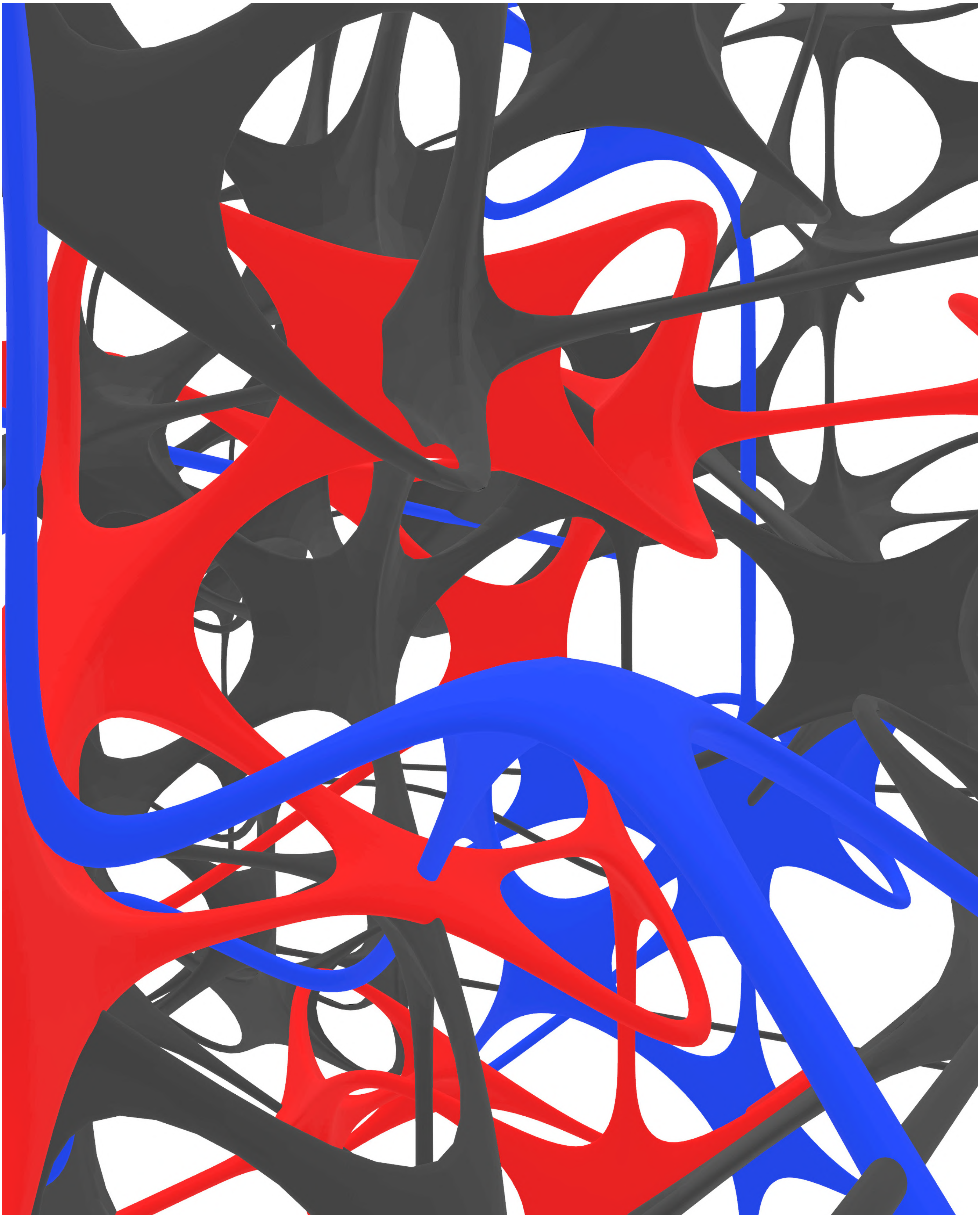

The Breathing Skeleton

Algorithmic Service Routing as a Tectonic Generator

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ASEM 01 - Master's Degree Project in Digital Architecture and Emergent Futures

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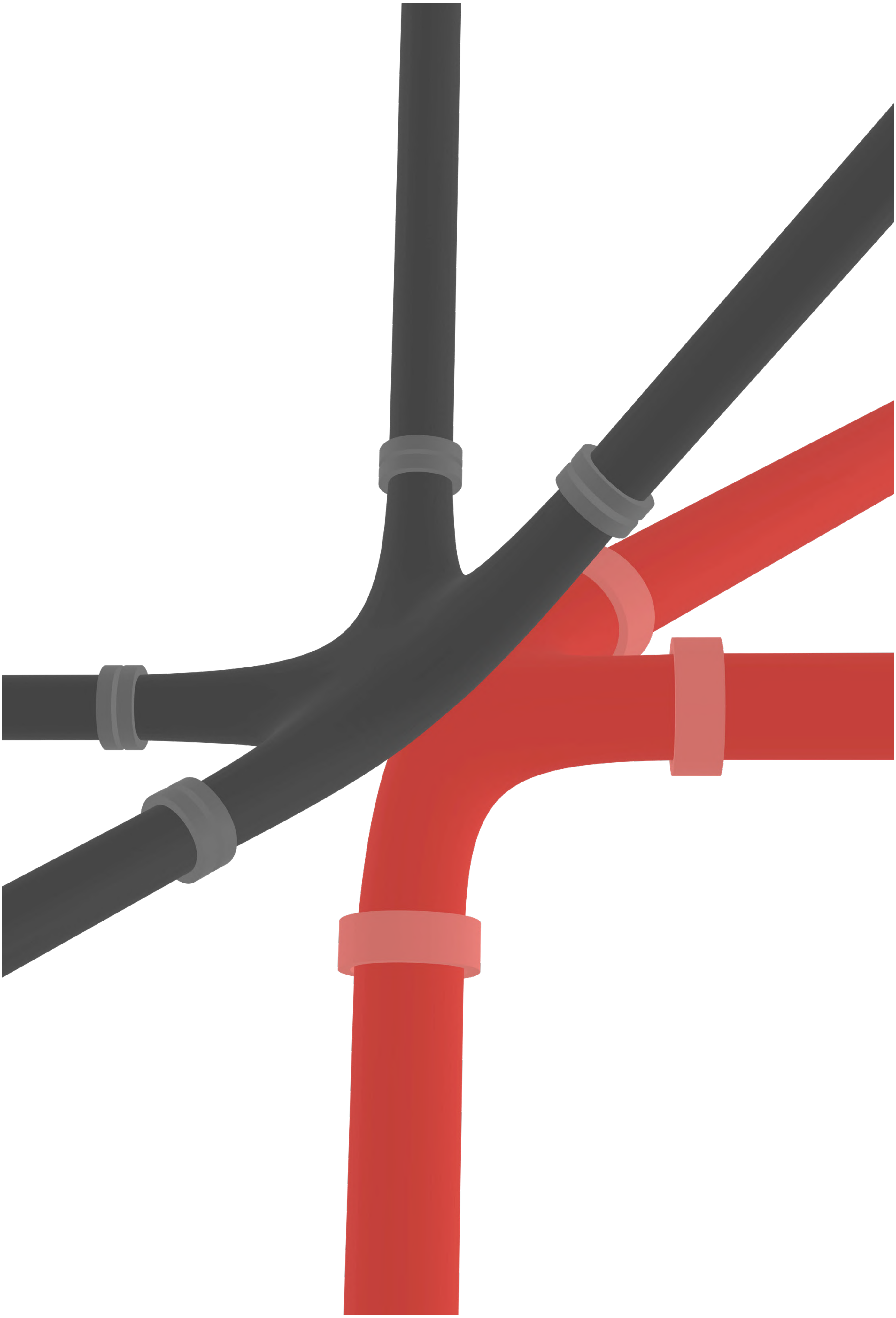

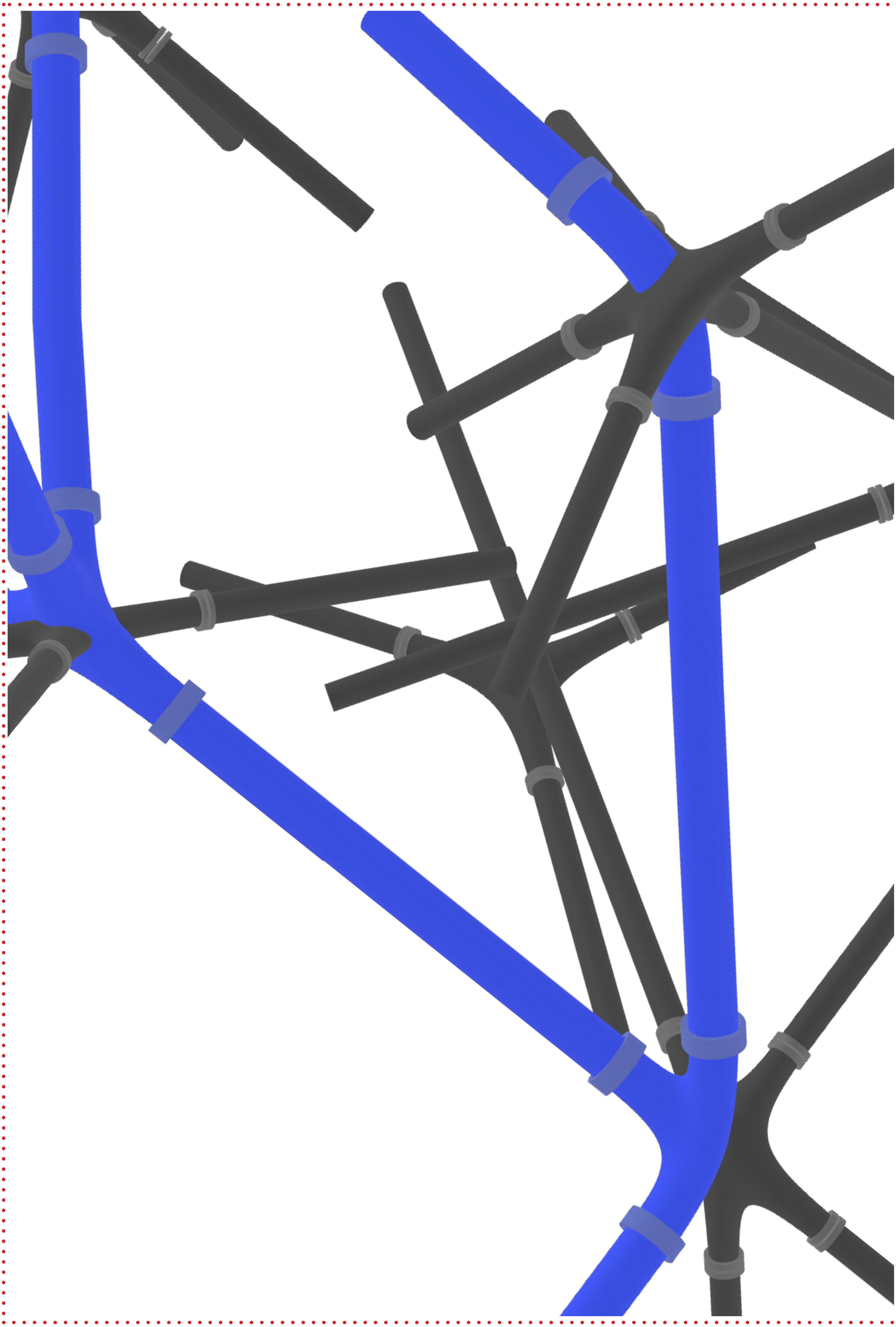

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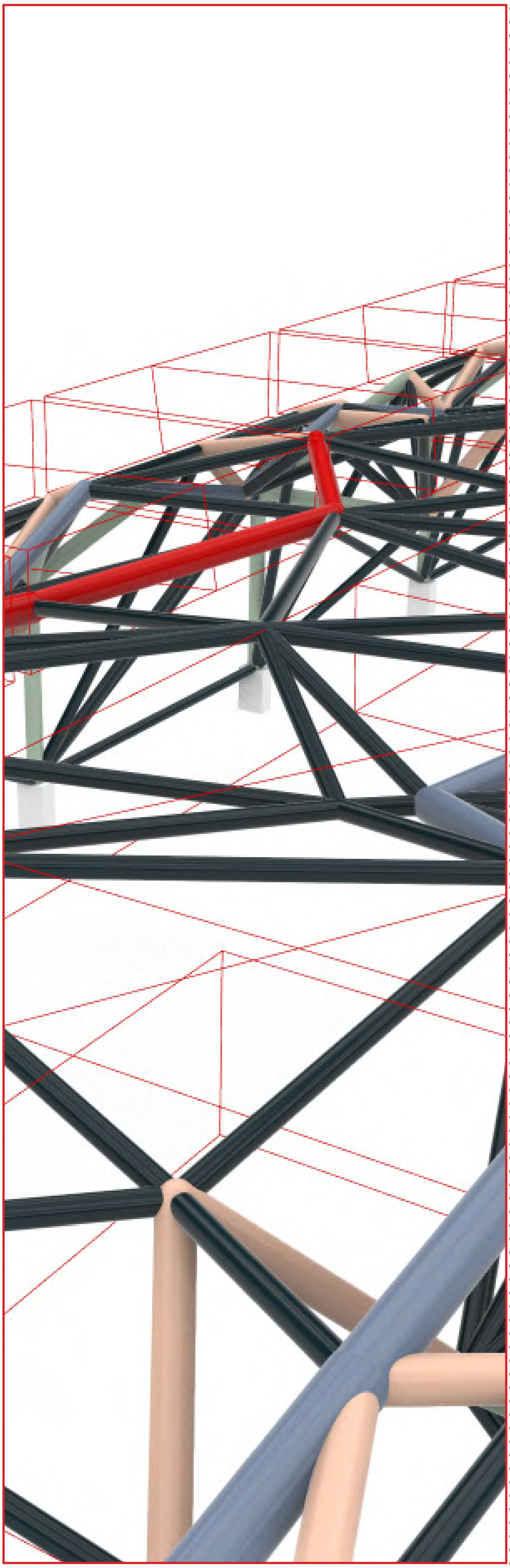
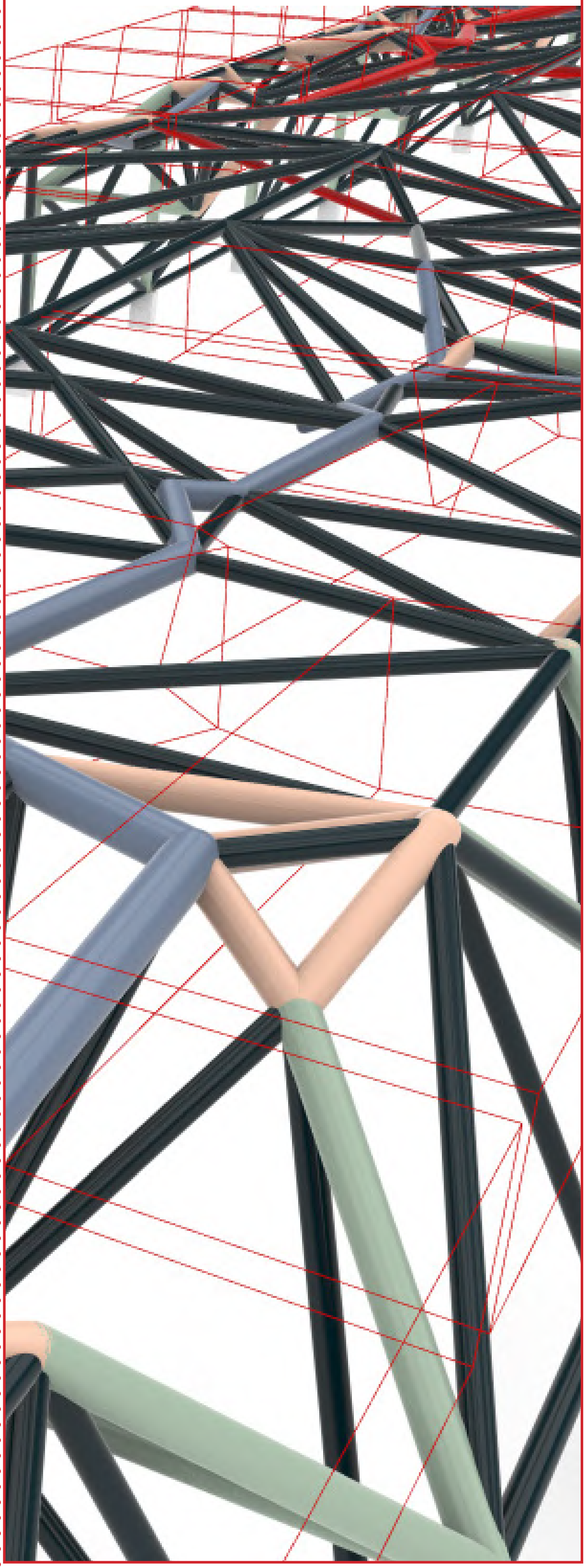
Abstract

The design process of buildings has historically treated mechanical,electrical, plumbing (MEP) Systems, particularly Heating, Ventilation and Air Conditioning (HVAC) as an afterthought which leads to compromised spatial qualities inefficient routing systems. This systemic marginalisation of environmental engineering withing architectural discourse has traditionally prioritised the visual form of the structural envelope over the thermodynamic performance of its interior. Consequently, modern architectural practices frequently encounter severe downstream conflicts during the construction phase, necessitating costly revisions and destructive structural compromises. (Abdelhameed & Saputra, 2020)

This thesis explores the integration of HVAC services during the conceptual architectural design stage using generative routing algorithms. Recognizing ventilation as the most space occupying building service, this project shifts away from traditional manual routing and explores computational path finding. Initial experiments with Agent-based Modelling (ABM) proved too chaotic and unstandardized, leading to the formulation of a custom rule-based logic utilising 'Minimum Spanning Trees' and 'Steiner Minimal Trees'. These algorithmic methodologies operate within the parametric environment of Grasshopper and Python, establishing rigorous mathematical constraints that prioritize orthogonal efficiency, structural clash avoidance, and optimal thermodynamic distribution metrics.

These algorithmic workflows are applied to a real world renovation case study, Academic Block 3 at the Indian Institute of Technology (IIT) Delhi. By developing Manhattan MST for the efficient rectilinear routing on the ground floor, and expressive Steiner trees on the first floor, the research culminates in a newly proposed lightweight top floor. Here, a 3D Steiner network dictates both the HVAC ducting and the structural framework simultaneously, featuring custom 3D joints that integrate air distribution and load transfer. The findings demonstrate that generative routing can elevate building services from hidden necessities to the primary architectural design drivers, bridging the intellectual and physical gap between the structural skeleton and the mechanical respiratory systems of a building.





1. Introduction

1.1 Background

In the contemporary architectural landscape, building services are increasingly recognised as fundamental to the success of any construction project. Heating, Ventilation and Air Conditioning (HVAC) systems act as the vital backbone of a building, yet they are frequently treated as a secondary afterthought during the conceptual design phase. This late integration of building service systems (BSS) often leads to time consuming modifications, increased costs and negative impacts on both the exterior aesthetics and interior spatial qualities of a structure (Al-Saeed & Al-Hajri, 2020).

The financial and spatial implications of these systems are staggering. The capital and installation costs of building services in modern commercial structures routinely consume 50% of the total construction budget, and in highly serviced facilities like sports centers, this figure can easily exceed 75% (Chudley & Greeno, 2012). Furthermore, the physical infrastructure of these services can take up to 15% of a building's entire internal volume (Chudley & Greeno, 2012). When architects fail to coordinate these massive infrastructural requirements early in the design process, it results in unsightly arrangements, lowered ceiling heights, and even the physical chiseling or breaking down of load-bearing structural members to accommodate mechanical systems. The coordination processes of overlaying two-dimensional drawings of different service systems, each designed by different specialized engineers, has been identified as a major cause of clashes and conflicts (Abdelhameed & Saputra, 2020).

As architectural historian Reyner Banham argues, the history of architecture has traditionally and falsely divided the art of building into two intellectually separate parts: the structure, which is celebrated, and the mechanical services, which have been historically excluded from academic discussion (Banham, 1969).

1.2 Why ventilation?

While plumbing and electrical conduits require spatial coordination, ventilation systems are undeniably the most space-occupying of all building services. The massive cross-sectional area of supply and return air ducts demands extensive initial planning to prevent spatial clashes with structural beams, drop panels, and suspended ceilings (Al-Saeed & Al-Hajri, 2020). Because air cannot be pressurised and routed through small, flexible conduits in the same manner as water or electricity, the geometry of HVAC ducts is inherently rigid and volumetric. Therefore, if architecture is to become more efficient, environmentally responsive, and honest in its tectonic expression, the routing of ventilation services must be prioritised and integrated into the conceptual stage of the design process.

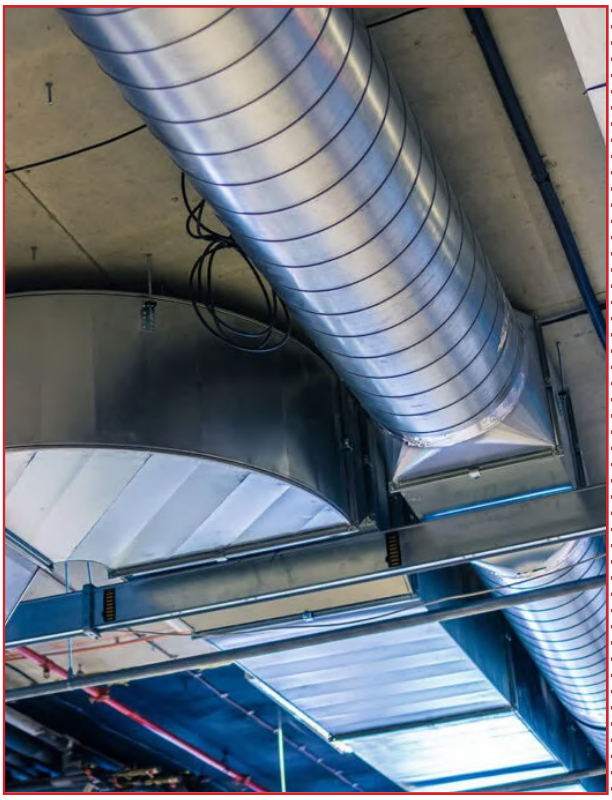


Fig 1

1.3 Motivation

The integration of mechanical systems has long been a defining challenge in modern architecture. While many traditional designs primary design attempt to conceal these utilities, visionary architects have historically used them as primary design drivers. Louis I Kahn famously addressed this through his philosophy of 'served and servant spaces' establishing a strict structural order that gave meaningful hierarchy to spaces harbouring mechanical ducts and pipes, rather than treating them as intrusions. Similarly, the Centre Pompidou revolutionised post-war architecture by exhibiting all building services externally, turning technical infrastructure into a celebrated aesthetic feature and maximizing interior flexibility. Building upon these precedents, this thesis argues that integrating HVAC systems during the early conceptual stage can elevate building services from hidden necessities to expensive architectural elements.

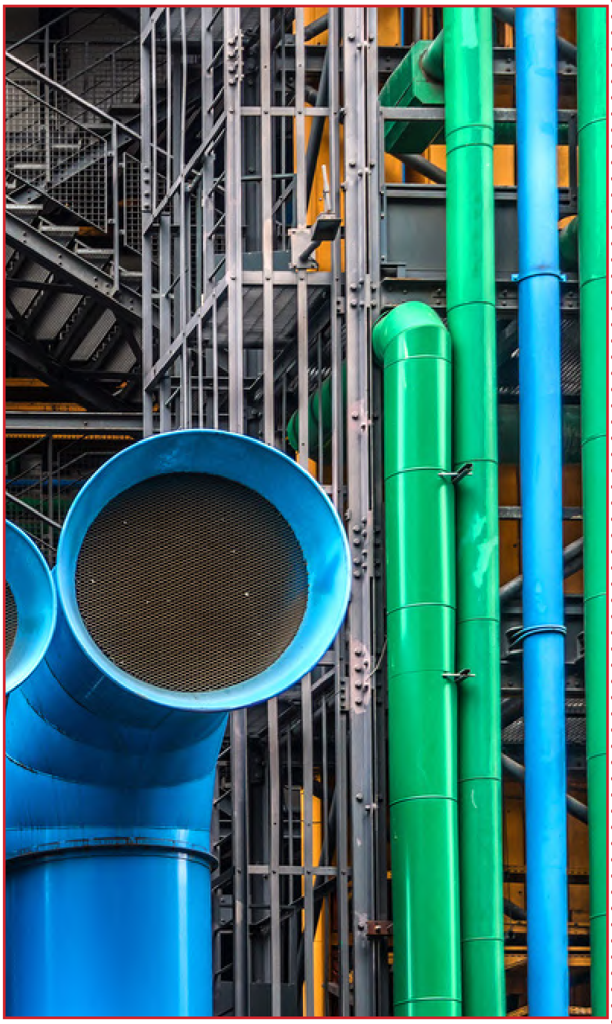


Fig 2

Fig 1 - Ventilation Ducts attached to the ceiling, www.enviguard.com
Fig 2 - Blue ducts on the facade of Centre Pompidou, Kiev Victor, Shutterstock

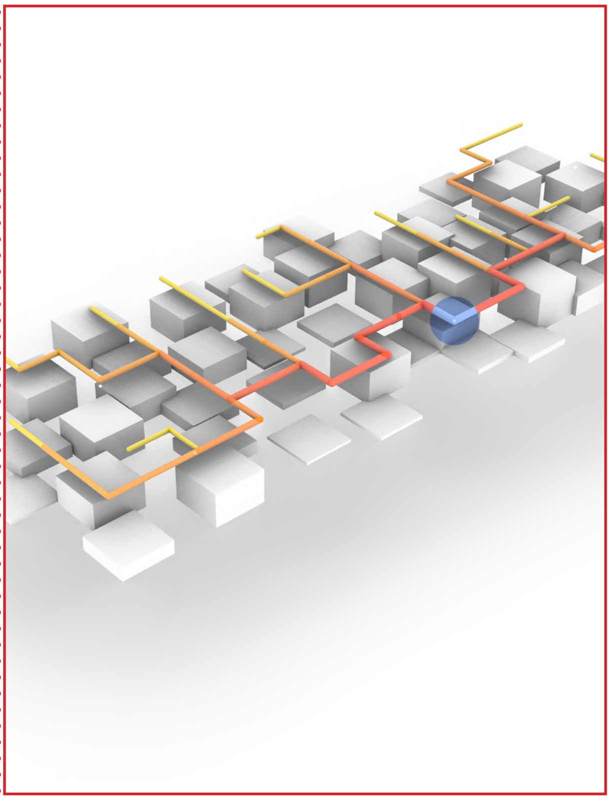


Fig 3

1.4 Computational Methodology

To achieve seamless service integration, this research investigates the application of generative routing algorithms. Initial explorations into Agent-Based Modeling (ABM) for duct routing revealed that the stochastic movement of autonomous agents was too slow, chaotic and lacked the standardisation required for practical HVAC layouts. Consequently, the methodology shifts towards a heavily controlled, rule-based path-finding system. This approach utilizes Manhattan Minimum Spanning Trees (MST) to calculate highly efficient, rectilinear paths, and Steiner Trees to introduce controlled 3D branching and non-orthogonal diagonal routing logic. By parameterizing these algorithms within a Python-driven computational environment, the designer gains the ability to rapidly simulate, evaluate, and optimize complex spatial networks before a single physical component is manufactured, effectively shifting the design paradigm from reactive clash detection to proactive clash avoidance.

Fig 4

Fig 1 - Simulation showing piping connections
Fig 2 - Image of IIT Delhi corridor, Bhavya Rishi

1.5 Case study application

The generative routing framework is validated through an alternate proposed renovation of Academic Block 3 at the Indian Institute of Technology (IIT) Delhi. Built between 1961 and 1968 by architect J.K. Chowdhury and structural engineer Gulzar Singh, the IIT Delhi campus is a landmark of modernist architecture characterised by its stark, exposed concrete form. The project brief required the renovation of the ground and first floors without compromising the existing historic structure, culminating in the addition of a new lightweight structure on the top floor/ terrace. By deploying Mahnattan MST for hidden efficiency on the ground floor and expressive 3D Steiner networks to dictate both the structural joints and HVAC routing on the upper levels, this thesis demonstrates how algorithmic pathfinding can bridge the gap between complex building services and structural architectural design.

1.6 Research questions

1. How can generative routing algorithms be utilised to integrate HVAC services seamlessly during the conceptual design stage?

2. How can pathfinding algorithms (such as MST and Steiner Trees) transition building services from hidden utilities into expressive architectural elements?

3. In what ways can a 3D generative network dictate both the structural system and the HVAC joint logic in a cohesive architectural intervention?

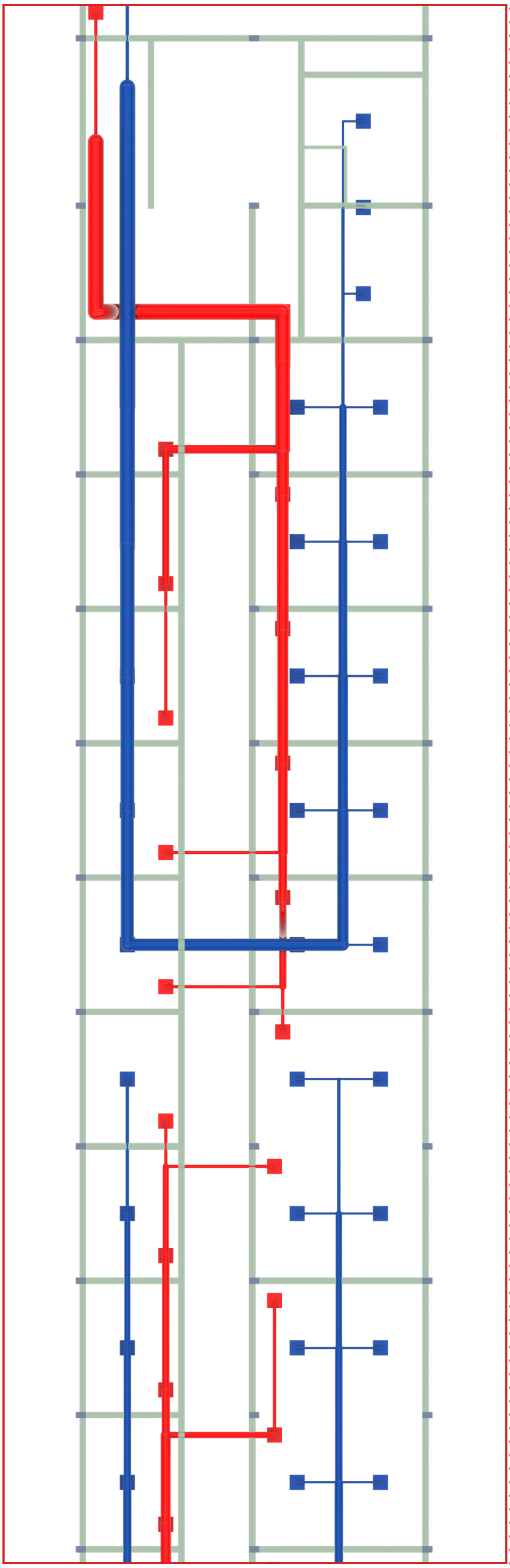


Fig 5

Simulation showing ducting logic

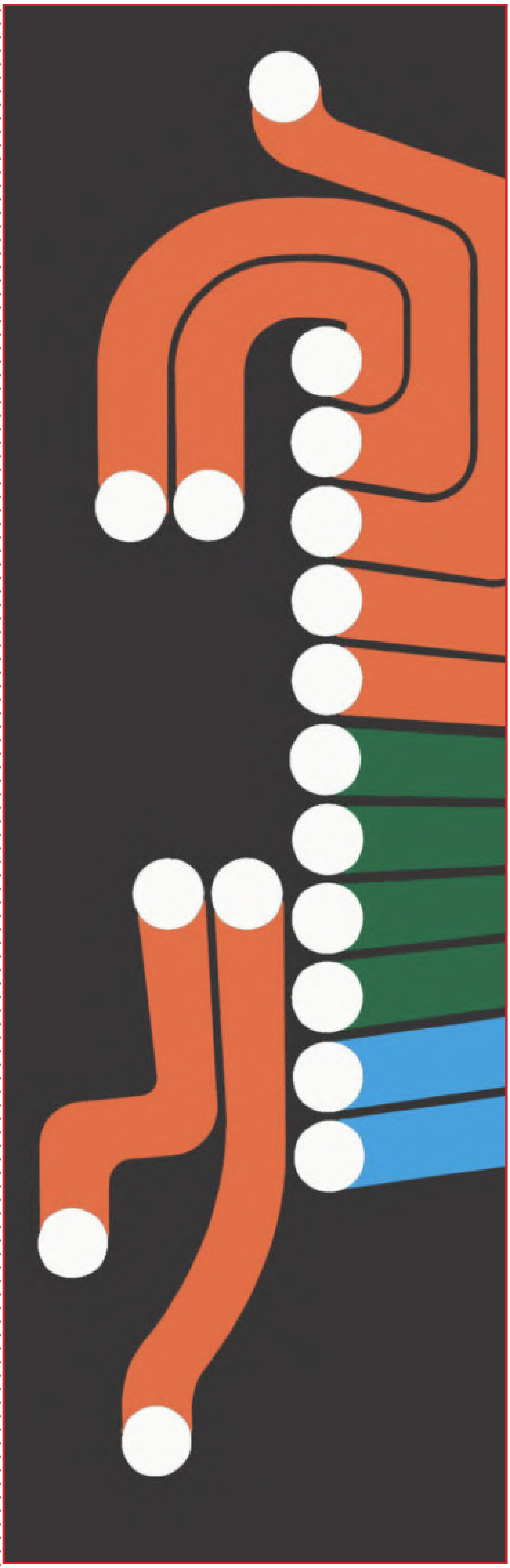


Fig 6

Cover Page, Architecture of the Well Tempered Environment, Reyner Banham

2. Literature Review

2.1 The Historical Marginalisation of Mechanical Services

In his seminal work 'The Architecture of the Well-Tempered Environment', Reyner Banham argues that the discipline of architecture has suffered from a fundamental flaw, the persistent intellectual separation of structure and mechanical services (Banham, 1969). Historically, architectural discourse has almost entirely excluded the topic of mechanical servicing, focusing overwhelmingly on the external forms of habitable volumes as revealed by their structures. Banham categorised environmental management into three distinct approaches.

The first is the "conservative" mode, reliant on massive, thermal storing structures.
The second is the "selective" mode, utilising features like overhanging roofs and louvered grilles to admit moving air while excluding visual intrusions and rain
The third is the modern "regenerative" mode, which relies on power operated systems like HVAC to actively control humidity and temperature.

The regenerative mode of environmental management is the hallmark of modern building technology. However, its relevance is especially prominent when evaluating the immense role that architecture and building construction play in global emissions (Banham, 1969). Banham highlighted that over reliance on newer regenerative technology was frequently used to cover up the shortcomings in designs that were solely focused on skin-deep ornamentations, putting the concept of a holistic, well-tempered environment on the back seat. Despite the profound alterations wrought in architecture by the electric lamp or air conditioning, the fact that these alterations were initially invisible in outward form denied them a primary place in the history of architecture, relegating them to the domain of engineers (Banham, 1969).

2.2 The philosophy of service integration: Kahn's Servant and Served Spaces

The challenge of integrating massive mechanical systems into the architectural form became a defining struggle of mid-century modernism. A foundational theoretical approach to the issue was developed by the eminent 20th century architect Louis I. Kahn. Kahn pioneered the concept of 'served and servant spaces', a philosophy that fundamentally categorises a building's footprint into strict functional hierarchies (Shih, 2020). In this paradigm, 'servant spaces' are the areas that contain utilities, mechanical equipment, HVAC ducts, exhaust shafts, and stairways, while 'served spaces' are the primary habitable areas designed for human use and unhindered occupation (Kareem, 2021).

Kahn was highly critical if the conventional practice of hiding mechanical systems behind dropped ceilings. He famously wrote in Perspecta in 1957: "The space order concept must extend beyond the harboring of the mechanical services and include the 'servant spaces' adjoining the spaces served. This will give meaningful form to the hierarchy of spaces" (Kahn, 1957). Kahn's strategy was to integrate these mechanical services directly into the structural order of the building, extracting them from hidden ceiling voids and giving them monumental form (Shih, 2020).

This philosophy is most vividly masterminded in the Richards Medical Research Laboratories at the University of Pennsylvania, constructed between 1957 and 1961. For this project, Kahn designed distinct monumental exterior brick shafts specifically to house the stairwells and massive air exhaust ducts (Brownlee, 2010). As Banham pointed out, by giving monumental external bulk to the accommodations for mechanical services in the Richards Laboratories, Kahn forced architectural writers to finally attend to the topic of environmental services in a way that no recent innovation had done (Banham, 1969). By pulling the 'servant' mechanical infrastructure to the exterior perimeter of the building, Kahn achieved maximum unobstructed, column free spaces for the 'served' laboratories inside (Brownlee, 2010).

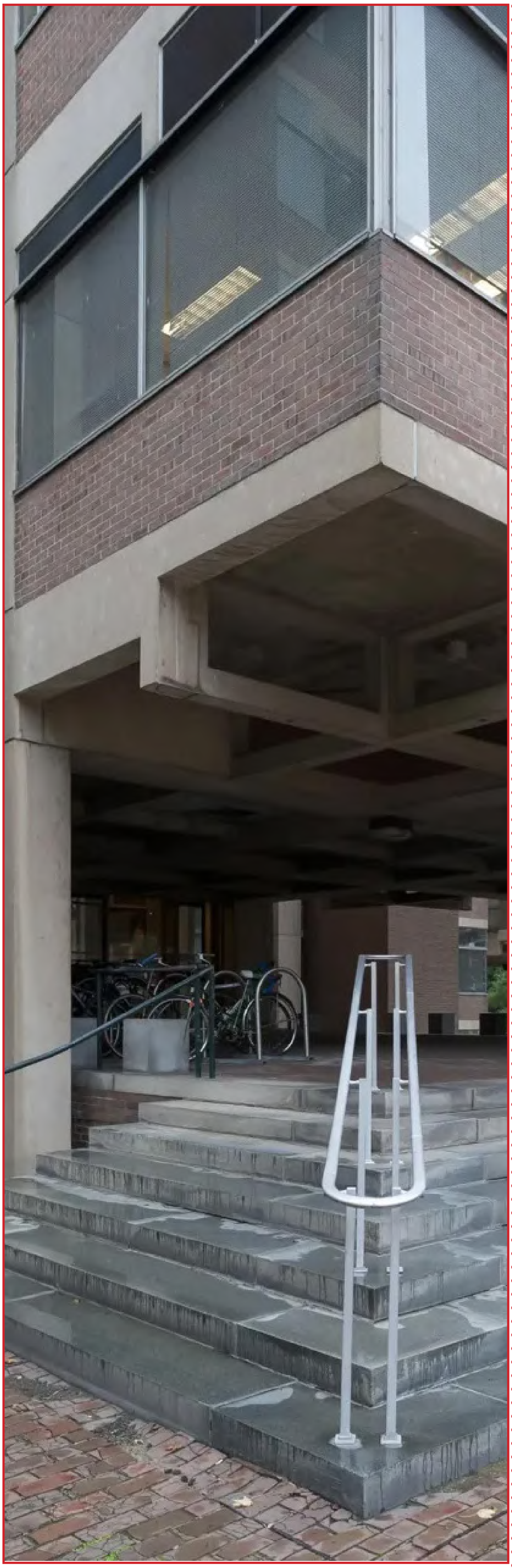


Fig 7

Space for ducts and other services in between beams, Richards Medical Laboratories, Xavier de Jaureguiberry, Archeyes

Fig 8

Space for ducts and other services in between beams, Richards Medical Laboratories, Xavier de Jaureguiberry, Archeyes

Kahn further refined this integration at the Salk Institute for Biological Studies in LA Jolla, California (1959-1967). Tasked with creating a facility that could accommodate constantly evolving scientific equipment without disrupting the research spaces. Kahn designed full height interstitial 'service floors' between the laboratory levels. These massive, occupiable structural trusses housed all the HVAC ductwork, piping, and electrical conduits, treating the mechanical services with the same tectonic reverence as the habitable rooms above them (Shih, 2020). This approach established a new moral seriousness in architecture, proving that mechanical systems when given their own dedicated structural expression, could define the monumental aesthetic of a building.

2.3 Structural Expressionism and the Centre Pompidou

While Louis Kahn sought to elegantly compartmentalise services within monolithic structural shafts or interstitial trusses, a radically different and far more explicit approach was taken a decade later. Driven by the technological optimism of the 1970s, the 'High-Tech Architecture' or 'Structural Expressionism' movement emerged. This architectural style sought to communicate the underlying structure and function of a building throughout its interior and exterior, treating mechanical systems and construction logic as integral parts of architectural expression (Banham, 1969).

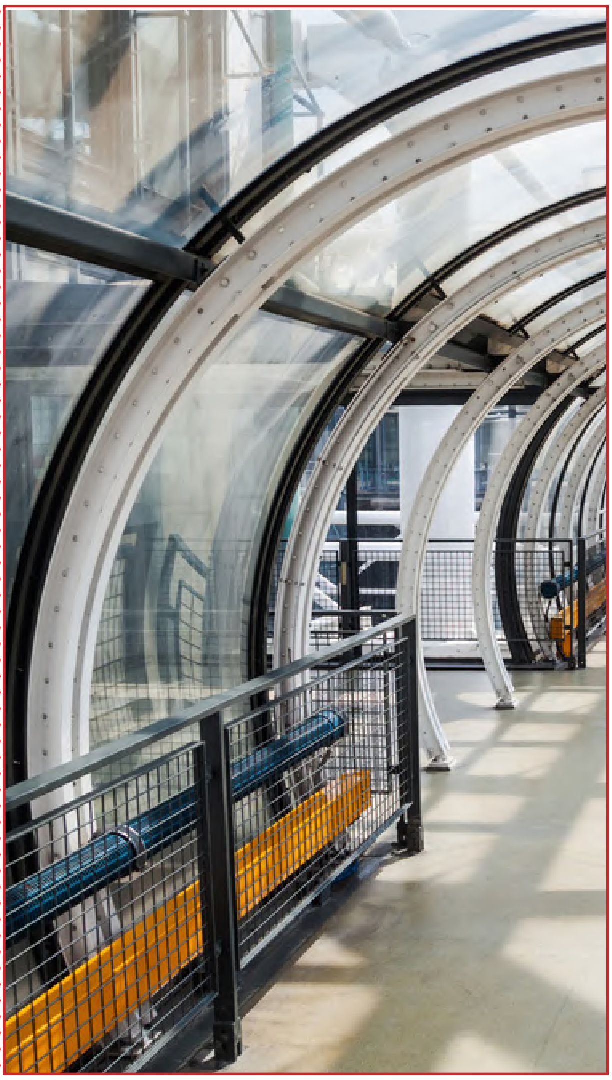


Fig 9

Tunnel corridor inside Centre Pompidou, Christian Mueller, Shutterstock

The apotheosis of this movement was the Centre Pompidou in Paris, realized between 1971 and 1977 by architects Renzo Piano and Richard Rogers. The Pompidou completely transformed the post-war architectural paradigm by turning the building 'inside-out' in a style sometimes referred to as 'Bowelism' (Hamzeian, 2018). Instead of reverting to traditional solutions like service cores or suspended ceilings, they chose to exhibit the technical infrastructure as the primary architectural facade. The structural stability of the building was achieved through massive 10-tonne cast steel elements called 'gerberettes', which held the externalized service lattice away from the main habitable floors.

As documented by architectural historian Boris Hamzeian, the evolution of the Pompidou's air-conditioning system reflects a profound shift toward integrating technical services as a new figure of architecture (Hamzeian, 2018). Initially conceived as simple functional tools, the air-treatment units and distribution ducts were re-imagined as symbolic and didactic devices designed to render the building a comprehensible, "man-scale machine". The architectural design iterations progressed rapidly, initially utilizing clipped-on air-treatment units located at the back of the building, the services were eventually transformed into a sophisticated 'three-dimensional wall' containing the distribution ducts directly on the facade. The new system consisted of individually controllable air-treatment units taking up about a third of the roof's floor area, pushing air down through a module of two ducts set into openings in the roof. To make this complex mechanical exhibition understandable and joyful to the public, the architects implemented a strict color code for the exposed services, blue for the air-conditioning and HVAC flows, yellow for electrical conduits, green for water circuits, and red for pedestrian circulation. The Centre Pompidou proved that building services do not need to be hidden inconveniences. Through deliberate design and technological transparency, HVAC ductwork became a celebrated, iconic architectural driver.

Fig 10

Gerberettes on the facade of Centre Pompidou, Francis Toussaint, ArchDaily

Fig 11

Gerberettes on the facade of Centre Pompidou, Francis Toussaint, ArchDaily

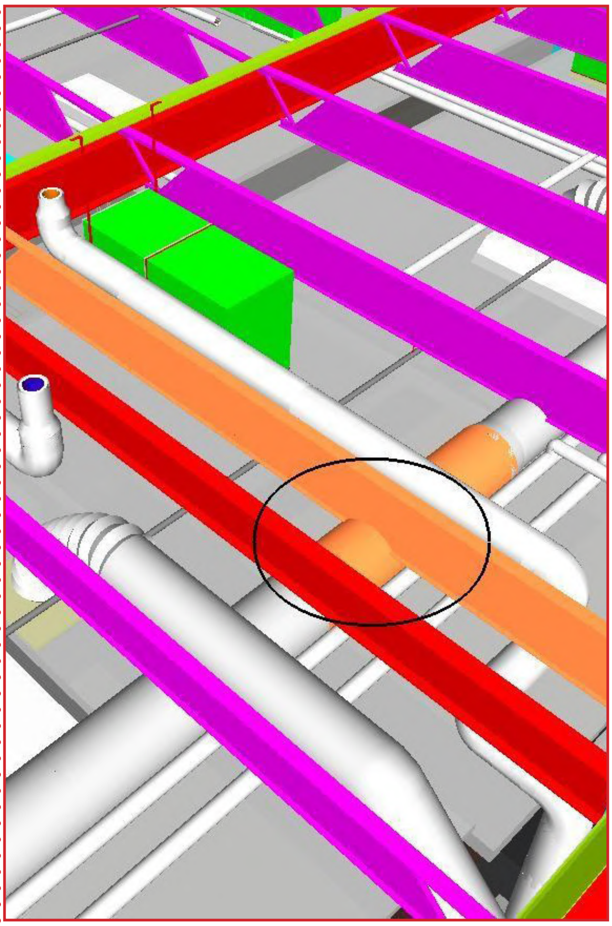


Fig 12

Image showing MEP clash and clash detection, https://bimandlayout.com/mep-clash-detection-services/

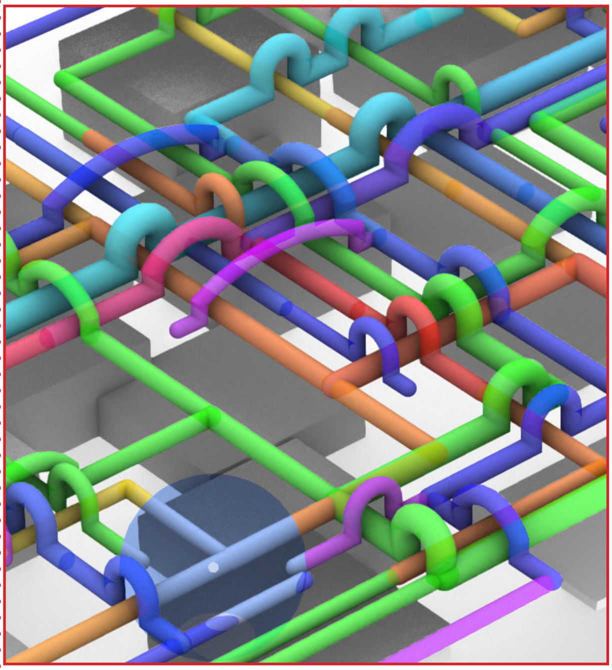


Fig 13
Simulation showing clash avoidance principles for multiple services running together.

2.4 The evolution from Clash Detection to Clash Avoidance

In the contemporary construction industry, the theoretical ambitions of Kahn and Rogers are met with rigorous constraints. The failure to integrate MEP systems early in the design phase is widely recognised as a primary cause of construction delays and budget overuse. Modern practice relies heavily on Building Information Modeling (BIM) to coordinate these systems. However, empirical evidence shows that the industry has historically favored 'clash detection' identifying spatial collisions between HVAC ducts and structural elements after the initial designs are completed, over proactive 'clash avoidance' (Al-Saeed & Al-Hajri, 2020).

When building services are not treated as integral components from the project's inception, the result is often the incoherent arrangement of plumbing systems, the physical chiseling or breaking down of load-bearing structural members to accommodate mechanical systems, and severe reductions in ceiling heights (Abdelhameed & Saputra, 2020). BIM approaches offer an effective assistance by creating multidisciplinary models that consolidate BSS into one detailed file, helping to discover overlaps; however, relying solely on reactive checking is inefficient.

Furthermore, integrating modern HVAC requirements into existing historic buildings presents severe difficulties. Contemporary HVAC design must often be implemented into these structures without destroying the original construction work, materials, or architectural design. For example, retrofitting historic estates frequently requires the use of specialized, small-scale systems to avoid massive structural alterations to fragile infrastructure. These precedents demonstrate that when retrofitting mid-century or heritage buildings, designers must find highly controlled, non-destructive routing strategies, necessitating a shift from manual, retrospective checking to automated, early-stage integration.

2.5 Generative Design and Graph Theory in MEP Routing

To address the need for early-stage clash avoidance and spatial integration, architectural research has increasingly turned towards generative design and algorithmic path-finding. Traditional manual duct design is highly iterative, prone to human error, and can result in fan energy waste due to network imbalance (Chen et al., 2022). By translating the building layout and required MEP terminal units into structured geometric graphs, algorithms can autonomously traverse the design space to synthesize optimal routing architectures.

Graph theory provides the mathematical foundation for these routing solutions. One of the most fundamental approaches is the Minimum Spanning Tree (MST), which connects a given set of nodes such that the total length of the edges is minimized without creating closed loops. In architectural applications, this is frequently constrained to a Manhattan Minimum Spanning Tree (MST), where movement is strictly limited to orthogonal X and Y axes, mimicking the rectilinear layout of traditional building grids (Zelikovsky, 1996). While Manhattan MSTs are highly efficient and align perfectly with standard construction protocols, simply connecting existing nodes often results in suboptimal overall duct lengths and forced, awkward right-angle turns (Bijl et al., 2014).

To overcome the limitations of the basic MST, advanced routing research utilizes Steiner Minimal Trees. The fundamental difference is that a Steiner tree is allowed to introduce brand new, auxiliary points into the network, known as Steiner points, that were not part of the original input set (Hwang et al., 1992). By calculating the optimal placement of these new intersection nodes, the algorithm can drastically reduce the total interconnect wirelength (or duct length) compared to a standard MST (Robins, 2007). Furthermore, removing the strict orthogonal Manhattan constraints allows the Steiner algorithm to generate radical, non-rectilinear diagonal connections in three-dimensional space. It is precisely this transition, from the hidden, rule-based efficiency of the Manhattan MST to the optimized, three-dimensional complexity of the Steiner Tree, that this thesis utilizes to transform HVAC routing into a generative architectural feature.

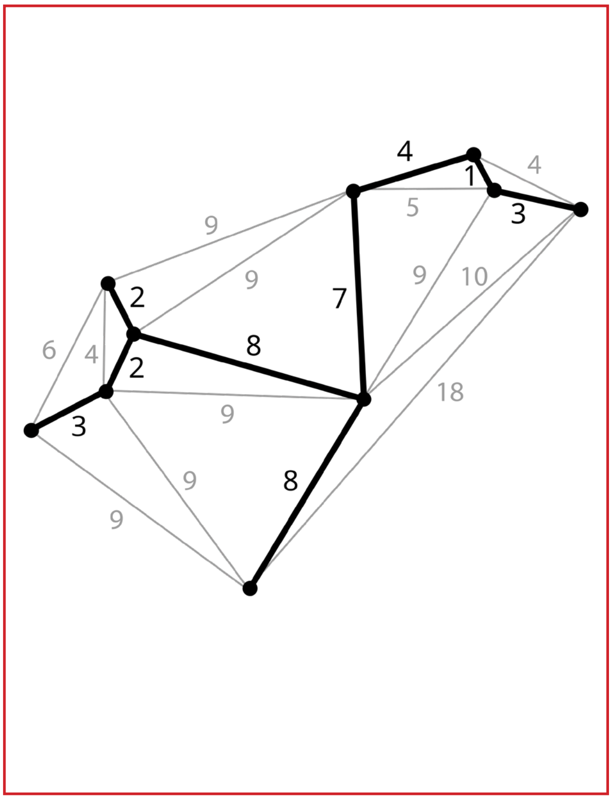


Fig 14 a

An image showing a Minimum Spanning Tree

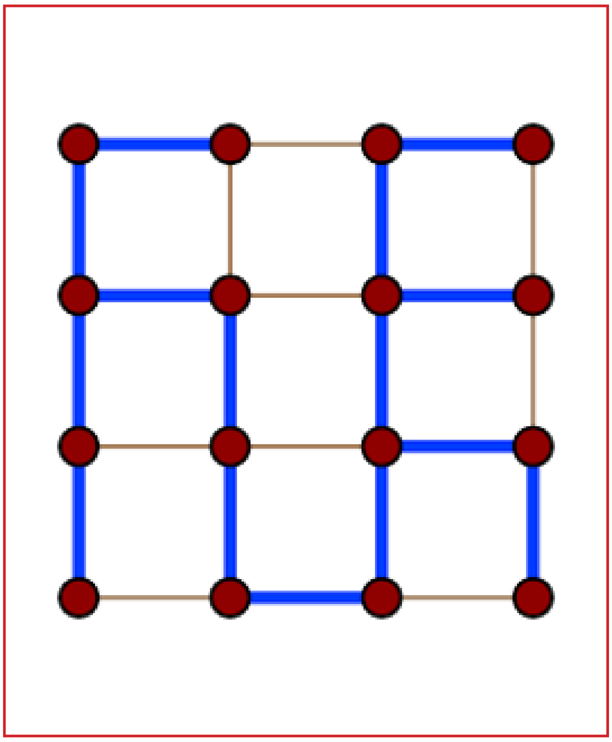


Fig 14 b

An image showing a Manhattan Minimum Spanning Tree

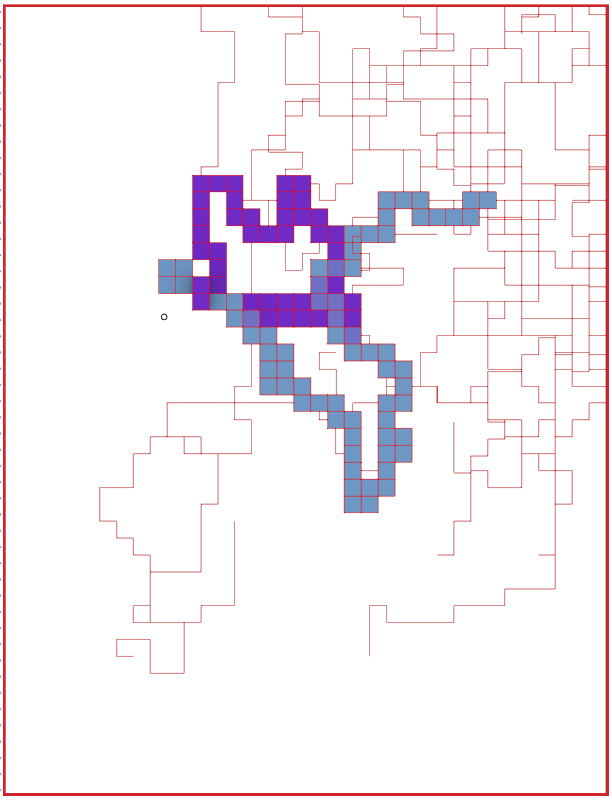


Fig 15

Simulation showing experiments with voxel based Agent Based Modeling

3. Analytical Frameworks and Algorithmic Workflows

To bridge the gap between the theoretical integration of services and modern computational capabilities, this research methodology focuses on algorithmic pathfinding for duct routing. The workflow documents the transition from early stochastic to highly controlled generative trees. This computational architecture is established utilizing Rhinoceros 3D and its algorithmic design plugin, Grasshopper. The core logic is driven by custom Python scripting components that leverage external libraries including Rhino.Geometry for 3D vector math and bounding box calculations, ghpythonlib.components for native Voronoi generation, and standard Python math and random libraries for geometric formulas and coordinate scattering

3.1 Initial Experimentation: Agent Based Modeling (ABM)

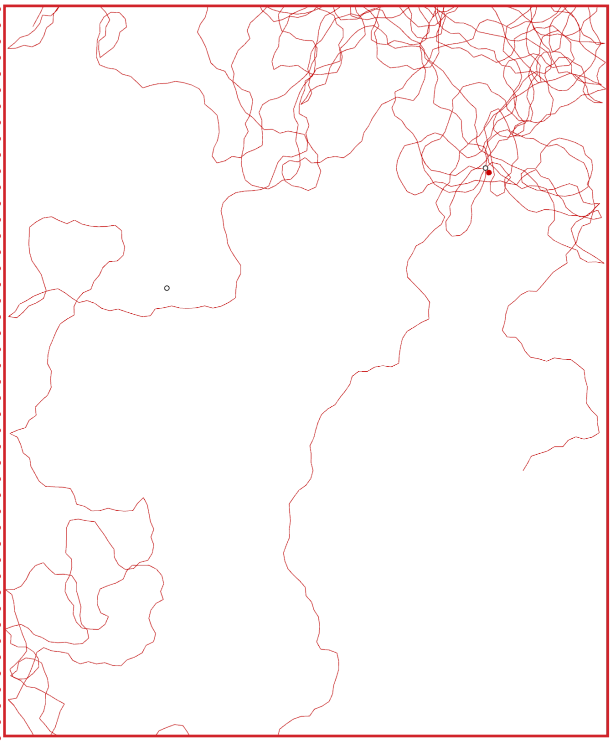


Fig 16

Simulation showing experiments with stochastic movement of based Agent Based Modeling

The computational investigation initially explored Agent- Based Modeling (ABM) to simulate the routing of HVAC systems through three dimensional space. The hypothesis was that autonomous digital 'agents' could act as localised decision makers, navigating a building's geometry to connect ventilation sources to terminal diffusers. However, extensive empirical testing in Grasshopper environment revealed profound systematic limitations. The stochastic, random movement of multiple individual agents interacting simultaneously resulted in chaotic, highly inefficient pathing. The lack of an overarching global objective meant that the collective behaviour of the swarm failed to produce the standardised and manufacturable routing required by the construction industry. Furthermore, the computational load required to resolve collision avoidance among hundreds of agents proved exceptionally slow, rendering it unviable for rapid conceptual iteration.

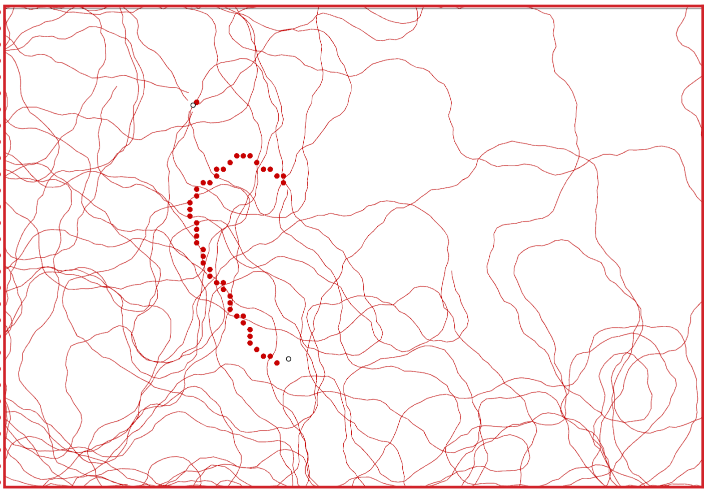


Fig 17a
Path Traceback from Stochastic movement

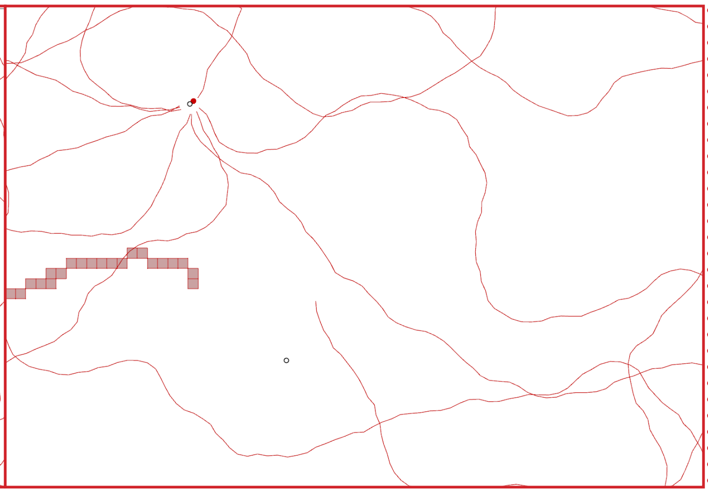


Fig 17b
Path Traceback with voxels from Stochastic movement

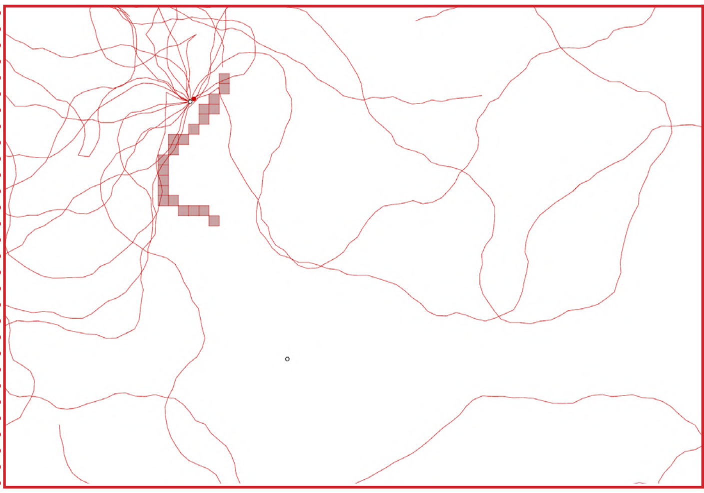


Fig 17c
Path Traceback from Multiple Stochastic Agents movement

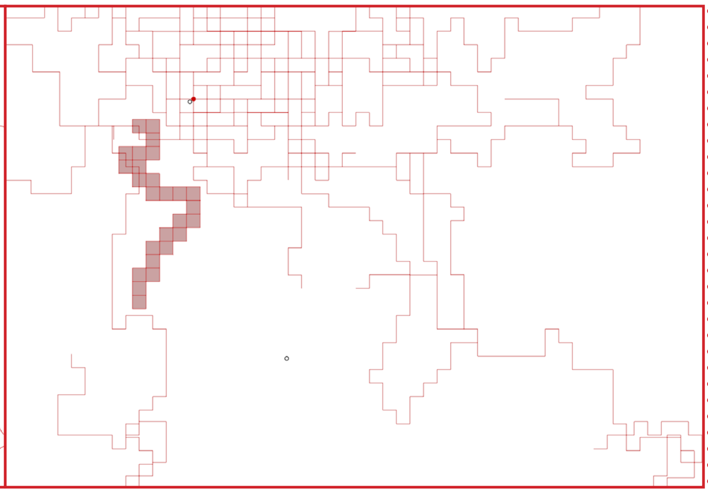


Fig 17 d
Path Traceback with voxels from Stochastic Manhattan movement

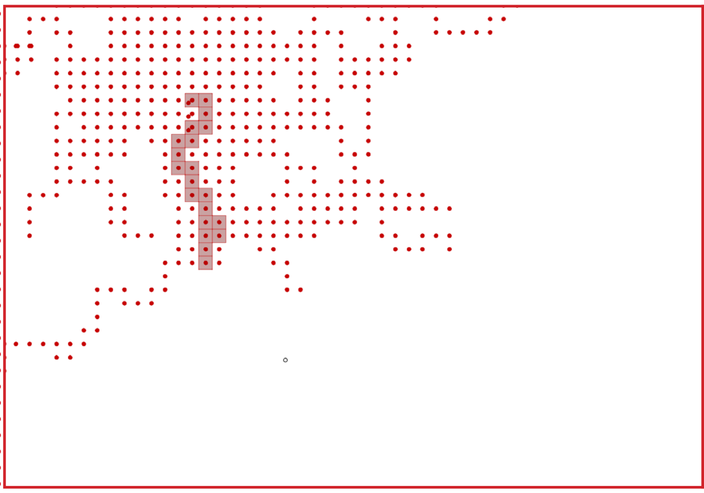


Fig 17e
Path Traceback from Multiple Stochastic Agent Swarm Movement

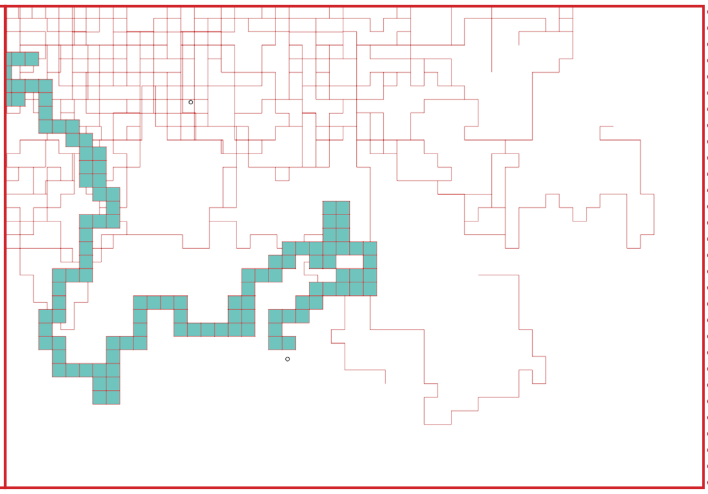


Fig 17 f
3D Path Traceback with voxels from Stochastic Manhattan movement

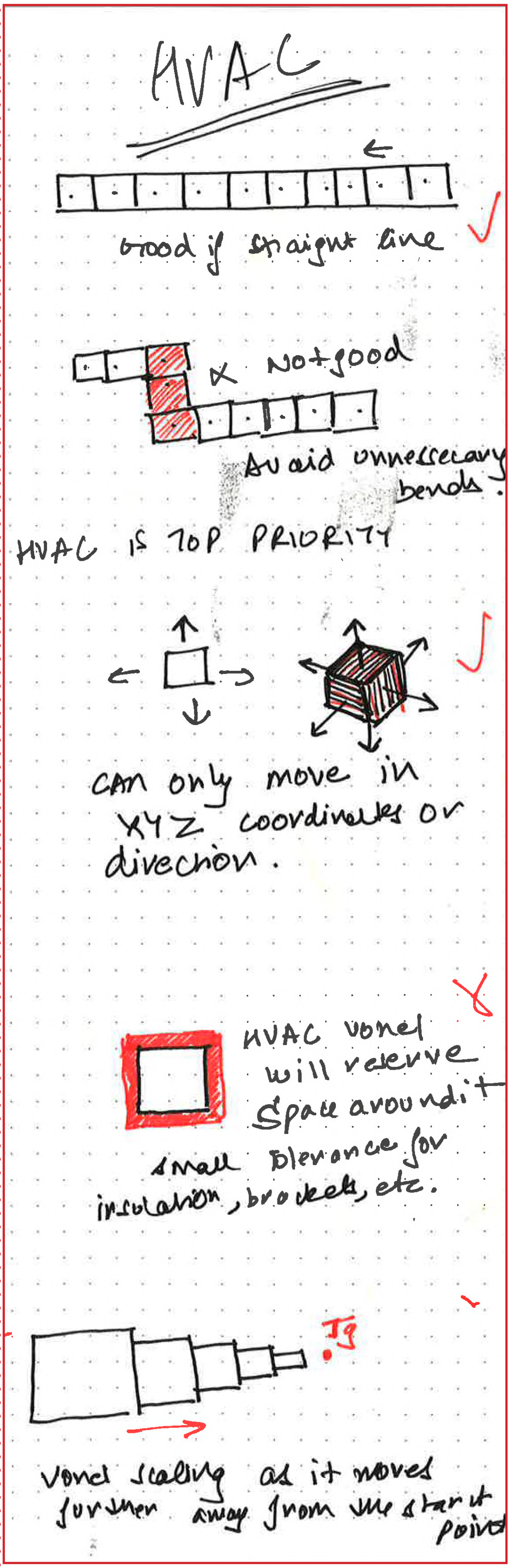


Fig 18
Sketches showing the formulation for computational rules

3.2 Formulation of "MyRules" for Generative Control

Realising that the stochastic nature of ABM was unsuitable for rigid building services, the methodology shifted toward a strictly constrained, rule-based algorithmic system dubbed "MyRules". This logic was formulated to gain absolute deterministic control over the generative routing, directly inspired by the rigorous structural hierarchies established by Louis Kahn. The core parameters of this system dictate:

1. Prioritisation of Linearity and Orthogonal Movement:

HVAC routing operates optimally with minimal air resistance. Therefore, the algorithm dictates that generative paths can only move in discrete XYZ coordinates or directions, enforcing a Manhattan grid logic. Straight lines are heavily favoured, while unnecessary bends are severely penalised in the code to prevent disruption of airflow and friction losses.

2. Mother Trunk Hierarchy:

To avoid the collective behavioural chaos of independent agents, the system establishes a rigid parent-child hierarchy. A primary agent acts as a massive 'Mother Trunk' that is larger in size and moves first to determine the primary service corridor. Subsequently, 'child agents' or sub-agents sprout later from this main trunk, peeling off to branch toward their respective terminal targets.

3. Voxel Space Reservation and Scaling:

Recognizing the physical realities of HVAC installation, the routing path is not treated as a mere 1D line but as a volumetric 'HVAC voxel'. The rule dictates that this voxel must reserve dedicated space around it to provide a necessary tolerance clearance for insulation, mounting brackets, and maintenance access. Programmatically, this is executed by computing a vertical clearance limit (VERT_CLEARANCE = max_h * 1.1) to establish a safe vertical buffer, and a lateral boundary offset (LAT_CLEARANCE = max_w * 0.1) ensuring surrounding structural geometry does not violate the duct's operational envelope. Furthermore, a 'voxel scaling' rule is applied, reducing the cross-sectional size of the duct as it moves further away from the start point, mimicking real-world pressure distribution and tapering.

4. Ceiling Attraction and Obstacle Avoidance:

The routing algorithm applies a vertical gravity like parameter where the HVAC duct has a continuous 'pull towards the ceiling'. When the generative path encounters pre-existing structural obstacles like beams or column, it is forced to make a calculated heuristic decision, which is, to route under the beam (which negatively reduces ceiling height) or route around the beam (which negatively makes the path longer).

5. Service Corridor:

To prevent chaotic sprawl of pipes, new routing agents are actively attracted towards already existing services. This creates consolidated, highly efficient multi-service corridors rather than isolated, independent runs. Furthermore, the script institutes a rigid spatial segregation between supply and return systems to prevent massive cross-collisions.

6. Dynamic Regeneration over Legacy Data:

To maintain optimisation during the highly iterative conceptual design phase, the algorithm is programmed to start entirely fresh whenever the architectural layout changes, actively discarding legacy data to prevent outdated, inefficient routing paths from persisting in new architectural iterations.

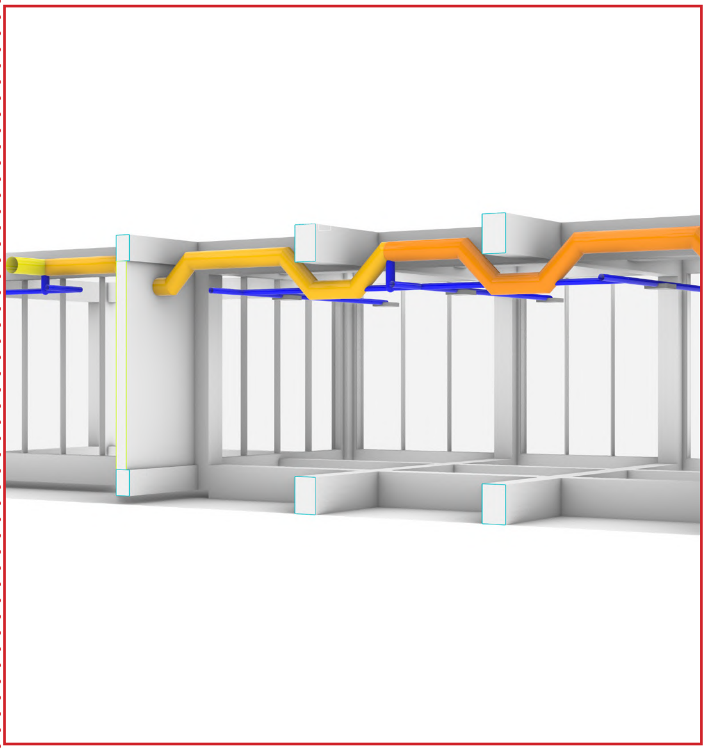


Fig 20
Conceptual testing of ducts bending below beams (obstacles)

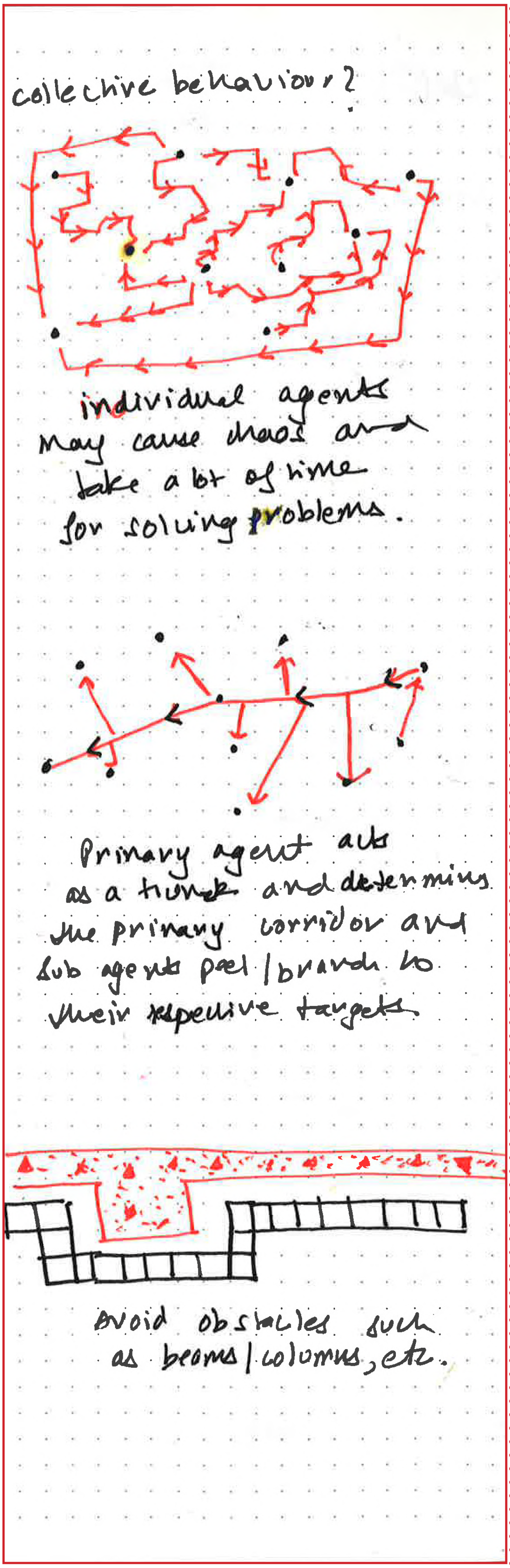


Fig 19
Sketches showing the formulation for computational rules

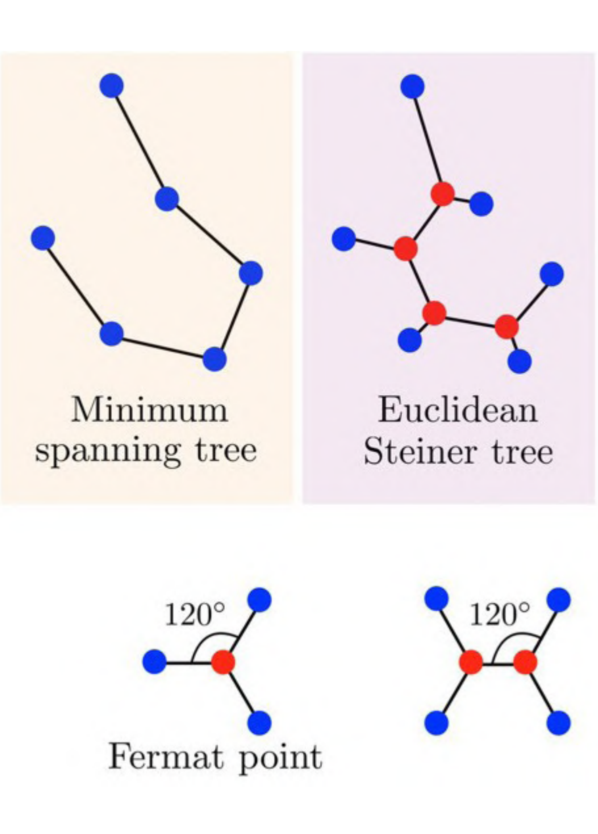


Fig 21
Basic Understanding of a Steiner Tree, where steiner points are introduced in between the main nodes to reduce the overall connection lengths

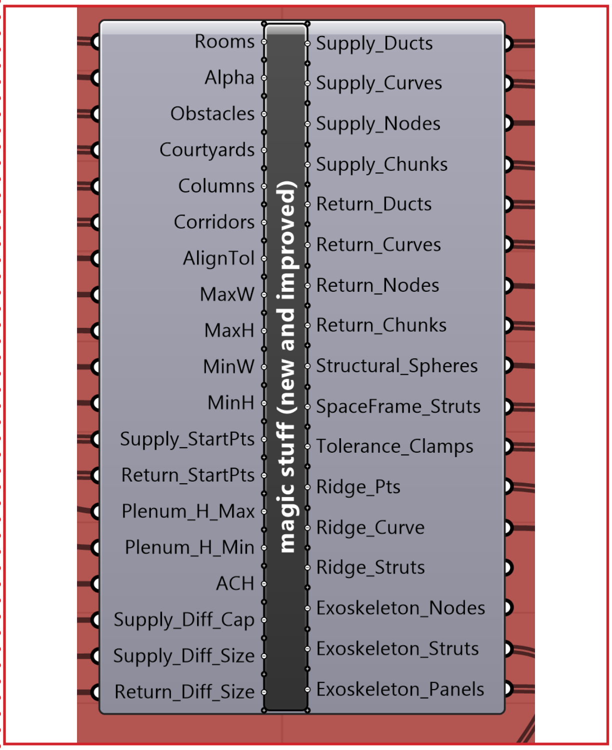


Fig 22
The grasshopper script node which shows different input and output parameters for the simulations

3.3 Pathfinding: Manhattan MST vs. Steiner Minimal Trees

To execute the established rules computationally, the workflow utilises the two distinct graph-theory path-finding algorithms outlined in the literature review to connect the HVAC nodes. The Manhattan MST ensures rapid, non-destructive routing across standardised structural grids, functionally primarily as an efficient background service matrix. Conversely, the implementation of the Steiner Minimal Tree allows for radical architectural expression, optimising total material usage through the algorithmic generation of the intersection nodes (Steiner Points) floating freely in 3D space. This dual algorithm approach permits the architect to dial the visibility of the building services from completely hidden to structurally expressive.

3.4 Summary of Computational Parameters

Variable Name	Description
alpha_val	Controls the optimization weight penalizing long branch segments in Steiner Trees.
max_w / min_w	Maximum trunk width / Minimum child branch width limits.
max_h	Maximum height constraint for duct scaling dimensions
ach_val	Air Changes per Hour required for thermodynamic distribution.
sup_cap	Capacity limits determining maximum cubic flow per supply diffuser.
p_min / p_max	Minimum and maximum elevation boundaries for the ceiling plenum.

4. Case Study Application: IIT Delhi Academic Block 3

To validate the generative routing framework against real world constraints, the algorithms are applied to a specific architectural intervention: an alternative proposed renovation and vertical extension of Academic Block 3 at the Indian Institute of Technology (IIT) Delhi.

4.1 Site Context and Historic Constraints

The IIT Delhi campus, situated in Hauz Khas, New Delhi was established in 1961 and constructed throughout the 1960s (Infrastructure Unit IIT D, 2016). The campus master-plan and its primary academic buildings were designed by the prominent Indian Architect J.K. Chowdhary, in collaboration with structural engineer Gulzar Singh (Photoink, 2019). Highly influenced by the ambition to forge a modern, scientifically advanced Indian identity, Chowdhary utilized a stark, Brutalist architectural vocabulary (Sanyam, 2016). The academic blocks are renowned for their monolithic exposed concrete facades, robust concrete structural grids, and integration with the undulating landscape (Zikre Dilli, 2020).

The project brief for the thesis proposes a highly sensitive renovation of the existing ground and first floor of the Academic Block 3. A key constraint is that the historic exposed concrete grid, which relies heavily on complex waffle slabs and deep structural beams (Arman, 2014), must remain completely unhampered. However, to address the modern space constraints of the growing institute, the proposal includes the erection of a completely new, lightweight steel structure superimposed as a top floor above the existing concrete building. This tiered approach allows the thesis to test different generative routing strategies floor by floor.

Fig 23
Images of Academic Block 3 at IIT Delhi, one of the oldest buildings in the campus.

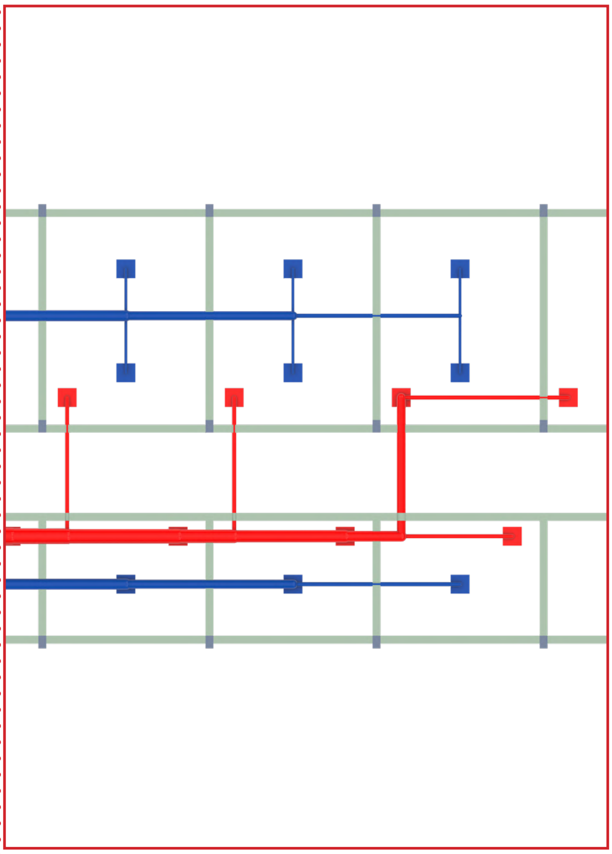


Fig 24
Zoomed in view showing the ducts. The Blue Ducts indicate Supply Air and Red Ducts indicate Return Air

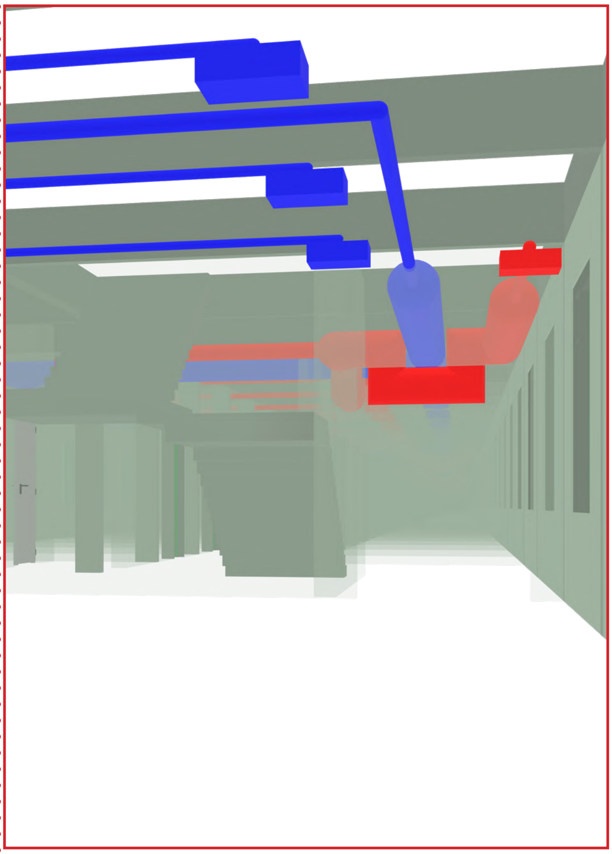


Fig 25
An interior view showing the Ducts for the Ground Floor

4.2 Ground Floor: Manhattan Efficiency and Concealment

On the ground floor, the architectural strategy prioritises reverence for the existing Brutalist structure and absolute spatial efficiency. Here, the algorithm deploys the Manhattan Minimum Spanning Tree (MST) method. Because the 1960s concrete framework relies on a strict orthogonal grid with deep waffle slab ribs, the Manhattan algorithm is perfectly suited to navigate this space. The algorithm generates a highly efficient, rectilinear duct routing system that functions as a concealed 'servant' network, driven by five primary computational phases:

1. Obstacle and Courtyard Classification:

The Python script initiates an environment mapping sequence that translates the floor plan into rigid Cartesian constraints. The script identifies impassable courtyards (void_zones) and inflates their bounding boxes laterally in the XY plane by a specific clearance metric (clear_xy = (max_w / 2.0) + LAT_CLEARANCE). This mathematical inflation establishes absolute "no-fly" coordinate boundaries, preventing any generated duct from routing through open architectural air. Simultaneously, overhead structural beams are evaluated against the working plenum height (plenum_z). If an obstacle lacks sufficient clearance beneath, it is registered as an impassable block_zone; if it permits safe passage beneath, it is tagged as a base_duck_zone where a specific height drop (duckZ) is enforced.

2. 2D Axis Alignment and Coordinate Snapping:

To emulate standard, manufacturable HVAC installation protocols rather than a chaotic spider-web of organic branches, the algorithm enforces strict grid snapping. By clustering the coordinate geometries of the source points and terminal rooms within a predefined alignment tolerance, the script automatically aligns the X and Y coordinate vectors of the proposed routing paths to the strict geometric grid of the historic Brutalist structure.

3. Greedy Graph Routing with Severe Penalty Heuristics:

The core pathfinding connects rooms iteratively using L-shaped Manhattan paths, guided by an aggressive mathematical penalty cost system to actively steer the geometry. Utilizing a custom wall_penalty(p1, p2) function, the script computationally "steps" along proposed connection segments at 200.0-unit intervals. If any sampled coordinate lands inside a mapped block_zone, it adds a massive deterrent cost (5000.0 points per intersection step) to force the algorithm to route around the column. Similarly, a crosses_void(p1, p2) function performs a 2D bounding box intersection test against the courtyards, any breach applies an absolute deterrent penalty (1000,000 cost units). If a connection optimally meets the middle of an existing duct, the script evaluates the line-intersection parameters ($0.01 < t,u < 0.99$) to dynamically split the edge and create a secure junction node.

4. Flow Calculation and Dynamic Sizing:

Once the 2D network topology is locked, the script recursively calculates the thermodynamic air flow load by summing the connections from the leaf nodes back to the central source. The cross-sectional radius of each duct segment is dynamically scaled proportionately to the square root of the accumulated airflow volume.

5. 3D Extrusion and 45-Degree Tangential Transitions:

Finally, the 2D network is extruded into a three-dimensional manifold. When a duct encounters a registered base_duck_zone (a concrete beam), the script calculates the geometric tangents to generate smooth 45-degree diagonal transitions. This bridges the standard plenum height down to the constrained duckZ limit, significantly reducing air friction and pressure loss compared to inefficient 90-degree vertical drops.

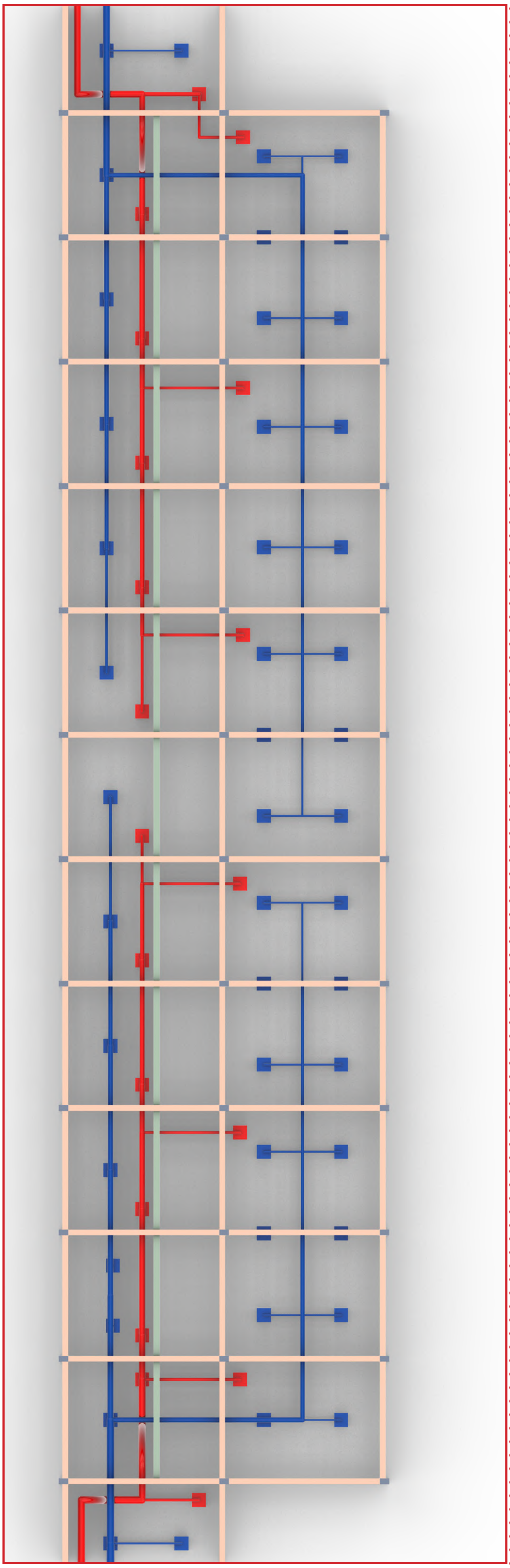


Fig 26
Part plan of the Ground Floor showing the Manhattan Ducting simulation

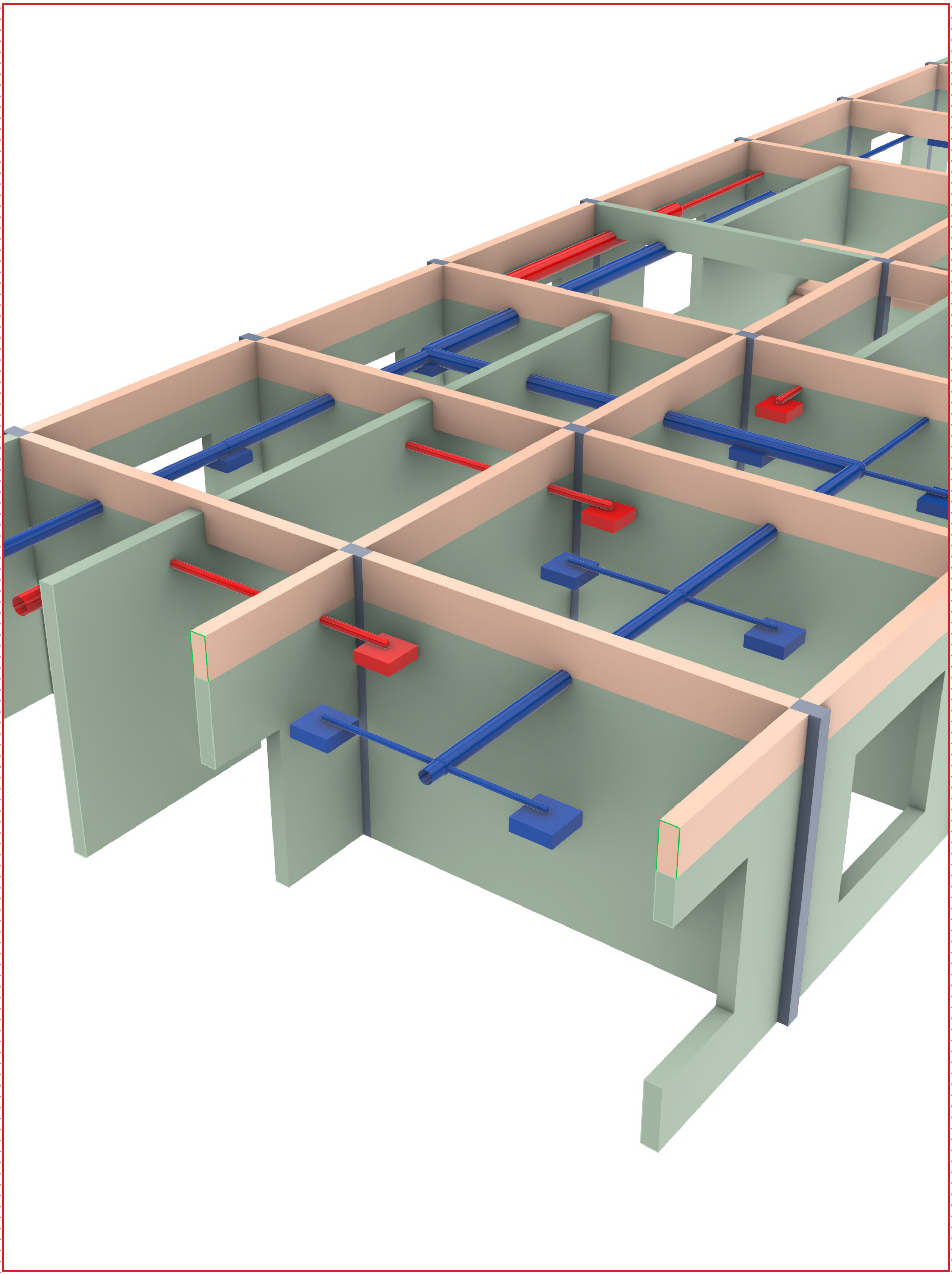


Fig 27
A 3D sectional view showing the Manhattan Duct Routing on the Ground Floor

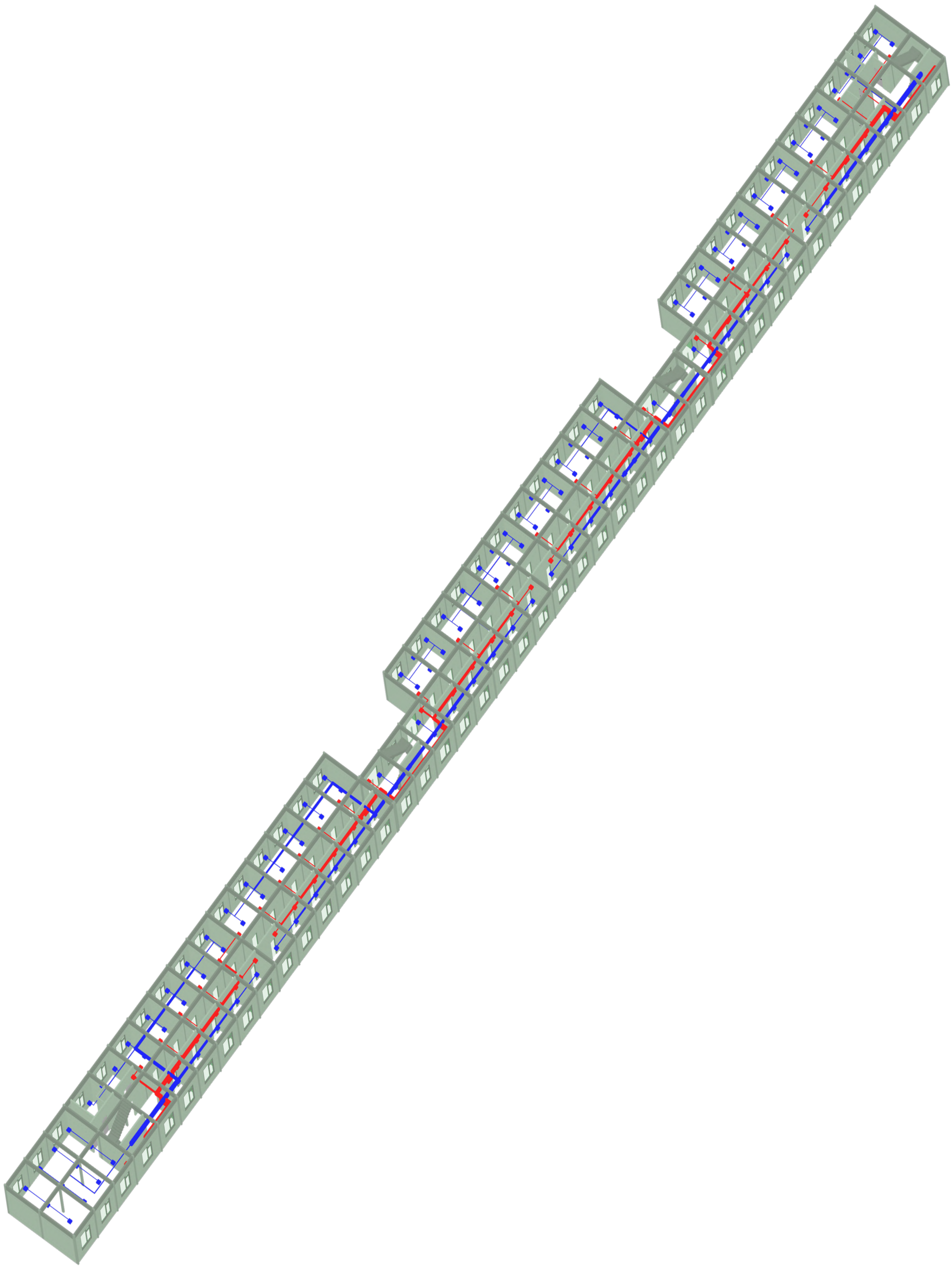


Fig 28
An axonometric view of the entire Ground Floor with the Manhattan Ducting System

4.3 First Floor: Voronoi Spatial Distribution and Steiner Expression

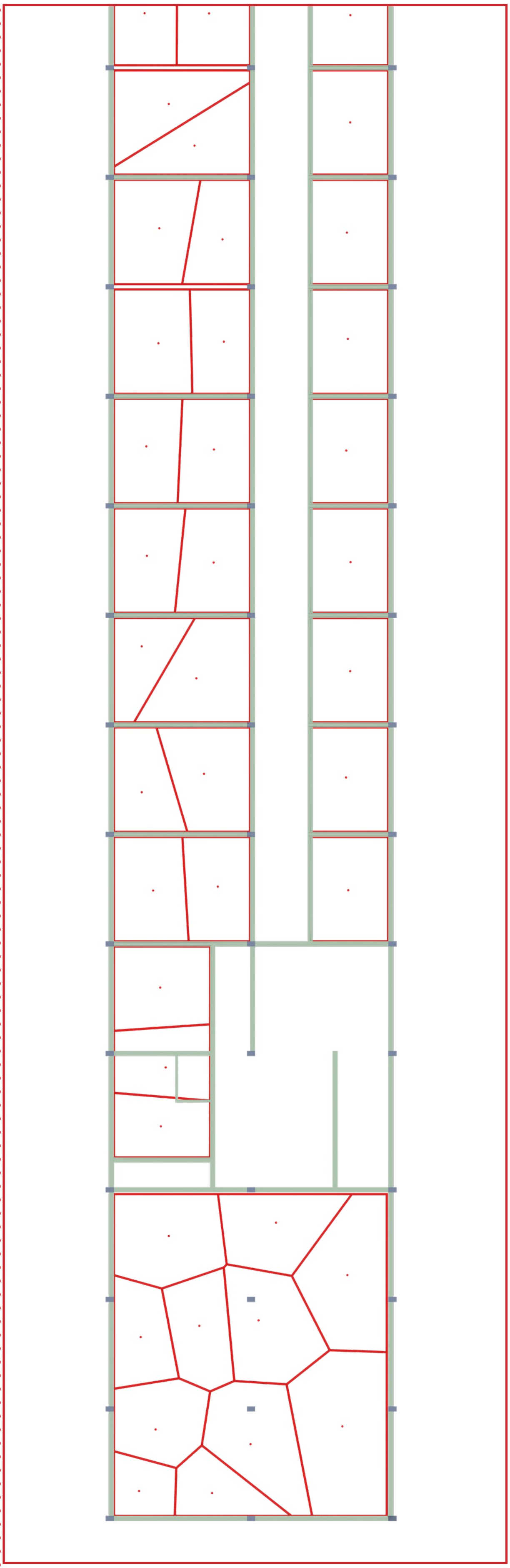


Fig 29
First Floor plan showing the location og points and cell division based on Llyod's Algorithm

Moving up to the first floor, the architectural narratives shifts dramatically. Inspired by the unapologetic exposure of services at the Centre Pompidou, the design utilises the generative routing as a highly visible aesthetic intervention. The algorithm deployed here operates in two distinct phases: Voronoi-based distribution of the terminal units, followed by the radical Steiner tree routing network.

Phase 1: Voronoi Relaxation for the Diffuser Placement

Before routing the ducts, the algorithm calculates the optimal, mathematically even placement of the HVAC diffusers across the ceiling. To overcome the inefficiencies of manual grid placement, the script employs Lloyd's Algorithm, iteratively constructing a Centroidal Voronoi Tessellation (CVT) (Du, Faber, & Gunzburger, 1999).

1. Volumetric Flow Calculation:

The script calculates the total room volume in cubic meters using formula for LXBXH. Multiplying this by the required Air Changes per Hour (ach_val = 6.0) yields the required airflow. Dividing this by the diffuser capacity (sup_cap = 400.0) provides the exact integer count of terminal spouts, clamped strictly between 1 and 30 units. The room's available height is clamped between p_min and p_max, and an average mid-height (calc_z) is established.

2. Llyod's Relaxation (The Optimisation Loop):

The algorithm generates initial random spout coordinates offset inwards by 500.0 units from the room's physical boundaries. It then executes a highly controlled optimization sequence consisting of a three-iteration loop utilizing the native ghcomp.Voronoi solver. In each iteration, it computes a Voronoi diagram strictly bounded by the room's rectangular footprint at the calculated average ceiling height:
Utilizing the rg.AreaMassProperties.Compute() method, the script calculates the precise geometric center of mass (centroid) of each irregular Voronoi cell and physically relocates the diffuser seed to this new centroid, achieving perfect spatial uniformity.

3. Corridor-Side Terminals (Return Diffusers):

Unlike supply systems that distribute fresh air, return systems extract stale air. To create an optimal cross-room air sweep, the script calculates a specialized distance evaluation function that measures the minimum Euclidean distance from every corner vertex of a room's bounding box to the designated architectural hallway boundaries. The algorithm selects the single corner that is geometrically closest to the corridor system. To prevent direct physical clashing with vertical walls, the algorithm computes a normalized directional vector pointing from this corner towards the absolute center of the room, and offsets the return target exactly 1000.0 units along this vector.

4. Dual Parallel Highway Trunks:

To prevent the massive main supply and return trunks from colliding within the primary architectural thoroughfares, the script establishes dedicated parallel highway zones. By reading the bounding boxes of the corridors, the script determines a central routing spine and applies a lateral offset distance mathematically defined as 1.5 x max_w. For horizontal corridors, the supply highway path is offset along the positive Y-axis, while the return highway path is offset along the negative Y-axis; for vertical corridors, the respective offsets are applied across the X-axis.

Phase 2: Steiner Tree Routing and 3D Expression

Once the Voronoi points are mathematically locked, the script deploys a non-Manhattan pathfinding algorithm. Freed from strict X-Y orthogonal constraints, it uses a path-biased Minimum Spanning Tree (MST) heuristic. The mathematical cost of connecting any two branches is heavily weighted by the alpha parameter using the equation:

$$C = d + (\text{alpha} \times d_{source})$$

where alpha defaults to 0.2. This mathematical constraint forcefully ensures that trunk lines remain oriented back toward the primary mechanical risers rather than spiraling outward.

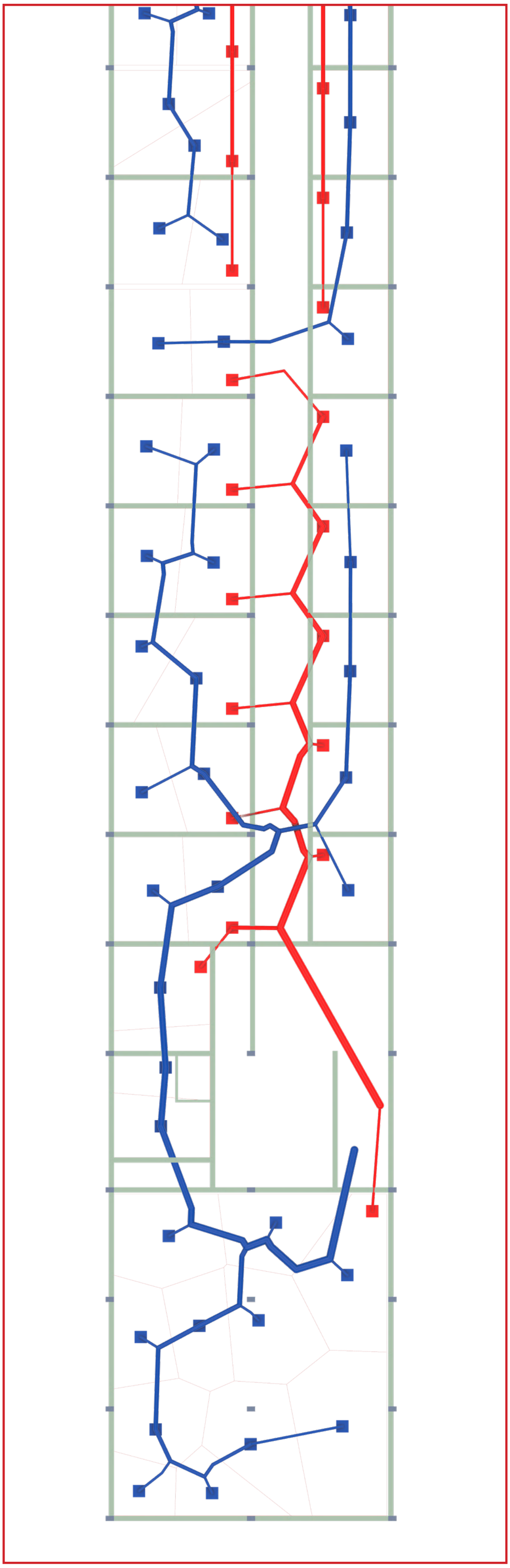


Fig 30
Part of the First Floor Plan with Steiner Tree Ducting Simulation

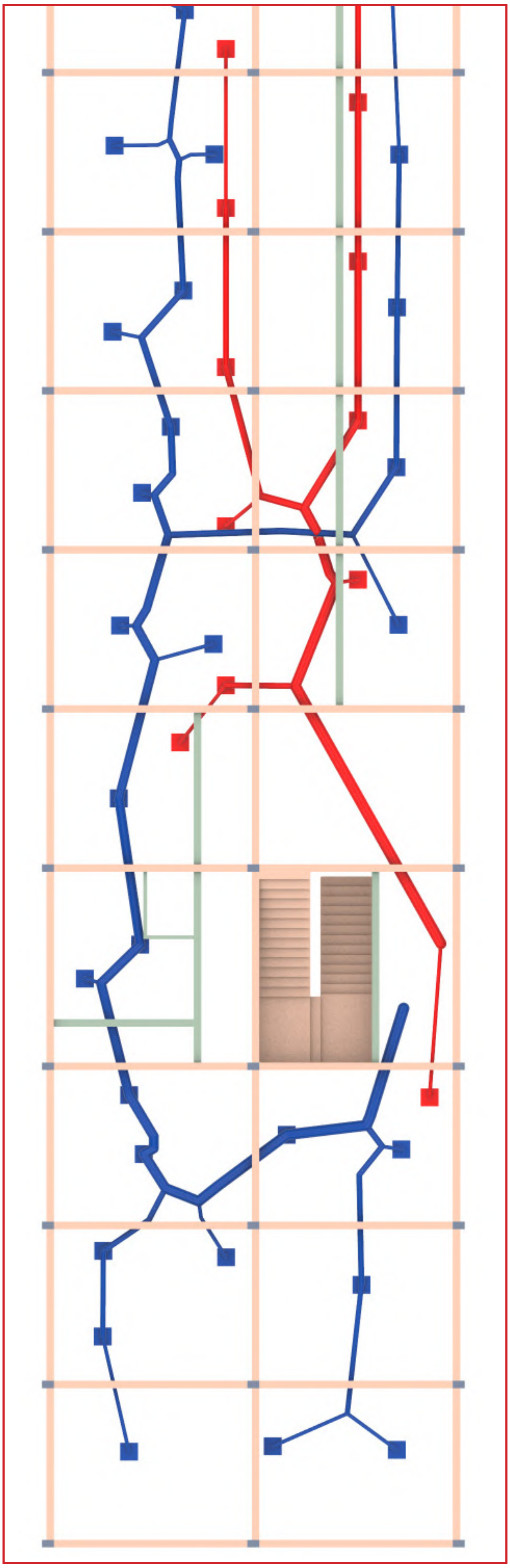


Fig 31
Different iteration of the First Floor Steiner Tree Duct Network. Different runs lead to different results.

Following the MST layout, the algorithm executes a Fermat-Torricelli optimization to inject auxiliary 3D junction nodes (Steiner Points). If a node connects to multiple branches, the algorithm proposes a candidate junction at their spatial center. It then executes a coordinate descent calculation over 15 iterations to physically pull the junction towards the optimal distance-saving location:

$$x_{new} = (\sum(pi/di))/\ (\sum(1/di)$$

The resulting HVAC network features complex, web-like diagonal interconnections. Painted in bold colors to contrast with J.K. Chowdhary’s exposed concrete, the ductwork acts as an expressive, sculptural canopy mapping the thermodynamic flows.

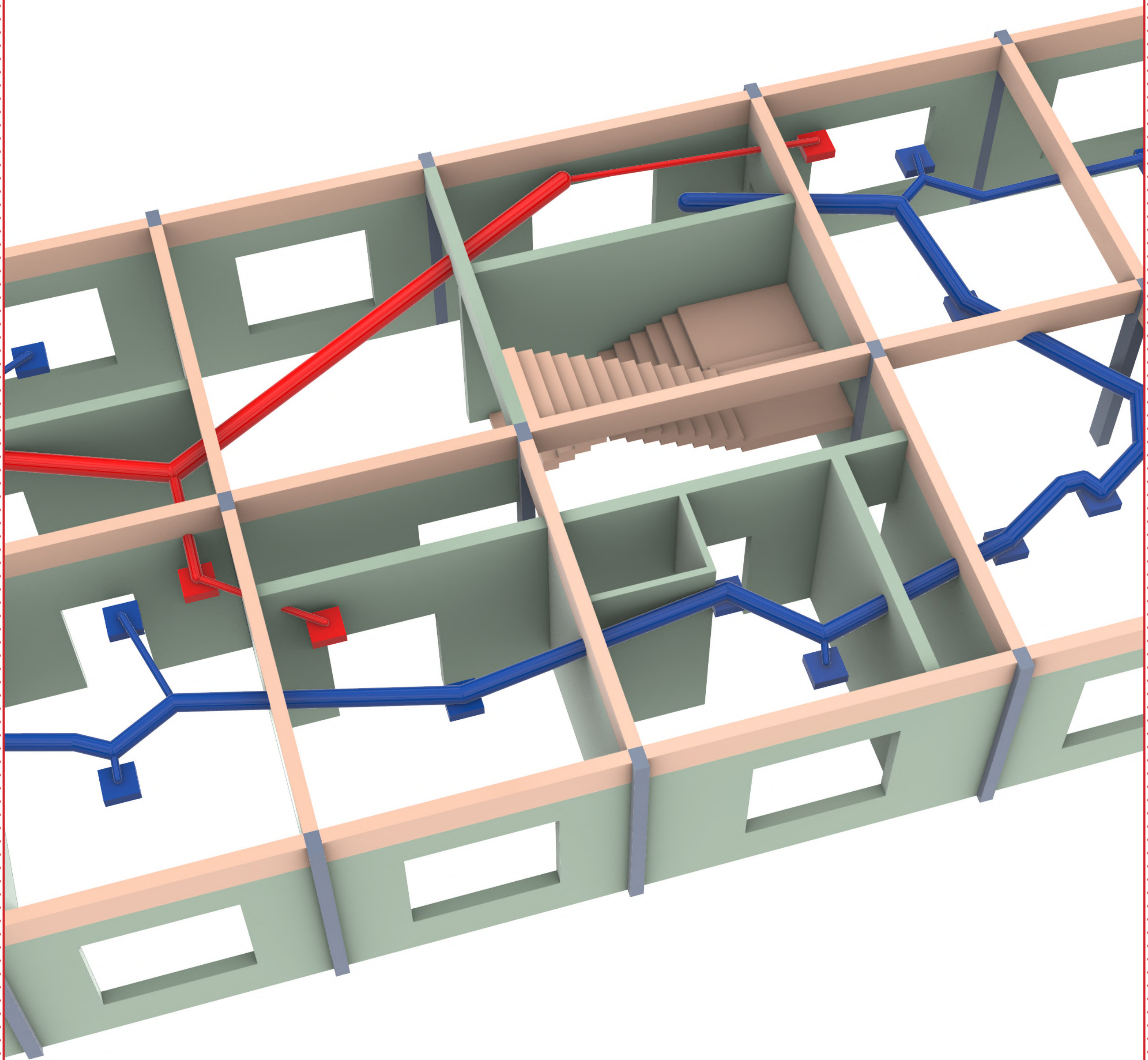


Fig 32
Zoomed in view of the Steiner Tree Duct Network on the First Floor

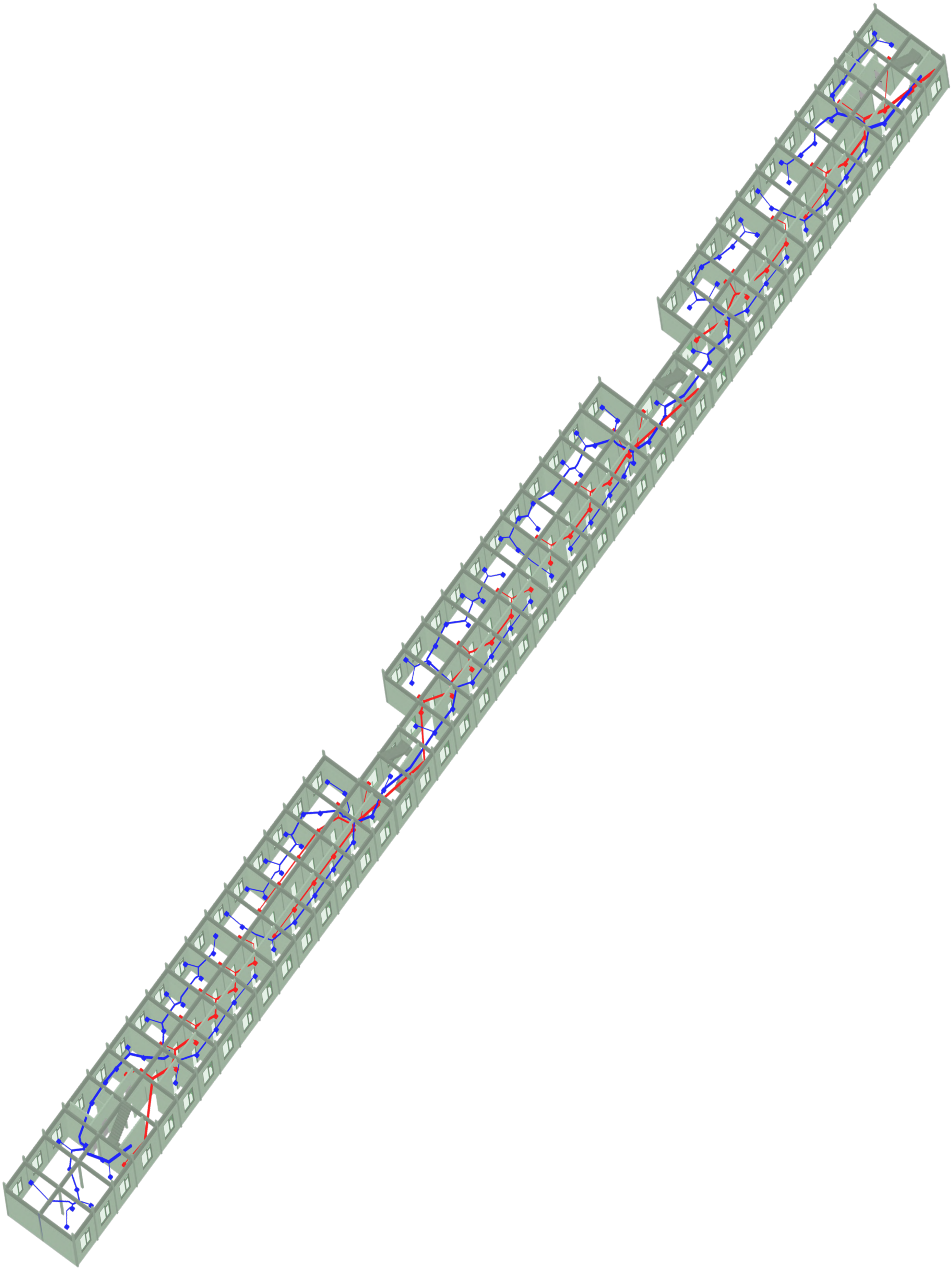


Fig 33
An axonometric view of the entire First Floor with the Steiner Tree Ducting Network

4.4 Top Floor: 3D Synthesis and HVAC Prioritised Space Frames

The newly added top floor represents the ultimate synthesis of the thesis: the complete inversion of traditional architectural hierarchies. In conventional building design, the load-bearing structure is established first, and mechanical services are routed through the remaining interstitial spaces, causing spatial compromises (Abdelhameed & Saputra, 2020). On the top floor, the data generated from the volumetric 3D HVAC network actually dictates the structural framework.

Phase 1: Volumetric Point Distribution and 3D Steiner Routing

Operating within an unconstrained three-dimensional volume, the script disperses the Voronoi-relaxed supply spouts vertically across the Z-axis. Depending on whether their index parity is even or odd, the targets are staggered vertically toward either the minimum or maximum safe plenum boundaries. This spatial array is then fed into Grasshopper's 3D Voronoi component (ghcomp.Voronoi3D), utilizing the room's overarching 3D bounding box as a physical container to partition the space into distinct volumetric service chunks.

Phase 2: 3D Steiner Network and BFS Flow Propagation:

A fully volumetric 3D Steiner Minimal Tree connects these dispersed targets back to the primary shafts. Within its three-way Steiner point generation loop, the script evaluates the spatial vectors of neighbor nodes; if the inverse distance weighting optimization yields a structural path length reduction exceeding 50.0 units, the new Steiner node is permanently accepted into the network geometry.

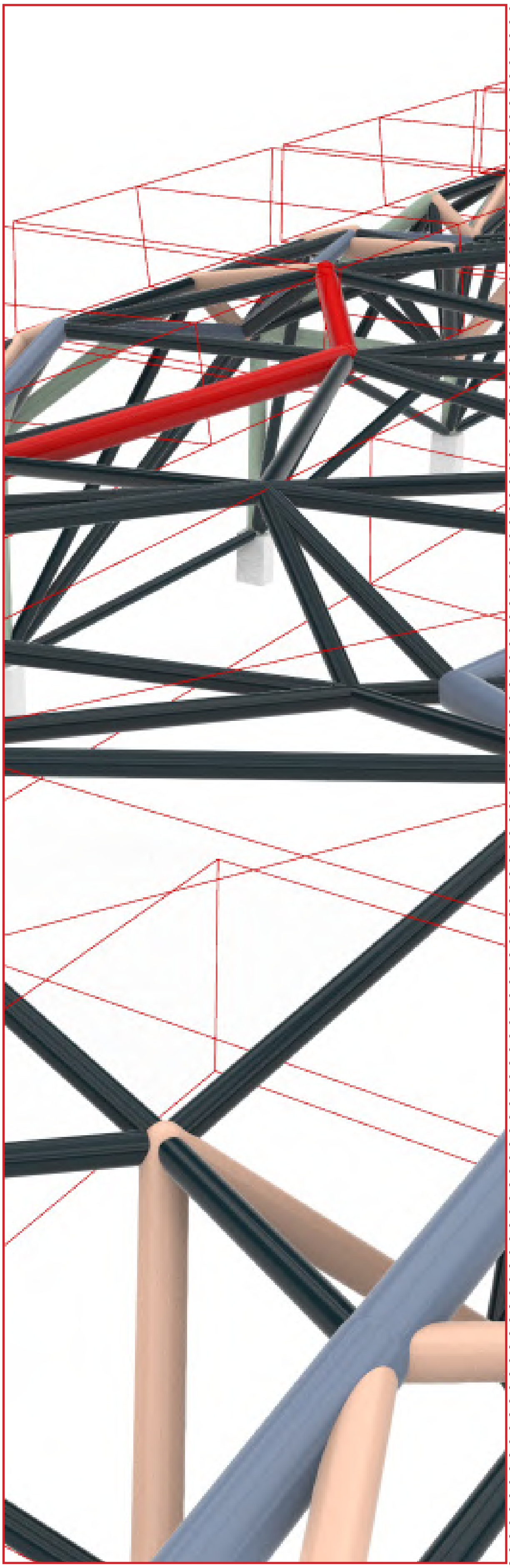


Fig 34
Zoomed in view of the Top Floor

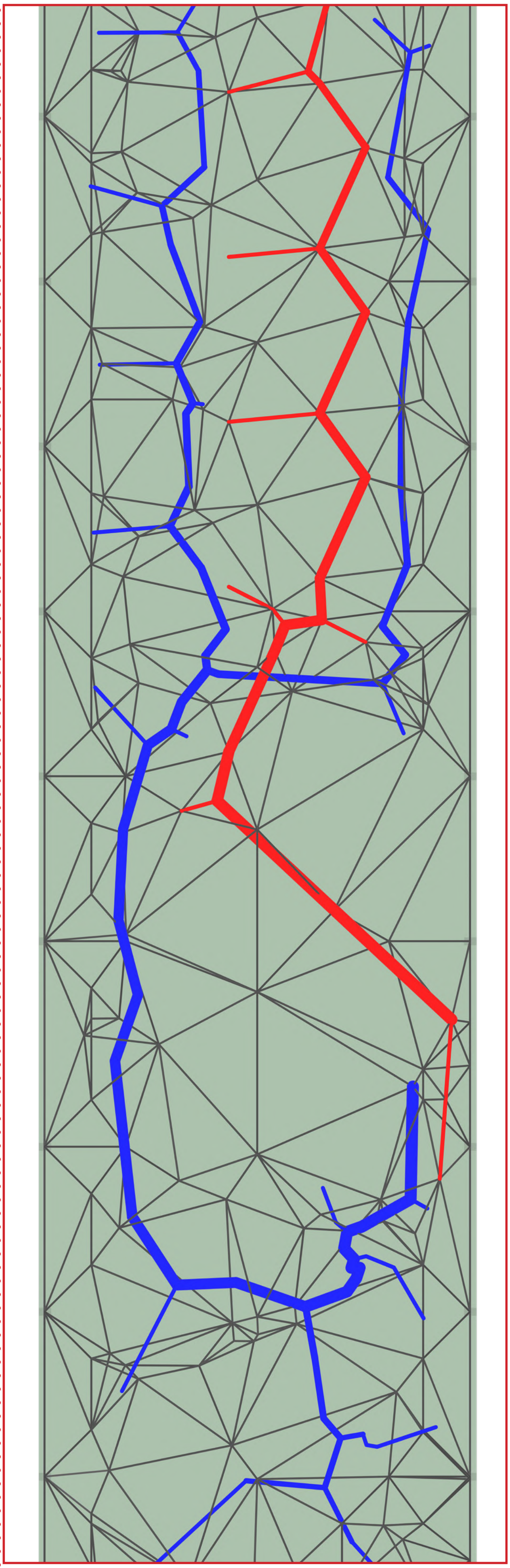


Fig 35
Part of the Top Floor Plan with 3D Steiner Ducting Network

To calculate the physical dimensions required for the structural nodes and ducts supporting this network, the script constructs an adjacency list and initiates a Breadth-First Search (BFS) algorithm starting from the root origin. The BFS traverses the active network, assigning a strict hierarchical depth parameter and parent node mapping to every single active branch. By iterating backward—from the extreme leaf nodes up to the central root—the algorithm aggregates flow weights representing thermodynamic demand counts. This backward propagation accurately sizes the Mother Trunk and all subsequent branches based on literal aerodynamic loads.

Phase 3: Space Frame Generation and Structural Constraints:

To physically support this floating network, the algorithm generates an interlocking equilateral space frame (Durfee, 1987) bridging the historic 1960s columns below to the new roof. The Python script applies two global mathematical constraints to guarantee standardized mass-manufacturing: a rigid grid density factor of 4800.0 and a uniform geometric strut span of 2400.0 millimeters. By forcing the mesh to resolve entirely into equilateral steel struts of this uniform dimension, the generative structure achieves immense spanning rigidity while remaining exceptionally lightweight.

Phase 4: 3D Printed Hollow Joints:

In standard construction, structural connection nodes and HVAC manifolds occupy the exact same spatial bottlenecks, leading to inevitable clashes (Abdelhameed & Saputra, 2020). This thesis tries to solves this by designing bespoke 3D-printed hollow nodes. Leveraging recent advancements in integrated 3D printing for structural cross joints, these generative nodes serve a dual purpose. They act as the load-transferring hubs for the standardized 2400 mm space frame struts, while their hollow internal cavities act as air distribution plenums, their internal diameters directly dictated by the BFS flow calculations. The structural frame itself breathes, fulfilling Louis Kahn's ultimate vision of integrating services directly into the structural order on a microscopic, generative level.

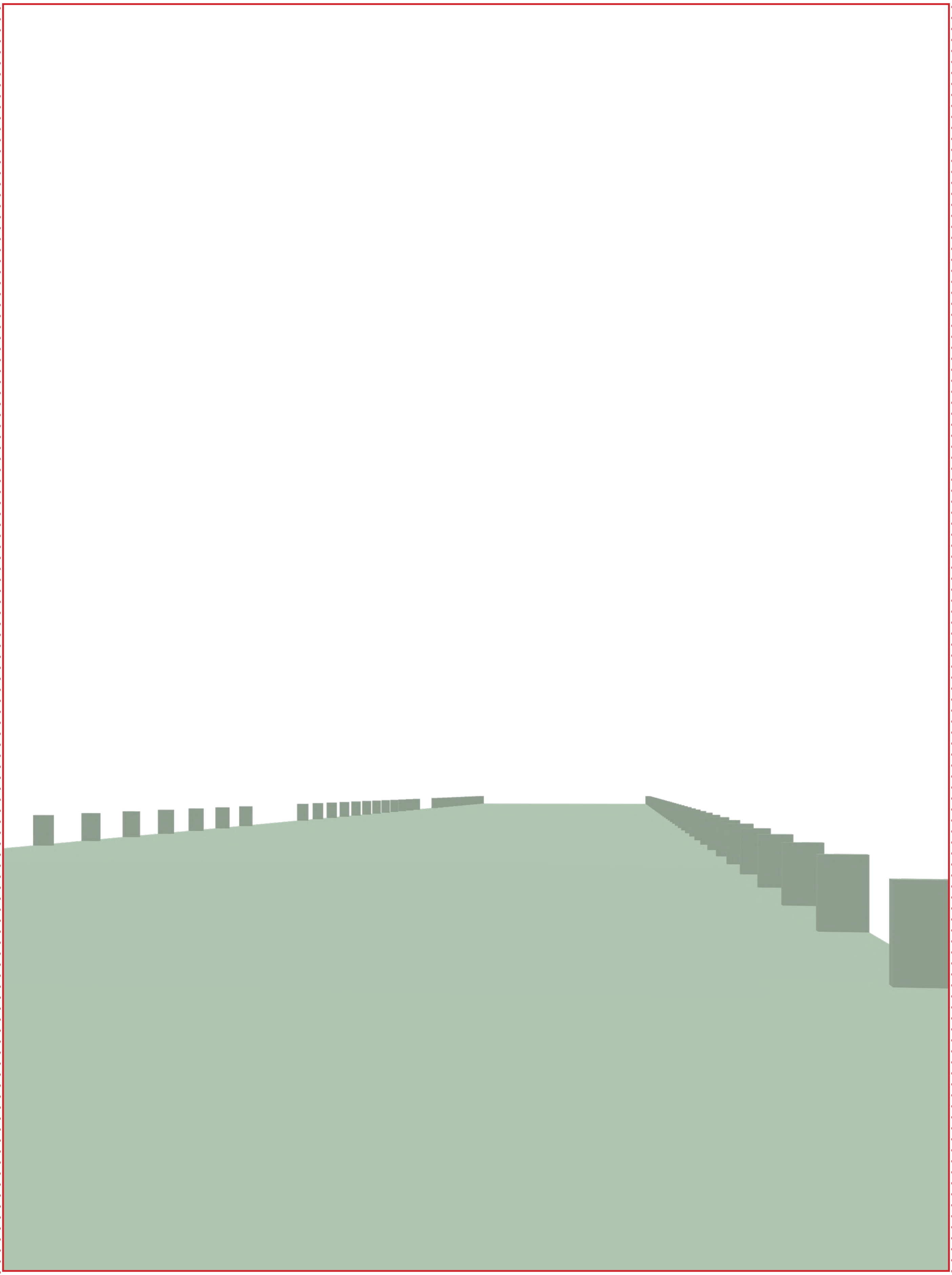


Fig 36
Base of the Top Floor showing the base floor and stub columns which act as anchors for the structure.

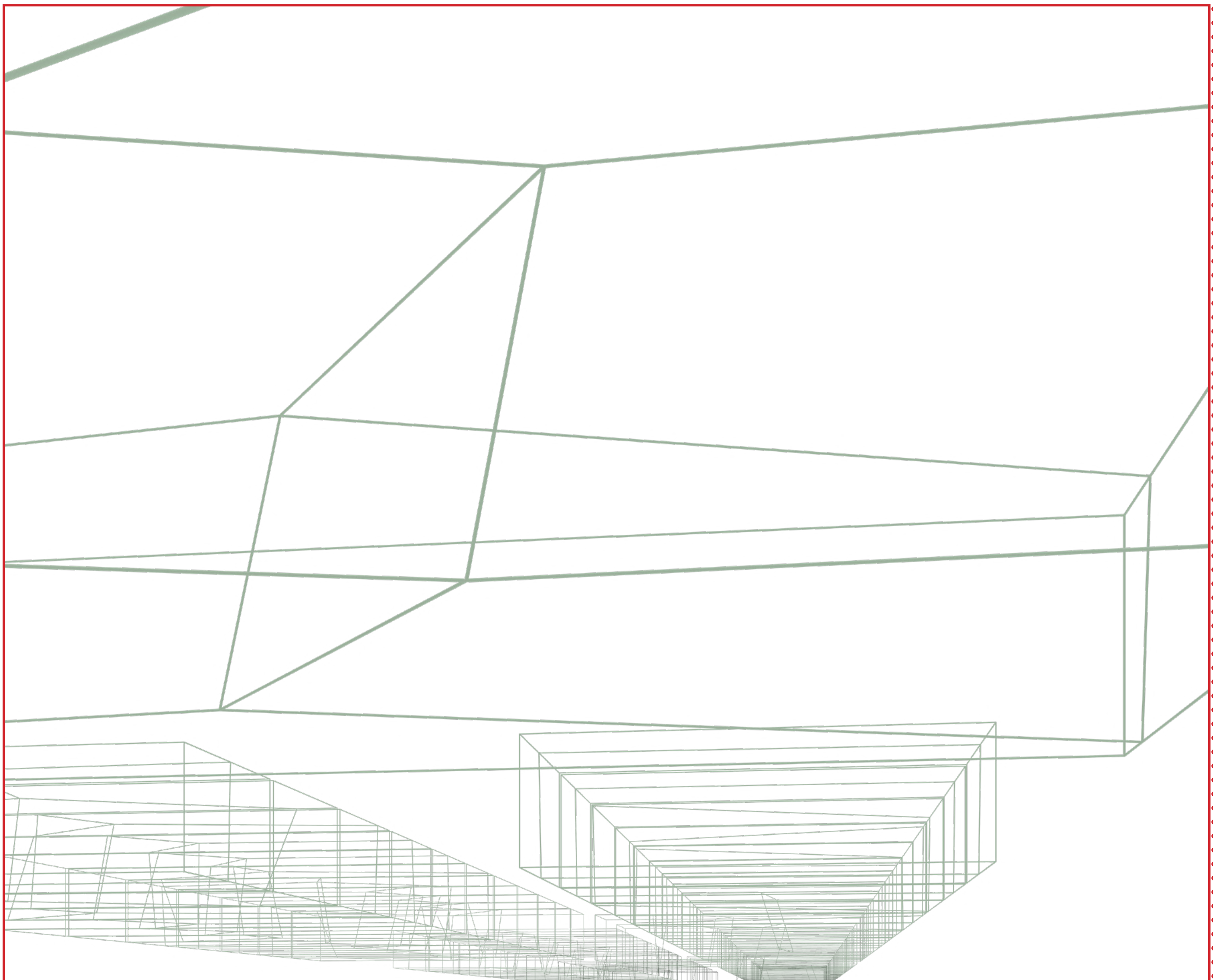


Fig 37
Introduction of 3D Voronoi Cells and Points based on Volumetric Llyod's Algorithm.

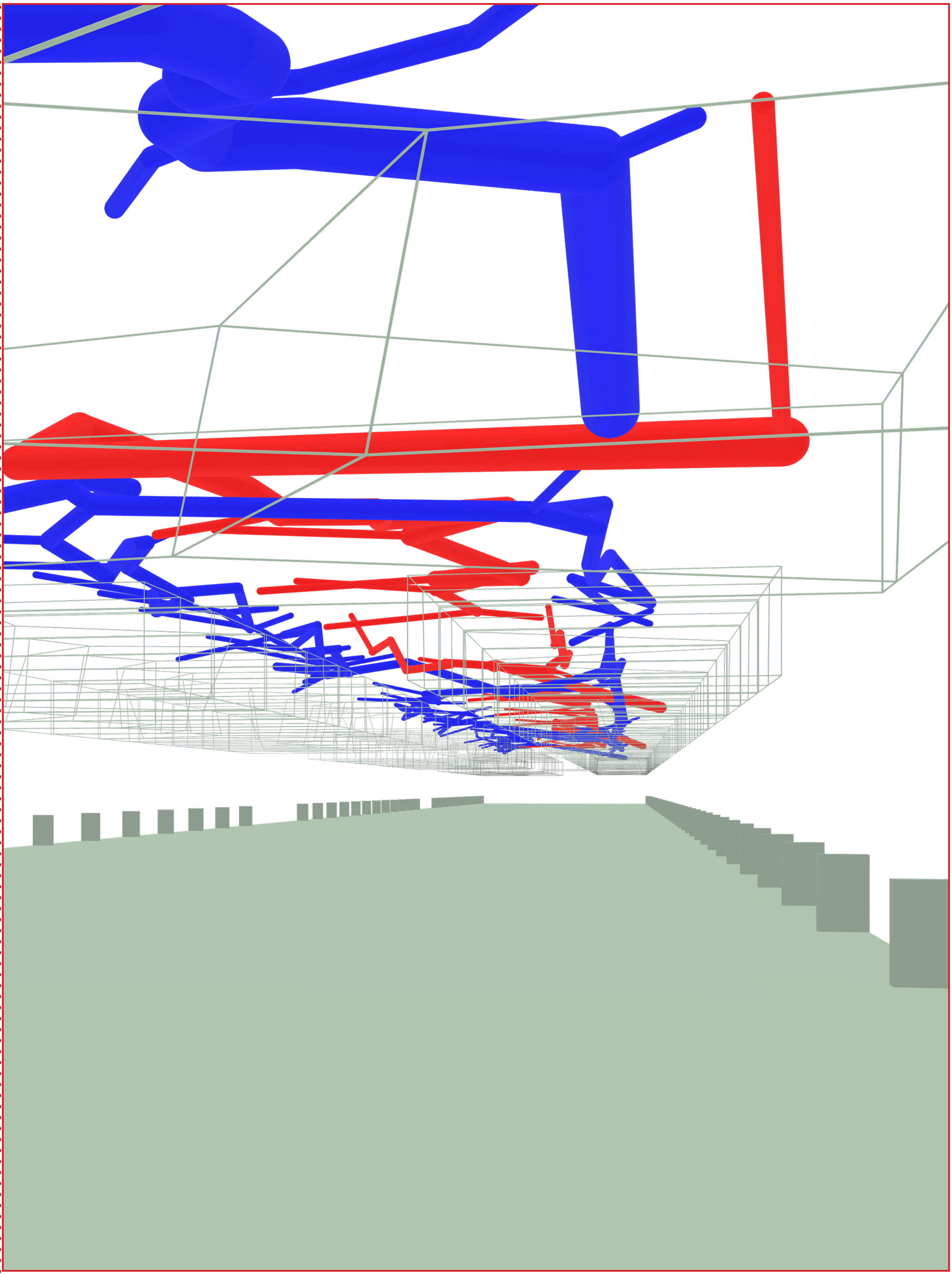


Fig 38
Top Floor showing the 3D Steiner Ducting Network, connecting the voronoi cells

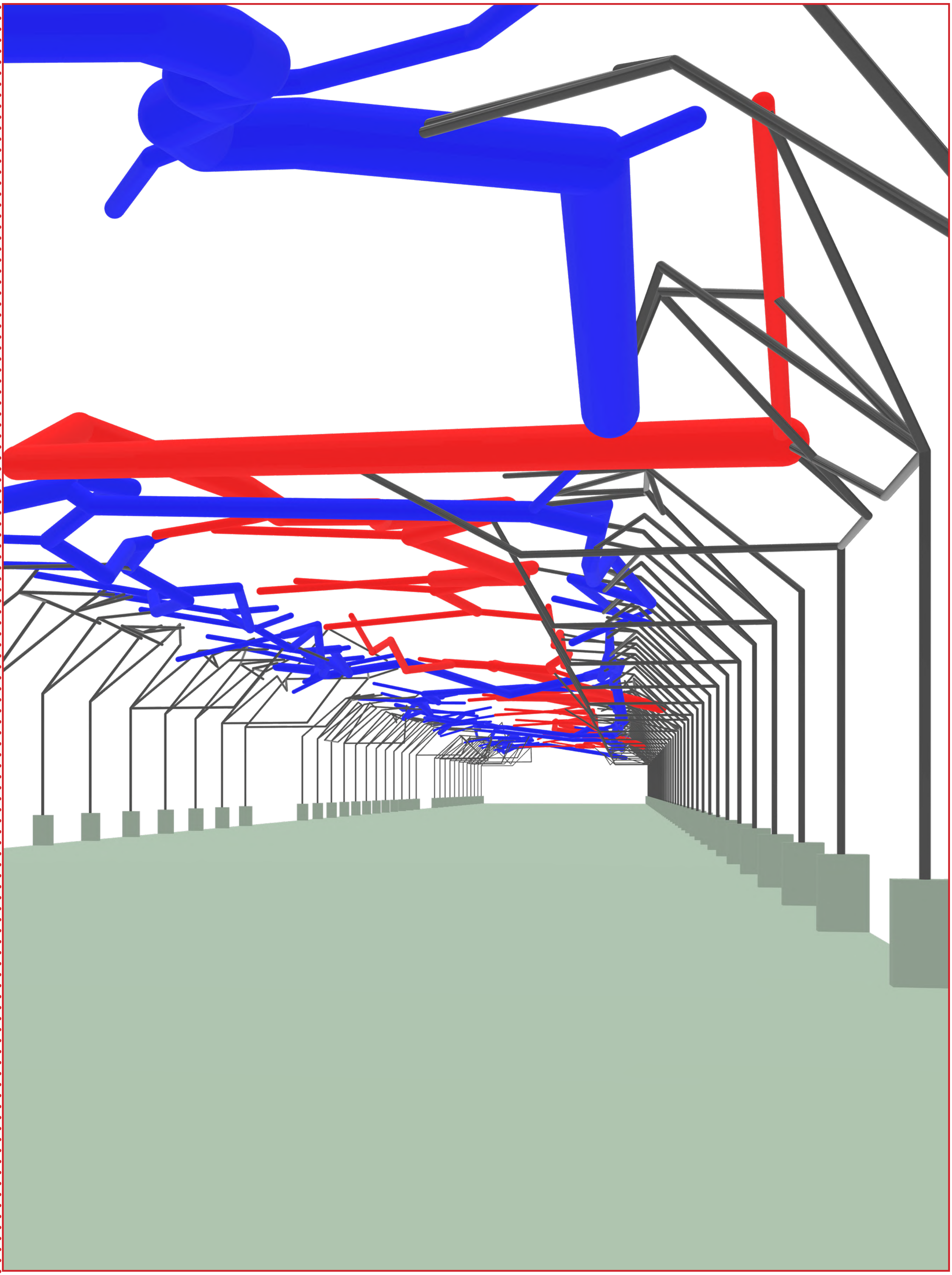


Fig 39
Connection of Ducts to stub columns which are the only available anchor points.

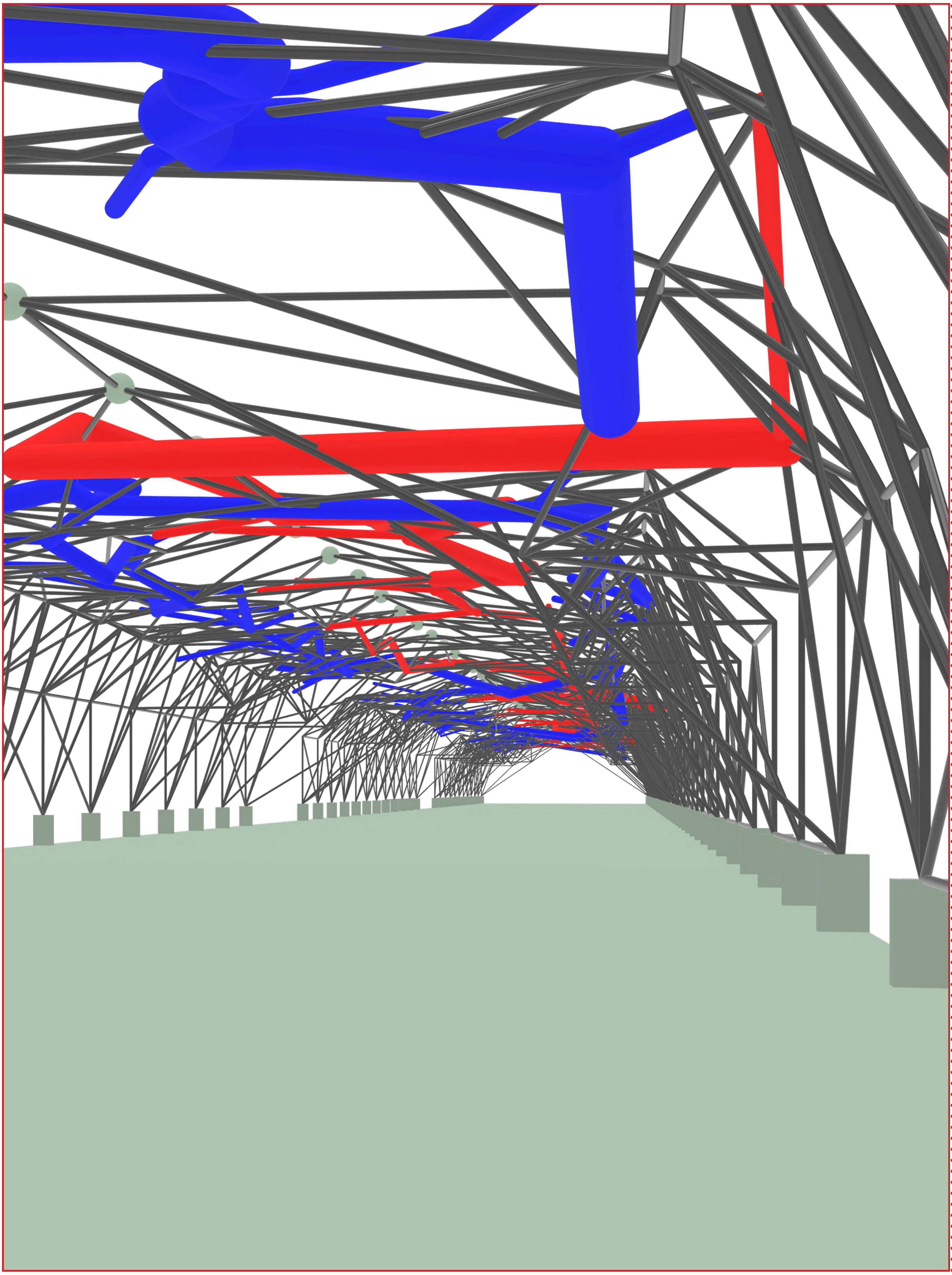


Fig 40
Making connections between the structural anchors and ducts, using limited angles

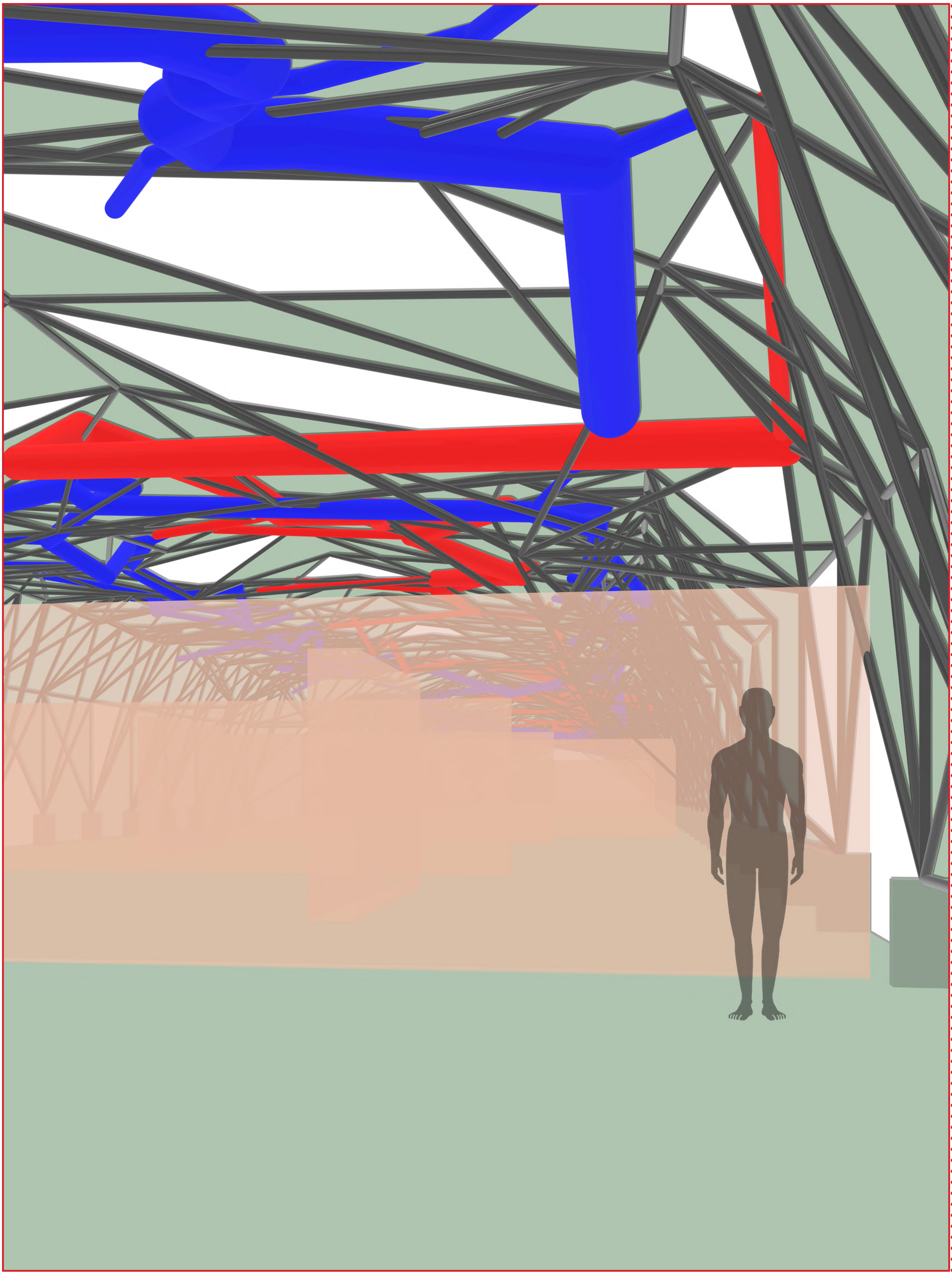


Fig 41
Paneling can be introduced to cover the structure and also internal walls based on the strucutral frame

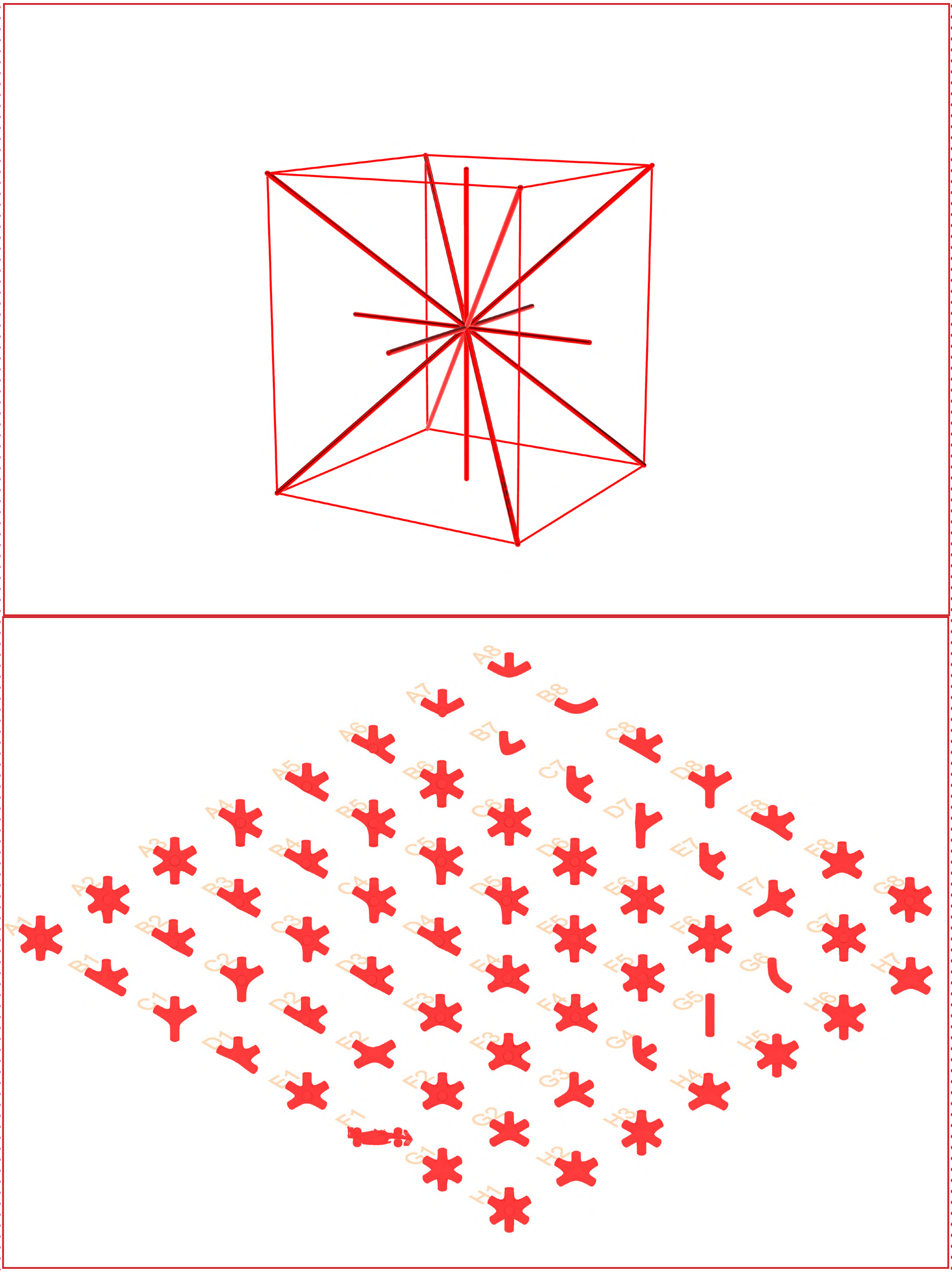


Fig 42
Inventory of available joints and limited angles based on the different iterations possible by connecting the centroid of the cube to its vertices or surface centroids.

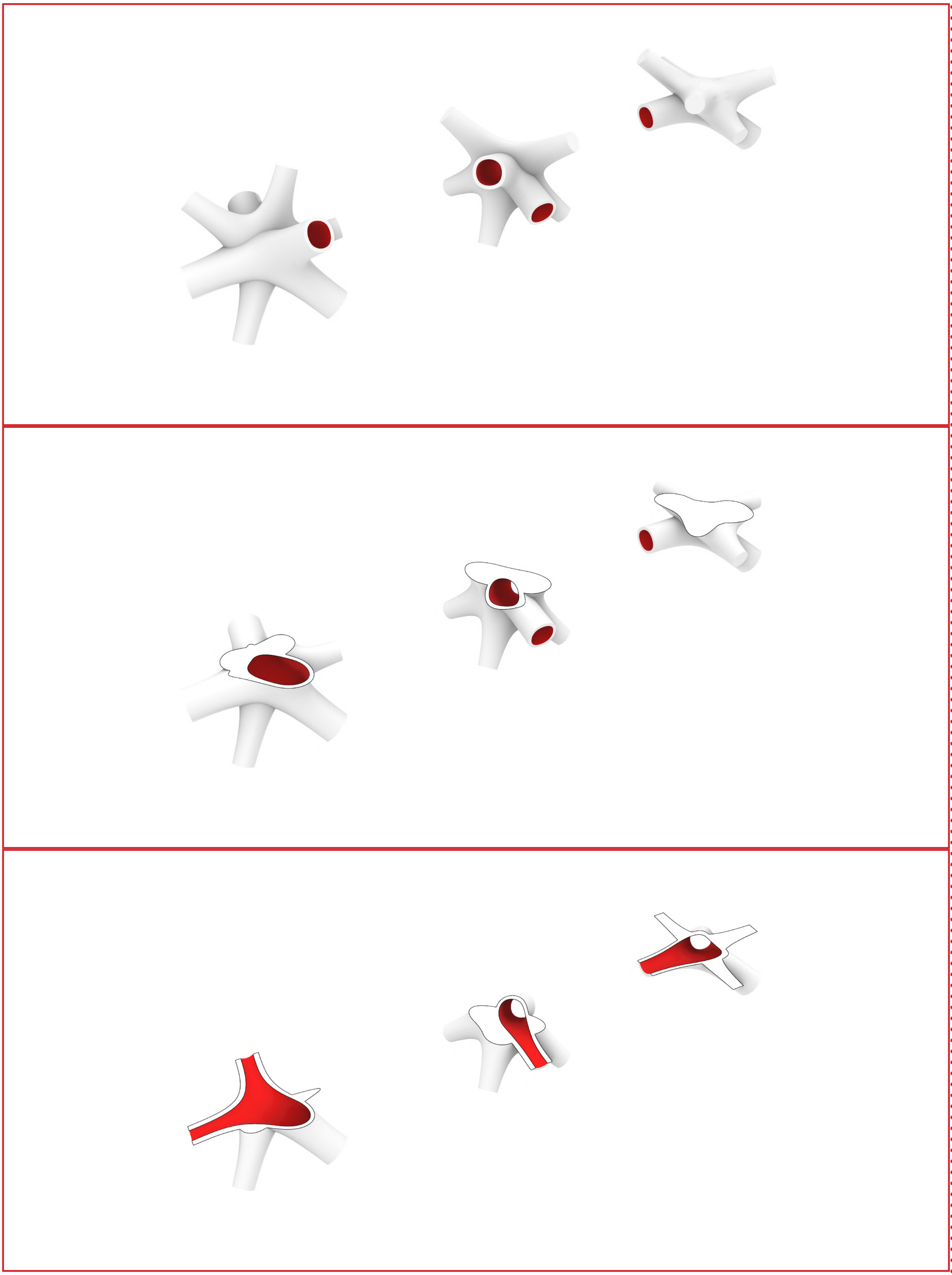


Fig 43
Series of sectional views showing how the joints have a mix of both solid and hollow cores for the dual purpose of both structure and ventilation

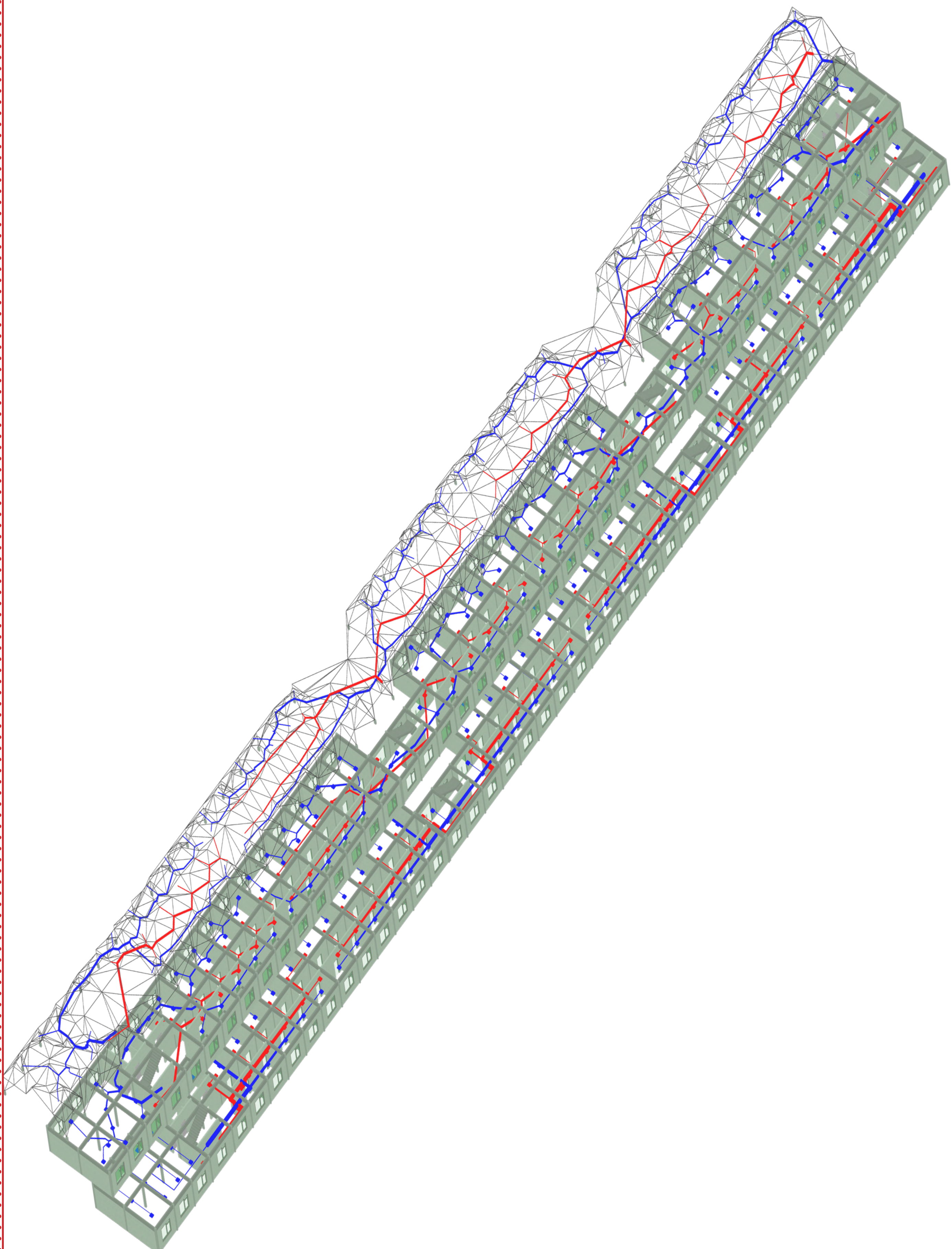


Fig 44
An axonometric view of all the floors together, showing the progression of the Ducting logic from the ground floor to the top floor

5. Results and Critical Discussion

The application of this algorithm framework to the IIT Delhi case study provides several critical insights into the viability and visibility of generative MEP design.

Algorithm Performance:
The transition from Agent-Based Modeling to graph-based path-finding proved highly successful. The Manhattan MST provided rapid, collision-free routing that respected the strict geometries of traditional construction. However, the application of the Steiner Tree algorithm yielded superior optimization regarding total material usage. By allowing the algorithm to calculate its own junction nodes (Steiner Points), the total linear length of the ductwork was measurably reduced, confirming previous hypotheses that non-Manhattan VLSI topologies significantly minimize interconnect lengths (Koh & Madden, 2000).

Aesthetic and Spatial Outcomes:
Architecturally, the project successfully demonstrated that services can dictate space. The stark contrast between the ground floor's hidden orthogonal efficiency and the first floor's chaotic, diagonal Steiner Web proves that algorithms can be tuned not just for engineering efficiency, but for specific aesthetic expressions. Exhibiting the 3D ductwork channels the mechanical reverence of the Centre Pompidou, echoing its evolution toward turning the distribution ducts into a genuine theme of the architectural facade (Hamzeian, 2018).

Constructibility Limitations:
The primary critique of the research lies in the physical realization of the top floor generative 3D joints. While topological optimization algorithms can theoretically design a node that handles both the structural load of the roof and the internal air pressure of the HVAC system, fabricating these dual-purpose nodes requires immense precision. While 3D printing is a viable and efficient way to manufacture the complex configurations of generative cross joints (Li et al., 2022), ensuring that these hollow nodes meet stringent fire-safety and acoustic insulation standards without creating massive thermal bridges remains a significant hurdle for future physical prototyping.

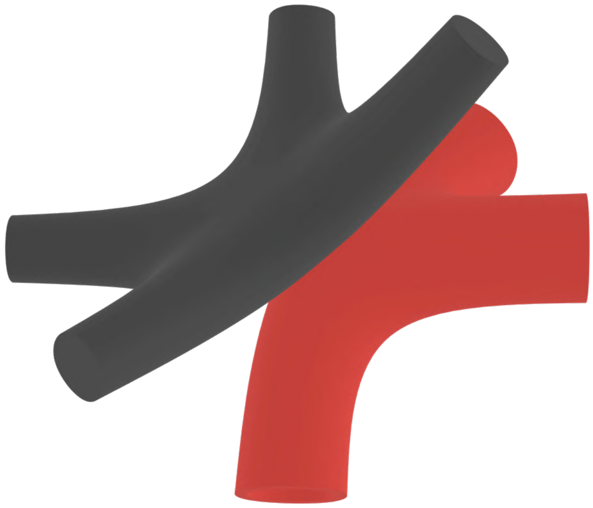


Fig 45
A view of the joint where Red represents the ventilation core and gray represents the structural core

Fig 46
Attachment of sleeves and flanges to the joints for connections to members

6. Reflections

Methodological Reflections

Traditional architectural workflows are fundamentally inefficient. Architects design a spatial shell in isolation, forcing mechanical engineers to cram HVAC infrastructre into leftover ceiling cavities. This sequential disconnect cause immediate coordination clashes, spatial waste, and financial losses. Designing HVAC first reverses this sequence. The architect's role shifts from drafting static geometry to defining the parametric constraints of the system, programming the baseline volumes, structural anchor points and algorithmic rules.
The mechanical engineer enters at a conceptual stage, not to fix spatial conflicts, but to co-author the network's logic. The engineer inputs parameters like Air Changes per Hour (ACH) and duct scaling rules. They then validate the generative output through computational fluid dynamics (CFD) and Finite Element Method (FEM) testing. This eliminates the constraint of a predefined container, the shell, and the internal systems are generated simultaneously.

Narrative Reflections

The case study site, a 216M brutalist building in Delhi demonstrates a clear progression from structural restriction to algorithmic freedom across its floors

Ground Floor

The routing is completely constrained by the existing 1960s concrete structure. It uses a strict Manhattan Minimum Spanning Tree (MST) running parallel to the structural beams and edges. The system is entirely secondary to the building's physical grid.

First Floor

The network breaks from the orthogonal grid using a 2D Voronoi Layout. The algorithm calculates room volumes to map optimised diffuser centroids, which them generate a non-grid branching network. This creates a direct spatial tension between the historic shell and the generative utility layout.

Top Floor

The vertical expansion achieves full systemic independence. Operating inside a 3D plenum within a lightweight 3D frame, supply and return ducts weave over and under each other in three dimensions without colliding. The network is completely decoupled from standard architectural grids, anchoring onto structural stub columns and intermediate ridge points between spans.

Physical and Spatial Performance

Exposing the entire structural utility network and eliminating internal ceilings makes the mechanical logic the primary architectural feature. The duct dimensions visually scale down as they move further from the source to maintain constant air pressure and volume, mapping the literal path pf the airflow.
To ensure the bespoke branching is fabricable, network angles are restricted to 61 specific joint iterations derived from mapping a cube's centre to its vertices and face centroids. The resulting 3D printed metal nodes are dual purpose, solid where they carry structural building loads and hollow to allow air to flow through, using internal sleeves and flanges to isolate mechanical air vibrations from the structure.

Using Llyod's Algorithm to calculate room columes and distribute diffuser centroids actively eliminates dead air pockets in awkward corners The architecture stops acting as a static container and functions as a mechanical lung, directly regulating the thermal micro-climate and air changes for the occupants.

Human and Phenomenological Experience

While the framework is proven computationally, the ultimate value if the system rests on the scale of human experience. Grounding this technical routing in a poetic and tactile reality changes how a user occupies the space. The raw math of the Voronoi iterations transforms into a sensory envelope, air distribution is no longer an invisible utility but a felt architectural presence.

By removing standard suspended ceilings, the complex ceiling landscape of 2D-printed nodes and tapering ducts brings the occupant into immediate contact with the building's internal system. The space behaves like a living organism. The gentle movement of air, balanced acoustic attenuation within the hollow structural nodes, and the elimination of stagnant perimeter zones after the thermal and auditory texture of the room. The system moves beyond technical efficiency to form an active, breathing environment designed around human comfort.

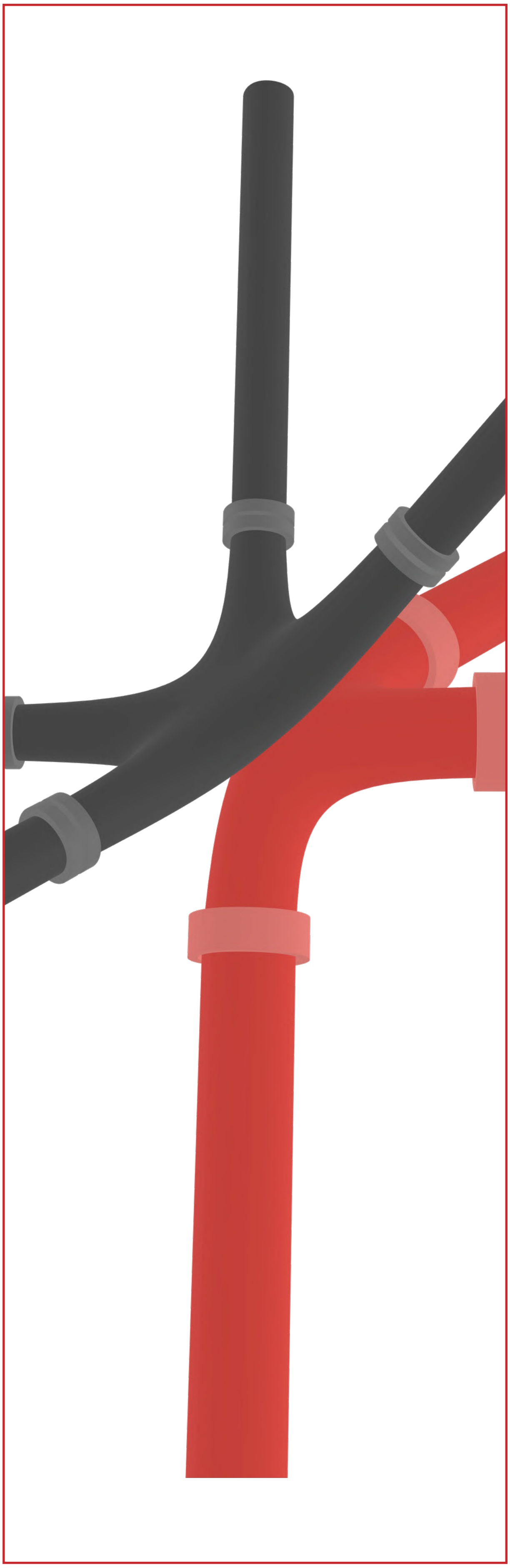
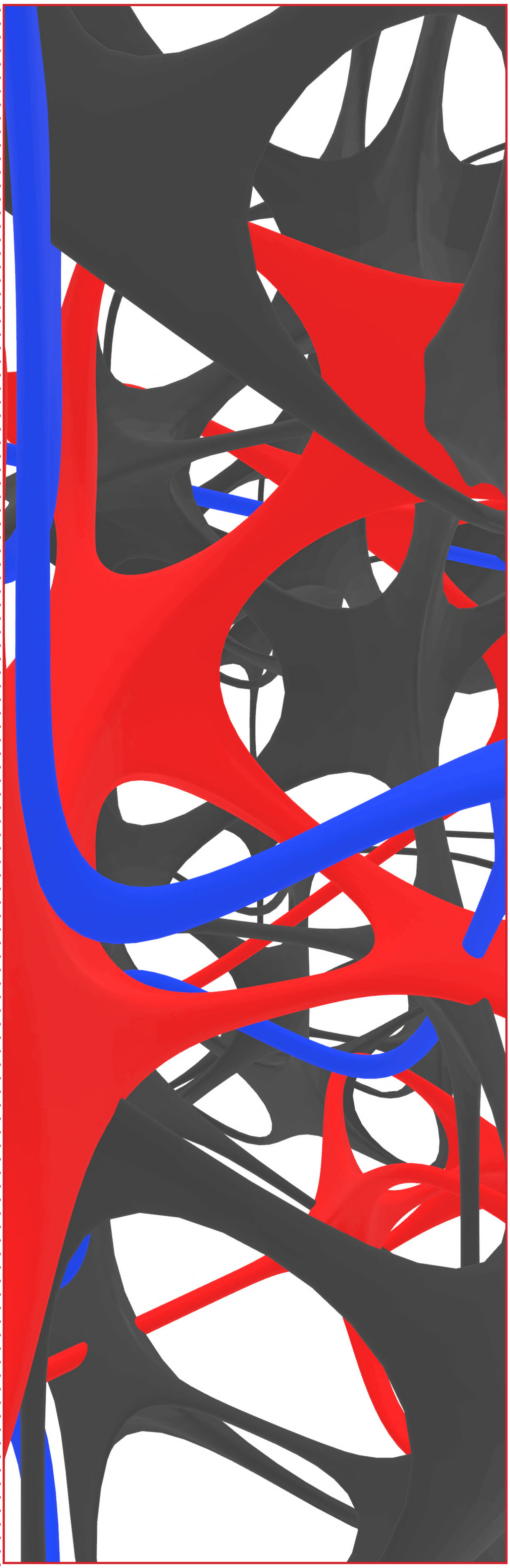


Fig 47
Connection of the joint with the subsequent ventilation and structural members



6. Conclusion and Future Outlook

This thesis definitively argues that HVAC systems form the critical backbone of contemporary architecture and must never be treated as an afterthought during the conceptual design phase. By analyzing historical precedents like Louis Kahn's Richards Medical Laboratories and Piano and Rogers' Centre Pompidou, the research established a foundation for celebrating technical infrastructure. By leveraging advanced generative algorithms, specifically the transition from Manhattan MST to Steiner Minimal Trees, architects can now automate the integration of complex building services directly into the spatial and structural logic of a project.

The application of this framework to the IIT Academic Block 3 renovation proves that generative routing can operate on a versatile spectrum, ranging from highly efficient, concealed rectilinear grids that respect historic concrete waffle slabs, to expressive, exposed 3D structural networks where the building's skeleton and its respiratory system are one and the same.

Future Research Possibilities

To transition this conceptual framework into industry-standard practice, future research must focus on validating the algorithmic outputs through rigorous engineering simulations. Advanced Computational Fluid Dynamics (CFD) must be run within the generated Steiner networks to verify that the non-orthogonal bends and generative 3D joints do not induce unacceptable pressure drops, friction losses, or acoustic turbulence (Nielsen, 2021). Furthermore, expanding the 'MyRules' logic to simultaneously route electrical conduits and plumbing drainage alongside the HVAC, while calculating clash avoidance between all three systems, will move the discipline closer to a fully automated holistic generative design environment.

7. References

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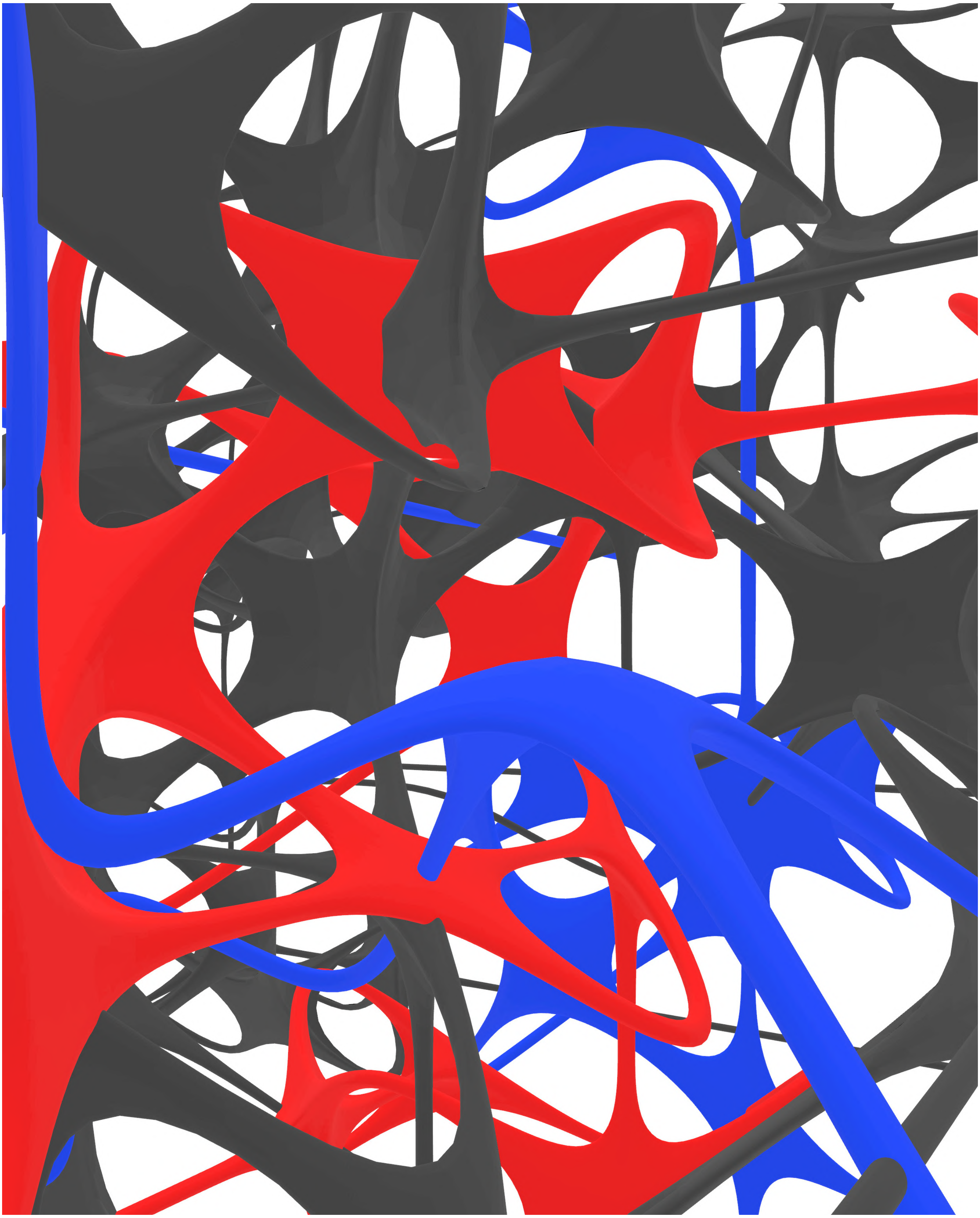

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