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Cellular Automata as Pedagogical Agents for Contextual AI in Ecological Architecture: A Human-Machine Collaboration

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Introduction: Negotiating Automation

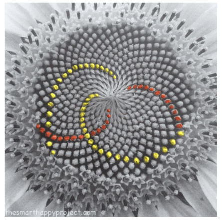
- buildings intelligently respond to both ecological and cultural variables
- increasingly facilitated by generative algorithms.
- AI trained on mainstream datasets possess a normative understanding of the world
- homogeneous both our design practices and outcomes.

how to embed contextual intelligence—both environmental + cultural—into automated workflows without reducing design to universalist optimization while facilitating designer creativity in the process?

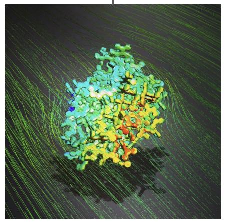
Intersecting Computational Challenge

Rule/Agent-based System
bridge environmental specificity yet faces scalability bottlenecks

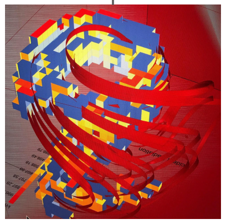
Machine Learning
promises acceleration but often operates in a contextual void



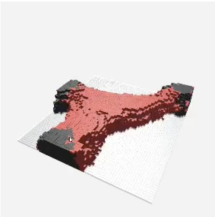
Bio- & Parametric



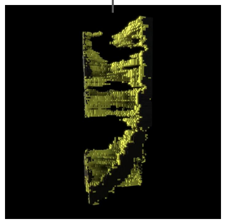
Cellular Automata



Genetic Algorithm



Voxel Training



Gesture Bias

pix2pix

Reframe this not as a replacement, but a pedagogical collaboration

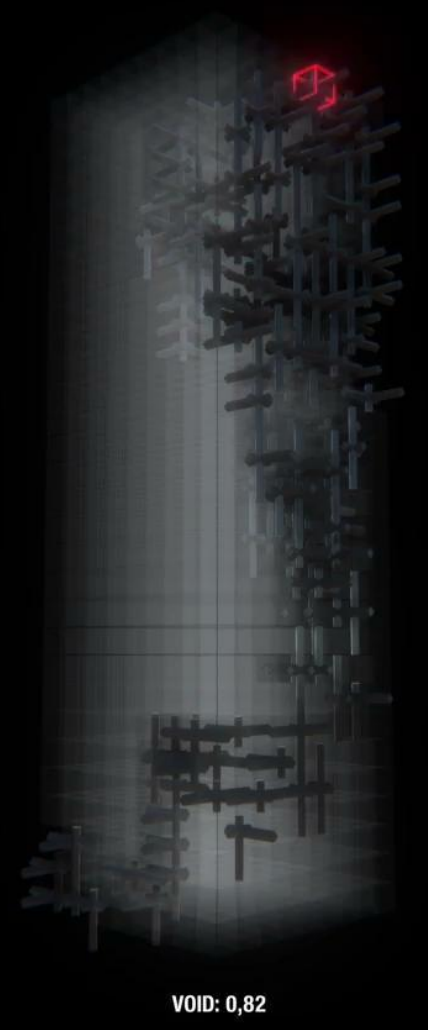
Cellular Automata (CA) helps contextualise ML tasks

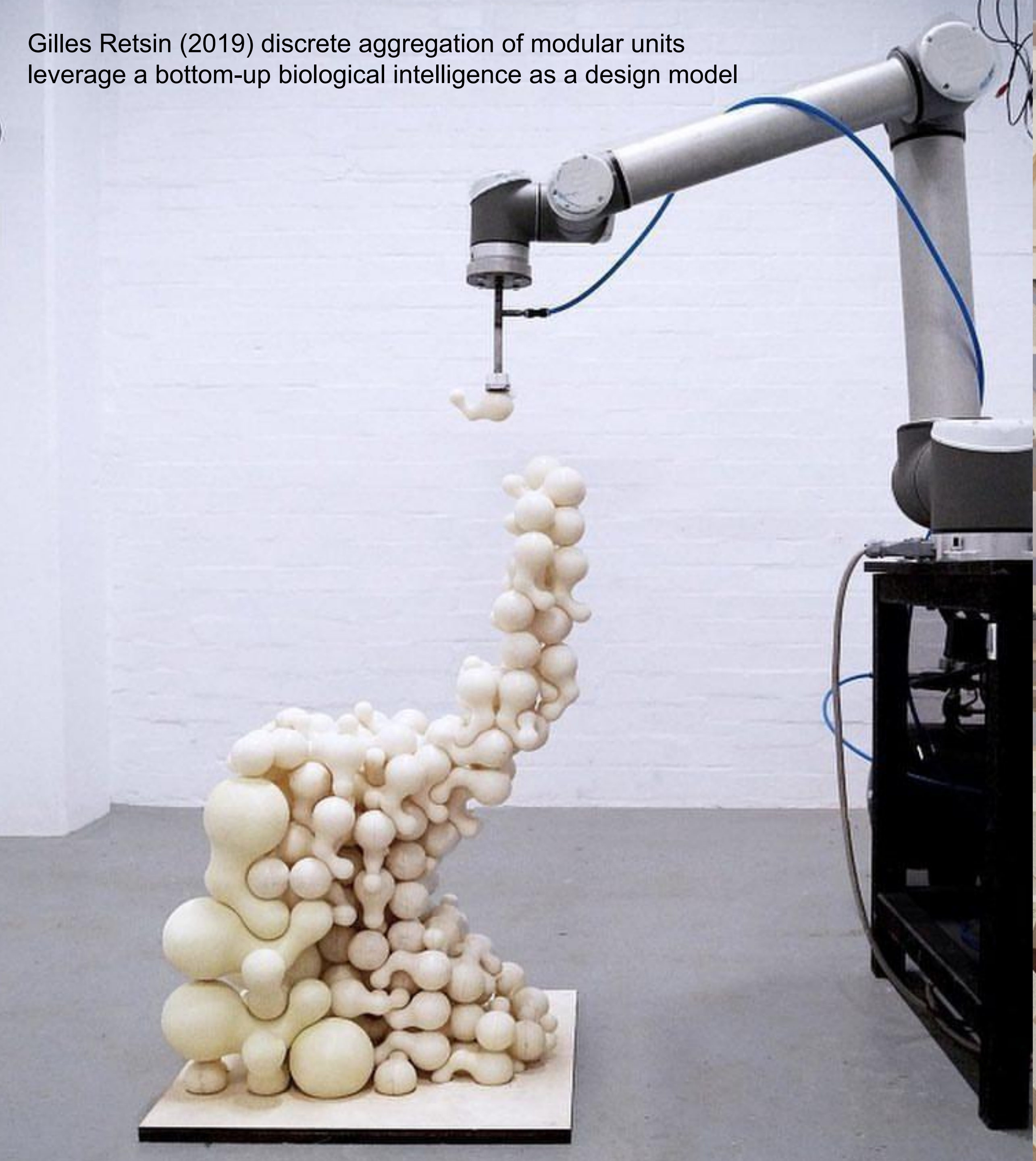
Machine Learning (ML) helps accelerate CA tasks

Problems Encountered in Previous Study

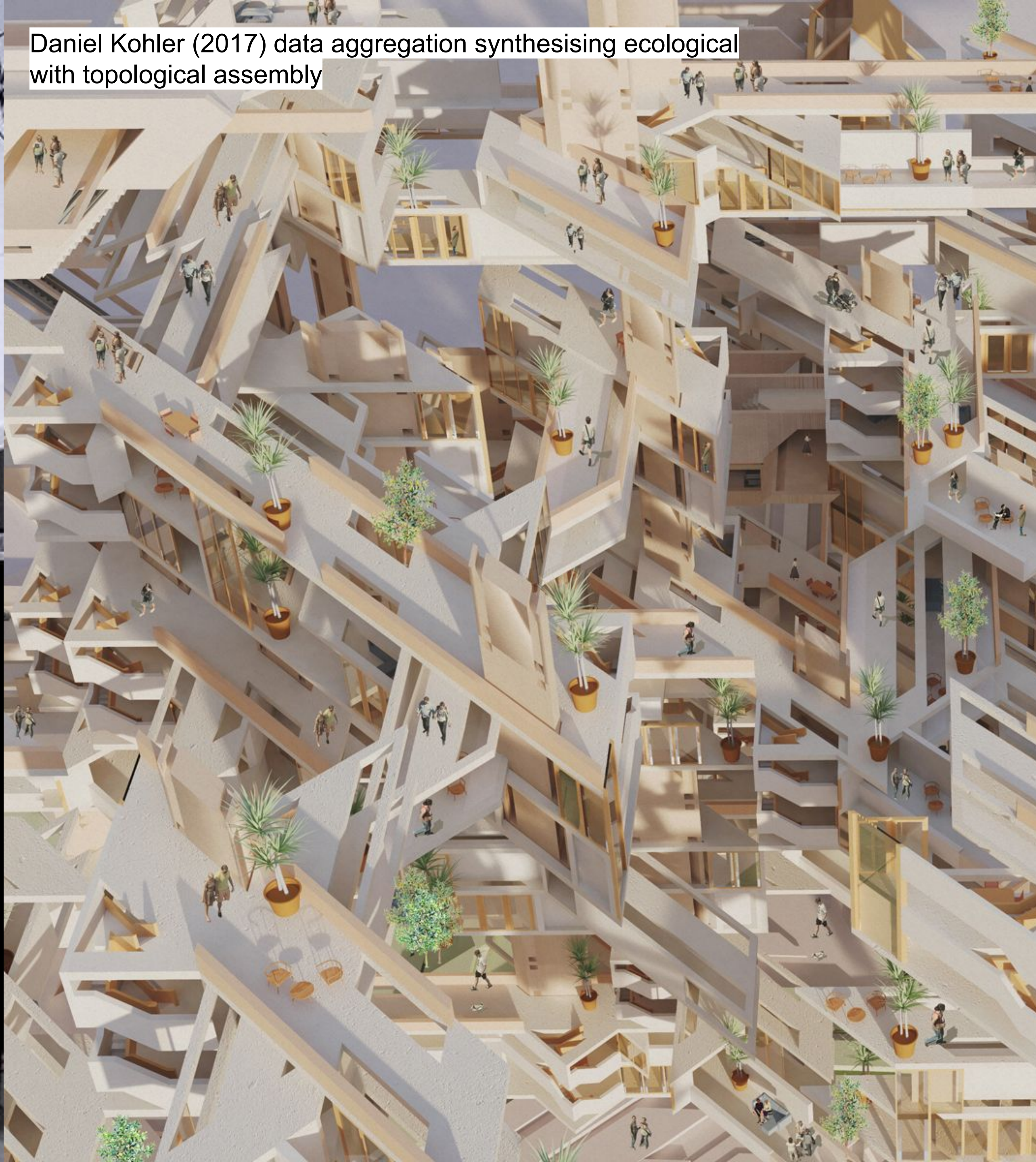
- Rigid discretization hindered more organic forms and cultural adaptation
- Inadequate control for contextual variables (local resources, aesthetics)
- Computational inertia in translating CA states to solutions.

To resolve this, we studied how recent advances in bio-inspired design synergised machine automation with human creativity.





Gilles Retsin (2019) discrete aggregation of modular units
leverage a bottom-up biological intelligence as a design model



Daniel Kohler (2017) data aggregation synthesising ecological
with topological assembly

Objectives

1. To capture into a ML model a design process that, originally would demand prohibitive computation, can be executed relatively instantaneously, and **test the pipeline in various design scenarios**
2. To **evaluate** the shift of CA from a computationally-heavy generator to **an intelligent pedagogical tool** for ML
3. To **analyse** how combinatorial tooling can help bridge **designer intuition (rule definition)** and **machine efficiency (pattern replication)** in automated workflows.

Methods

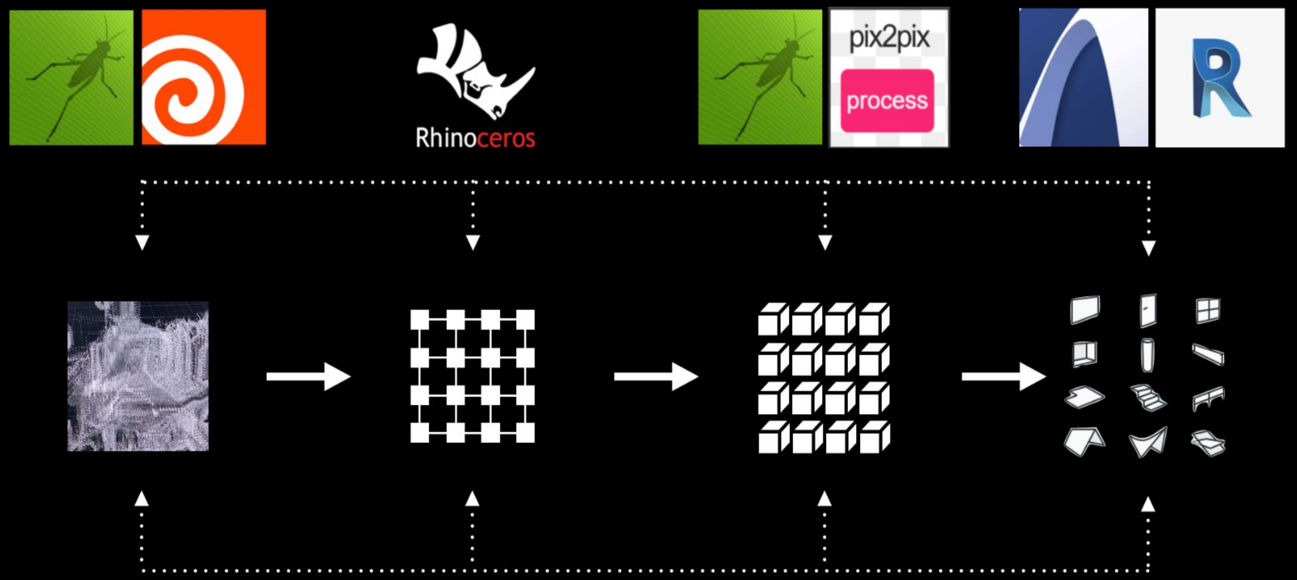
1. **Experiential Workshops**
2. **Performance Benchmarks**
3. **Conflict Framing**

Phase 1: Synthetic Pedagogy

CA simulates site constraints (e.g., solar incidence) into discrete cell states, generating a synthetic dataset.

These become training protocols for PyTorch-based pix2pix GANs to accelerate the simulation.

Houdini dynamically recalibrates the pixels into voxels through growth algorithms, translating simulation data into 3-dimensional data proxies.



Phase 2: Cross Contextualise

With 20 architects across 12 countries working in teams of 4:

Each team selected a site in their local context with documented climatic/cultural constraints,

Deploy steps in Phase 1 to train AI and accelerate design iteration for each site.

Refined outputs via human-machine feedback loops.

Phase 3: Benchmarking

We quantified computational trade-offs: CA's precision versus ML's speed, storage demands, hardware scalability.

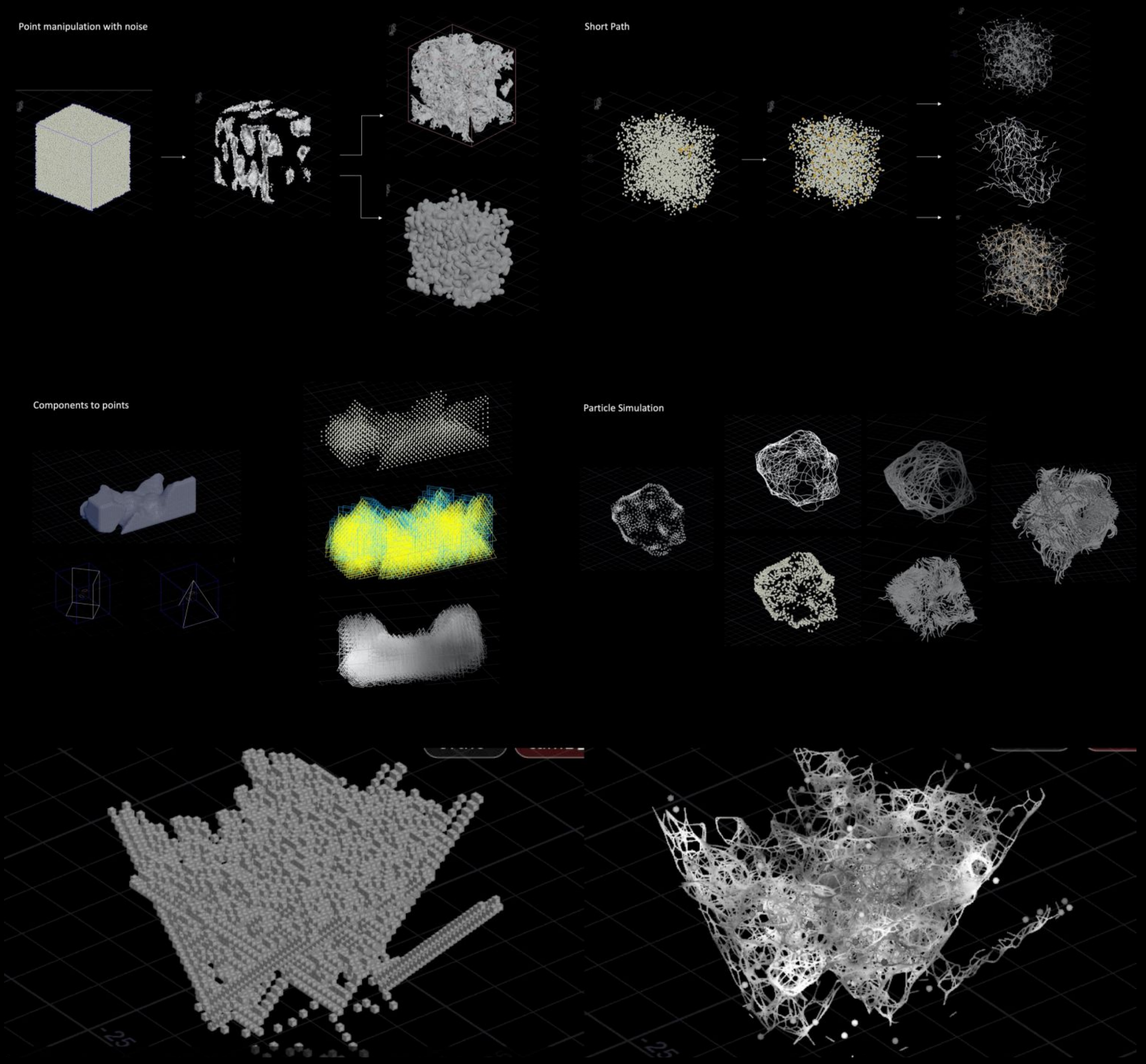
Reflect with participants the human-machine protocols in the process and frame conflicts for improvement in the next phase.

Results

SELECTED PROJECTS

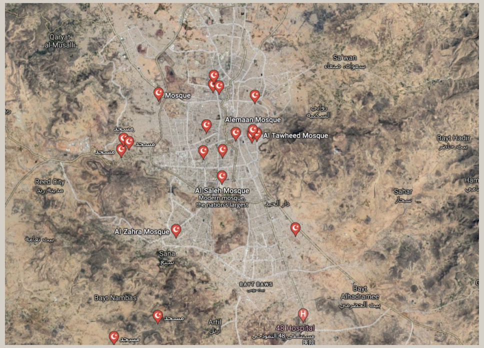
the same combinatorial pipeline can give emergence to vastly different design results, the two samples are:

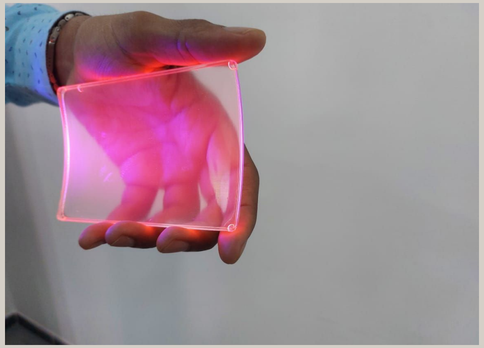
- with different contexts / local organisms as inspiration
- relatively close to the equator, but suffer from different climatic concerns
- hybridising active and passive solar strategies into one design
- with surrounding environments of relatively scarce resources due to socioeconomic / geographical factors.
- context as the curriculum.



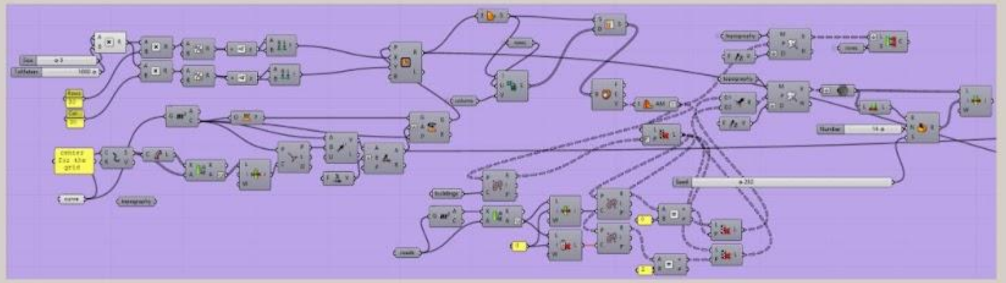
Sanna Refugee Tower, Yemen by Chowon Kang, Yutong Zhang

Low-rise refugee shelter in resource-scarce urban fabric, upcycling discarded shipping containers into PV-integrated energy-resilient blocks, tackling Modular Integrated Construction (MiC) challenge.

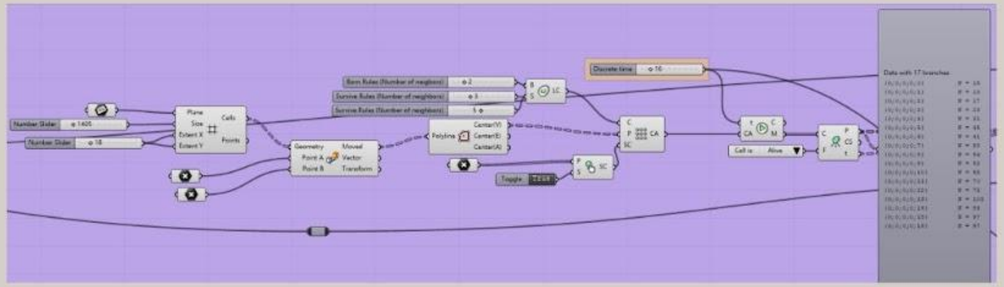




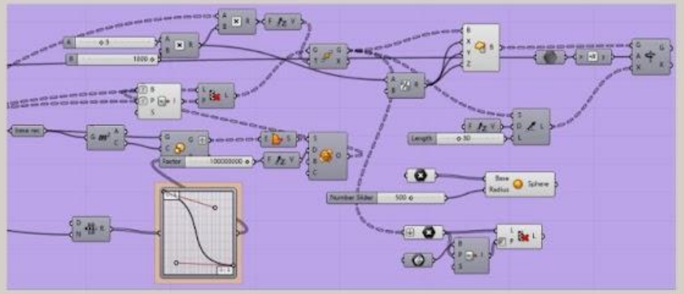
Step 1: Seed Definition
Using existing surroundings including Mosque as restrictions for generating the initial points, which would be later used as starting seeds for CA calculation.



Step 2: CA Definition
With seeds as pre-defined factors, Rabbit is used to generate a series of points based on certain self-growing rules. In the meantime, the building height is also controlled not to be higher than the Mosque.

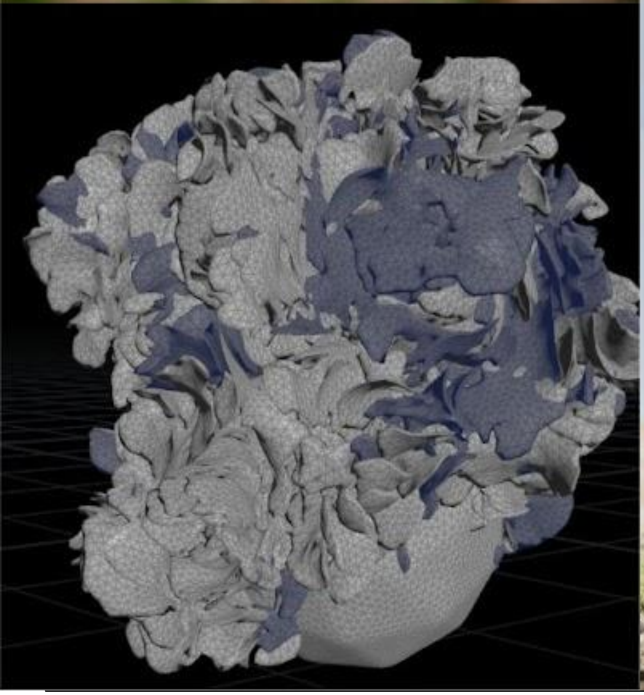


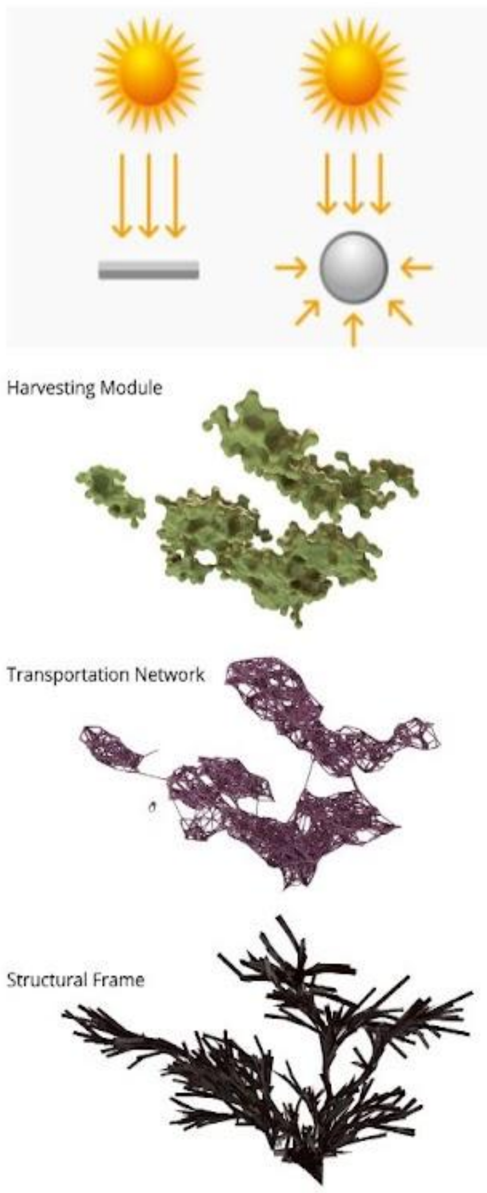
Step 3: Voxel Generation
Points generated from CA are acting as base planes for voxels, with additional scaling factors to influence the overall form.

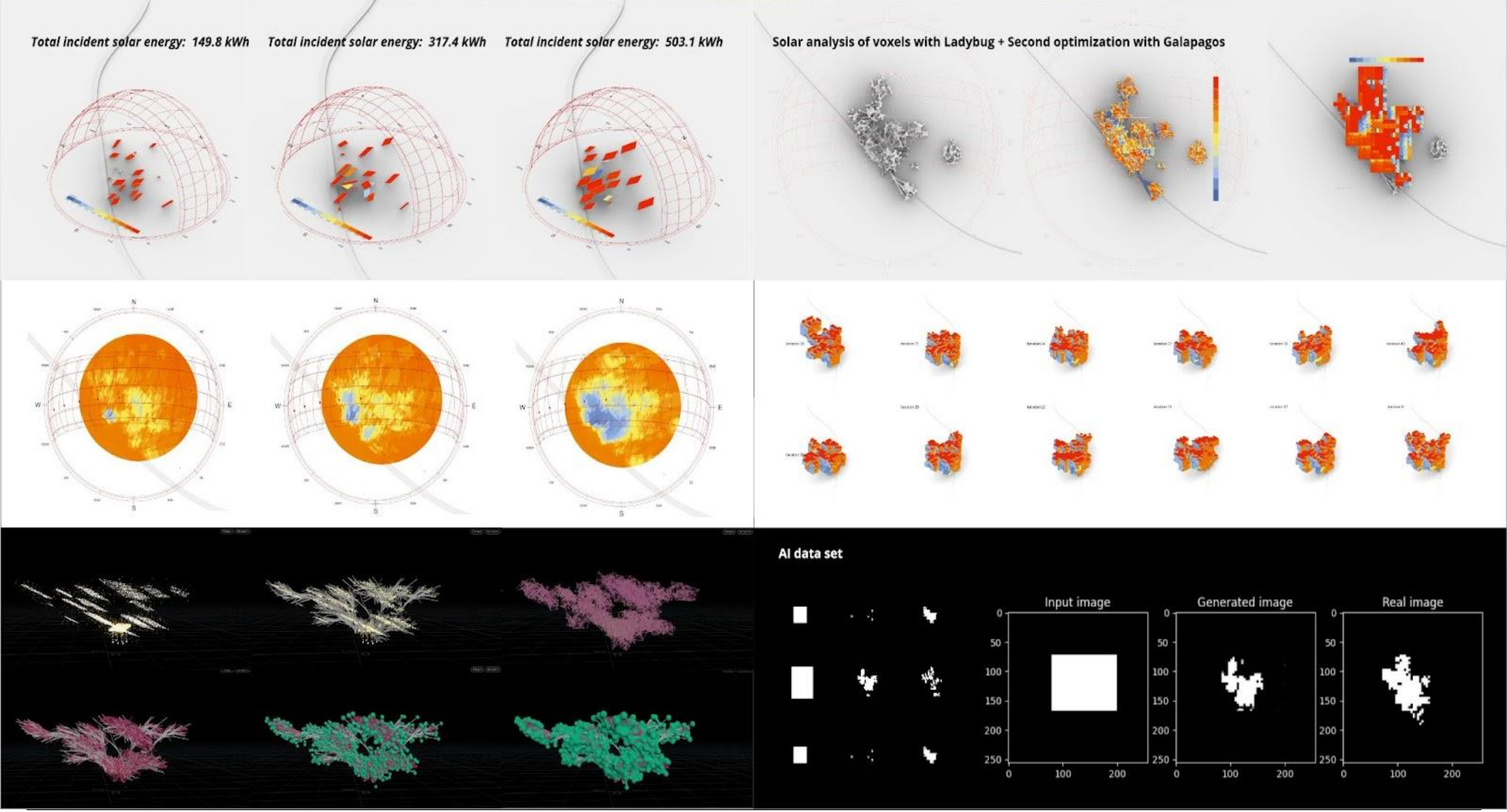


L1ch3nic Sph3ribl0b5, Peru

Carlos Rivera, Manuel Halim, Gao Xiang, and Mason Mo







Total incident solar energy: 149.8 kWh
Total incident solar energy: 317.4 kWh
Total incident solar energy: 503.1 kWh
Solar analysis of voxels with Ladybug + Second optimization with Galapagos
N
W
E
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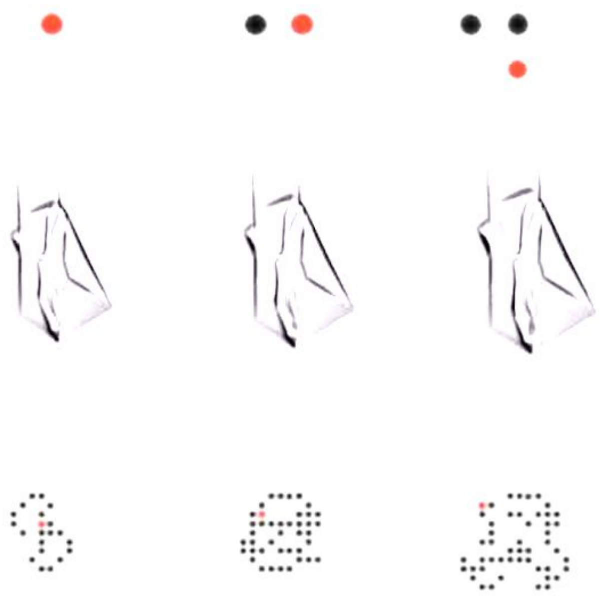
AI data set
Input image
Generated image
Real image

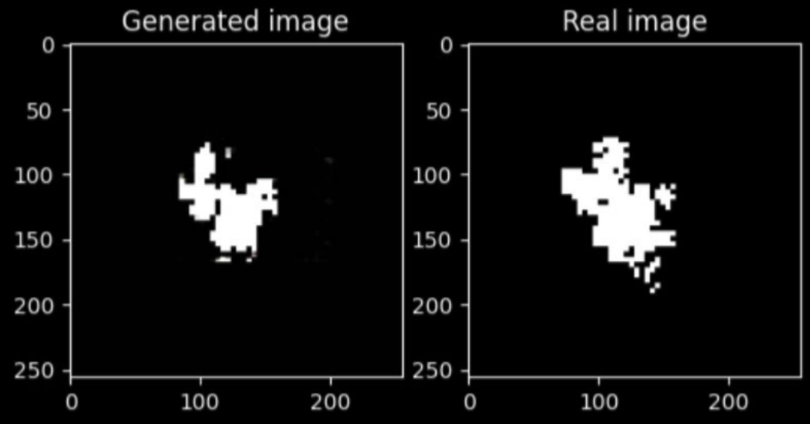
ANALYSIS 1

Contextual AI Acceleration for Design Diversification



Aspect	Sanna Refugee Tower, Yemen	L1ch3nic Sph3ribl0b5, Peru
Context	Desert climate, resource scarcity, Alawi Mosque site, port country.	Highland trails, water/electricity scarcity.
CA's Role	Solar instances dictated modular aggregation of containers—inspired by marine sponges' non-competitive growth.	Simulated lichen's moisture-harvesting thallus structure.
AI's Role	Optimised LSC-window orientations and provide diverse design options very fast.	GANs transformed solar data into spherical-cell arrays.
Human's Role	Voxel proxies minimized computation; designers minute articulation resolve unit continuity in the outcome.	Bio-form discretization into voxels enabled CA-to-ML knowledge transfer.
Key innovation	Diversified modular integrated construction methods, controlled by environmental inputs.	Spherical topology and lichen-inspired vapor capture formalized environmental intelligence into discrete CA rules—later accelerated by ML for rapid highland-adaptive prototyping.

Comparative Benchmarking: Computational Performance



ASPECT	**CA**	**GAN**
Iterations/ Generations	900–1000 evolutions for convergence.	600 training iterations, 500 samples, 256x256 px each.
Compute Time	6–7 hours for 900–1000 generations.	8–10 hours on GPU. After training = ~instantaneous.
Data Storage	70 GB for 900–1000 evolutions.	2–4 GB (200 MB checkpoints × 12 saves over 600 iterations).
Intermediate Data	High (simulation outputs, population states).	Moderate (gradient updates, logs).
Hardware	CPU (parallelization limited by simulation bottlenecks).	GPU-accelerated (training); CPU/GPU for inference.
Scalability	Time/data grow linearly with generations.	Storage scales with checkpoints; training time depends on the dataset.
Use Case Suitability	Context with little data; generating synthetic data	Data-rich context; almost instantaneous inference.

Discussions

Intelligence as Negotiated Collaboration

We argue that automation's value lies in structuring this triad:

- Humans define priorities (cultural needs, solar thresholds),
- CA formalizes them into discrete, teachable rules,
- ML learns and accelerates application.

This work probes three shifts:

- From Automation to Pedagogy: CA structures contextual biases as teachable protocols for ML.
- Biomimicry as Operational Logic: Lichen/sponge aggregation became computational distribution rules—not metaphor.
- Hybrid Workflows as Necessity: Human priorities steer CA; CA trains ML; ML accelerates human creativity.

Tensions: Computation vs. Spontaneity

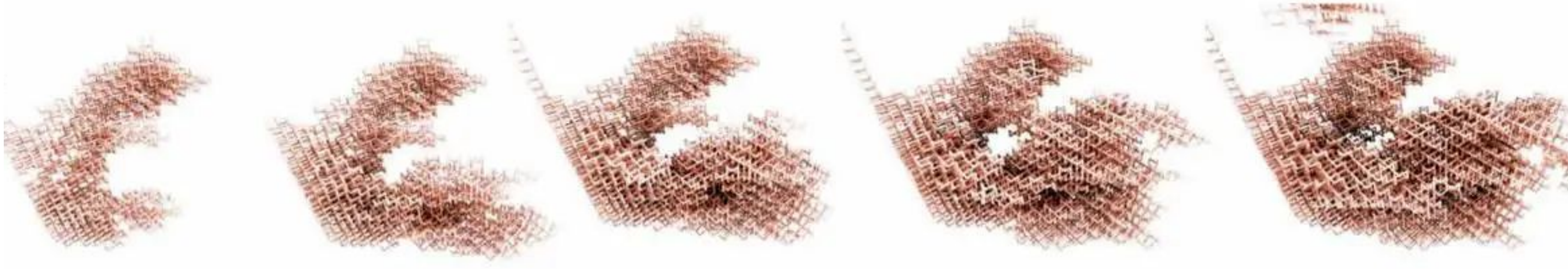
Human intervention as modular input within combinatorial pipeline to prevent computational bottlenecks:

- Discretizing continuous bio-forms vs. aggregating discrete units,
- Balancing voxel resolution against computational load,
- Negotiating micro-scale inaccuracies in ML outputs.

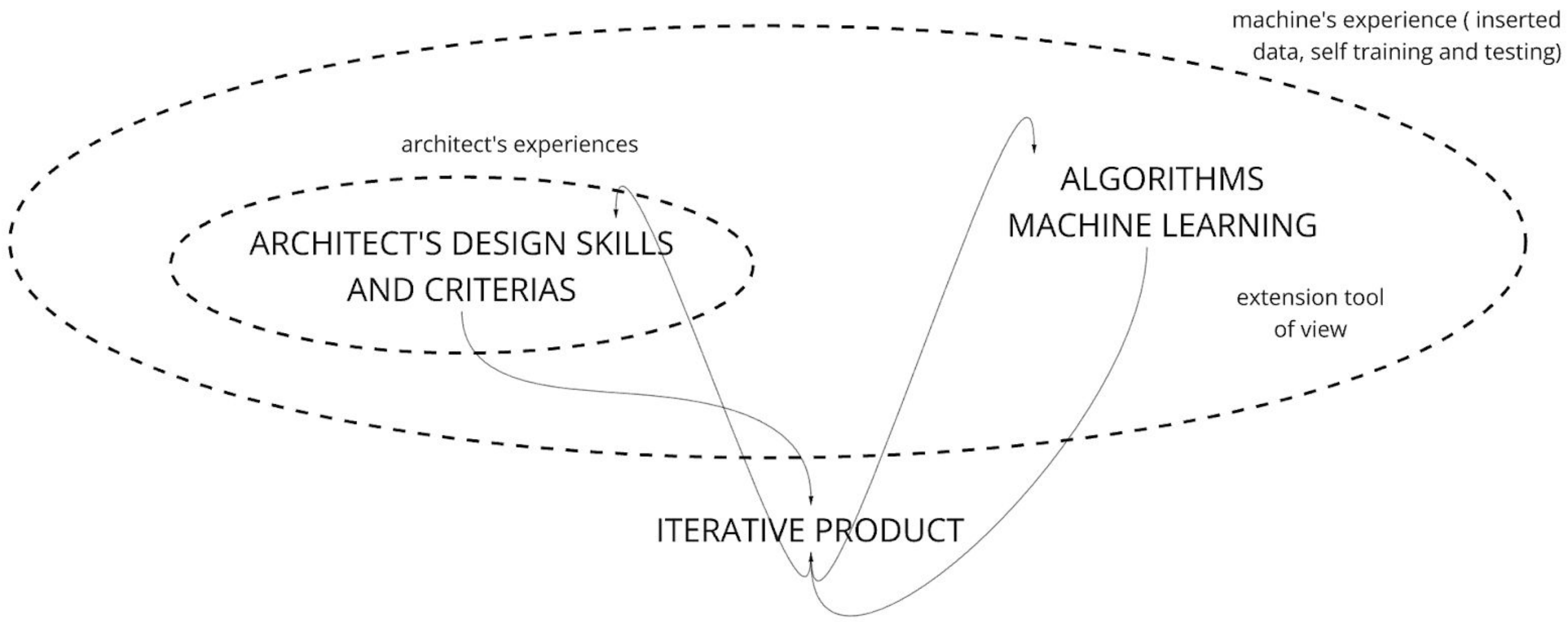
Limitations persist:

- Synthetic datasets risk closed-loop detachment from real-world performance,
- Cultural adaptation relies on designer intuition (aka tacit knowledge),
- Voxel interoperability remains underdeveloped.

The process underscored collaboration as multi-scalar: human-machine (intent vs. automation), machine-machine (CA-to-ML pedagogy), and human-human (negotiating contextual diversity), ultimately highlighting a tension between dynamic, self-configuring proposals and the static, perpetual realities of built architecture.



Participants Feedback



"We architects base our design skills and criterias on personal learning experiences. AI does pretty much the same, with the difference that it has **the capacity of choosing combinatorial paths of data.**"

"Decisions made by the architect, evaluated by machine, getting a product, and going back again in the loop."

"The future of design relies on **self-configuring architecture**, we can make such accurate proposals that can adapt to the slightest environmental changes; **per month, per day, per hour, per minute**. This fact clashes with the reality of today's architectural products: the static, the perpetual."

The study revealed **a negotiated choreography between human and synthetic intelligence**, with participants deploying variable workflows: initiating processes through parametric forms, manipulable data points, or solar-simulated voxel grids.

This minimised processing labour but introduced **micro-scale discontinuities, mediated by designers** through either discretizing continuous forms or aggregating units with connectors.

We conclude that **scalable intelligence in architecture is not autonomous—but collaboratively constructed**. Machines must learn as students of ecological and cultural wisdom, with architects as interpreters of computational nuance.

To tackle solutionism homogenising forces, we must continue to engineer frameworks for negotiating tension. **Efficiency gains demand reintroducing human agency in supervising computational singularity—contextual AI**.

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