Reimagining the Urban Form of Jeddah through Genetic Algorithm Optimization and AI-Based Visualization

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Abstract: This research explores the reimagining of Jeddah's urban form through the integration of genetic algorithm optimization and AI-based visualization techniques. Facing challenges of low-density sprawl, insufficient public spaces, extreme climate conditions, and limited cultural integration, Jeddah requires innovative computational approaches to create sustainable, efficient, and culturally responsive urban environments.

Our study employs genetic algorithms to optimize urban layouts and massing generation, focusing on creating well-connected street networks, maximizing accessibility, balancing land use diversity, optimizing shadow impact, and enhancing daylight availability. These optimizations are complemented by AI-based visualization techniques that transform abstract computational outputs into compelling visual representations.

Keywords: Urban Form, Genetic Algorithm Optimization, AI Visualization, Computational Urban Design, Jeddah

1. Introduction

1.1 **The Urban Tapestry of Jeddah**

Jeddah presents fascinating urban contradictions that make it an ideal subject for computational design exploration. The city unfolds like a historical narrative written in stone, glass, and steel each neighborhood telling a different chapter of Saudi Arabia's evolution. From the narrow, winding alleys of Al-Balad with their coral-stone buildings to the sleek high-rises along the Corniche, Jeddah embodies the tension between preserving cultural heritage and embracing modernization.

Recent decades have seen conflicting trends: glass-clad towers representing global modernity alongside growing efforts to restore Al-Balad and reconnect with architectural heritage. This tension creates both the challenge and opportunity that our research addresses.

1.2 **Understanding Urban Form**

Urban form isn't just about aesthetics or arrangement—it's the physical manifestation of social, economic, and cultural forces that shape how we experience cities. It encompasses the three-dimensional configuration of urban elements that define both the character and functionality of urban environments.

Traditional approaches to urban form design have been largely manual, linear, and designer-driven. They rely heavily on intuition, zoning regulations, and conventional tools like hand-drawing and CAD.

Our research proposes a fundamentally different approach—one that is algorithmic, iterative, and data-driven. By basing layout generation on performance criteria and optimization techniques, we can explore thousands of possible urban configurations and identify those that best respond to Jeddah's specific challenges.

1.3 **Research Question & Objectives**

How can Genetic Algorithm Optimization and AI-based Visualization be integrated to reimagine and enhance the urban form of Jeddah in a performance-driven and visually communicative way?

Our research has two primary objectives:

1. **Genetic Algorithm Optimization of Urban Form**: We aim to develop and implement genetic algorithms that can generate and evaluate urban layouts based on specific performance criteria relevant to Jeddah's context.
2. **AI-Generated Visualization of Urban Form**: We seek to utilize AI-based techniques to create compelling visual representations of the optimized urban forms.

1.4 **Challenges and Opportunities**

Analysis of Jeddah's urban development reveals several critical challenges that shape the city's urban form:

- **Low-Density Development & Monofunctional Zoning**
- **Lack of Public Spaces and Green Spaces**
- **Climate Extremes**
- **Limited Integration of Cultural Identity**

These challenges present corresponding opportunities for computational design approaches: evolving high-density yet walkable neighborhoods with mixed-use zoning; integrating green corridors with street layouts; optimizing building placement for passive cooling and shading; and exploring traditional architectural patterns within contemporary urban forms.

2. Literature Review

2.1 **The Evolution of Computational Urban Design**

Several key studies have shaped our understanding of how genetic algorithms can be applied to urban design problems. Makki et al. (2019) demonstrated how evolutionary algorithms could generate urban morphologies that respond to multiple objectives simultaneously. Their work showed that computational methods could discover unexpected design solutions that human designers might overlook due to preconceived notions or limited exploration capacity.

Koenig et al.'s (2017) framework for generating urban master plans at scale is particularly relevant to our approach. Their research illustrated how computational methods could rapidly evaluate thousands of design alternatives against performance criteria like solar access, walkability, and density.

However, there remains a significant gap in the literature regarding the application of these methods to Middle Eastern urban contexts. Most studies focus on European or North American cities with different climatic conditions, cultural patterns, and urban challenges than those found in Jeddah.

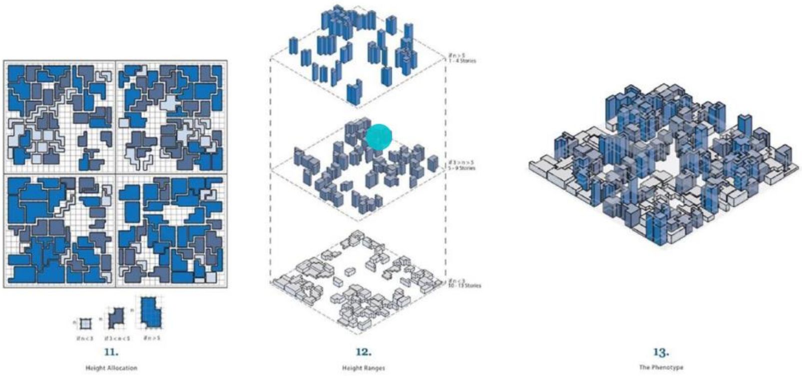

Fig. 1. *The design of social and cultural orientated urban tissues through evolutionary processes*

2.2 **AI in Architectural Visualization**

The integration of artificial intelligence in architectural visualization has transformed how we communicate design intent. Traditional rendering techniques often produced sterile, idealized images that failed to capture the lived experience of urban spaces. AI-based approaches offer new possibilities for creating more evocative and communicative visualizations.

Recent advances in diffusion models for 3D asset generation have dramatically improved the quality and efficiency of architectural visualization. Hunyuan3D 2.0, for example, represents a significant leap forward in generating high-resolution 3D assets from text prompts.

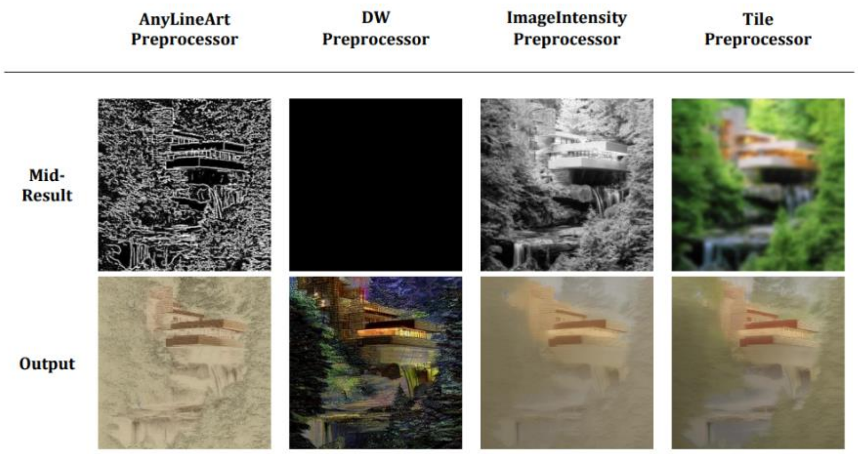

Fig. 2. *AI-D. ALGORITHMIC EXPERIMENTS WITH AI TO AID DRAWING*

2.3 **Research Gap and Contribution**

Our review of the literature revealed several significant gaps that this research aims to address:

1. Limited application of genetic algorithm optimization to Middle Eastern urban contexts, particularly regarding climate-responsive design in hot arid environments.
2. Insufficient integration between performance-driven optimization and culturally sensitive design approaches that respect local architectural traditions.
3. Few studies that combine genetic algorithm optimization with AI-based visualization in a cohesive framework for urban design.
4. Lack of research on how computational approaches can address the specific urban challenges of rapidly developing cities like Jeddah, which face tensions between modernization and cultural continuity.

By addressing these gaps, our research contributes to the emerging field of computational urban design in several ways. It demonstrates how genetic algorithms can be adapted to the specific conditions of Saudi Arabian cities, integrates performance optimization with cultural sensitivity, and develops a framework for combining computational design with AI visualization.

3. Methodology

3.1 **Genetic Algorithm Approach**

For addressing Jeddah's urban challenges computationally, genetic algorithms emerged as the most promising approach. Unlike deterministic methods that follow predefined rules, genetic algorithms mimic natural evolution—allowing unexpected solutions to emerge through mutation, crossover, and selection processes.

We structured our genetic algorithm optimization around two main components:

First, the **Urban Layout Optimization** focused on developing climate-responsive, high-density urban layouts with integrated green corridors. This component addressed Jeddah's challenges of low-density sprawl and insufficient public spaces by generating street networks and land use patterns that prioritize walkability and connectivity.

Second, the **Massing Generation** component translated optimized layouts into three-dimensional building forms. This addressed the challenge of creating volumetric representations that respond to Jeddah's climate while referencing traditional architectural patterns.

To implement these components, we assembled a toolkit of specialized software: Grasshopper and Rhino for 3D modeling, LadyBug for environmental analysis, DeCodinG Spaces and Meta City Generator for urban analysis, and Wallacei as the optimization engine implementing the NSGA-2 algorithm. This workflow explores the domain of parametric modelling and its efficient use in designing and urban framework which is accessible, liveable and environment responsive.

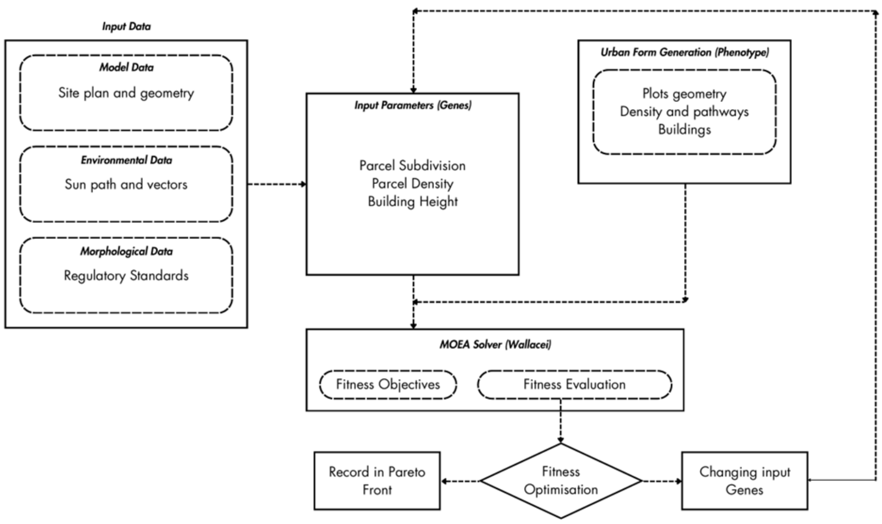

Fig. 5. ***Urban Layout & 3D Massing Optimization Setup***

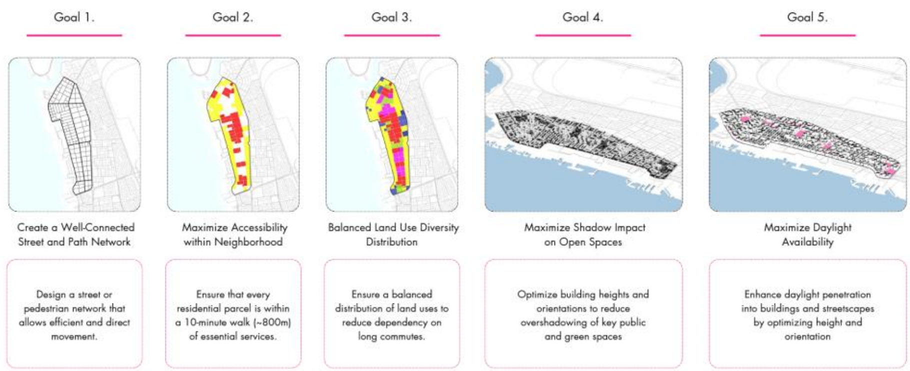

Fig.4. *The Experiment's Design Goals*

3.1.1 Constructing the Parametric Definition

The parametric definition that formed the basis for genetic algorithm optimization followed a systematic process that we refined through multiple iterations:

We began by selecting a site in eastern Jeddah that exemplified the city's urban challenges. Next, we introduced a foundational street network controlled by a "plot threshold gene" that allowed the algorithm to explore different connectivity patterns. The site subdivision into parcels formed the basic urban grain, with street offsetting defining the widths for vehicular and pedestrian movement.

Land use allocation proved particularly challenging. Using MetaCity Generator, we developed a system that assigned parcels based on both connectivity values and proximity relationships. Commercial uses gravitated toward highly connected streets, while residential areas formed clusters with shared green spaces.

For buildable area generation, we defined footprints within each parcel based on setback rules and coverage ratios. Building volumes emerged by extruding these footprints according to height parameters, with variation based on orientation and program type.

3.1.2 **Design Goals and Fitness Criteria**

The genetic algorithm optimization was guided by five key design goals that directly addressed Jeddah's urban challenges:

1. **Creating a Well-Connected Street and Path Network**: This goal aimed to design a street network that allows efficient and direct movement while creating a distinctive urban character.
2. **Maximizing Accessibility within the Neighborhood**: This goal ensured that every residential parcel was within a 10-minute walk (~800m) of essential services.
3. **Balancing Land Use Diversity Distribution**: This goal promoted a mix of uses throughout the urban fabric, reducing the need for long commutes and creating more vibrant neighborhoods.

4. **Maximizing Shadow Impact on Open Spaces**: This goal optimized building heights and orientations to create comfortable outdoor environments in Jeddah's hot climate.
5. **Maximizing Daylight Availability**: This goal ensured adequate daylight penetration into buildings and streetscapes by optimizing height relationships and building orientations.

These goals were translated into fitness criteria for implementation in Wallacei, allowing the algorithm to evaluate and rank different design solutions based on their performance across multiple objectives.

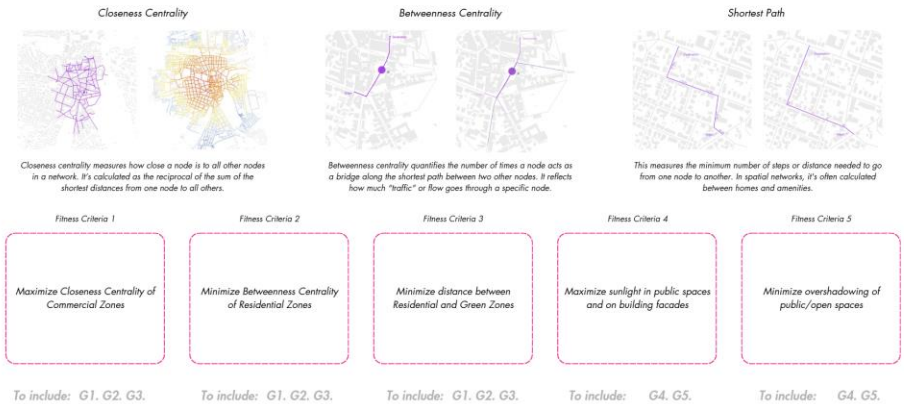

Fig.5. *Fitness Criteria for Implementation in the Wallacei.*

3.1.3 Simulation Results and Pareto Front Analysis

The primary simulation was conducted through 40 generations each having 20 individuals in each generation. By observing the Pareto front solutions throughout the process, the solution with a good trade-off between all the fitness objectives were extracted for further observations. The standard deviation graphs indicated convergence toward optimal solutions, followed by a clustering process which grouped together the solutions with similar trade-off trends (which is used to narrow down the search space). This process helped in identifying the individual solutions with top ranks across different generations. Trade-offs were evident: solutions that performed well in maximizing centrality sometimes lagged in minimizing betweenness, reflecting the characteristic nature of urban performance metrics.

Each phenotype was analysed for its buildable area and massing potential. Building volumes were extruded from plots according to coverage ratios and FAR (Floor Area Ratio) values. The MetaCity Generator automated the massing process, producing height variation and volumetric diversity across the urban fabri

Fig.6. *Best Solution with Building Massing*

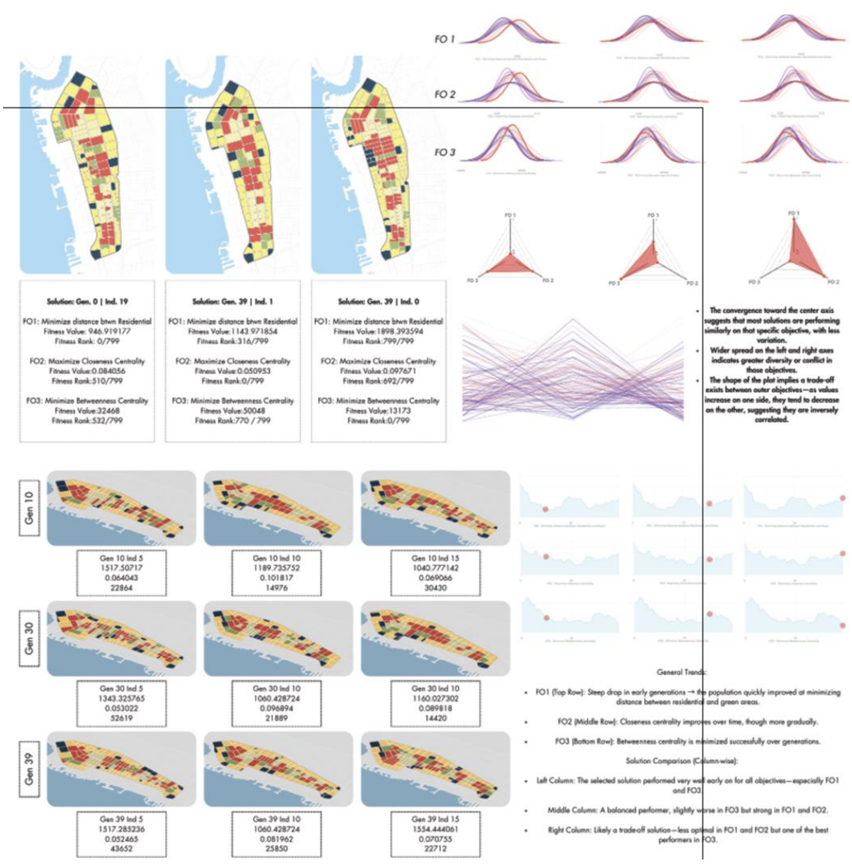

Fig.7. *Simulation 1 (Pareto Fronts).*

3.1.3 *Average Clustering Linkage - Extracting the best Solution*

Average Clustering Linkage refers to one of the clustering methods used during the Selection phase, specifically when grouping solutions based on their similarity in objective values or phenotypes (depending on what you choose to cluster).

Color Groupings (Clusters):
The plot shows multiple clusters each indicating a group of similar solutions based on average similarity across all three fitness objectives.
Solutions in the same cluster exhibit a similar overall pattern across objectives.
Fitness Trade-offs:
Some clusters (e.g., green or blue) perform better in F03 but worse in F02, while others (e.g., yellow) perform better in F01 and F02 but worse in F03.
This highlights the trade-off relationships between objectives—a typical result in multi-objective optimization.
Solution Selection:
Use the cluster centroids to choose representative solutions that best align with your design priorities.

Fig.7. *Average Clustering Linkage - Extracting the best Solution*

3.1.4 Sequential Simulation and Further Optimization

The primary goal of the sequential simulation is to optimise the massing on top of the optimised layout through the first simulation. The gene pool is now expanded to include plot density and building orientation and the optimisation was done against a new set of fitness objectives which are solar radiation on building and shadow on ground. Now the observations were made for 100 generation of 50 individuals each.

The secondary set of objectives were added to the initial ones, forming a comprehensive five-objective optimization framework. The simulation achieved balanced solutions where radiation due to the sunlight was maximized, and shadows on public areas were minimized.

Goal	Develop a street network that maximizes accessibility within a 10-minute walking radius using centrality metrics (closeness, betweenness, shortest path), ensuring strong pedestrian connectivity and equitable access to amenities.
Fitness Objectives	*1.Minimize distance between Residential and Green Zones* *2.Minimize Betweenness Centrality of Residential Zones* *3.Maximize Closeness Centrality of Commercial Zones* *4.Maximize sunlight in public spaces and on building facades* *5.Minimize overshadowing of public/open spaces*
Phenotype	Urban network layout, which includes: Street network geometry, Nodes (intersections), Parcel subdivision
Gene Pool	1.Parcel Subdivision: Controls block/parcellation logic from network 2.Plot Density: Determines the Height of the Buildings 3. Building Orientation: Optimizes the Radiation on the Facade

Algorithm Setting for Simulation 1.

Generation size	Generation Count	Population Size	Crossover Probability	Crossover distribution Index	Mutation Distribution Index	Simulation Runtime
50	100	5000	0.9	20	20	1Hr 32Min 07Sec

Algorithm Setting for Simulation 2.

Generation size	Generation Count	Population Size	Crossover Probability	Crossover distribution Index	Mutation Distribution Index	Simulation Runtime
50	100	5000	0.9	20	20	3Hr 41Min 52Sec

Fig.7. *Sequential Simulation*

Fig.7. *Sequential Simulation Results*

3.1.5 Results - **Optimized Urban Layouts**

The genetic algorithm optimization process generated a fascinating array of urban layout solutions. The best-performing designs often echoed patterns found in traditional Middle Eastern urbanism while incorporating contemporary performance requirements.

The optimized street networks diverged significantly from the rigid grids typical of recent Jeddah development. Instead, they featured hierarchical systems with main arteries for efficient circulation complemented by narrower, sometimes winding secondary streets that created intimate neighborhood spaces.

3.1.6 Results - **Three-Dimensional Urban Form**

The 3D massing models emerging from the optimization process showed interesting parallels with the skyline of Al-Balad, with varied building heights creating a distinctive urban silhouette. The optimized massing wasn't uniform or repetitive but featured strategic variations that responded to environmental and functional requirements.

3.2 **AI Visualization Techniques**

The second major component of our methodology involved AI-based visualization techniques that transformed abstract computational outputs into compelling visual representations.

For image generation, we employed several AI models: text-to-image generation converted textual descriptions of urban scenarios into visual representations; style transfer applied artistic styles to urban visualizations; and context-aware image synthesis generated images that responded to specific urban contexts and environmental conditions.

The 3D massing models were enhanced through AI-based texturing techniques: material assignment automatically applied appropriate materials to different building types; texture synthesis generated realistic textures based on architectural style and context; and lighting simulation enhanced visual realism through accurate lighting and shadow rendering.

These visualization techniques bridged the gap between abstract computational outputs and intuitive visual understanding, making the optimized urban forms more accessible to stakeholders and decision-makers.

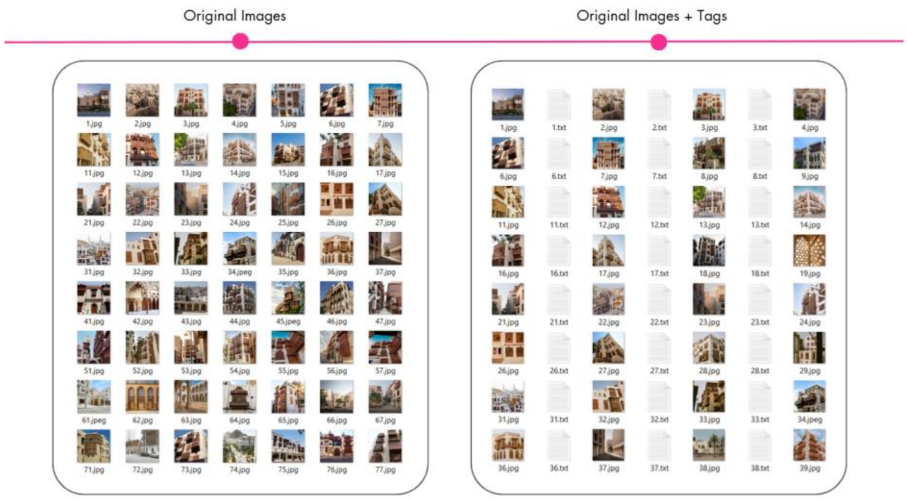

Fig 8. *Data Sets*

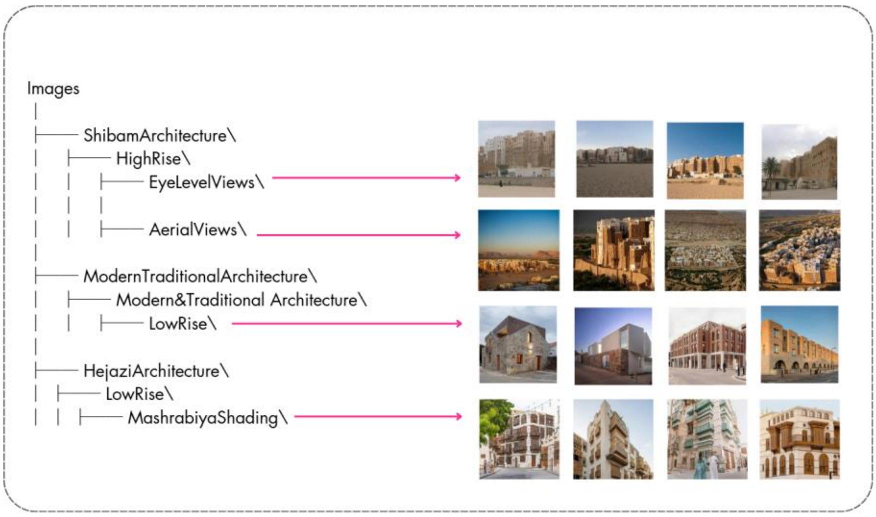

Fig 9. *Folder Hierarchy*

Fig 10. *With & Without LoRA Model*

3.2.1 **Results - AI-Generated Visualization**

The AI visualization techniques transformed the abstract computational outputs into compelling visual narratives that communicated both the performance benefits and experiential qualities of the optimized urban forms.

The street-level perspectives revealed vibrant urban environments with comfortable microclimates created by the optimized building configurations. Shaded walkways connected pocket parks and neighborhood centers, while building facades featured contemporary interpretations of traditional elements like mashrabiyas and roshan windows.

Aerial visualizations illustrated how the optimized urban pattern created a distinctive identity for the development while integrating with the surrounding context. The contrast between the organic, performance-driven layout and adjacent conventional developments was striking—highlighting how computational design can create more sophisticated and responsive urban environments.

4. Ray Casting

Texture mapping is a crucial process in 3D modelling, enabling the projection of 2D image textures onto 3D geometries for realistic visualization. Traditional texture mapping methods often rely on predefined UV mappings, which can be complex and time-consuming for irregular geometries. This project proposes a ray-casting-based technique to automate and enhance the accuracy of texture projection in Grasshopper.

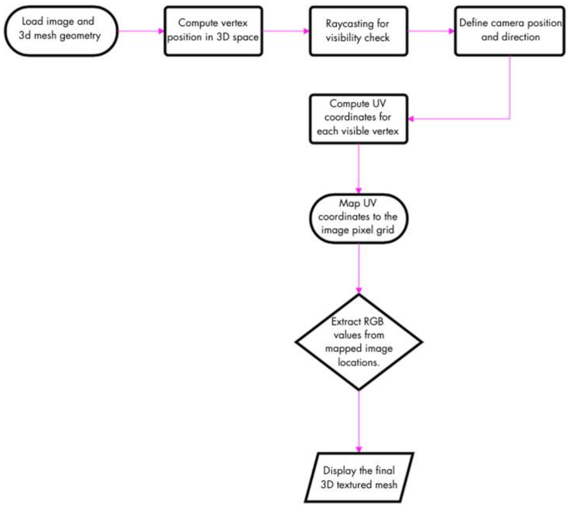

Fig. 1. Ray Casting Process

4.1 Visible Vertex Determination

In the process of image projection, it is essential to identify which vertices of the 3D mesh are visible from the defined camera position. This is achieved through ray casting, where rays are projected from the camera towards the 3D geometry. If a ray directly intersects a vertex without obstruction, that vertex is considered visible; otherwise, it is occluded by other parts of the mesh.

Process of Visibility Check:

- Define the Camera Position and View Direction: A virtual camera is placed in the scene, simulating the viewpoint from which the image projection occurs.

- Cast Rays from the Camera to Each Vertex: Rays are projected from the camera origin towards all mesh vertices.

- Check for Occlusions: If a ray reaches a vertex without intersecting another surface first, the vertex is visible. If another surface blocks the ray before reaching the vertex, it is occluded and ignored for texture mapping.

- Importance of Visible Vertices: Ensures that only the front-facing parts of the mesh receive image projection, avoiding texture distortion. Prevents incorrect mapping on occluded regions, maintaining realism and accuracy. It helps in efficient computation by eliminating unnecessary projections on hidden surfaces. Once visible vertices are identified, their UV coordinates are computed and mapped to the image for accurate texture retrieval.

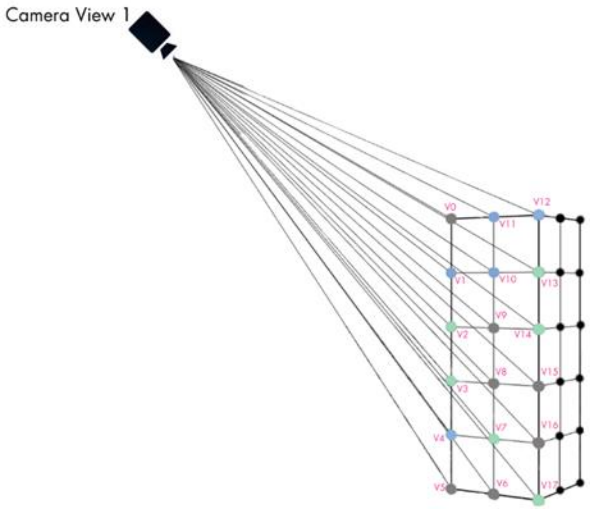

Fig. 2. Visible Vertices from Camera_1 location

4.2 Retextured Geometry

Objective:

The objective of retexturing geometry in this project is to achieve accurate and photorealistic texture mapping by integrating ray-casting-based visibility analysis with image-based rendering techniques. Inspired by hybrid geometry- and image-based approaches, this method enhances the precision of texture projection onto 3D models while addressing challenges such as occlusion, perspective correction, and seamless alignment of images with complex geometries.

- By leveraging ray casting in Grasshopper, this workflow ensures that textures are mapped only onto visible vertices, reducing distortion and improving realism. The process involves:
- Determining visible vertices through a computational ray-casting method.
- Computing UV coordinates for each visible vertex based on camera alignment.
- Extracting pixel data from the image to accurately transfer color information onto the 3D mesh.

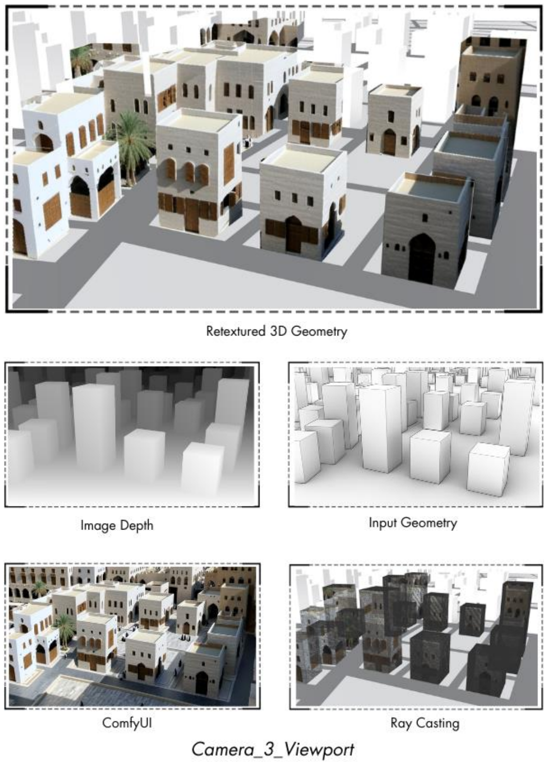

Fig. 3. Retextured Geometries

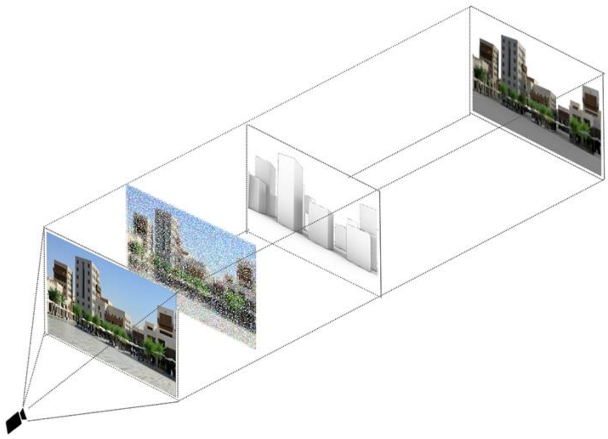

Fig. 4. Ray Casting Diagram

3.3 Results

Improved Texture Clarity with Increased Quad Count

- As the number of quads in the mesh increases, the projected texture becomes sharper and more visually accurate.
- Higher quad density results in better alignment of image pixels with geometry, reducing distortions and artifacts.
- This aligns with traditional image-based rendering techniques, where finer subdivisions enhance texture fidelity.

Time Computation

- The time required for computation increases as quad count rises, due to the larger number of vertices and visibility checks.

RGB Values Computation for Visible Vertices

- Each visible vertex is assigned an RGB color based on the average pixel values from the projected image.
- Higher quad counts provide more precise RGB assignments, leading to smoother and more continuous color transitions across the mesh.
- Lower quad counts cause color bleeding and blocky artifacts, as each vertex covers a larger texture area.

5. Discussion

5.1 Interpretation of Results

The results of our research demonstrate the significant potential of integrating genetic algorithm optimization with AI-based visualization for reimagining urban form in Jeddah. Several key insights emerge from our findings that have broader implications for computational urban design.

The environmental performance improvements demonstrated by the optimized designs are especially significant in Jeddah's challenging climate context.Our AI-generated visualizations proved essential in translating abstract computational outputs into comprehensible design representations. This addresses a common criticism of algorithmic design approaches—that they produce solutions that are optimized but difficult to interpret or appreciate visually.

5.2 Comparison with Traditional Approaches

Our computational approach offers several advantages over traditional urban design methods that we believe are worth highlighting.

Traditional urban design typically explores a limited number of alternatives due to time and resource constraints. In our case, the genetic algorithm approach evaluated thousands of design variations, systematically exploring the solution space to identify optimal configurations.

The computational analysis revealed significant differences between algorithm-generated layouts and those produced through traditional design processes for similar sites in Jeddah. While traditional designs often rely on professional intuition, our computational approach provided quantitative evidence for design decisions.

Conventional urban planning often addresses different performance aspects sequentially or in isolation. Our computational approach enabled simultaneous consideration of multiple criteria, revealing synergies and conflicts between different urban performance dimensions.

5.3 **Limitations and Challenges**

Despite its promising results, our research encountered several limitations and challenges that warrant consideration.

The optimization process relies on accurate input data regarding existing conditions, environmental factors, and urban patterns. In the context of Jeddah, comprehensive urban data was sometimes limited or inconsistent, requiring assumptions and simplifications that may affect the precision of the results.

The integration of genetic algorithm optimization with AI visualization involves significant computational resources, potentially limiting accessibility to practitioners without specialized technical knowledge or equipment. Some of our optimization runs took several days to complete, and the AI image generation required substantial GPU resources.

5.4 **Future Applications and Development**

Our research opens several promising avenues for future application and development in the context of Jeddah and beyond.

The computational framework we've developed could be adapted to different scales and contexts within Saudi Arabia. From neighborhood-level interventions in existing urban areas to large-scale new developments, the approach offers a flexible methodology for performance-driven urban design.

6. Conclusion

6.1 **Summary of Findings**

Our research has demonstrated the significant potential of integrating genetic algorithm optimization with AI-based visualization to reimagine the urban form of Jeddah. Through this computational approach, we've addressed key challenges facing Jeddah's urban development while creating a framework for more sustainable, efficient, and culturally responsive urban environments.

The genetic algorithm optimization process successfully generated urban layouts that balance multiple performance criteria, including connectivity, accessibility, land use diversity, shadow impact, and daylight availability. These optimized designs showed remarkable improvements over conventional urban patterns, with enhanced walkability, reduced solar exposure, more efficient land use distribution, and better environmental performance.

The AI-based visualization techniques transformed abstract computational outputs into compelling visual representations that effectively communicate design intent and performance. These visualizations bridged the gap between technical optimization and intuitive understanding, making the computational results accessible to diverse stakeholders.

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