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Irregular Material - Design Interaction: Combinatorial Tetrahedral Assemblies from Vulcanized Fiber

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Abstract

This paper presents a hybrid analog–digital workflow for a full-scale tetrahedral installation fabricated from vulcanized fiber (VF), a cellulose-based industrial material that deforms during drying and stabilizes once cured. The research investigates how material-induced variability can be coordinated with design-space variability within a discrete structural system. The aggregation is based on the Sommerville type 1 tetrahedron, using tetrahedral, pyramidal, and rhomboid components connected through direct face-to-face joints and extended wooden-stick connections. In the design phase, multiple configurations are possible through changes in grid orientation, component placement, connection distribution, and face orientation. After fabrication, wet VF sheets are cut, folded, and dried without rigid formwork, producing distinct components. These parts are 3D scanned, catalogued, and computationally implemented into a digital workflow that mediates discrepancies through connection tolerances, overlap variation, stick-length adjustment, and face reorientation. The selected configuration is assembled using augmented-reality guidance. The project demonstrates that material transformation can be integrated without abandoning architectural intent or buildability. By coordinating both variabilities, the workflow produces partially unforeseen spatial and functional outcomes, showing how uncertainty can expand discrete spatial structures beyond predetermined design intention alone.

Keywords: Tetrahedral structures, vulcanized fiber (VF), material-induced deformation, discrete aggregation systems, space-filling geometry, hybrid analog–digital design, compatibility-based assembly, augmented reality construction, material variability

1. Introduction

The integration of computational design and digital fabrication in architecture has enabled the precise coordination of geometry, structure, and production. Parametric modeling environments and simulation tools allow complex spatial systems to be developed with a high degree of control, aligning design intention with material realization (Picon [1]). Within these frameworks, variability is typically incorporated as a bounded and predictable condition, governed through parametric constraints (Schumacher [2]) or performance-driven optimization (Menges [3]). Discrete design approaches have similarly expanded architectural variability through combinatorial systems composed of serial elements, where spatial differentiation emerges through aggregation rather than continuous form manipulation (Retsin [4]). Yet such systems generally rely on the geometric consistency and interchangeability of parts, assuming stable material properties and controlled fabrication processes.

More recent work has addressed irregular or non-standard components in reuse, stock-based design, and custom differentiation, where elements are selected from existing inventories or intentionally produced to introduce variation (Cousin *et al.* [5]; Amtsberg *et al.* [6]). These approaches expand the capacity of design systems to engage non-uniform parts through scanning, matching, clustering, or assignment algorithms, including linear programming techniques such as the Hungarian Method. While effective, they require complex computational implementation, substantial resources, and highly specific technical knowledge, which can limit low-threshold or lightweight forms of experimental design exploration. More importantly, the variability they address is generally based on geometrically differentiated but materially stable components. Components may differ in shape, size, or orientation, but their relevant geometric properties are typically resolved through computational organization, adaptive positioning, or customized interfaces, while material behavior itself remains relatively stable throughout the process. Parallel research in material-driven design has explored material transformation as a generative factor, especially in biological, responsive, or living systems, where growth, adaptation, and changing material states contribute to design processes (Imhof *et al.* [7]). However, transformative agencies are often located in explicitly biological or living matter, while industrially manufactured materials are more commonly approached as stable, controllable, and geometrically predictable.

Across these fields, two general forms of variability can be distinguished. The first may be described as design-space variability: a condition most evident in discrete architectures, where design intention is defined through rule-based systems that allow construction elements to be recombined into multiple possible configurations. The second may be described as material-induced variability: a condition in which the transformative behavior of matter actively affects the architectural result. The gap addressed by this paper concerns how these two forms of variability can be coordinated within a discrete structural system. In this context, material transformation is neither external to the design process nor limited to biological or living systems. At the same time, bottom-up material-induced variability is not treated as the sole driver of form but as something negotiated with top-down design intention, organizational constraints, and specific architectural goals. The aim is therefore to develop a framework in which material self-forming and architectural form-finding operate together, expanding spatial possibilities beyond those prefigured by the designer without diminishing the role of design intention.

To this end, the research investigates a tetrahedral discrete aggregation system derived from the Sommerville type 1 tetrahedron and fabricated from vulcanized fiber (VF), a cellulose-based industrial material that undergoes significant morphological and mechanical change during drying. The tetrahedral system provides a geometrically rigid and reconfigurable organizational framework, while VF introduces a material process capable of transforming that framework from within. While VF is typically distributed as dry, flat sheets with stable geometry, this research engages it in its pre-cured wet state, obtained from the manufacturing process as continuous rolled sheets. During drying, VF contracts, warps, and stiffens in partly unpredictable and non-repeatable ways, causing individual parts to diverge from their intended geometry and affecting assembly, connectivity, and spatial configuration.

Against this background, the paper proposes a hybrid analog–digital workflow in which material-induced deformation is integrated into the formation of the structure rather than eliminated. Computation is re-positioned from a predictive, optimizing, or simulating tool to a mediating framework between intended organization and material self-forming. The central question is therefore: how can geometrically rigid and predictable structural systems—such as tetrahedral discrete assemblies—incorporate material transformation while maintaining organizational coherence, buildability, and architectural intent? The paper addresses this question through the design and construction of a full-scale VF-based spatial installation. The hypothesis is that the interaction between design-space variability and material-induced variability generates partially unforeseen architectural, spatial, and functional outcomes. In this built pavilion, material deformation, connection tolerances, and assembly constraints collectively shape the resulting structure, providing an empirical basis to evaluate the proposed method. By coordinating material variability within a discrete structural system capable of producing multiple organizational outcomes, the research contributes to material-dependent design methods in which uncertainty expands spatial possibilities beyond those presumed by design intention alone.

2. Material and System

2.1. Vulcanized Fiber

Vulcanized fiber (VF) is a cellulose-based material produced through the chemical treatment of layered paper or cotton fibers, resulting in a dense, homogeneous sheet with high tensile strength and stiffness once cured. As a biopolymer and precursor to modern thermoplastics, VF has unique structural characteristics, it has a 4 times higher tensile and 10 times higher compression resistance compared to glulam timber, but with a deformation factor of 2.5 under load and double the weight (Scholz *et al.* [8]). In standard industrial use, VF is supplied as dry, flat sheets with stable and predictable geometry. In this research, however, the material is engaged in its pre-cured wet state, obtained directly from the manufacturing process as continuous rolled sheets prior to final drying. In this condition, VF undergoes significant morphological and mechanical transformation as it transitions from wet to dry. The drying process induces contraction, surface warping, and localized bending, driven by internal stresses, gravity, and environmental conditions (Fig. 1). Because these transformations occur without formwork, each element develops a unique, non-repeatable geometry. As moisture content decreases, the material progressively stiffens, stabilizing into a rigid form that retains the deformation acquired during drying. The resulting components therefore deviate from their initial geometric definition. This behavior introduces a form of material-induced variability that cannot be fully predicted or simulated in advance and directly affects the assembly of multiple parts within a structured system.

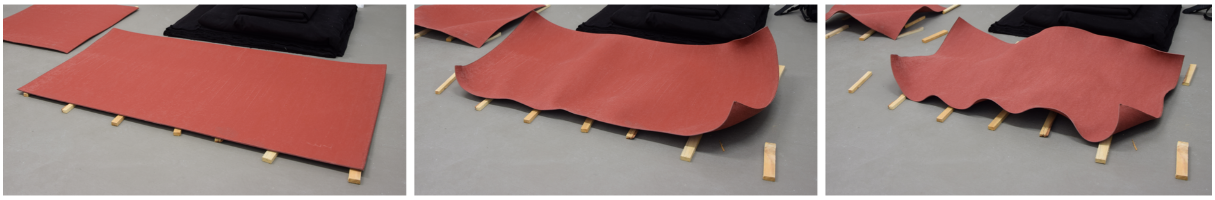

Figure 1: Drying process of a flat sheet of VF over the period of two weeks.

2.2. Tetrahedral Aggregation System

The spatial system is based on a discrete aggregation of tetrahedral units derived from space-filling geometries, specifically the Sommerville type 1 tetrahedron, one of the tetrahedral space-fillers discussed in Goldberg's classification [9]. Unlike regular tetrahedra, Sommerville-type tetrahedra tile Euclidean space, providing a geometric basis for a continuous three-dimensional organizational field. In this research, this logic is formalized through three component types: single tetrahedral units, double units forming pyramidal elements, and triple units forming rhomboid elements (Fig. 2).

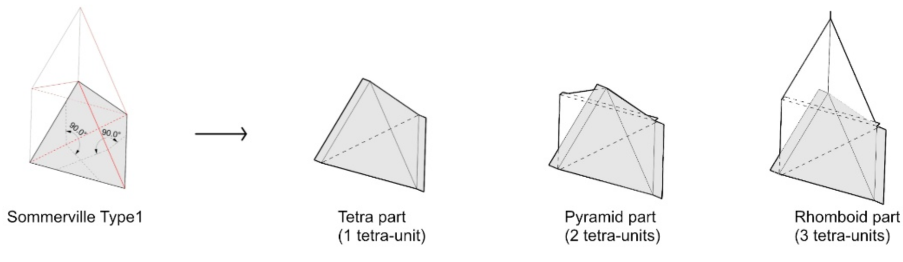

Figure 2: Tetrahedron "Sommerville Type" and part types.

These components share the same tetrahedral logic while offering different volumetric and functional capacities, including larger faces that can contribute to stability, density variation, and potential horizontal surfaces for use. Tetrahedral configurations are structurally relevant due to their geometric rigidity: their triangulated faces resist deformation without changes in edge length. In the proposed system, this rigidity is combined with shifted face-to-face connections and linear linking elements, forming a three-dimensional network in which local connectivity defines global geometry. Under ideal conditions, the system assumes precise correspondence between components, allowing consistent alignment of faces, edges, and connection axes. This makes the tetrahedral aggregation an appropriate test case for observing the effects of material-induced deformation, connection tolerance, and part-specific variability.

2.3. Material—System Implications

Within this research, the tetrahedral aggregation is not treated as a fixed geometry to be reproduced, but as an organizational framework capable of accommodating material transformation. Each unit is fabricated from VF in its pre-cured wet state and subsequently deforms during drying. This produces variations in edge length, face planarity, and connection surfaces, affecting how components can be positioned, overlapped, and linked within the system. These material-induced differences interact with the intended aggregation logic in two ways. First, they affect buildability at the local level, since connection points no longer correspond exactly to the intended geometry. Second, they influence the global configuration, because the placement and orientation of each distinct part modify the spatial relationships within the overall assembly. The system therefore requires a degree of adaptability and construction tolerances. The implication is that the final structure is not determined by the intended geometric model alone. It emerges through the coordination of two forms of variability: design-space variability, defined by the possible organizational configurations of the tetrahedral system, and material-induced variability, produced by the self-forming behavior of VF during drying.

3. Design, Fabrication, and Case Study

The design process is structured as a hybrid analog–digital workflow that operates through successive transformations between intended geometry and material realization. Rather than following a linear sequence from design to construction, the method establishes a feedback loop in which material behavior informs and modifies the design as it develops. The workflow integrates analog modeling, digital definition, material fabrication, digital capture, computational adaptation, and guided assembly. The full-scale installation, composed of 42 VF parts, serves as a test case through which each stage of this process is implemented and evaluated.

3.1. Analog Design and Intended Geometry

The initial design phase is developed through a combination of physical modeling and digital definition, establishing the fabrication logic of individual components and the fundamental aggregation principles of the system. Early-stage exploration is conducted through paper-based models, which serve not primarily to define form but to investigate how flat sheet material can be transformed into volumetric units, how these units can be assembled through basic face connections, and how aggregation emerges from these operations. Through these studies, the relationship between planar geometry, folding sequences, and volumetric formation is first established. Paper models are used to test how tetrahedral units can be constructed from flat sheets, how edges and faces can be joined, and how variations in orientation affect aggregation patterns. This phase defines the fabrication logic of the components and the baseline aggregation behavior but does not yet introduce differentiated connection strategies or spatial articulation.

These principles are subsequently translated into a digital system based on intended tetrahedral geometry, derived from space-filling configurations related to the Sommerville type 1 tetrahedron. At this stage, the system operates under conditions of geometric consistency: all units are geometrically ideal, and the aggregation assumes exact alignment of faces, edges, and connection axes. The digital system provides a controlled environment in which the aggregation logic can be further specified and adapted to architectural requirements. It is within this digital phase that connection strategies are defined. Two connection types are introduced. Type 1 consists of direct face-to-face connections between adjacent tetrahedral units, producing compact aggregations that closely follow the underlying space-filling organization. Type 2 consists of extended connections mediated by linear wooden sticks positioned between units, allowing components to be separated while maintaining structural continuity. In addition to these two physical connection types, the aggregation employs two connection orientations. Connection A follows the logical orientation of the tetrahedral grid, extending the aggregation along its primary organizational directions. Connection B connects through an adjacent face of the tetrahedron, introducing a change in the local orientation of the grid and enabling directional shifts within the aggregation. The combination of connection types and orientations expands the range of possible configurations, allowing the aggregation to shift from compact, space-filling arrangements toward more differentiated spatial organizations (Fig. 3).

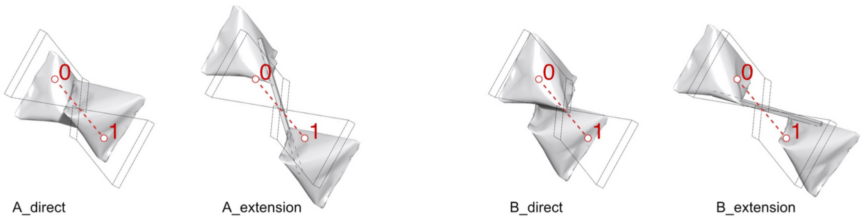

Figure 2: Connection types in the aggregation system

Within this intended design framework, architectural criteria are introduced and resolved through the assignment of connection strategies, component positions, and orientations within the virtual tetrahedral space. The aggregation should allow circulation through and under the structure, packing, as well as the incorporation of simple functions such as seating or leaning. The controlled use of extended connections produces gradients of density, ranging from compact clusters to more open and permeable regions. Crossing these architectural criteria also with the virtual tetrahedral space and the connection types establishes design-space variability. Multiple valid configurations remain possible through diverse iterations with component placement, orientation, and the distribution of connection strategies (Fig. 4). Among these possibilities, the selected design (Fig. 4, right) is oriented to generate horizontal surfaces, enabling potential functional uses such as seating, leaning, or support. To enable this condition, the underlying tetrahedral grid is oriented diagonally relative to the ground plane, allowing selected faces of the tetrahedral units to operate as horizontal surfaces.

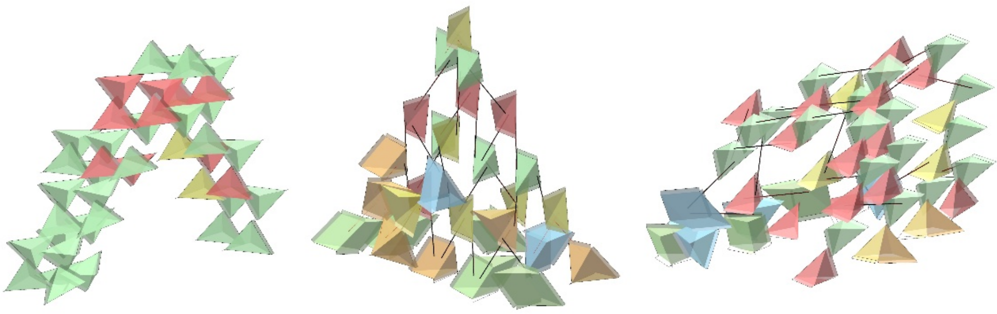

Figure 4: Different design variations.

The resulting model defines an intended geometry and organizational logic that integrates fabrication principles, connection strategies, and architectural requirements. Importantly, this phase establishes the complete set of possible connection types and spatial configurations available to the system. Subsequent stages do not introduce new organization and connection logics but operate through the adaptation and redistribution of these predefined strategies in response to material transformation. The intended geometry therefore acts as a controlled reference framework, against which the effects of material-dependent variability are introduced and negotiated.

3.2. Fabrication and Material Transformation

The fabrication phase translates the intended tetrahedral geometry into physical components using vulcanized fiber (VF) sheets in their pre-cured wet state. Based on the unfolding logic established during the design phase, 42 flat sheets are manually cut and folded into volumetric units corresponding to the three component types of the system: tetrahedral, pyramidal, and rhomboid units. The formation process follows a defined sequence of edge connections that transform planar material into closed volumetric shapes through geometric constraint and initial fixation (Fig. 5).

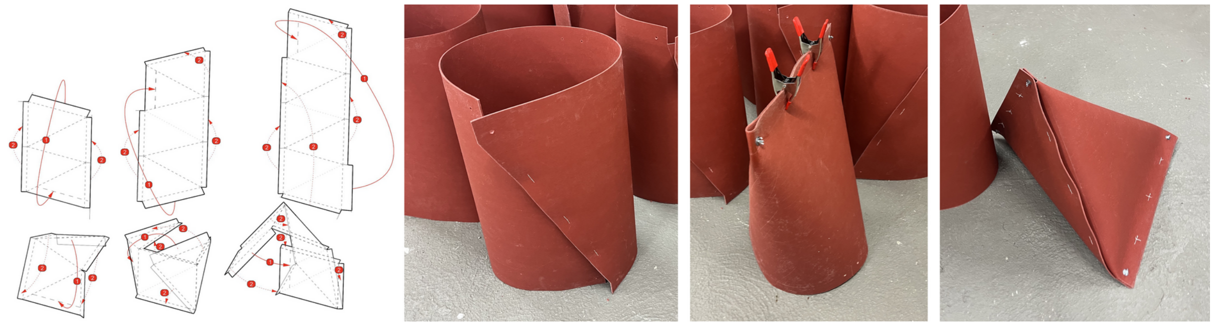

Figure 5: Unroll forms for different part types (left). Production steps of tetrahedral building parts (right).

Once formed, the components are left to dry without rigid formwork. During this period, which extends for approximately two weeks, the material undergoes significant morphological and mechanical transformation. As moisture evaporates, the VF contracts, warps, bends, and progressively stiffens. These transformations are driven by internal stresses within the material, gravity, local environmental conditions, and slight differences in the fabrication process. This transformation introduces the second form of variability investigated in the research: material-induced variability. Unlike the design-space variability established during the intended design phase, which arises from multiple possible organizational configurations, material-induced variability emerges directly from the behavior of the material itself. Because the drying occurs without geometric constraint, each component develops a distinct configuration that cannot be exactly repeated (Fig. 6).

Figure 6: Drying rack (left). Transformation of a tetra-part in the drying process (right).

As a consequence, the fabricated parts diverge from their intended tetrahedral geometry. While the overall topological identity of each component remains recognizable, its morphological properties change. Variations emerge in edge lengths, face planarity, angles, and curvatures. These deviations are particularly relevant at the locations where components are intended to connect, as geometric correspondence between faces and edges can no longer be assumed. The fabrication process therefore produces a heterogeneous family of 42 elements derived from the same geometric template but exhibiting unique morphological characteristics.

3.3. Digital Capture and Computational Re-Aggregation

Following fabrication and material transformation, the process re-enters the digital domain through the digital capture of the as-built geometry of all fabricated components. Each of the 42 VF parts is recorded using high-resolution 3D scanning, producing detailed mesh models that register their actual geometry, including local deformations, edge irregularities, and surface warping. The scanned data is processed and organized into a digital catalogue, in which each part is treated as a unique geometric instance. This catalogue replaces the uniform components of the intended model with a set of differentiated elements, each characterized by its specific geometry and connection conditions.

Because each VF unit differs geometrically, its placement within the aggregation directly affects both local connectivity and the overall configuration. Reassigning parts or altering their orientation within the same organizational logic—calculated with the Wasp plugin for Grasshopper—produces spatial variations while remaining within the intended design framework. Various reconfigurations based on the same set of parts are therefore calculated and subsequently adapted to the actual geometry of the fabricated components. This adaptation is performed through a Grasshopper script using the Kangaroo physics engine. The scanned components are inserted into the predefined organizational framework as unique geometric entities whose dimensions and connection interfaces differ from the intended tetrahedral model. For each configuration, the script simulates the interaction between all components simultaneously, adjusting their relative positions and orientations while attempting to satisfy the predefined connection relationships. The adaptation operates through the tolerances embedded in the connection strategies: in Type 1 connections, discrepancies are primarily absorbed through variation in face overlap; in Type 2 connections, through variation in stick length. In specific cases, Connection B allows a local change in orientation through an adjacent face, enabling punctual adjustments where accumulated deformation would otherwise affect buildability or structural support. Through iterative relaxation, the system adjusts the placement of each part to accommodate geometric discrepancies and accumulated deformation within each configuration. The organizational logic established during the design phase remains fixed, while the geometry is allowed to adapt within defined constraints. The simulations therefore seek equilibrium states in which all components fit together as closely as possible while preserving the intended spatial organization, connectivity, and overall tetrahedral structure. This process produces a set of configurations with distinguishable morphological differences (Fig. 7).

Figure 7: Variations depending on different positions of the deformed VF elements and their mutual adaptation.

Nevertheless, the redistribution of the available components within the organizational framework is not entirely aleatory. In particular, the larger pyramidal and rhomboid units are preferentially positioned in lower areas of the structure. Due to their increased volume, weight, and relatively more stable geometry, these components provide greater structural support and offer larger usable surfaces, making them suitable for ground-level placement and for accommodating functional interactions such as seating or leaning. From the set of possibilities, one configuration is selected for further development (Fig. 7, left).

The selected adaptation exhibits enough degree of discrepancy from the ideal intended design to make the effects of material transformation and material participation clearly legible within the overall structure, while still satisfying the criteria of buildability, structural coherence, and the architectural intentions defined during the design phase.

3.4. Physical Assembly

Following the selection of the adapted configuration, the installation is assembled at full scale using augmented reality (AR) guidance (Fologram within a HoloLens headset). The digitally adapted model generated in the previous stage serves as the direct reference for construction, providing the spatial coordinates, orientations, and connection relationships of all components within the final configuration. Rather than relying on conventional drawings or physical templates, the assembly process is guided through holographic overlays that visualize the intended position of each element directly within the construction space (Fig. 8).

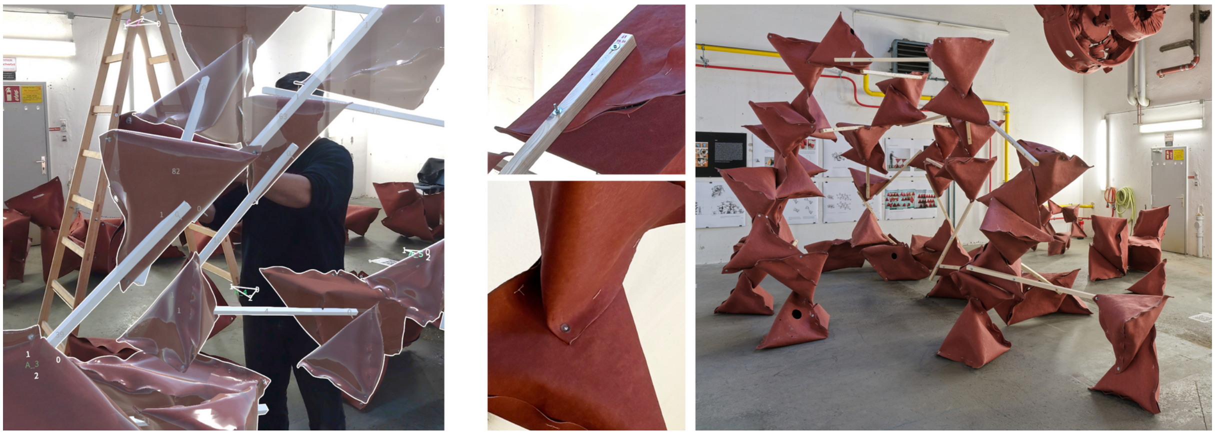

Figure 8: AR-guided assembly (left), joint details(middle), and final installation (right).

The use of AR is particularly relevant due to the geometric uniqueness of all fabricated components. Since each VF unit differs from the intended tetrahedral geometry and from every other unit, conventional assembly methods based on repetition or standardized positioning become less effective. AR allows each component to be positioned according to its specific role within the adapted configuration, ensuring correspondence between the digital model and the physical structure. Because the principal geometric discrepancies have already been accommodated during the computational adaptation stage, only minor adjustments are required during construction. Small corrections occur primarily in relation to construction tolerances, local alignment conditions, and material flexibility at connection interfaces. The use of AR minimizes the need for on-site reinterpretation and incremental deviation throughout the construction.

4. Evaluation and Discussion

The evaluation focuses on how two forms of variability—design-space variability and material-induced variability—operate together within a discrete structural system. The first is formal and organizational: before fabrication, the virtual tetrahedral space supports multiple configurations capable of satisfying the same architectural criteria, including circulation, density variation, buildability, and usable surfaces. The second emerges after fabrication, when the 42 VF components cease to function as interchangeable units and become distinct geometries with specific connection conditions. This is evidenced by the measurable difference between the intended and adapted configurations: the overall form departs from the initial model through an average displacement of approximately 15cm and a maximum displacement of approximately 50cm. These values do not indicate constructional inaccuracy. They register the extent to which material self-forming modifies the selected design instance. The organizational logic remains stable, yet its geometric realization is transformed through the actual behavior of the fabricated parts. This has direct implications for buildability. In a geometrically rigid tetrahedral aggregation, precise correspondence between parts would normally be assumed. Here, however, buildability depends less on exact reproduction of the intended geometry than on the capacity of the connection system to integrate material discrepancies. Type 1 connections allow variation through changes in face overlap, while Type 2 connections allow variation through adjustable stick lengths. These tolerances make it possible to incorporate non-identical parts while maintaining coherence. In this sense, precision is not eliminated but relocated: it no longer refers to identical repetition or exact correspondence with an ideal model, but to the controlled management of relationships between differentiated parts. The installation therefore demonstrates that coherence and stability in discrete systems can operate within a range of admissible variations through the interplay of connection strategies, local density, and support distribution.

Architecturally, the interaction between the two variabilities expands the spatial possibilities of the system beyond those presumed by design intention alone. The intended criteria—passage under and through the structure, differentiated density, and usable surfaces—remain present, but their exact manifestation is altered by the material transformation of the components. Horizontal surfaces, for example, are present but not geometrically exact, with an average inclination of approximately 7° and a maximum inclination of approximately 20°. Rather than invalidating their function, this produces approximate and situated conditions of use. The space is therefore not fully prescribed, while still remaining legible and usable within the initial architectural framework. This partial indeterminacy suggests that users can interpret and appropriate the space in ways that extend beyond those originally anticipated by the designer. Rather than enforcing a single mode of occupation, the incorporation of material variability in the built structure opens opportunities for alternative uses, encouraging multiple readings and forms of engagement with the installation.

The evaluation therefore indicates that the contribution of the workflow is not simply the accommodation of irregular parts, but the coordination of different sources of variability within one design and construction process. Design-space variability establishes an open but structured field of possible organizations; material-induced variability transforms the selected organization through the behavior of VF; and computation mediates between both without eliminating uncertainty. The result is a material-dependent design method in which uncertainty becomes productive, expanding spatial and organizational possibilities while maintaining buildability and architectural intent.

5. Conclusion

This paper has presented a hybrid analog–digital workflow for the design and construction of discrete tetrahedral aggregation systems using vulcanized fiber (VF) in its pre-cured wet state. The research investigates how material transformation can be integrated into a discrete structural system without being reduced to error, correction, or loss of control. Through the full-scale installation, the study demonstrates that design-space variability and material-induced variability can be coordinated within a common organizational framework. Their interaction shows that architectural form is neither fully predetermined by design intention nor solely produced by material behavior but negotiated through a workflow that combines rule-based organization, material self-forming, digital adaptation, and guided assembly. The built installation also demonstrates that geometric exactness is not the only condition for coherence and buildability in discrete structural systems. Instead, coherence emerges through the persistence of the organizational logic, while buildability is achieved through tolerances embedded in the connection strategies. The project therefore redefines precision not as identical repetition or exact correspondence with an ideal model, but as the controlled management of relationships between differentiated parts. In this sense, computation shifts from functioning primarily as a predictive instrument toward acting as a mediating framework capable of integrating materially transformed components into viable structural and spatial configurations. At the architectural level, the research shows that uncertainty can expand spatial possibilities beyond those initially presumed by design intention. The material transformation of VF modifies the exact manifestation of circulation, density, and usable surfaces, producing a spatial condition that remains structured yet partially indeterminate. This allows the installation to suggest rather than prescribe use, opening the possibility for alternative modes of occupation and interpretation. The significance of the project lies in proposing a design methodology in which variability becomes an operative condition of architectural formation. Rather than treating uncertainty as a problem to be minimized, the workflow incorporates it into the generative logic of the system. Architectural control is reconsidered not as the exact specification of form but as the capacity to organize the interaction between designed intention and material agency. Future developments will extend this approach toward systems assembled directly in the wet state of the material, when VF is at its weakest mechanically. While the aggregation remains structurally stable in this condition, the structure progressively stiffens as the material dries, simultaneously undergoing spatial transformation through contraction and geometric reconfiguration. This opens the possibility for installations operating through continuous wet–dry cycles in outdoor environments, where environmental exposure repeatedly alters the geometry and mechanical behavior of the system.

Ultimately, the project proposes a shift from designing fixed architectural objects toward designing frameworks capable of incorporating transformation itself. Architecture is therefore approached not as the stabilization of matter into predetermined form, but as the structured negotiation between intention and the continuous self-forming capacity of material systems.

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