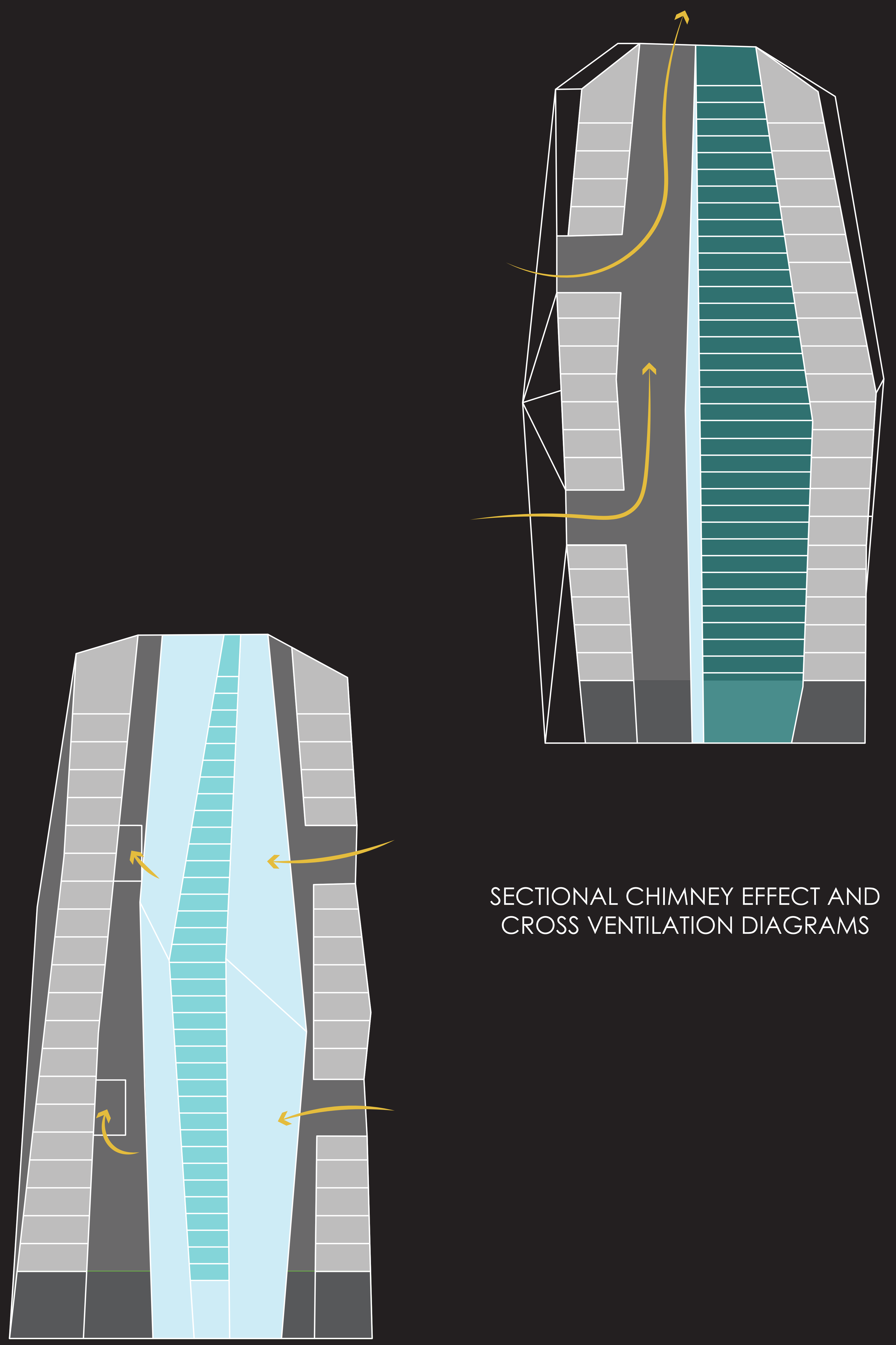
MID SPRING THROUGH MID FALL WIND ROSE



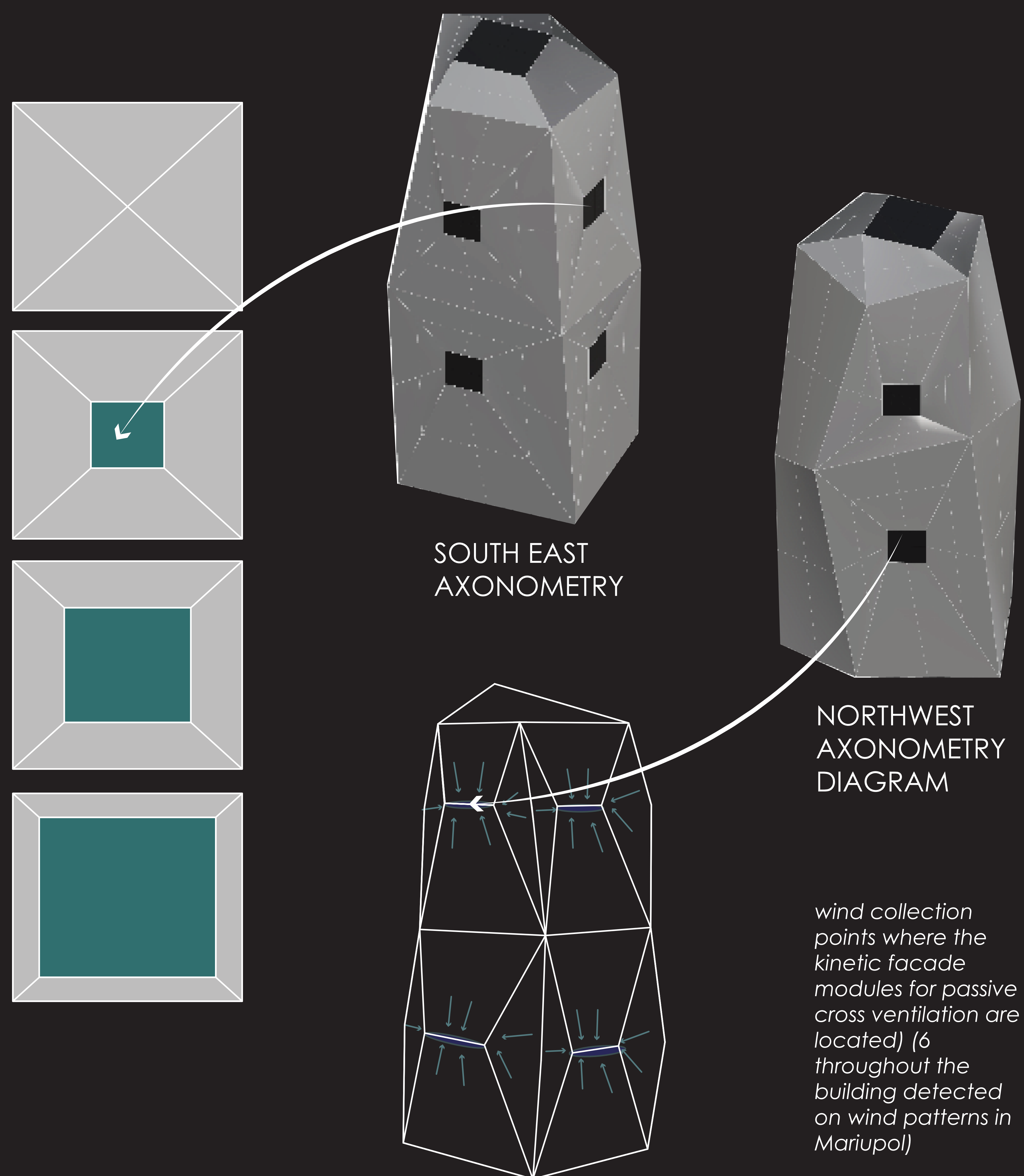
CONCEPT



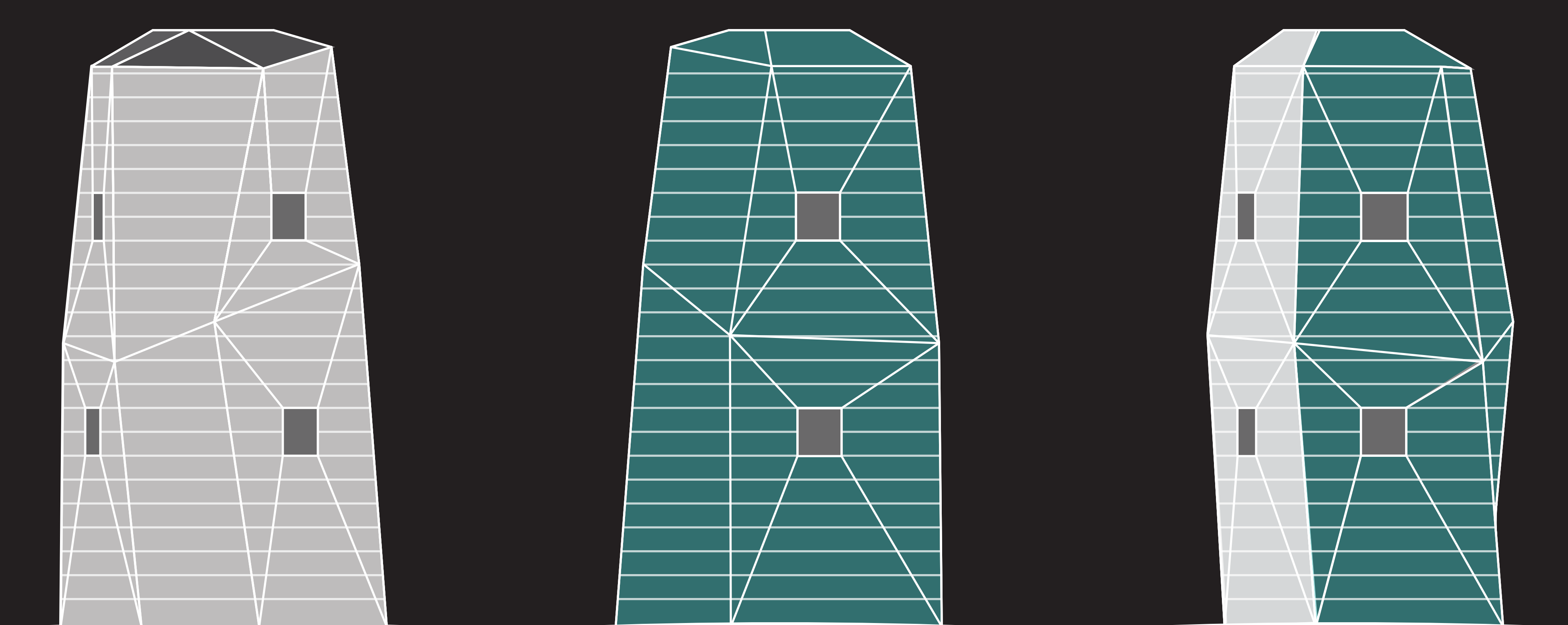
SOUTH EAST & NORTH WEST AXONOMETRY FORM DIAGRAM



SECTIONAL CHIMNEY EFFECT AND CROSS VENTILATION DIAGRAMS




*wind collection points where the kinetic facade modules for passive cross ventilation are located) (6 throughout the building detected on wind patterns in Mariupol)*



SOUTH ELEVATION DIAGRAM FULLY CLOSED

NORTH ELEVATION DIAGRAM FULLY CLOSED

WEST ELEVATION DIAGRAM FULLY CLOSED

### Data Center vs. Other Spaces

HVAC and Energy Usage
Data Centers: Require robust and continuous cooling due to high heat generation from servers. Energy usage is heavily skewed towards cooling systems, often necessitating specialized solutions like in-row cooling, liquid cooling, or hot/cold aisle containment. Primarily need cooling throughout the year, even in colder climates, due to internal heat generation. Rarely require heating.
Other Spaces (Offices, Labs, etc.): Generally have more balanced HVAC needs. Seasonal variability with a need for heating in colder months and cooling in warmer months.

### Shared Heating

Energy Sharing: Walls that open to adjacent spaces allow for the transfer of excess heat from the data center to office and lab areas, reducing heating needs.
Heat Recovery Ventilators (HRVs): capture heat from the air being exhausted from the data center and use it to warm fresh air entering the auditorium.
Capture waste heat from servers and use it for heating other parts of the building or nearby facilities.

### Dynamic Cooling Zones in Data Center Program Walls

Movable partitions to create dynamic cooling zones, optimizing cooling distribution and reducing energy use.
Cross Ventilation: When the facade opens, it should allow air to flow throughout the space, exiting through strategically placed vents or openings on the opposite side.

### Passive Ventilation with Kinetic Facades and walls

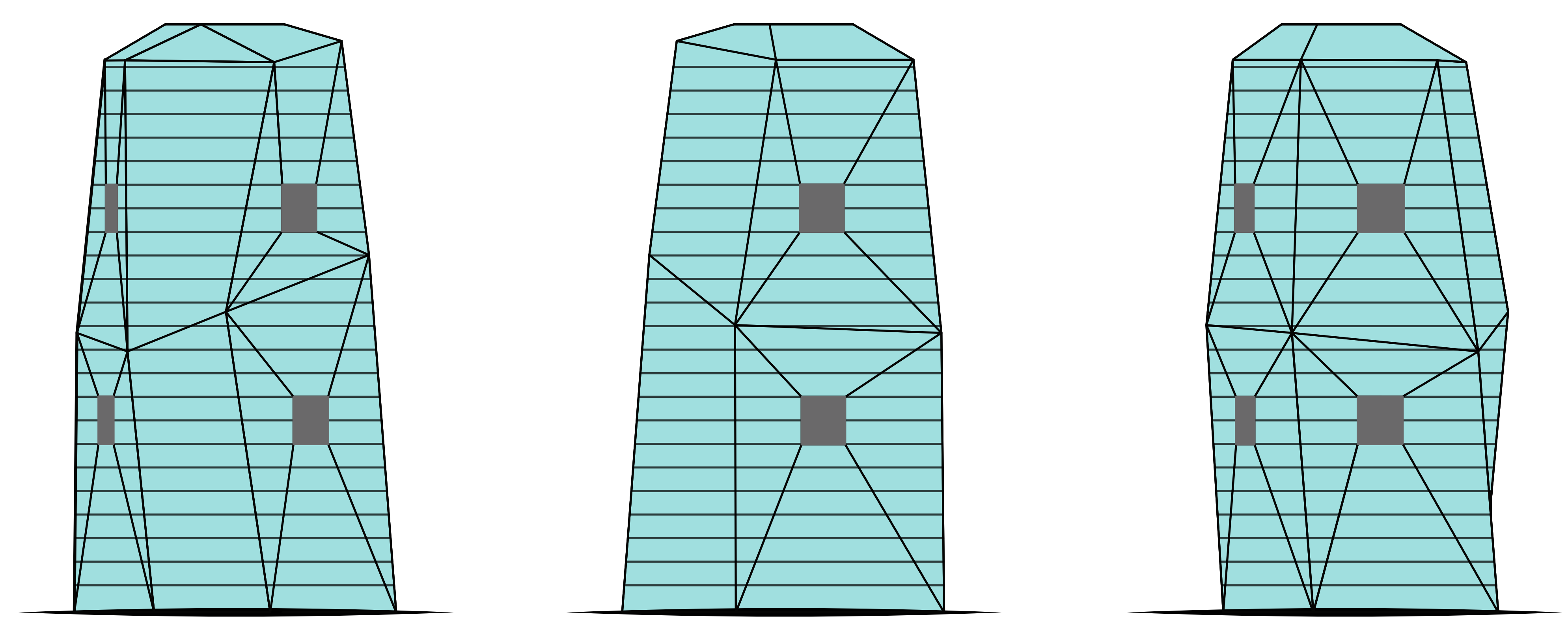
Natural Cooling: Facades that open based on wind sensors allow for natural ventilation, reducing reliance on mechanical cooling systems.
Responsive Building Skin: Adapts to environmental conditions, enhancing comfort and energy efficiency.
Dynamic Openings: Wind Sensors automate the opening of facade elements, allowing for natural air flow based on wind direction and speed.

### Kinetic Roof for Heat Management

Heat Dispersion: A roof that opens to release heat can effectively manage internal temperatures, especially in server areas.
Adds a dynamic element to the building's architecture.

### Green Spaces and Biophilic Design

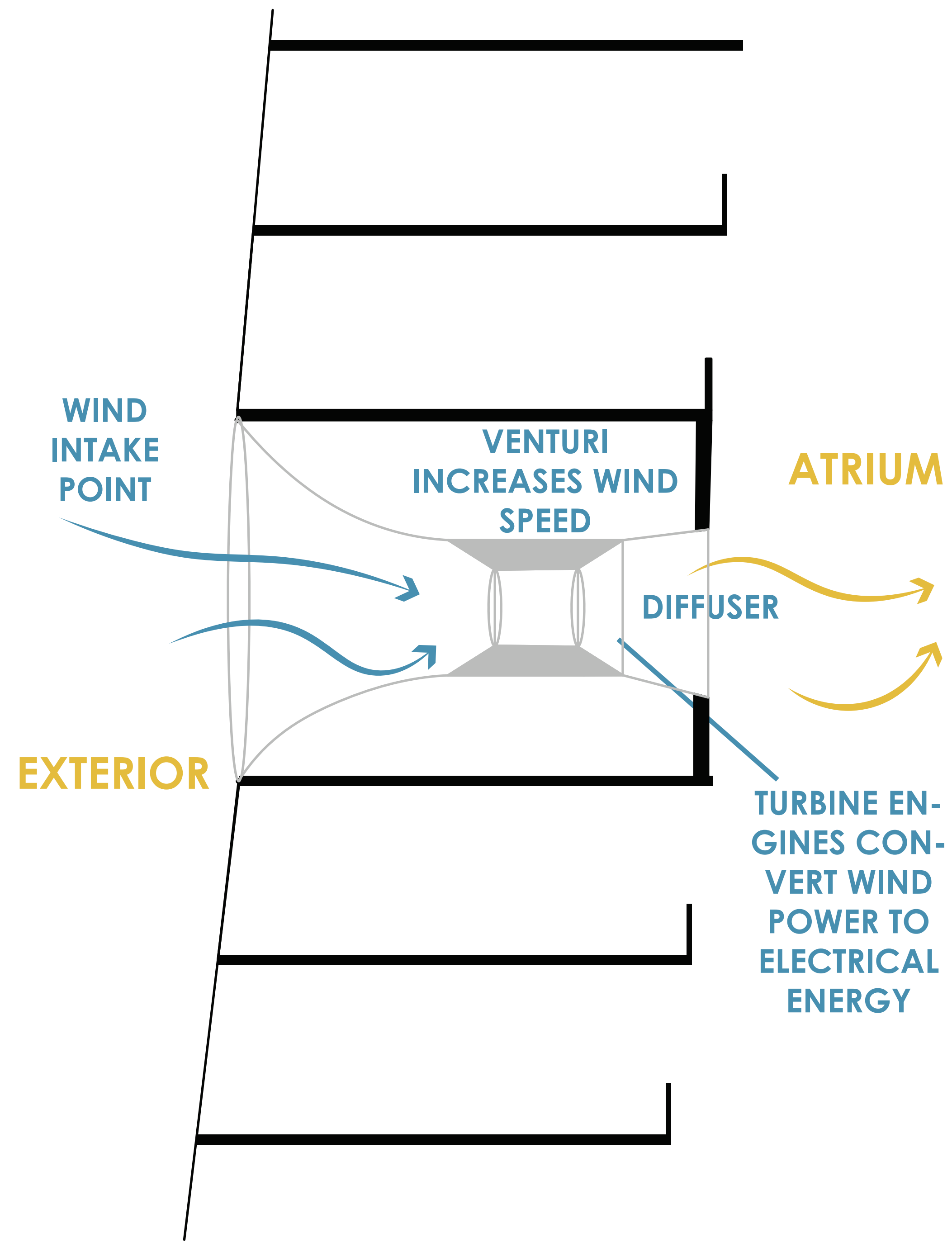
Air Quality and Well-being: greenery and air quality sensors as well as cross ventilation features improve indoor air quality and provide a natural, calming environment.



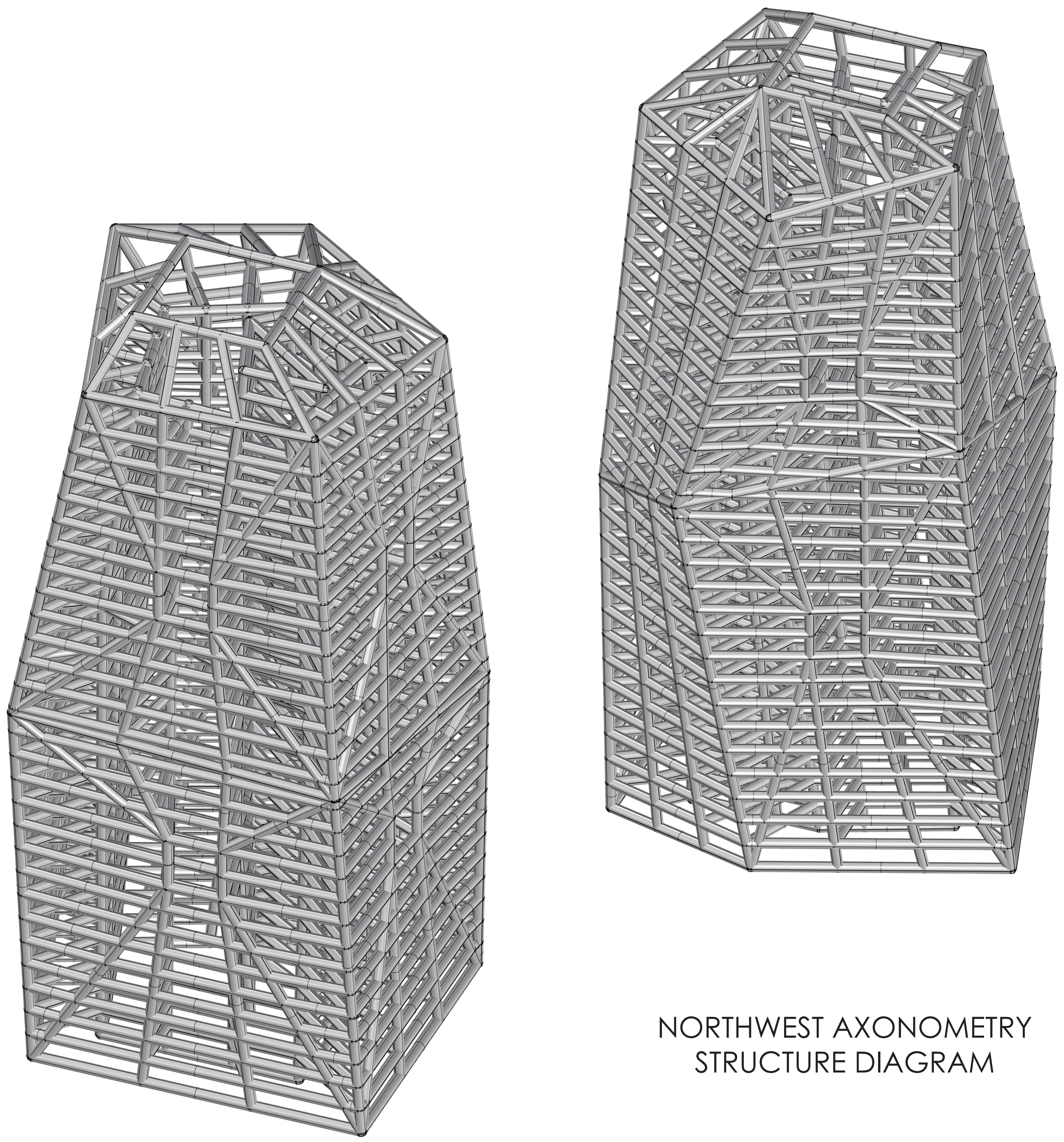
SOUTH ELEVATION DIAGRAM FULLY OPENED

NORTH ELEVATION DIAGRAM FULLY OPENED

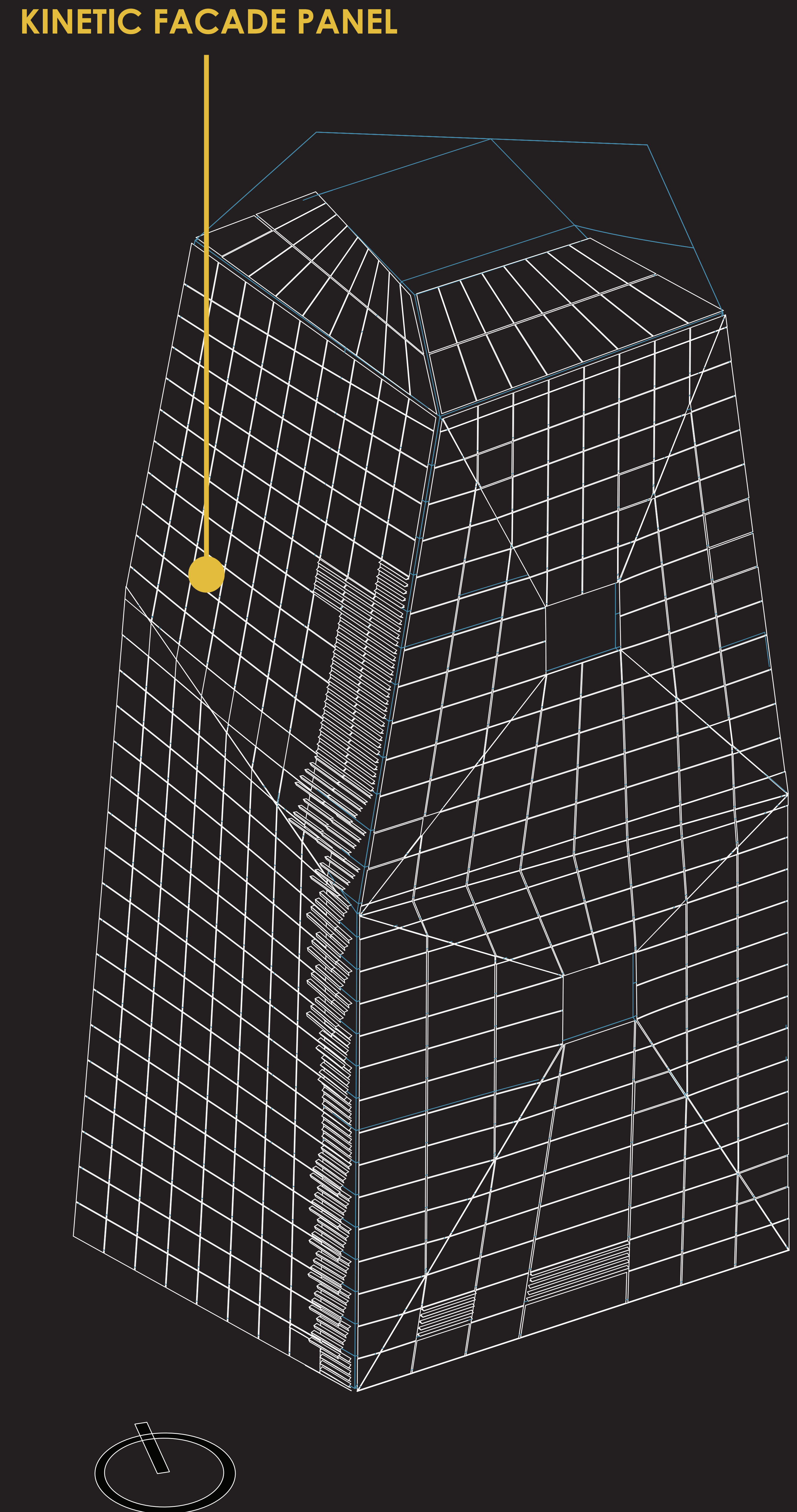
WEST ELEVATION DIAGRAM FULLY OPENED



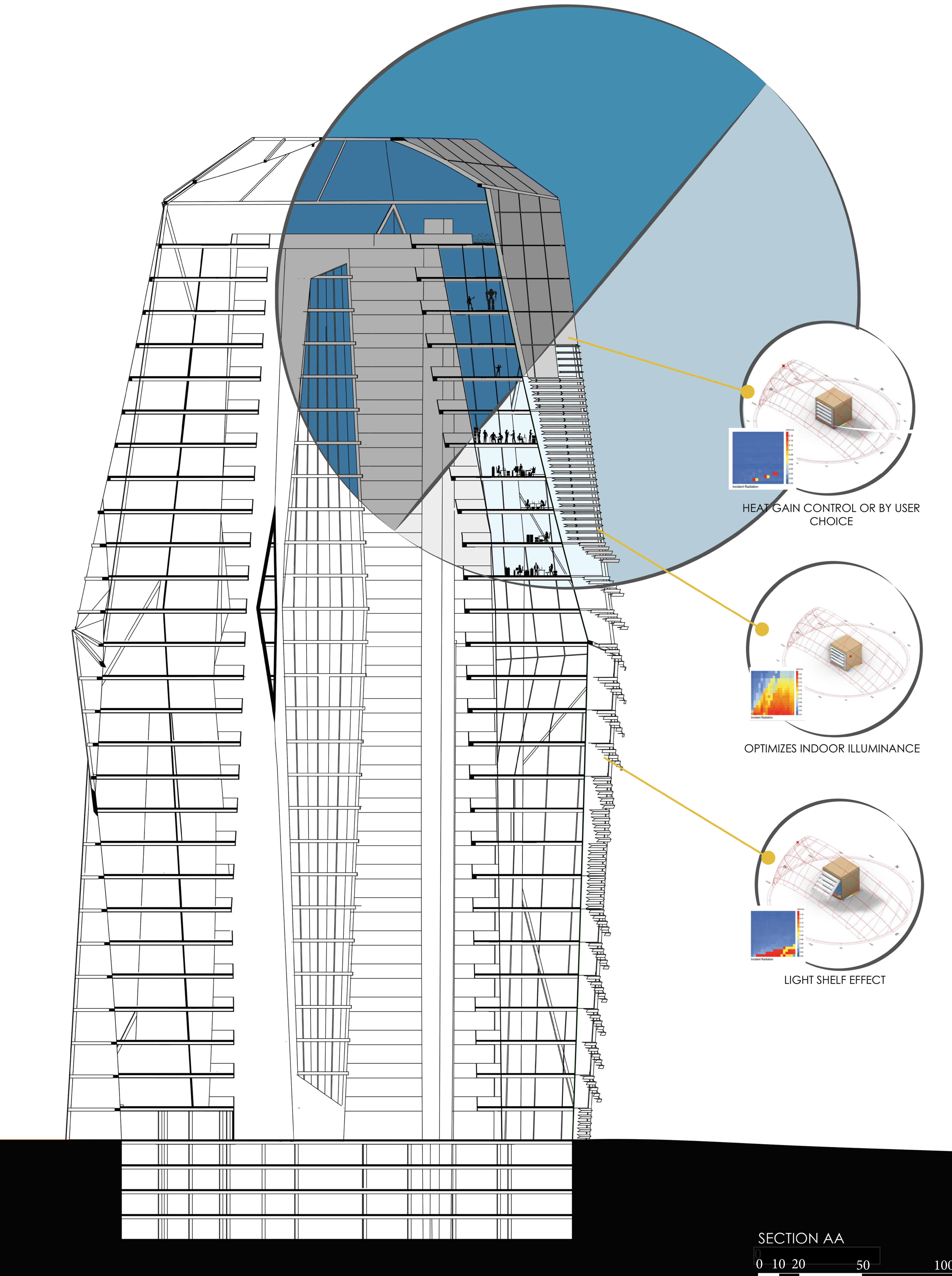

*WIND ENERGY HARVESTING TURBINES INSTALLED AT FOUR NORTHERN CROSS VENTILATION POINTS ENLARGED SECTION DIAGRAM*



NORTHWEST AXONOMETRY
STRUCTURE DIAGRAM




SOUTHEAST AXONOMETRY STRUCTURE DIAGRAM

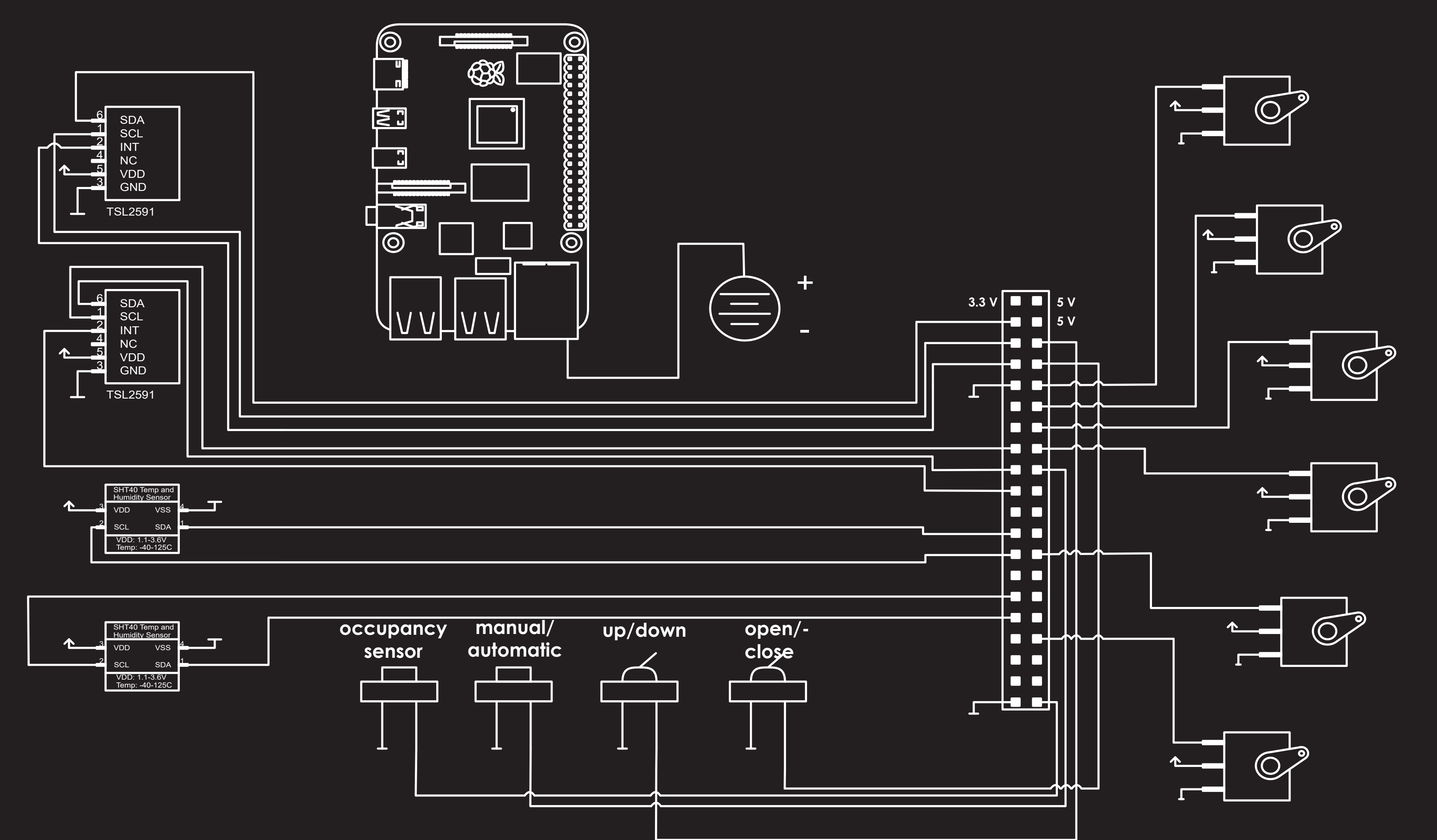


SECTION AA

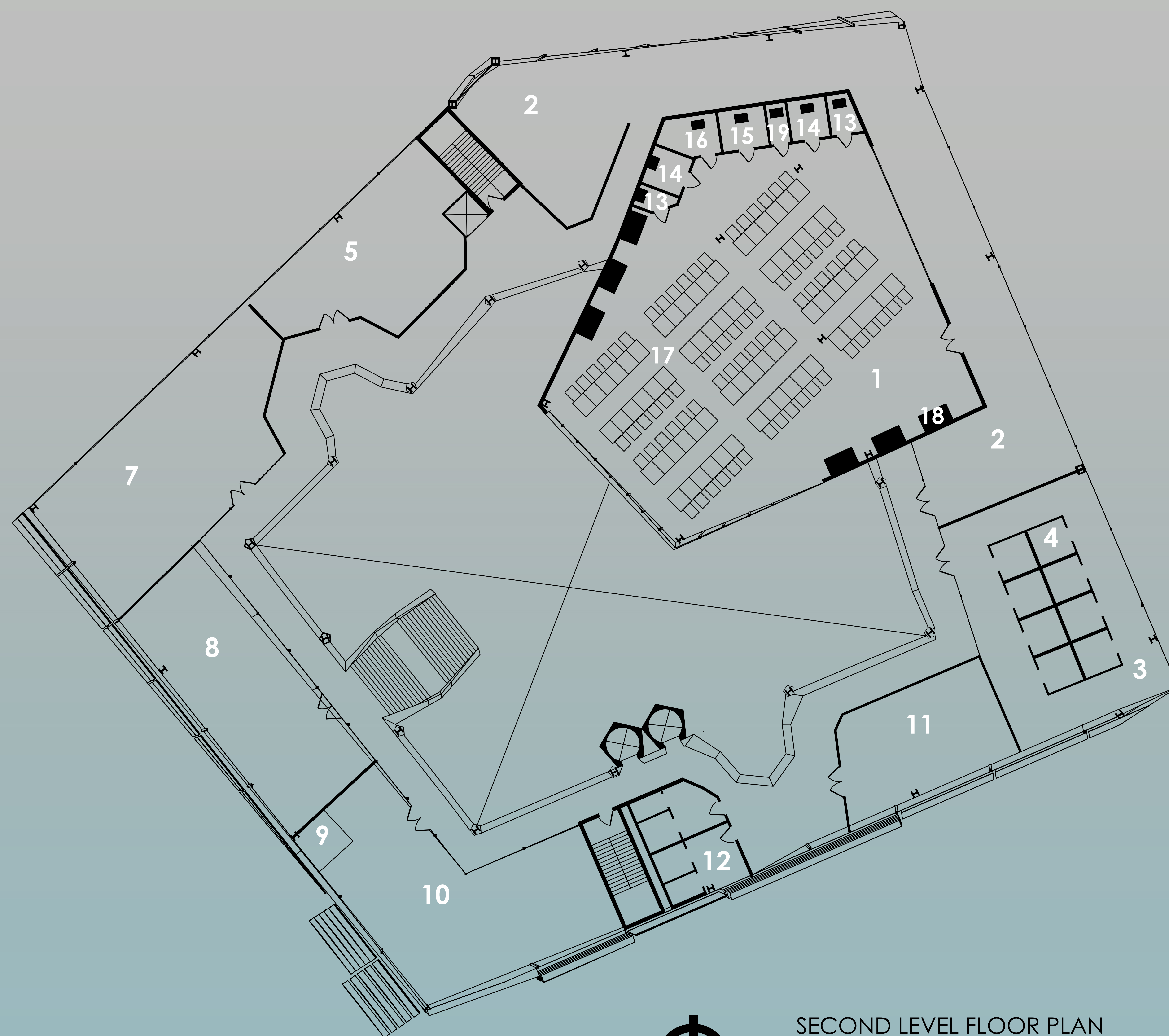
*In-progress prototype photos under different illuminance conditions*

*Responsive panels of prototype (figure above) dynamically adjust to changing environmental conditions to control natural light and reduce solar heat gain. This kinetic facade design is used in the design of data center.: by regulating the sunlight entering office spaces, the kinetic façade optimizes the lighting environment for employees while minimizing the heat load, thus decreasing the demand on the building's HVAC system. It is controlled through an interconnected network of sensors and a centralized control system. Each panel adjusts based on the data received, responding individually or collectively to create optimal shading and cooling conditions throughout the day. The panels could also be programmed to respond to weather forecasts, also adjusting to protect against anticipated heat or glare. Such adaptability would allow the façade to complement the building's overall energy management strategy, ensuring office spaces remain comfortable and productive while reducing energy consumption.*

*The kinetic façade is designed to seamlessly integrate with other information systems in the building, such as the Building Management System (BMS), which provides a centralized control interface. This integration allows the façade to communicate with HVAC, lighting, and security systems, synchronizing their operations for optimal energy management. For example, by monitoring and predicting sunlight exposure through strategically placed sensors, the kinetic façade can inform the HVAC system to adjust its cooling output in response to changing solar loads. In the same way, it interacts with the lighting system to optimize artificial light usage by using the available natural light in the office spaces. This interconnected approach supports this thesis goals by creating a responsive, intelligent building envelope that adapts dynamically to environmental changes. By reducing energy consumption and improving interior climate control, the kinetic façade not only enhances building sustainability but also contributes to occupant well-being and productivity.*



1. INTELLIGENT DATA CORE
2. PUBLIC EXHIBITION AREA OF INTELLIGENT DATA CORE OPERATIONS  VIEWING GALLERY WITH TOUCHSCREEN PANELS
3. INTERACTIVE LEARNING CENTER
4. VR ROOMS WITH HOLO TILE FLOOR
5. ROBOTICS TOY STORE
6. ENTRANCE POINTS
7. SMART APPLIANCE CENTER
8. TECH GADGET AND SMART HOME DEVICES
9. COFFEE MAKING ROBOTIC STAND
10. TECH LOUNGE
11. WORKSHOP
12. BATHROOM
13. TRANSFORMER
14. POWER SUPPLY AND UPS
15. SAFETY EQUIPMENT
16. CLIMATE FACILITIES
17. RACKS
18. CRAC
19. UPS BATTERY




SECOND LEVEL FLOOR PLAN
SCALE: 1/64''=1'

0 10 20 50 100


## 1. OPEN OFFICE AREA

*To accommodate a flexible seating arrangement for various teams, adaptable for different project needs and collaborative work. Modular workstations with ergonomic, movable furniture and kinetic partitions that can be reconfigured according to team size and project requirements. Desks with built-in power and data connections, and wireless charging pads. Ambient intelligence systems to adjust lighting and climate based on occupancy and environmental conditions.*

## 2. PRIVATE OFFICES AND MEETING ROOMS

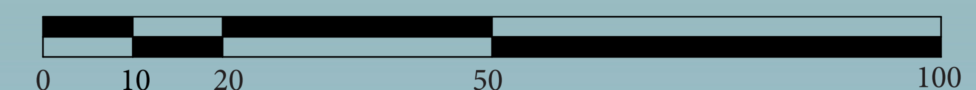
*To provide space for focused work and confidential meetings. Glass walls that can switch from transparent to opaque for privacy - electrochromic glass walls from atroum side. Each room equipped with smart displays and connectivity for seamless digital collaboration. Smart desks with touch screen surface capabilities, ergonomic chairs, and storage units that maximize space efficiency.*

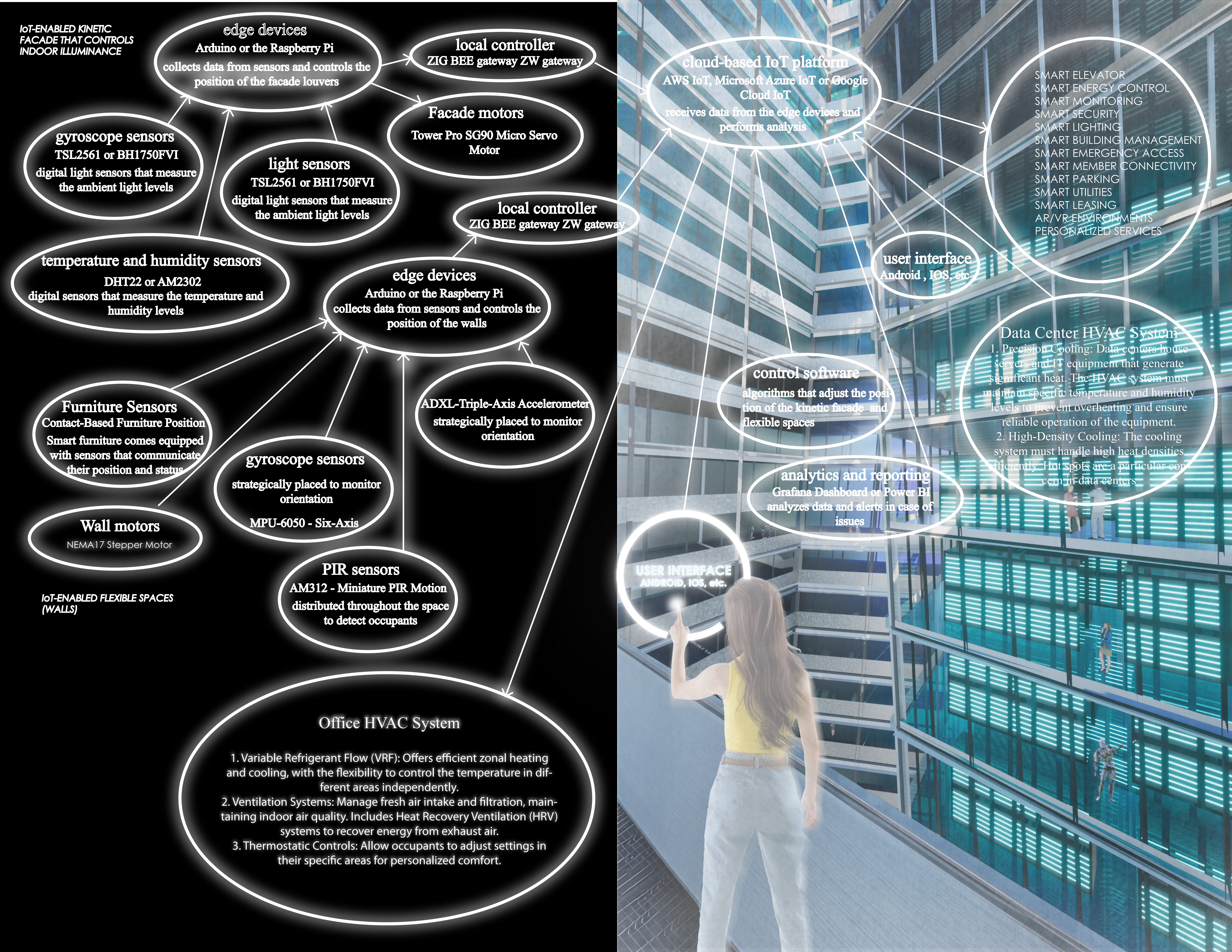
## 3. VR ROOMS

*Dedicated spaces for VR meetings, simulations, and presentations to enhance design, training, and client interactions. Soundproof rooms equipped with high-performance VR headsets and tracking systems, comfortable viewing chairs, adjustable lighting, and holo tile floors.*

4. SUPPORT ELEMENTS KITCHEN
5. DATA FARMING
6. BATHROOM
7.PRINTING ROOM / STORAGE AREA
8. TRANSFORMER
9. POWER SUPPLY AND UPS
10. SAFETY EQUIPMENT
11. CLIMATE FACILITIES
12. RACK
13. CRAC
14. UPS BATTERY
15. MODULAR GREEN WALLS

TWENTY FIFTH LEVEL FLOOR PLAN
SCALE: 1/64''=1'




IoT-ENABLED KINETIC FACADE THAT CONTROLS INDOOR ILLUMINANCE
edge devices
Arduino or the Raspberry Pi
collects data from sensors and controls the position of the facade louvers
local controller
ZIG BEE gateway ZW gateway
Facade motors
Tower Pro SG90 Micro Servo Motor
gyroscope sensors
TSL2561 or BH1750FVI
digital light sensors that measure the ambient light levels
light sensors
TSL2561 or BH1750FVI
digital light sensors that measure the ambient light levels
local controller
ZIG BEE gateway ZW gateway
temperature and humidity sensors
DHT22 or AM2302
digital sensors that measure the temperature and humidity levels
edge devices
Arduino or the Raspberry Pi
collects data from sensors and controls the position of the walls
Furniture Sensors
Contact-Based Furniture Position
Smart furniture comes equipped with sensors that communicate their position and status
ADXL-Triple-Axis Accelerometer
strategically placed to monitor orientation
gyroscope sensors
strategically placed to monitor orientation
MPU-6050 - Six-Axis
Wall motors
NEMA17 Stepper Motor
PIR sensors
AM312 - Miniature PIR Motion
distributed throughout the space to detect occupants
IoT-ENABLED FLEXIBLE SPACES (WALLS)
Office HVAC System
1. Variable Refrigerant Flow (VRF): Offers efficient zonal heating and cooling, with the flexibility to control the temperature in different areas independently.
2. Ventilation Systems: Manage fresh air intake and filtration, maintaining indoor air quality. Includes Heat Recovery Ventilation (HRV) systems to recover energy from exhaust air.
3. Thermostatic Controls: Allow occupants to adjust settings in their specific areas for personalized comfort.
cloud-based IoT platform
AWS IoT, Microsoft Azure IoT or Google Cloud IoT
receives data from the edge devices and performs analysis
SMART ELEVATOR
SMART ENERGY CONTROL
SMART MONITORING
SMART SECURITY
SMART LIGHTING
SMART BUILDING MANAGEMENT
SMART EMERGENCY ACCESS
SMART MEMBER CONNECTIVITY
SMART PARKING
SMART UTILITIES
SMART LEASING
AR/VR ENVIRONMENTS
PERSONALIZED SERVICES
user interface
Android , IOS, etc
Data Center HVAC System
1. Precision Cooling: Data centers house servers and IT equipment that generate significant heat. The HVAC system must maintain specific temperature and humidity levels to prevent overheating and ensure reliable operation of the equipment.
2. High-Density Cooling: The cooling system must handle high heat densities efficiently. Hot spots are a particular concern in data centers.
control software
algorithms that adjust the position of the kinetic facade and flexible spaces
analytics and reporting
Grafana Dashboard or Power BI
analyzes data and alerts in case of issues
USER INTERFACE
ANDROID, IOS, etc.

# CHAPTER VI

- Conclusion
- Used Sources
- List of Figures
- Appendices

# *CONCLUSIONS*

This thesis has explored the transformative potential of Industry 4.0 and 5.0 within architectural design, emphasizing the integration of smart technologies to enhance building autonomy and the user experience. The research has demonstrated how the incorporation of IoT, kinetic façades, and smart building management systems can significantly improve operational efficiency, sustainability, and user comfort.

Proposed design for a data center integrated within a mixed-use complex along with a developed kinetic façade prototype represents a step toward realizing buildings that dynamically interact with their surroundings to optimize energy use and indoor environmental quality. By using real-time data analytics, such systems can respond to changing environmental conditions and user needs, illustrating a shift from static architectural forms to dynamic, responsive structures.

Further studies could explore the integration of such architectural solutions within the broader context of smart city infrastructure. Research could focus on the interoperability of building systems with urban energy grids, transportation networks, and public services to enhance the overall efficacy and sustainability of urban environments.

# USED SOURCES


Alves, Joel, Tânia M. Lima, and Pedro D. Gaspar. "Is Industry 5.0 a Human-Centred Approach? A Systematic Review." Processes 11, no. 1 (January 7, 2023): 193. https://doi.org/10.3390/pr11010193.

"Industry 5.0: Towards More Sustainable, Resilient and Human-Centric Industry." Research and innovation, January 7, 2021. https://research-and-innovation.ec.europa.eu/news/all-research-and-innovation-news/industry-50-towards-more-sustainable-resilient-and-human-centric-industry-2021-01-07_en.

Law, Marcus. "Energy Efficiency Predictions for Data Centres in 2023." Data Centre Magazine, December 30, 2022. https://datacentremagazine.com/articles/efficiency-to-loom-large-for-data-centre-industry-in-2023.

Cano-Suñén, Enrique, Ignacio Martínez, Ángel Fernández, Belén Zalba, and Roberto Casas. 2023. "Internet of Things (IoT) in Buildings: A Learning Factory" Sustainability 15, no. 16: 12219. https://doi.org/10.3390/su151612219

Manganelli, Matteo, Alessandro Soldati, Luigi Martirano, and Seeram Ramakrishna. "Strategies for Improving the Sustainability of Data Centers via Energy Mix, Energy Conservation, and Circular Energy." Sustainability 13, no. 11 (May 28, 2021): 6114. https://doi.org/10.3390/su13116114.

Bajer, Marcin. "IoT for smart buildings-long awaited revolution or lean evolution." 2018 IEEE 6th International Conference on Future Internet of Things and Cloud (FiCloud): pp. 149–154. 2018. IEEE.

Sezer, Omer Berat, Dogdu, Erdogan and Ozbayoglu, Ahmet Murat. "Context-aware computing, learning, and big data in internet of things: a survey." IEEE Internet of Things Journal Vol. 5 No. 1 (2017): pp. 1–27.

Shah, Syed Faisal Abbas, Iqbal, Muhammad, Aziz, Zeeshan, Rana, Toqir A, Khalid, Adnan, Cheah, Yu-N and Arif, Muhammad. "The role of machine learning and the internet of things in smart buildings for energy efficiency." Applied Sciences Vol. 12 No. 15 (2022): p. 7882.

Abdou, Ossama A. "Effects of luminous environment on worker productivity in building spaces." Journal of architectural engineering Vol. 3 No. 3 (1997): pp. 124–132.

Verma, Anurag, Prakash, Surya, Srivastava, Vishal, Kumar, Anuj and Mukhopadhyay, Subhas Chandra. "Sensing, controlling, and IoT infrastructure in smart building: a review." IEEE Sensors Journal Vol. 19 No. 20 (2019): pp. 9036–9046.

Židek, Kamil, Pitel', Ján, Adámek, Milan, Lazorík, Peter
and Hošovsky, Alexander. "Digital twin of experimental smart manufacturing assembly system for industry 4.0 concept." Sustainability Vol. 12 No. 9 (2020): p. 3658.

Broo, Didem Gürdür, Bravo-Haro, Miguel and Schooling,
Jennifer. "Design and implementation of a smart infrastructure digital twin." Automation in Construction Vol. 136 (2022): p. 104171.

Chevallier, Zoé, Finance, Béatrice and Boulakia, Benjamin Cohen. "A Reference Architecture for Smart Building Digital Twin." SeDiT@ ESWC: pp. 1–12. 2020.

[Eneyew, Dagimawi D, Capretz, Miriam AM and Bitsuamlak, Girma T. "Toward Smart-Building Digital Twins: BIM and IoT Data Integration." IEEE Access Vol. 10 (2022): pp.
130487–130506.

Batistatou, Adamantia, Vandeville, Florentin and Delevoye- Turrell, Yvonne N. "Virtual reality to evaluate the impact of colorful interventions and nature elements on spontaneous walking, gaze, and emotion." Frontiers in Virtual Reality (2022): p. 61.

Wang, Hao, Chen, Xiaowei, Jia, Fu and Cheng, Xiaojuan."Digital Twin-Supported Smart City: Status, Challenges and Future Research Directions." Expert Systems with Applications (2023): p. 119531.

Mäkivierikko, Aram, Shahrokni, Hossein andKordas, Olga. "Designing energy feedback for a local social network." Energy and Buildings Vol. 199 (2019): pp. 88–101.

Jia, Ruoxi, Jin, Baihong, Jin, Ming, Zhou, Yuxun, Konstantakopoulos, Ioannis C, Zou, Han, Kim, Joyce, Li, Dan, Gu, Weixi, Arghandeh, Reza et al. "Design automation for smart building systems." Proceedings of the IEEE Vol. 106 No. 9 (2018): pp. 1680–1699.

Minoli, Daniel, Sohraby, Kazem and Occhiogrosso, Benedict. "IoT considerations, requirements, and architectures for smart buildings—Energy optimization and next generation building management systems." IEEE Internet of Things Journal Vol. 4 No. 1 (2017): pp. 269–283.

Voicu, Razvan Cristian and Chang, Yusun. "Stages of coopnet: A multipath parallel link architecture for next-gen networks." 2021 International Wireless Communications and Mobile Computing (IWCMC): pp. 592–597. 2021. IEEE.

Voicu, Razvan Cristian and Chang, Yusun. "Cooperative Networking Using Passive Discovery For Dynamic Environments." 2022 International Wireless Communications and Mobile Computing (IWCMC): pp. 1279–1284. 2022. IEEE.

Voicu, Razvan Cristian and Chang, Yusun. "Towards Programmable
Networking With CoopNet: A Horizontal Parallel Multipath Approach." 2023 International Conference on Computing, Networking and Communications (ICNC): pp. 111–116. 2023. IEEE.

Globa, Anastasia, Costin, Glenn, Tokede, Olubukola,Wang, Rui, Khoo, Chin Koi and Moloney, Jules. "Hybrid kinetic facade: fabrication and feasibility evaluation of full-scale prototypes." Architectural Engineering and Design Management Vol. 18 No. 6 (2022): pp. 791–811.

Kuhn, Tilmann-Eugen. "Design, Development and Testing of Innovative Solar-Control Facade Systems." Ph.D. Thesis, Ph. D. Thesis. National and Kapodistrian University of Athens, Athens. 2016.

Labib, Rania. "Façade Internet of Things (FIoT): A Human-Sensing, Two-Façade Communication Approach to Achieve Glare Reduction, Optimized Daylighting, and Solar Energy Collection." Ph.D. Thesis. 2019.

Ham, Sungil, Cho, Heayon, Lee, Hyunsoo and Lee, Ghang. "Prototype development of responsive kinetic façade control system for the elderly based on Ambient Assisted Living." Architectural Science Review Vol. 62 No. 4 (2019): pp. 273–285.

Al Khafaji, Ibtisam Abdulelah, and Raz Kamaran. "The Influence of Spatial Flexibility to Improve Sustainability of Interior Design by Using Smart Technology (Case Study –Future Smart Home in Iraq)." European Journal of Sustainable Development 8, no. 4 (2019): 438. https://doi.org/10.14207/ejsd.2019.v8n4p438.

Pereira, Ana C., Anabela C. Alves, and Pedro Arezes. "Augmented Reality in a Lean Workplace at Smart Factories: A Case Study." Applied Sciences 13, no. 16 (2023): 9120. https://doi.org/10.3390/app13169120.

Salamaga, Diana, David A. Guerra-Zubiaga, and Razvan Cristian Voicu. "Intelligent Facade Innovation (IFI): Using IIOT, Digital Twin, and next-Gen Architecture Designs." Volume 3: Advanced Manufacturing, October 29, 2023. https://doi.org/10.1115/imece2023-113117.

Kim, Dong-Hyun, Hieu Trung Luong, and Trang Thao Nguyen. "Optimizing the Shading Device Configuration of Kinetic Façades through Daylighting Performance Assessment." Buildings 14, no. 4 (April 8, 2024): 1038. https://doi.org/10.3390/buildings14041038.

Jalali, Sara, Eleonora Nicoletti, and Lidia Badarnah. "From Flora to Solar Adaptive Facades: Integrating Plant-Inspired Design with Photovoltaic Technologies." Sustainability 16, no. 3 (January 29, 2024): 1145. https://doi.org/10.3390/su16031145.

Bellini, Pierfrancesco, Paolo Nesi, and Gianni Pantaleo. "IOT-Enabled Smart Cities: A Review of Concepts, Frameworks and Key Technologies." Applied Sciences 12, no. 3 (February 3, 2022): 1607. https://doi.org/10.3390/app12031607.

"Spark." ArchDaily. Accessed May 1, 2024. https://www.archdaily.com/office/spark.

"The Spark." Snøhetta. Accessed May 1, 2024. https://old.snohetta.com/projects/388-the-spark.

Zotov, Victor, et al. "Victor Zotov's Team." ReMariupol. Accessed April 20, 2024. https://remariupol.com/en/visions/victor-zotovs-team.

# LIST OF FIGURES


1. Snøhetta. The Calgary Central Library. Photograph. Accessed May 1, 2024. https://old.snohetta.com/uploads/images/5161879305f-cad29d66bb43881234f6d_2048w.jpg

2. ArchDaily. Interior View of a Modern Building. Photograph. Accessed May 1, 2024. https://images.adsttc.com/media/images/5b2c/ffc6/f197/ccff/3900/0120/slideshow/2018015_N4.jpg?1529675707.ww

3. Bloomberg. "Heat Map of The Edge, Amsterdam." Photograph in "The Edge: The World's Greenest Building." Accessed May 7, 2024. https://www.bloomberg.com/features/2015-the-edge-the-worlds-greenest-building/img/Edge-heat-map.jpg.

4. PLP Architecture. "Positioning." Photograph. Accessed May 7, 2024. https://plparchitecture.com/wp-content/uploads/2022/04/Positioning-150x100.jpg.

5. New Atlas. The Edge Amsterdam: World's Most Sustainable Office Building. Photograph. Accessed May 7, 2024. https://assets.newatlas.com/dims4/default/ef31493/2147483647/strip/true/crop/900x506+0+47/resize/1200x675!/quality/90/?url=http%3A%2F%2Fnewatlas-brightspot.s3.amazonaws.com%2Farchive%2Fthe-edge-amsterdam-worlds-most-sustainable-office-building.jpg.

6. Human-Computer Interaction at Virginia Tech. "FutureHAUS." Photograph. Accessed May 6, 2024. https://hci.icat.vt.edu/content/hci_icat_vt_edu/en/research/futurehaus/jcr:content/content/adaptiveimage.transform/xl-medium/image.png.

7. "FutureHAUS Hover Animation." GIF. Accessed May 6, 2024. https://uploads-ssl.webflow.com/5c1d1ab7ea7f43456ec6c44d/5f9f7e-7b5619ec3174465c37_FH-hover-2.gif.

8, 9. Bedi, Guneet, Ganesh Kumar Venayagamoorthy, and Rajendra Singh. "Development of an IOT-Driven Building Environment for Prediction of Electric Energy Consumption." IEEE Internet of Things Journal 7, no. 6 (June 2020): 4912–21. https://doi.org/10.1109/jiot.2020.2975847.

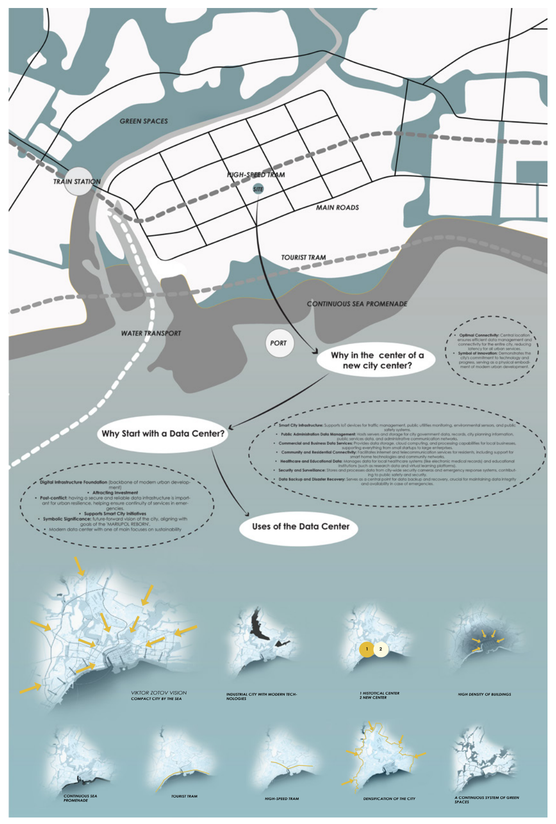
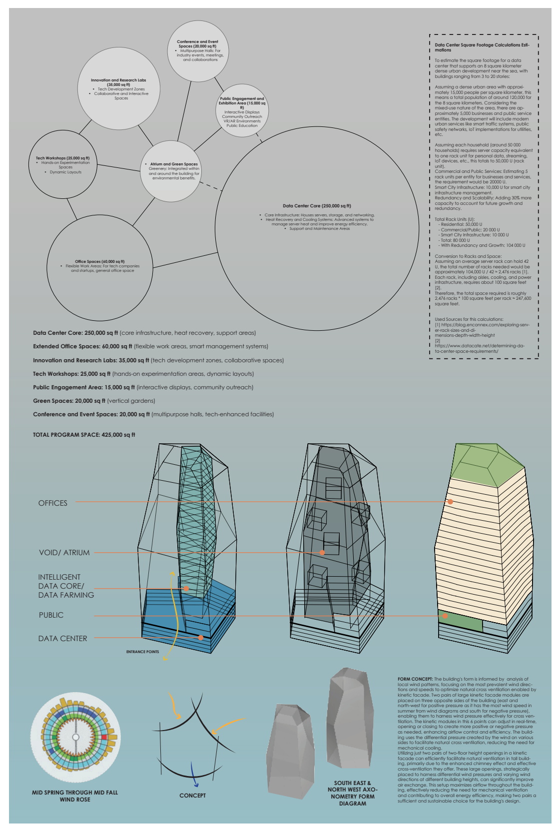
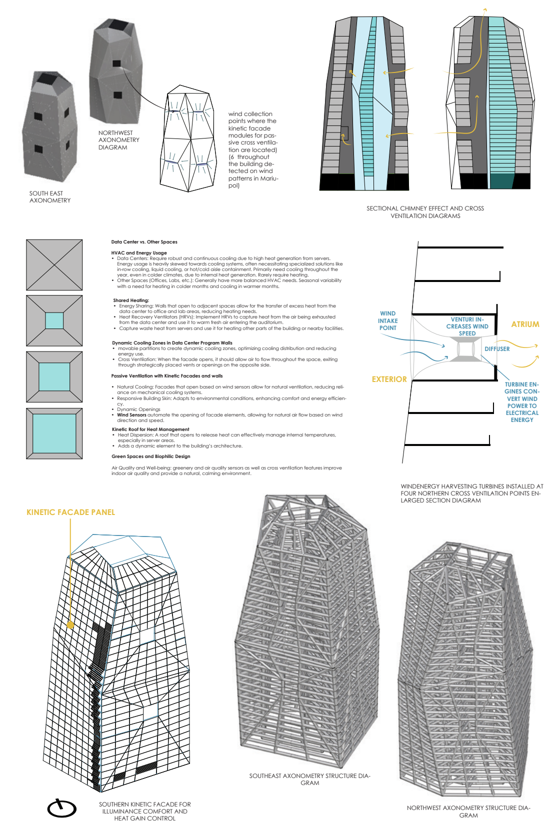
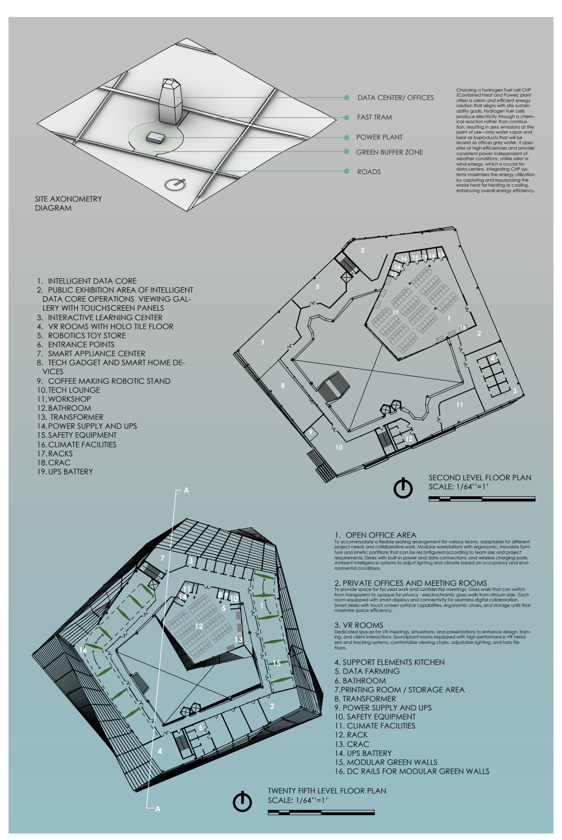
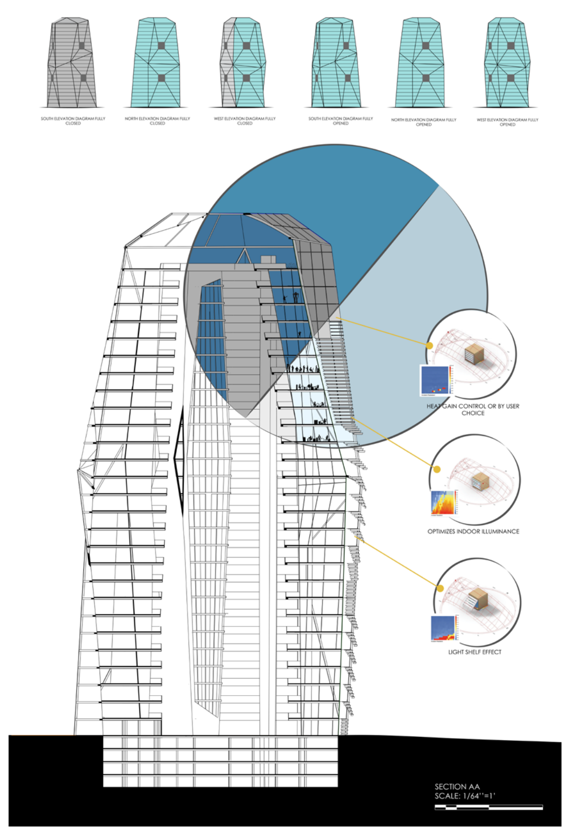
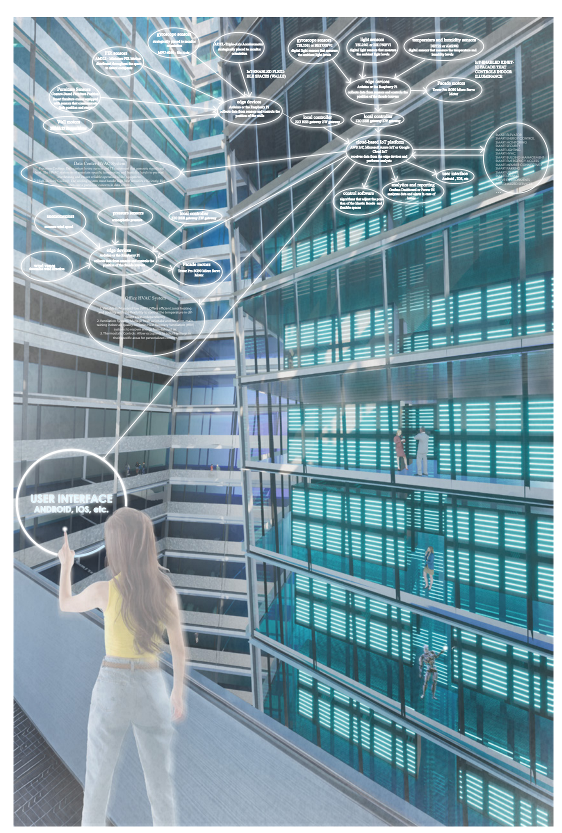
10. "The Wall Street Journal." "Title of Image." Accessed May 1, 2024. https://images.wsj.net/im-526298/8SR.

11. Smith, Amanda. "Schematic showing heat flow in a building CHP unit." Figure in [Title of Publication]. ResearchGate. Accessed May 6, 2024. https://www.researchgate.net/profile/Amanda-Smith-56/publication/326127794/figure/fig3/AS:647333704368130@1531347790787/Schematic-showing-heat-flow-in-a-building-CHP-unit.png.


# APPENDICES

*conceptual sculpture*

# APPENDICES

*some final boards*

# THANK YOU