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Parametric material autopsies for generative crafting

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ABSTRACT: This research investigates the intersection of parametric design, AI-driven exploration, and bio-tectonic strategies to develop adaptive, ecologically responsive urban modules. By transforming industrial waste into responsive components, the study integrates digital and analog into a cohesive design process. The methodology is structured around three core practices: “Parametric Autopsies of Local Upcycling Material”, “AI-Driven Design Exploration”, and “Constructive Bio-tectonic Scenarios for Regenerative Environments”. These practices foster dynamic, site-specific solutions that align with ecological principles, creating scalable frameworks for sustainable urban regeneration. Findings demonstrate that combining parametric material autopsies, generative AI, and hybrid fabrication can lead to innovative design interfaces. These prototypes showcase the potential of integrating upcycled materials into nature-responsive urban systems, paving the way for resilient, green cities that support both human and ecological well-being. This study lays the groundwork for future explorations in regenerative architecture, offering a vision for collaborative, adaptive urban environments.

1 INTRODUCTION

In recent years, parametric design has evolved into a pivotal approach within architecture and urban planning, reflecting the confluence of computational design, ecological sensitivity, and innovative material practices. At the core of this shift, the integration of digital technology and artificial intelligence (AI) into the design process has introduced unprecedented levels of responsiveness and adaptability, enabling architects to address complex and dynamic environmental challenges. This study, conducted within the framework of the Responsive Ground Research Lab, aligns with a growing body of research focused on developing sustainable, adaptive, and ecologically conscious urban environments. By transforming industrial waste into functional bio-tectonic modules, the research aims to merge parametric design thinking, AI-driven exploration, and material upcycling to offer innovative solutions for problematic urban spaces in need of ecological interventions. In this design process, AI is considered not merely as a form-generating tool, but as an entity that reveals orientations, behaviors, and potentials. This project is an ongoing research effort within the Responsive Ground Research Lab, where process-oriented developments continually uncover new design innovations and discoveries.

1.1 *Background*

Parametric design thinking builds on mathematical and computational principles to generate adaptable, data-driven design outcomes. Parametric design uses algorithms to define design parameters and plays a pivotal role in the process. In this regard, (Kolarevic, 2003) defined digital generative systems as; “The digital generative processes are opening new territories for conceptual, formal and tectonic exploration, articulating an architectural morphology focused on the emergent and adaptive properties of form. The emphasis shifts from the ‘making of

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form' to the 'finding of form' which various digitally based generative techniques seem to bring about intentionally. In the realm of form, the stable is replaced by the variable, singularity by multiplicity." This approach suggests that instead of focusing solely on the outcome, the process itself becomes the primary output. Researchers such as Schumacher (2008) have championed parametricism as a movement that could redefine architectural language, offering an almost infinite array of design possibilities through variable parameters. The potential of parametric design to produce flexible and resilient structures is particularly relevant to urban areas that face rapid environmental and social changes. With this framework, "research through design" encourages iterative explorations that bridge theoretical and practical domains, as highlighted in contemporary studies that focus on how computational models influence design practices (Carpo, 2011; Kolarevic, 2003; Hensel, et al., 2008). This framework enables the Responsive Ground Research Lab's pursuit of "infinite variability," where design scenarios are developed as adaptable ecosystems rather than fixed structures.

The research-through-design model increases the number of parameters emerging during the process, providing a more diverse and open-source process model compared to conventional design thinking. Real-world data collected through digital tools forms a complex network of relationships for design. This approach enables a site-sensitive perspective and facilitates the parametric autopsy of industrial waste. Through this autopsy, new insights into the concept of bio-tectonics are revealed, viewing waste not merely as a form but as a bio-tectonic component embedded with design parameters. Burry and Burry (2010), in their book explaining algorithmic thinking and parametric design techniques through architectural projects and cases, emphasize processes where potential outcomes coexist rather than a static or single-option process: "Through digital computation, architects have regained mathematical literacy. This transformation offers a new spatial and temporal context, free from the static Cartesian constraints of the two-dimensional drafting plane, enabling a meta-zone of multiple simultaneous possibilities" The literature, including works by Menges and Knippers (2015), Reichert et al. (2014) underscores the role of parametric design in expanding design possibilities. Through interfaces like Rhino 3D and Grasshopper, designers can simulate iterative variations, allowing for the exploration of complex surfaces and adaptable modules that respond to real-world conditions.

The integration of AI in design exploration has influenced the approaches used in parametric and bio-tectonic design, particularly in addressing complex urban challenges. AI-supported parametric design thinking allows for the generation of diverse design variations by adjusting multiple variables, a process aligned with the "research through design" model. AI's role extends beyond traditional design frameworks by enabling the examination of intricate parametric relationships that surpass the limitations of conventional, human-devised models. AI-driven design enables the generation of adaptable modules and structures responsive to specific environmental needs, addressing emerging ecological concerns. Rather than simply replicating existing forms, AI employs data-driven learning to propose outputs that offer alternative perspectives and unconventional design solutions, fostering unexpected engagements for designers. German et al. (2019) highlight how AI can create surprising design variations, revealing novel possibilities that might not have been initially anticipated by designers. Additionally, AI's capacity to simulate real-time scenarios provides designers with insights into how structures react to various forces and environmental conditions without the traditional constraints of modeling techniques. This capability is explored in studies such as Choi and Zhang (2024), who examine AI's potential in enhancing the design process, optimizing morphology, and creating simulations that approximate real-world conditions. AI, based on statistical learning, extracts principles from multiple observations. Rather than using rigid, context-free rules, it allows for the study of data within specific contexts. This AI-driven approach improves our understanding of site-specific conditions in architecture, while also strengthening the link between research and practice (Chaillou, 2022). Although AI is often perceived as a single methodological approach, it includes a wide range of tools, methods, and strategies that go beyond any one approach (Shermeen & Emmanouil, 2022). This versatility enables AI to support a wide range of design functions, thereby enriching the design process.

Bio-tectonics combines biological principles with tectonic frameworks, enabling the creation of structures that interact with and respond to ecosystems. Literature on bio-tectonic systems emphasizes their role in advancing sustainable urbanism by proposing materials and modules that harmonize with local ecologies (Oxman, 2016; Hensel, 2013). The biological principles underlying bio-tectonics allow for the exploration of sub-concepts such as behavior, orientation, production methods, production skills, and self-organization capabilities. Such interfaces hold the potential to catalyze ecological awareness within urban spaces, a subject of inquiry in recent research (Kieren & Timberlake, 2004). As Estévez (2016) mentioned, "Today, understanding the moment when amorphous masses of cells organize themselves into an initial structural level is relevant for the architect. Architecture should also respond to structural, physical, economic and efficiency stresses, as living beings do. How to respond is something that we can learn from nature (i.e., bio-learning)". Estévez (2005) also termed this approach "digital organicism". The transformation of industrial waste into bio-tectonic elements presents an innovative step in the reclamation of urban environments, promoting circular economy principles by reimagining waste as a building resource.

The integration of digital fabrication and analog craft techniques exemplifies research through a design approach that investigates both the precision of digital tools and the tactile qualities of manual production. Robotic fabrication studies by Gramazio & Kohler (2014) demonstrate how advanced manufacturing processes, such as robotic arms and 3D printing, expand the designer's control over intricate, bio-inspired forms. These technologies facilitate the creation of micro-environments within urban landscapes, aligning with bio-tectonic principles by introducing algorithmically generated, ecologically integrated modules. In this ongoing research project, analog and digital tools are being explored theoretically, with the selected tools playing a critical role in defining design parameters throughout the process. According to Lynn (1999), there are three fundamental properties of organization in a computer that are different from the characteristics of inert mediums such as paper and pencil: topology, time, and parameters. These three properties should be discussed, beginning with the principles of perceptual entities, continuing with the implications that materiality raises for the relationship between time, and shape and concluding with a discussion of processes and parameters that can be stored in these timed surfaces. By formulating a set of rules and constraints, designers can create generative models that optimize the potential of upcycled materials. This active crafting approach ensures that the resulting parametric urban interfaces are not only visually appealing but also functional and contextually relevant. Erdman et al., (2006) write about how these organizational principles are at work not only in the context of their practice, but in the design work itself, which stretches across a variety of design disciplines to incorporate areas of expertise particular to information and interaction design, as well as a number of manufacturing and fabrication technologies.

1.2 *Research approach*

The project is based on research through design models, integrating both theoretical exploration and practical production processes. This approach is not limited to theoretical analysis but also proposes extending into hands-on, iterative production stages. A cyclical and regenerative model is proposed, recognizing the interconnected nature of urban ecosystems and rejecting linear thinking. Specifically, this model emphasizes a design perspective oriented toward sustainable and ecological awareness, aiming to address complex issues within urban ecosystems. The integration of theoretical and practical production methods is central to the Responsive Ground Research Lab's research approach. Theoretical insights lay the groundwork for understanding the ecological, technological, and social implications of design, while hands-on production provides tangible, adaptable modules for testing within urban spaces. This dual approach allows for a synthesis where conceptual ideas can be tested in real-world scenarios, advancing ecological consciousness in design and establishing a basis for practical, sustainable interventions. Furthermore, this model enables a deep exploration of bio-tectonic elements, not only as theoretical constructs but as implementable solutions that bridge design theory and practice.

The use of industrial waste in this research is motivated by the potential to repurpose discarded materials as components of urban micro-environments. Rather than focusing on the form or function of the material, the approach emphasizes uncovering the inherent information within the waste. By performing a "parametric autopsy" on the industrial waste, specific parameters are discovered, transforming the waste into a bio-tectonic component. These parameters include the material properties, behavior under certain forces, methods of production, and the relationships formed during its creation. This process marks the beginning of a responsive design approach, where the intrinsic characteristics of the waste guide its integration into the design as a responsive, adaptable element.

The use of AI in this research is not focused on directly generating images but rather on guiding the parameters that shape the design process. The study emphasizes the dialogue between the AI-generated imagery and the existing design concepts, rather than the final image itself. Typically, the AI-generated visuals are sequentially arranged using animation techniques, allowing the observation of dynamic changes over time, which are then represented through diagrams. The design process progresses simultaneously; after defining the parameters of industrial waste as bio-tectonic components, new parameters derived from the AI-generated diagrams are integrated into the design. This approach facilitates the merging of digital and analog processes, resulting in a dynamic and adaptive design outcome. The lab's research framework is both interdisciplinary and cross-methodological, combining parametric design, AI, and digital-analog synthesis to push the boundaries of urban ecological design. In each phase, technology serves as both a medium and a collaborator, where AI assists in expanding creative boundaries and challenging conventional practices, while digital-analog synthesis facilitates the realization of flexible, adaptive modules. This holistic integration ensures that each element contributes to a cohesive framework capable of addressing the demands of urban ecosystems through sustainable, context-aware interventions.

2 METHODOLOGY

2.1 *Process model*

This process is structured around three core practices that shape its experimental approach: Parametric Autopsies of Local Upcycling Material, AI-Driven Design Exploration, and Constructive Bio-tectonic Scenarios for Regenerative Environments. Each practice offers a distinct perspective for examining and developing design possibilities: beginning with parametric principles that establish adaptable frameworks, continuing with AI methods that expand generative capabilities, and concluding with bio-tectonic strategies focused on ecological regeneration. Together, these practices foster the exploration of responsive and sustainable design solutions by iterating on initial concepts and evolving them through computational and ecological insights (Figure 1). Instead of following a linear sequence, these practices function in a cyclic and iterative manner, enabling continuous reflection and refinement throughout the research. This approach allows insights from one practice to dynamically inform the others, creating a feedback loop that enhances adaptability and responsiveness. By revisiting and refining design assumptions, this iterative process facilitates the development of an integrated framework for experimental design that is flexible, sustainable, and well-suited for regenerative environments.

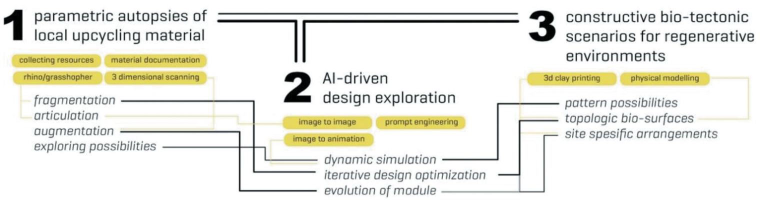

Figure 1. Core practices of process model.

2.2 *Core practices*

2.2.1 *Parametric autopsies of local upcycling material*

The process begins with the parametric analysis of locally sourced upcycling materials. This stage focuses on identifying adaptable and contextually relevant frameworks that enable the repurposing of industrial waste into potential material solutions. Through parametric principles, this analysis emphasizes material constraints and opportunities, forming the structural foundation for the experimental design processes (Figure 2). The selected industrial waste for study is disposable paper cups, one of the most common consumed materials in Türkiye. As this is an ongoing project, the choice of cups was made as a preliminary experiment to explore the parameters of the study. After the cup was digitally modeled parametrically, bio-tectonic elements were investigated. The seam from the manufacturing process was cut, and the cup was rotated around a single point to explore its potential applications.

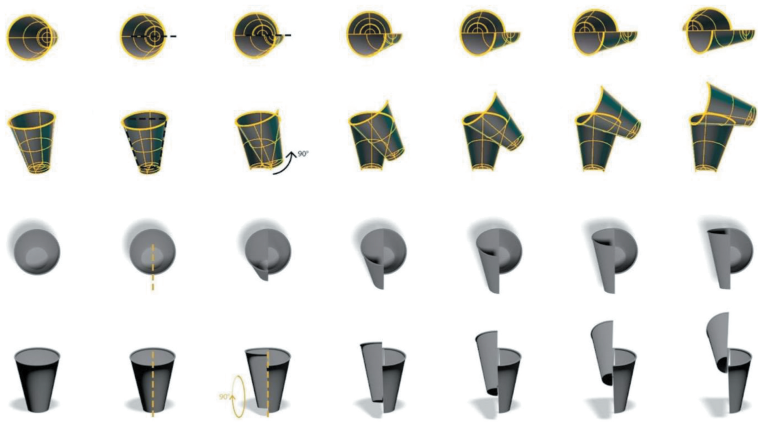

Figure 2. Sample of parametric autopsy of the upcycling material.

2.2.2 *AI-Driven design exploration*

Building on the parametric frameworks, this phase integrates AI methodologies to expand the generative capacities of the design process. AI mediums are applied to explore diverse design permutations, enabling the identification of novel configurations that may not be intuitively accessible. This computational approach supports the broadening of design potential by synthesizing complex patterns and responding to the material characteristics established in the initial stage (Figure 3). The AI utilized in this phase are not static image generators but are designed to respond dynamically to changes in real time. For this reason, we employ platforms such as Krea AI and Runway AI, which enable responsive, adaptive interactions. The module developed through the parametric autopsy is integrated into these mediums, where it reacts instantaneously to variations in AI intensity and prompt inputs.

Additionally, AI is leveraged to formulate design strategies, allowing for a more data-driven and adaptive decision-making process. By analyzing contextual parameters such as environmental conditions, structural constraints, and material behaviors, AI-driven insights inform the development of spatial organizations and modular configurations. This enables a more holistic approach, where generative design strategies evolve through iterative feedback loops. This research focuses on these dynamic changes, using them as a basis to establish new parameters derived from AI-driven interactions.

2.2.3 *Constructive bio-tectonic scenarios for regenerative environments*

Third practice introduces bio-tectonic strategies aimed at ecological regeneration. This approach emphasizes the constructive integration of design within regenerative ecosystems, focusing on bio-tectonic interfaces that contribute to sustainable urban environments. These scenarios are intended to facilitate the ecological responsiveness of the design by incorporating principles of bio-tectonics and material adaptability, fostering environmentally aligned solutions. The project will begin with a simple module that evolves into more complex articulated forms, allowing for the creation of responsive structures. These forms will be generated based on the logic of expanding scenarios, focusing on fluid and porous geometries that enhance environmental efficiency.

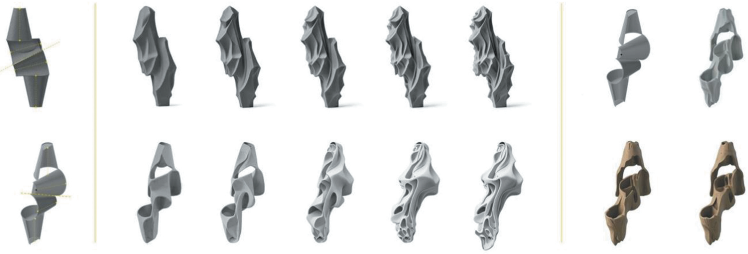

Figure 3. Sample of AI-Driven expand scenarios.

Computational optimization will refine surface curvatures to effectively manage water, sunlight, and vegetation. Integrated channels and perforations will direct these environmental elements, and a parametric gradient of permeability will be used to control earth interactions. Lightweight, earth-resistant materials, such as bio-based composites or recycled polymers, will be proposed for the structure. Structural stability will be ensured through computational analysis to optimize earth scenarios and environmental parameters (Figure 4).

Figure 4. Possibilities of *Regenerative Environments.*

The process focuses on modular connection points, maintaining simplicity while enabling diverse attachment configurations. Flexible parametric adjustments allow variations in openings, overlaps, and rotations, ensuring adaptability. Additionally, nested or interlocking forms facilitate the seamless integration of individual pieces into larger, more complex assemblies. Since the process progresses simultaneously, bio-tectonic strategies continuously evolve, with new relational networks emerging from the generated parameters. The initial cut, informed by the production data from industrial waste, extends into patterns formed by the resulting modules. New site-specific parameters are introduced as solutions to urban problems, creating regenerative scenarios tailored to specific contexts.

3 FINDINGS

The convergence of these practices—AI-driven design exploration, bio-tectonic integration, and parametric variability—suggests a transformative approach to urban intervention. Rather than adhering to linear, one-size-fits-all design paradigms, the literature underscores the importance of flexible, circular design models that promote ecological resilience. AI's role is particularly salient in supporting "adaptive intelligence" in design, where solutions can evolve over time in response to ecological and socio-economic demands. This perspective is echoed by Kolarevic (2003), who advocates for adaptive, generative models that accommodate urban complexity and unpredictability. The paper cup, in its original form, was quite limited and did not allow for expansion or exploration of its potential. To increase its surface area and reveal its possibilities, the cup was cut, guided by production data rather than a random choice. As this is an ongoing project, the surface was observed by rotating it parametrically around a single point. For future studies, additional information derived from the parametric autopsy of the cup can be incorporated. In this paper, the potential of the cup when rotated at a 90-degree angle was investigated. An iterative modular system was proposed, allowing multiple cups to be connected and expanded. Design variations generated have been simulated in AI medium such as Krea, Midjourney, Vizcom AI and Tripo 3D to test how the modules would behave in different urban scenarios. For example, variations have explored how these modules could be integrated with functions such as micro-habitats and collecting rainwater to support vegetation. Future iterations will explore the possibilities of using different angles. These iterations will be examined in more detail in the next phase and tested alongside the material's possibilities.

The feedback loop created through the AI-driven design process has had a positive impact on the overall design approach. The parametric methodology is inherently dynamic and open to change, which is why we seek similar responsive characteristics in the AI medium we use. Rather than relying on a single static image, we gather a series of images that capture variations in real time. These images are analyzed using a diagrammatic approach to study the variability, which in turn helps identify new parameters for the design process.

The patterns formed by these modules were replicated and tested both in Rhino software and through AI mediums. This exploration allowed us to generate scenarios that demonstrate how the system functions, replicates, and adapts, revealing potential configurations of voids and solids as well as its adaptability to chosen sites. These scenarios illustrate the communication network of the design process, showcasing how industrial waste can be integrated analogously to form constructive structures. As this is an ongoing project, the application phase is still under investigation. In future iterations, the industrial waste modules will either be dipped into responsive materials and arranged according to a specific system, or a robotic arm will be used to extrude material in a three-dimensional form.

4 CONCLUSION

This research situates itself within the intersection of parametric design, AI, and hybrid production methodologies to develop adaptive, ecologically responsive urban designs. By synthesizing these areas, the study explores innovative pathways to transform industrial waste into constructive modules, reshaping urban spaces with sustainable, forward-thinking design solutions.

The integration of parametric autopsy, AI-driven design exploration, and bio-tectonic strategies demonstrates a methodology that enhances adaptability and ecological responsiveness. The iterative feedback loop between these practices enables continuous refinement of design parameters, resulting in flexible modules that can respond dynamically to urban challenges. The practical outcomes include modular elements derived from upcycled materials, showcasing a scalable model for urban regeneration. This approach aligns with the broader vision of creating resilient, nature-integrated communities, fostering a symbiotic relationship between the built environment and natural ecosystems. The combined use of multiple digital and analog, including parametric design methods, AI, 3D scanning, material, and robotic arms, enhances the multidimensional nature of this research. This integration of diverse technologies ensures that the design process remains responsive to real-world data and adaptable to complex urban contexts, bridging the gap between theoretical exploration and practical implementation. Future research will aim to integrate advanced AI algorithms and explore new materials, expanding the generative capabilities of the design process. The ongoing exploration of site-specific applications will further enhance the regenerative potential of biotectonic urban frameworks.

In conclusion, the innovative blend of upcycling, AI, and digital fabrication in this project offers a transformative vision for urban development, particularly through the integration of earth-based responsive articulations such as sun protection, water collecting, and vegetation nodes with soil injection. By prioritizing sustainability, adaptability, and ecological awareness, this research sets the stage for a future where green cities thrive while maintaining a deep connection to the earth. The project envisions a built environment that actively responds to the natural world, where architectural forms evolve to offer dynamic solutions to environmental challenges. Sun protection is integrated into the design through responsive shading systems, which adjust to the intensity and angle of sunlight, reducing energy consumption and enhancing thermal comfort. Water collection is facilitated by carefully designed channels and surfaces that direct rainwater towards storage or irrigation systems, optimizing water usage in urban landscapes. Additionally, vegetation nodes with soil injection allow for the nurturing of plant life in urban areas, enhancing biodiversity and improving air quality by creating green, self-sustaining ecosystems. These earth-based articulations work in unison, guided by AI-driven design and computational analysis, to promote environmental efficiency and resilience. Through the co-creation of smart parametric urban interfaces, this project paves the way for a more harmonious and adaptive urban future, where the built environment supports both ecological health and human well-being.

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