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Algorithmic modeling of functionally graded metamaterials in 3D printed building envelopes

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Abstract

Recent development of powder-bed additive manufacturing promises to enable the production of architectural structures that combine high resolution and articulation with economies of scale. These capabilities can potentially be used for functionally graded metamaterials as part of the building envelope and structure, paving the way for new functionalities and performances. However, designing such multifunctional structures requires new design and modelling strategies to control, understand, and generate complex geometries and their transcalar interdependencies. The work presented here demonstrates a modeling framework that can unite multiple generative and organizational algorithms to create a unified, 3D printable building element that integrates a range of functional requirements. Our methods are based on an understanding of stigmergic principles for self-organization and developed to allow for a wide range of application scenarios and design intents. The framework is structured around a composite modeling environment based on a combination of volumetric modeling and particle-spring systems, and is developed to negotiate the large scalar range necessary for such applications. We present here a prototype demonstrator designed using this framework: Meristem Wall, a functionally integrated building envelope fabricated through a combination of powder bed 3D printing and CNC knitting.

Keywords Metamaterials, Algorithmic modelling, Stigmergy, Additive manufacturing, Architecture, Functionally graded materials, Building envelope

1 Introduction

The promise of additive manufacturing (AM) of cost-efficient complexity (Berman, 2012) is particularly well suited to the architecture and construction industry (Hager et al., 2016), which on one hand is always producing one-off designs, and on the other represents a synthesis of several performance requirements and functions. In many AM techniques currently used in construction (such as concrete FDM) this advantage is limited as high resolution comes with a significant cost and time penalty (Ko, 2021). One of the exceptions is particle bed 3D printing, which has the potential for simultaneously achieving high speed, large volume, and high-resolution prints (Wangler et al., 2016). These AM processes are currently employed primarily to produce metal casting molds but may soon be adapted for use in the construction industry where appropriate powders and binders could result in more sustainably produced, high performance building components.

When such solutions are available it will be feasible to fabricate large scale components with very high complexity starting from sub-mm scales. This potential raises a question: what added value can be brought into architecture through complex form, and what are the methods for generating and managing this complexity?

In this article we describe the design model developed for the generation of a architectural building envelope that incorporates multi-functional integration. The prototype relies on geometry that would not be possible to

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Fig. 1 Meristem Wall exhibited in Venice, Italy

fabricate without additive manufacturing technology. Through intricate and specific geometries, several functions spanning a wide range of scales are embedded in the direct component production of the project demonstrator, called *Meristem Wall* (Fig. 1). The research question focuses on how algorithmic design processes can be used to create a highly complex material geometry rather than on the functional performance of the prototype itself. This geometry is characterized by monolithic functional integration and transcalar interdependence.

1.1 Particle-bed 3D printing

Particle-bed 3D printing is an additive manufacturing technique where layers of material are successively deposited to produce an object. The material deposition takes place in two alternating stages. A layer of particles is deposited by a coater, after which a nozzle lays a liquid to bind the particles together. These two steps alternate until the geometry is completed and the bound geometry is contained inside the bed of loose particles. When these are removed, the bound particles have retained the intended geometry. There are three main technologies for particle-bed 3D printing: Selective Binder (or Cement) Activation, Selective Paste Intrusion, and Binder Jetting (Lowke et al., 2018). The latter was the one employed in the fabrication of the project described here.

This technology has several advantages. The resolution can be very high, depending on the size of particle used, while maintaining a high print speed even for large volumes. Furthermore, since the bonded geometry is supported by the layers of loose particles below, a high range of geometries with features such as overhangs can be fabricated that is not feasible with extrusion techniques which are currently the main AM alternatives for large volume prints.

Since the early development of the technology for architectural use by Dini in 2007 (Soar & Andréen, 2012), a few projects have emerged in the realm of architecture and construction. Among these are the Digital Grotesque series by Dillenburger and Hansmeyer (2013), which utilized the same technology and material system as *Meristem Wall*. It pushed the limits of resolution and generative design for elaborate geometries with the focus on ornamentation, as a placeholder for the potentials of the technology (Lowke et al., 2018). A footpath bridge was built with the same technology in 2016, by Acciona and Dini. It was fabricated in concrete, and the geometry incorporated the static forces (Jackson, 2016).

Today several material systems for use with this technology are starting to emerge, notably those based on geopolymer, cement, and waterglass binders, that speak to a future potential for particle-bed 3D printing in architecture (Chun et al., 2023; Xia & Sanjayan, 2016).

1.2 Functional integration

Typical for contemporary building construction systems is the separation of functional elements into distinct components where interdependence is avoided to a high extent (Knippers & Speck, 2012). This is the result of both engineering and manufacturing constraints. In the case of the former, it is due to requirements of performance predictability, where interdependence of parameters results in prohibitively complex analyses. In the case of the latter, it is due to mass production logic which relies on standardization and simplification. With the emergence of digital fabrication and design technologies, particularly AM, this industrial logic is shifting: mass customization enabled by complex simulation allows for the creation of structures which are inherently multifunctional (Menges, 2008).

Such functionally integrated multiscale structures are common in biological structures and are the focus of increasing interest in various engineering fields (Liu & Jiang, 2011). Following similar principles, it may be viable to produce architectural monolithic[1] structures, where functional performance is achieved within a single material through adaptation of the geometry. In such a structure, different functional requirements may overlap and interact, creating the opportunity for synergies as well as conflicts. *Meristem Wall* is a speculation of what such an architecture may look like – it incorporates speculative functionality achieved by a fluid, monolithic, and highly complex design. These functions may be very different from each other, relying on altogether different logics or functional mechanisms. For example, they can be derived from mechanical properties such as structural integrity and heat conductivity, from connectivity or process-based constraints, from biological interactions, or from the way the architecture is experienced by humans – as aesthetic or cultural considerations. Navigating this complex design-space requires tools that are capable on the one hand of coordinating and negotiating these trade-offs and interactions non-linearly, and on the other can describe and assess each functional mechanism according to its own logic or notation. This is fundamentally different from conventional multi-parameter optimization, which assumes that all dependencies can be described through a uniform, mathematical language (Varenne, 2013).

1.3 Modeling for additive fabrication

Particle-bed 3D printing technologies facilitate the production of high resolution, high customization outputs, thus enabling the fabrication of performative, functionally graded metamaterials that gain extended, new, and beneficial properties through their geometry (Li et al., 2020). However, this ambition requires novel approaches to modeling and design to manage the resulting formal complexity.

Mesh or NURBS models, tools that define volumes in space through boundaries, are not well suited to describe metamaterials as these rely on specific and highly articulated geometries that are computationally demanding to represent due to the high ratio of boundary to volume. Additionally, mesh models are error-prone when altered locally, due to vertex mismatches or topological errors, and NURBS models are constrained to globally similar B-splines. An alternative way of representing geometries is volumetric modeling (Li et al., 2020), where the volume is represented in a 3-dimensional array of voxels that can be either solid or void—though it is also possible and sometimes necessary to extend the dimensionality of the data to incorporate further levels of information, e.g., for multi-material printing, variable density, or simulation purposes (Svilans et al., 2022).This logic is similar to the particle-bed 3D printing technology, with the full print bed volume containing aggregate particles (voxels) that are either bound by the deposition of the binder (active) or loose (passive), and so the two are highly compatible for the process of design to fabrication (Bernhard et al., 2018).

Volumetric models thus describe geometry not through vertices that connect through faces and edges or mathematically continuous formulae, but with 3-dimensional locations of the voxels, and a function $f(x, y, z)$, where v is the distance from the point to the boundary that defines the inside from the outside geometry, the signed distance field (SDF) of the volume (Bernhard et al., 2018). This allows for highly localized Boolean operations such as unions and subtractions, that are solved arithmetically and therefore efficiently. The volumetric model allows a fast conversion to a mesh surface that is then used for the 3D printing slicing software.

In this project, volumetric modeling was used in combination with other algorithms, as a virtual environment where other sets of data were merged and coordinated through a 2-way, iterative process. Multiple algorithms were used in the modelling of various functional features. Most significant of these was the use of particle-spring systems for the creation of the main channels running through the wall. Particle-spring systems have the benefit of being locally defined and simulated, allowing for complex self-organization of an arbitrary number of independent but interacting systems. Such systems are typically used in architecture and building engineering for structural form-finding, as has been elegantly demonstrated by e.g., Antoni Gaudí and Frei Otto, and which are today used by means of computer simulations rather than material models (Kilian & Ochsendorf, 2005; Williams, 2001). The algorithms and their interactions are described in the following section.

2 Material and methods

2.1 Design parameters

This research was carried out through the explorative design of a prototype or probe, Meristem Wall, which was conceived as a curtain wall that fully integrates many aspects of the building envelope in a single entity. The modeled and fabricated section measures 2.1 m in height, 1.25 m in width, and has a thickness of up to 0.7 m. The geometry of the wall does not have an outside and inside per se, as it is formed from a gyroid-like surface. However, in this paper we will refer to three zones of the

[1] *Monolithic* is here used in the material sense:"consisting of a single piece of homogeneous material as opposed to a composite material or an assembly of multiple parts" (en.wiktionary.org/wiki/monolithic as of 2024–03-09).

envelope. These are the outer side (the zone closest to the exterior of the building), the interior side (the zone closest to the building interior), and the internal zone of the wall/envelope (the zone in between the interior and outer side of the envelope). The geometry of the 3D printed component of the Meristem Wall is visualized for further clarity in video 1–3 (supplemental information).

The prototype was designed for several defined functional requirements, each corresponding to particular geometric features in the resulting structure. Some of these functions are more discrete, whereas others demonstrate greater fluidity and overlap. The nature of these functional responses is speculative; while they are modelled on qualified assumptions and documented research, they are only evaluated qualitatively through the making of the prototype. The purpose of these functional features is not to test the validity of the underlying assumptions, but to set a complex design task that can only be navigated through multiple simultaneous transcalar interdependencies. The physical output was conceived as an exhibition artefact intended to probe, visualize, and demonstrate the opportunities offered by advanced additive fabrication for building envelopes. The different functional aspects of the wall are as follows:

2.1.1 Transient network

The base structure of the wall consists of a reticulated network of channels that connect the interior and the exterior boundaries of the wall. This network has two main functions: to provide a base for the structural integrity of the wall, and to form a mass transport mechanism that allows air, heat, and moisture to flow through the wall in a controlled manner. This is modelled on mechanisms derived from functional studies of termite mound physiology described and quantified by (Andréen & Soar, 2023). This network creates tunable air connection and regulated passage between the building, the interior of the wall, and the building's outdoor environment.

The network is formed from nodes and edges arranged in a body-centered cubic lattice with a valence of 8 (Fig. 2). The lattice structure has an edge length of approximately 20 mm, and a channel radius of 4 mm, efficiently carrying loads through the volume in all directions. It leaves an in-between space that holds the potential to act as either insulation or buffering, by being infilled with phase-change materials or insulation.

The mass transfer mechanism of the reticulated network relies on transient airflows, and in nature similar mechanisms allow the termite mound to maintain a humid interior in arid climates while exchanging necessary respiratory gasses (Turner, 2000). The narrow diameter and high tortuosity of the channels limits steady flows through the wall caused by temporary pressure differentials such as wind but can be activated through mechanical actuation of small oscillations which give rise to large scale turbulence. This turbulence can be used to affect mass transfer rates, and thus to regulate flow of heat or moisture through the structure (Andréen & Soar, 2023).

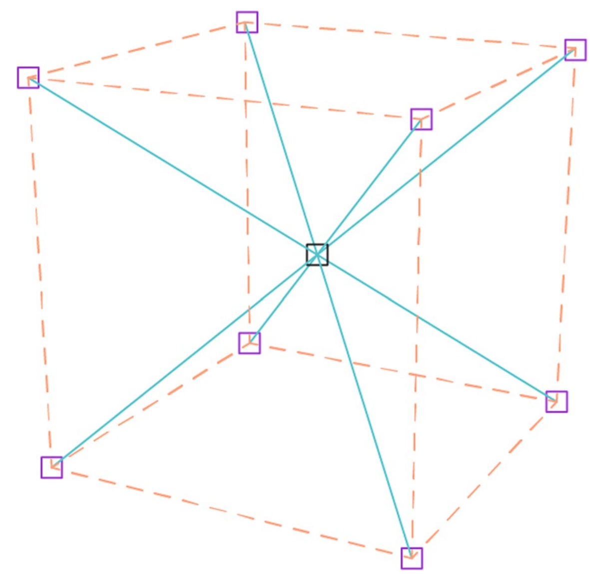

Fig. 2 Unit cell of initial network structure. Each node (black) has eight neighboring nodes (purple), connected via edges (blue)

2.1.2 Nonhuman ecosystem niches

The outer portion of the wall is intended to function as a habitat for a diverse and native ecosystem, incorporating organisms ranging from microbes and fungi to plants, insects and small mammals or birds. This is achieved through spatial variation on the outer side (Fig. 3), as well as an active modulation of the moisture levels through the transient flow network. The exterior is convoluted, exhibiting a range of features scaled to promote varied microclimates, moisture retention, and physical capacity for seeds and organic matter to anchor and accumulate. The surface is not intended to be planted but rather colonized, and for a succession of species to lead to a long-term stable ecosystem inhabiting the wall.

2.1.3 Installations

The wall segment incorporates an electrical and water utility network (Fig. 4). The connections are formed by channels that are intended for post-assembly fitting of flexible PP or HDPE conduits. The channels are optimized with regards to curvature to facilitate installation and replacement and connected to standard wall boxes fitted in the printed wall surface. The installation channels span larger scales than the demonstrator, pointing to connections across the building.

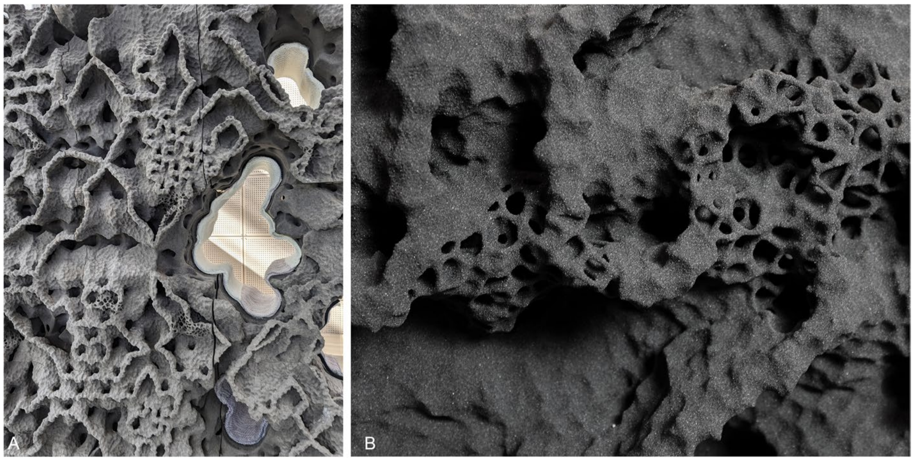

Fig. 3 Bioreceptivity. **a** A diversity of size, orientation, and shape of niches on the external façade. **b** Micromodulation of the surfaces (feature size down to 3 mm)

2.1.4 Interior surface

The interior side of the wall is not a solid surface. Its boundary is open to the internal zone of the wall and defined by the interior endpoints of the transient network channels as well as the fitted wall boxes and windows (Fig. 5). To these, a custom CNC knitted wall textile was designed and fitted. This textile defines the building's interior space, its color, aesthetics, and acoustics. Additionally, it acts as a filter for dust and particle ingress through the channels (Fig. 6).

2.1.5 Fabrication, transport, and assembly

The final design considerations were the fabrication, transport, and assembly process, which imposed a specific set of constraints on Meristem Wall, as its production was intended primarily for exhibition in Venice during the Biennale Architettura 2021. The components were fabricated by Voxeljet AG using a Voxeljet VX4000, using quartz sand and furan binder. The dimensions of the print bed are 4 * 2 * 1 m, which would have allowed the production of the full envelope section to be made in a single piece. However, due to handling and transportation constraints, the wall was subdivided into 21 pieces, each weighing less than 30 kg (and thus possible to be handled by a human worker). These components required the addition of connecting details for the assembly, as well as additional features addressing overall structural integrity. In a non-prototype fabrication scenario, it is likely that the wall would be fabricated in larger segments, adapted for large scale transport and on-site assembly. The printed components were post-treated by Sandhelden GmbH with an epoxy resin to achieve a surface finish able to withstand shipping, assembly, and outdoor exhibitions for at least 6 months.

2.2 Modeling environment

The wall was modeled through a series of algorithms designed to accommodate the different design parameters and requirements. These algorithms are based around a volumetric model (Fig. 7c) which was initially created through a self-organizing process (Fig. 7b) based on designer-set boundary conditions (Fig. 7a). This volumetric model allows for subsequent modifications of the wall (Fig. 7d) and is the template from which meshed print files are created (Fig. 7e).

2.2.1 Particle-spring networks

The boundary condition of the wall was set to include several aspects, including the complete volumetric envelope, the window openings, and all endpoints for the installation networks, in this case electrical and water. These design constraints functioned as the input of a self-organizing particle-spring system, which allowed for the negotiation of long- and short-range connectivity as well as collision avoidance of the different connectivities without resorting to Boolean operations that would interrupt the channels.

In our model topology was predetermined, but the specific geometry of the network was developed through the form-finding algorithm. The particle-springs were organized into four distinct networks: representing the electrical network (A) the water piping (B), and the double reticulated network (C, D) which fills the dual purpose of defining the wall structurally and the transient mass transfer mechanism (Fig. 7b). Fixed endpoints, either in three dimensions or constrained to an abstract surface, were defined for each network, and in some instances also with tangents for these endpoints. The networks were defined internally through subdivisions into nodes and edges, and

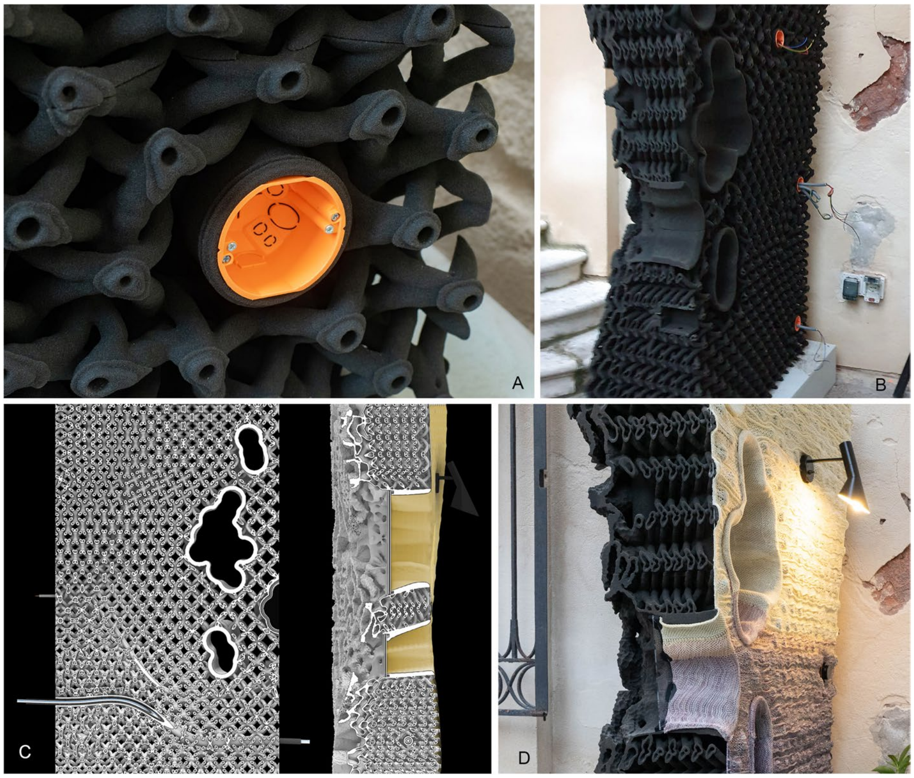

Fig. 4 Electrical installation. **a** Swedish standard wallbox fitted in socket. **b** Electrical installation in the assembled prototype. **c** Sections through computer model showing channels and fittings. **d** Working installation

Fig. 5 Windows. **a** Printed geometry prior to installation of the window. **b** Final assembly, textile and windows fitted to printed geometry

then each edge was defined as a simulated axial spring which can change length but exerts force when it deviates from its rest length, inversely proportional to the deviation (Fig. 8a) (Kanellos & Hanna, 2008). Additional forces were introduced, creating repelling forces between nodes belonging to different networks (Fig. 8b). The magnitude of these forces was dependent on the distance between the nodes, larger forces for nearby particles and decreasing force as the distance increases. Through a process of dynamic relaxation, the particles found a position in space which balanced the internal continuity of the path with collision avoidance relative to the other networks (Fig. 8c). The particle spring networks were defined and processed using Kangaroo (Piker, 2017) and Houdini (SideFX, 2020),

Fig. 6 Custom textile fitting. **a** The textile knitting pattern corresponds to functional and aesthetic requirements, with a uniform, dense pattern forming a filter over each air channel opening. **b** Side views showing knitted pockets that act to fix the textile to each channel opening which is equipped with a corresponding ridge

the latter which was necessary to process the very large number of nodes and interrelations of the transient network of the full-scale model.

Furthermore, the particle-spring connections were subject to an additional constraint, which acted to maintain a 0-degree angle between two opposing springs or edges. The effect of this constraint is a smoothness of the resulting geometry. The weighting of this force was relatively small in the transient networks, allowing these pathways a high degree of flexibility with highly varied local curvature and with an enforced tortuosity to increase the flow resistance to laminar through-flow. On the other hand, the electric and water networks had a strong weighting for straightness. Through the dynamic relaxation process, this results in a uniformly distributed curvature of the pipe, minimizing the resistance to threading of pipe-in-pipe hardware in the wall. Thereby, the system was optimized for installation and replacement of such hardware.

The different behaviors of the particles were controlled through the addition of various forces, such as outlined above. Every force was individually tied to a desired behavior and added independently to the particles. The system is thereby flexible to further additions or removals of certain behaviors, and an overall distribution that satisfies all the conditions to a lesser or greater degree is found through the progressive relaxation of the particle springs.

2.2.2 Transition to volumetric space

The particle-spring model was used to generate a volumetric model of solids and voids. The space in the boundary volume is subdivided according to a 3-dimensional matrix, creating a list of points in space $P(x, y, z)$. The relative distance (dR) to the closest points on networks C and D was calculated for each point P_i:

$$dR = \frac{|P_i - P_C|}{|P_i - P_D|}$$

If each point (voxel) near $dR = 0.5$ is filled with solid material, a volumetrically defined iso-surface is created at the midpoint of the two networks. By varying the threshold value, the relative position of the isosurface is shifted towards one of the networks: a threshold value of 0.1 will create a surface that intersects every point in space that is at 10% of the distance from network C to network D (Fig. 8d). The isosurface was calculated using ChromodorisBV, a Grasshopper3D plugin (Johansson, 2021).

The volumetric model (Fig. 7c) was created using the resulting relative distance field in combination with a varying threshold value as shown in Fig. 9, using Houdini (SideFX, 2020). This resulted in a channel network centered around the transient network springs, with a radius of the channels determined by the threshold value dR. The other set of channels was similarly generated from a constant distance, determined by the hardware installation requirements, to the corresponding springs. As the

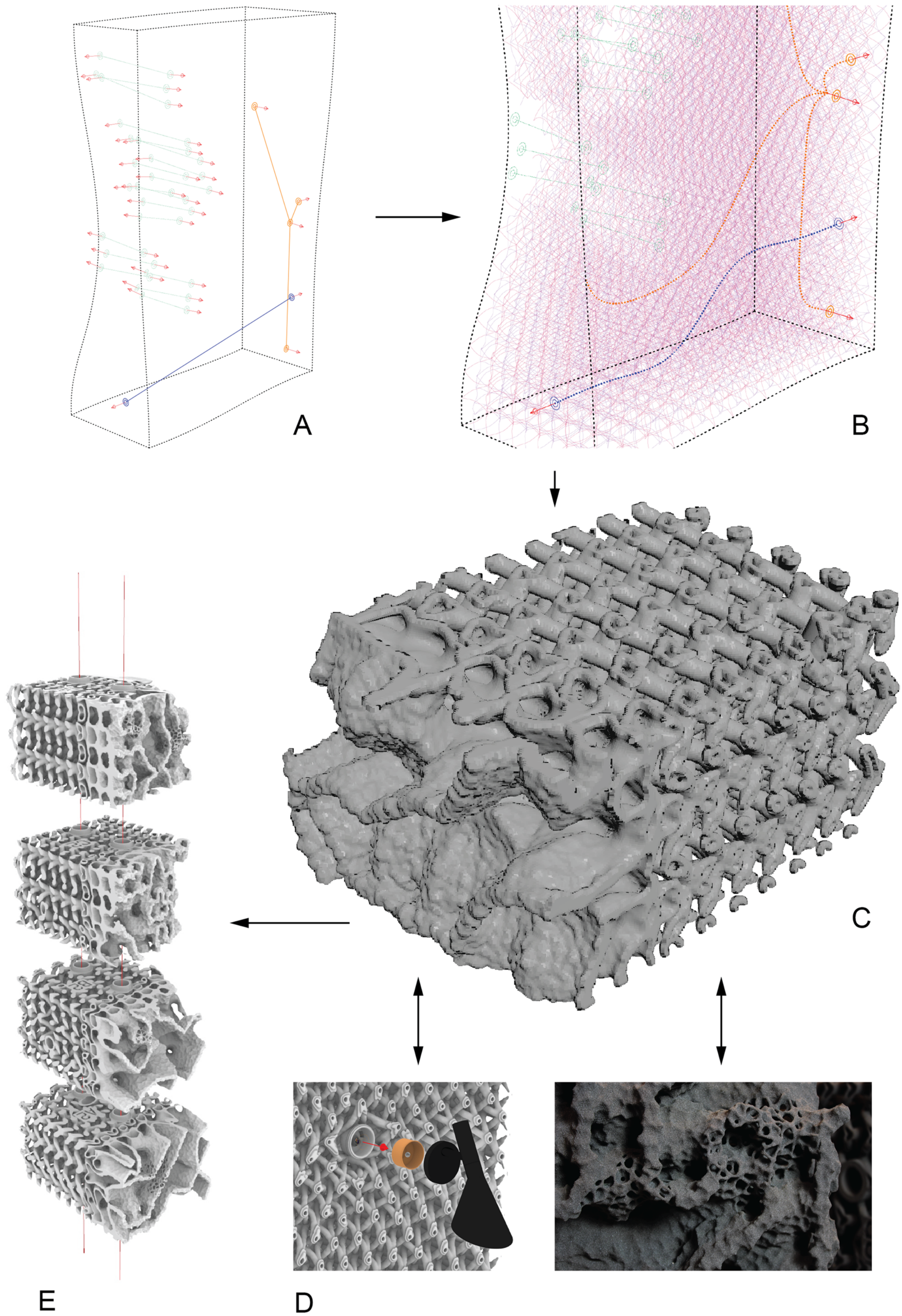

Fig. 7 Interaction of modeling algorithms

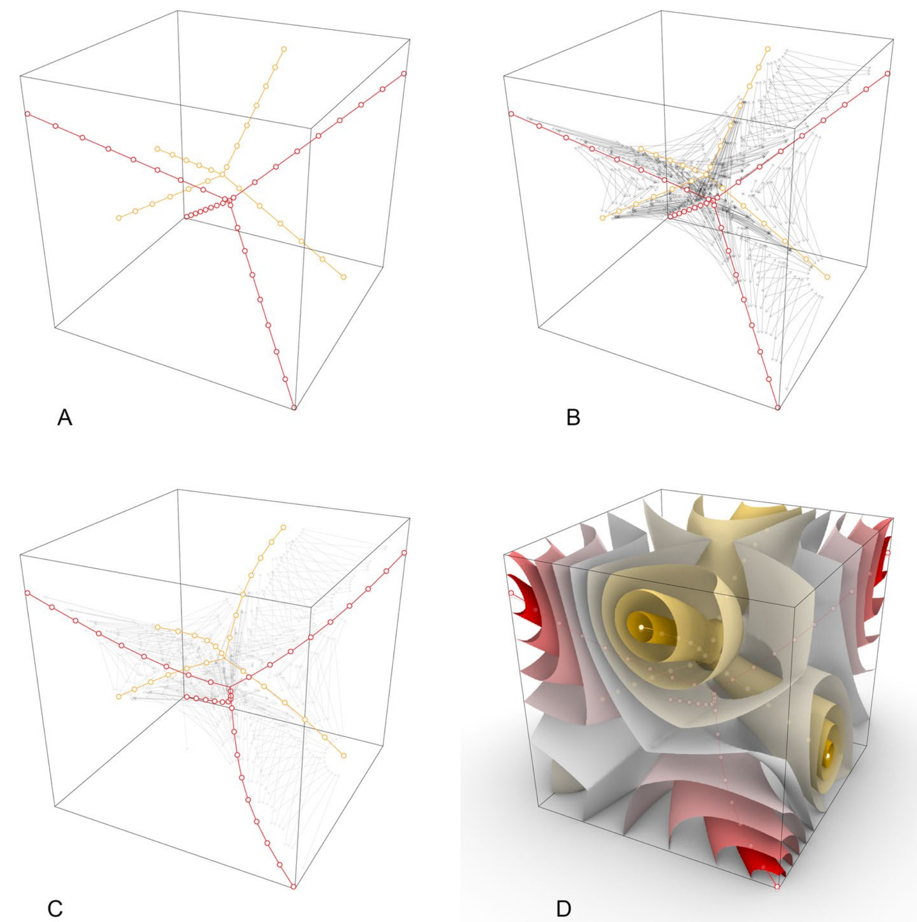

Fig. 8 Generative principles of particle spring networks and isosurface. **a** Initial topological definition of networks (red and yellow) and chain-linkage of springs. **b** Repulsion forces between network 1 and 2. **c** New geometric equilibrium. **d** Different isosurfaces at relative distances from 0.1 (red), through 0.5 (grey), to 0.9 (yellow)

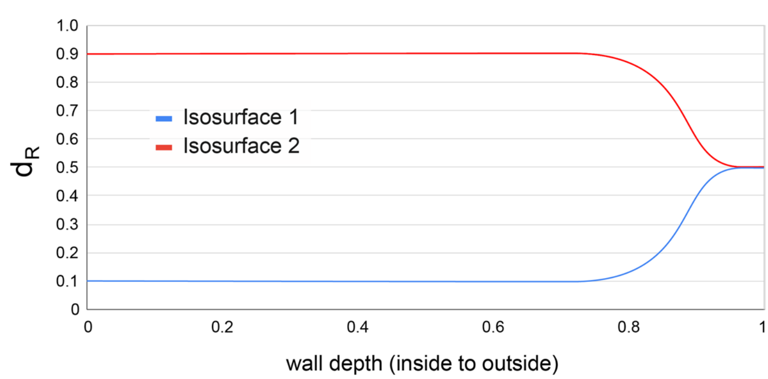

Fig. 9 Threshold values for isosurfaces as function of wall depth (proximity to interior)

threshold value varies with its proximity to the outside of the wall (Fig. 9), the network of channels changes at its outer extreme, transitioning from two distinct sets of tunnels to a folded surface (Fig. 3), which serves as a weather shield and the bioreceptive zone, while maintaining the connectivity of the channel network and therefore the controlled permeability of the wall as a whole.

2.2.3 Adaptations in volumetric space

Once the basic volumetric model was generated, it was used as a digital environment for further manipulations of the model geometry. Volumetric models are exclusively locally defined, essentially consisting of a matrix of data points. This brings the advantage that any change to part of the volume can be made independently and does not degrade the overall quality or nature of the volumetric representation. Several manipulations of this model were made at various scales, in order to accommodate specific functional requirements.

2.2.4 Bioreceptivity

To enhance the bioreceptivity of the zone facing the exterior environment, three different geometric transformations were applied at different scales: a progressive merger of "nests" to create a varied distribution of physical and ecological niches (Fig. 3a), a localized erosion to generate cm-scale porosity and provide starting points for debris and seed capture (Fig. 3b), and surface texturing (Fig. 3b).

The first algorithm, nest merging, operated in the particle-spring model. This was achieved by selectively removing some of the outermost edges in the particle-spring network, which resulted in the formation of larger pockets and surfaces in the outer layer of the isosurface, leading to a large variation in size, orientation, and connectivity. The resulting variability of microclimate and conditions was intended to promote the establishment of a rich and diverse ecosystem. The outer extremes of the particle-spring network were furthermore shifted downwards, creating (on average) a downward and outward slope favoring rainwater runoff while still permitting local pools to form, further enhancing microclimate variability and promoting colonization.

The latter two algorithms (erosion and texturing) operated on the volumetric model itself. The erosion algorithm was achieved through local application of a 3-dimensional Voronoi pattern where the inside of the Voronoi cells were removed, leaving a lattice framework encasing small hollows capable of holding organic matter (Fig. 3b). The texturing resulted from a noise displacement of the surface and combines with fine texturing resulting from the fabrication process to facilitate bioadhesion. As the transformations (particularly the local erosion) were computationally intense, it would have not been possible to introduce such features in a global manner, but the volumetric model enabled a local approach where a section of the model was isolated, and the algorithm operated on exclusive adjacent data.

2.2.5 Modeling of pipes and inserts

The centerlines and thus the curvature and position of the pipe channels were defined in the particle spring model which facilitated not only relative pathfinding of all channels but also their connectivity to a wider building context. The wallboxes were made for light fixtures, electric sockets, and switches to be later mounted (Fig. 4). These were designed to fit the specific geometries of prefabricated standardized components, the centerline of the piping, and aligned with the vectors of the boundary of the interior area. Additionally, to facilitate attachment of the textile, the geometry of the channel ends was adapted to incorporate hooking ledges (Fig. 6b). These geometries were added to the volumetric model through Boolean operations in the voxel field, as the geometric tolerances necessary to fit standardized are very precise, while their vector-based representation in the in the earlier stages of the design model (particle-spring network) influenced the equilibrium state of other features and elements of the wall, avoiding clashes and overlaps between features.

2.2.6 Fabrication, assembly, subdivision

Once the model reached a finalized result, the volumetric model was processed for manufacturing and assembly. Its subdivision introduced considerations for joining and structural support, which were resolved through a combination of plugs with inserts and continuous holes through the center of the model where physical rods could be inserted. Once finalized, the segments were individually exported in mesh format for slicing in printer software and printed commercially.

Once shipped, the *Meristem Wall* was assembled in situ at the Time Space Existence exhibition at the Biennale Architettura 2021 in Venice, Italy where it was exhibited for the 6 months (Fig. 1) (Goidea et al., 2022).

2.3 Modeling and fabrication of interior fabric surface

The textile is an example of the possibilities knitting offers in terms of custom functional integration within a single production process. The textile was modeled based on the volumetric model of the 3D printed structure and adapted to its specific geometry. The 3D knit was produced as a single piece on a 7-gauge Steiger Libra 1.130 flatbed knitting machine using PES multicolored yarns. It features channels for fixing the edges using rods, openings following the shape of the windows and lamp within the wall, varied stitch densities, ribs, and integrated straight inlays for attaching to the 3D printed structure. Four stitch densities are combined flowing seamlessly into each other and echoing the geometry and patterns of the exterior surface. Three of the four patterns use a stitch and tuck pattern

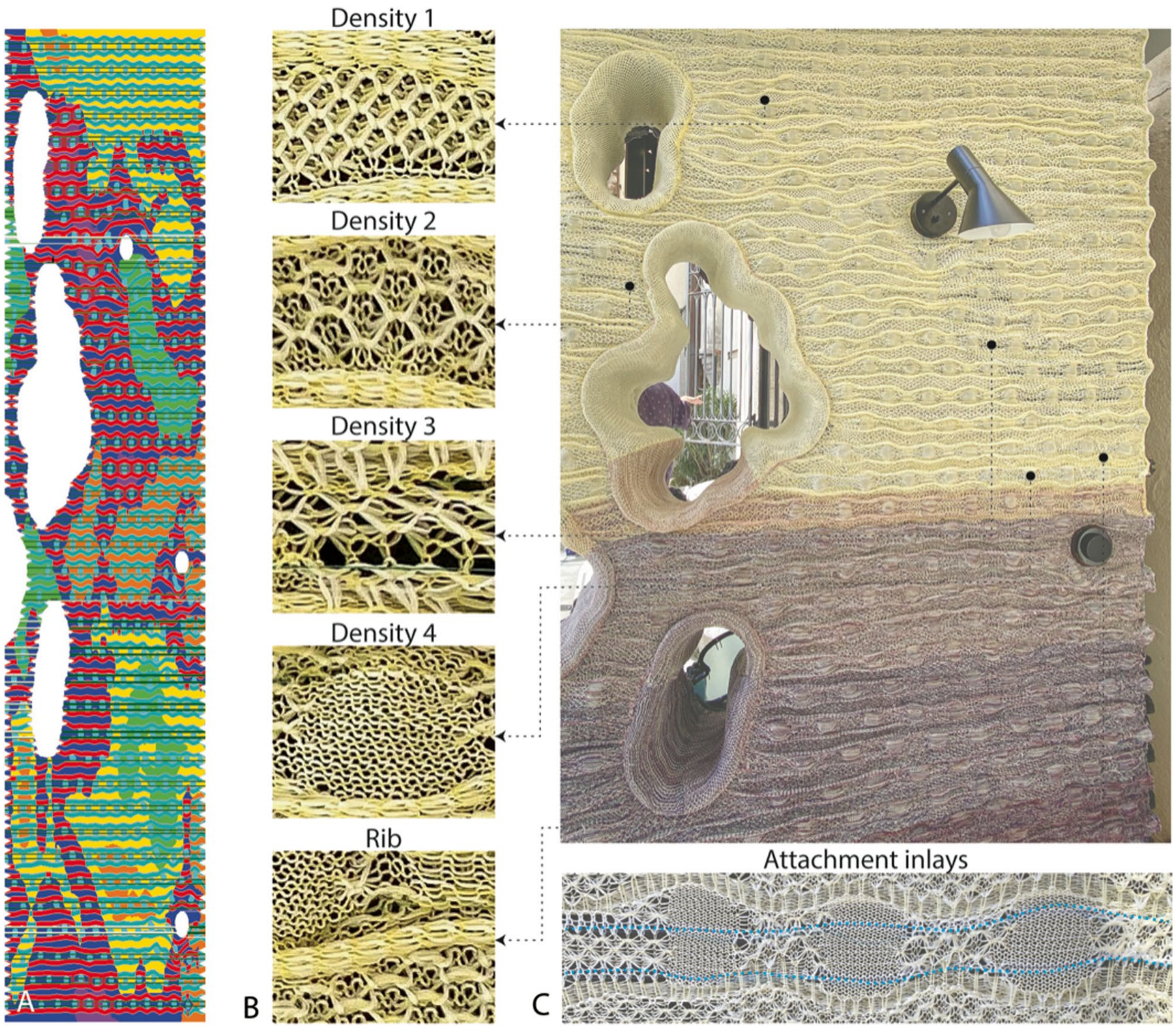

Fig. 10 Machine knitting pattern, densities, and features of the Meristem Wall

combination that helps achieve separate tightness, while the fourth is a plain knit pattern aligning with the air inlets from the transient channels (Fig. 10b), performing the role of a filter letting through air but preventing larger particles or small animals from entering the building. Their arrangement is also highlighted by varying height ribs that flow horizontally along the surface. Finally, horizontal nylon inlays aligning with the top and bottom edge of each inlet row are set within the textile during production (blue threads in Fig. 10c). These inlays locally exit the surface of the textile on the backface and are used for aligning, attaching, and tightening the textile on the wall. Figure 6b shows the section of the 3D printed attachment articulations where the inlays loop around the inlets.

For producing the textile, a CNC file is generated by importing a bitmap representation of the desired densities and features. Each color zone within the bitmap is assigned a specific combination of machine operations. An overview of the pattern color pattern as used within the machine code is given in Fig. 10a.

3 Results and Discussion

The primary goal of the Meristem Wall was to demonstrate the integration of multiple functional aspects within a 3D printed design, and to develop a design system capable of complex, functionally derived, and interdependent geometry. Part of this goal was for the functional requirements to be satisfied not through discrete components, but through a continuous articulation of the material, resulting in a functionally graded metamaterial. The geometric features associated with the different functional requirements were highly varied in their scale and nature and were not derived from a formal hierarchy. This required a design model that was able to negotiate a design space between a set of different algorithms, and where the specific algorithms and their relation to each other were not fixed but subject to change. Existing design tools address some aspects of this, but also have limitations. Parametric modelling retains the relationships between geometric features throughout the modelling process but are based on one-way linear dependencies that force a hierarchy and static relationship between the algorithms. Nonlinear design models exist, as is exemplified in e.g. form active structures (Deleuran et al., 2016), and these take into account dynamic feedback. Their limitation, that we seek to address here, is that the computational pipeline is based on a known, fixed, and uniformly defined structural simulation. Within an integrated structure like the Meristem Wall, a design pipeline needs to manage not only a uniform structural system, but an indeterminate and heterogenous mix of functional logics.

3.1 Scalar domains

One of the most crucial aspects of this differentiation of functional requirements was the variation of scale and boundary conditions for different functional features. These range from highly articulated but also localized features – such as the surface erosion for bioreceptivity (Fig. 3b) and the tolerance of electrical fittings (Fig. 4a) – to those with a low geometric complexity but large extents – such as the pipe network – that are dependent on connectivity and continuity at scales an order of magnitude larger than the demonstrator itself (Fig. 4c). The nature of a 3D printed architecture results in the potential for the inclusion of a continuum of functional elements that operate at different scales but are integrated in the same structure. We use the term transcalarity to refer to the scalar interdependence within a complex system, and while difficult to manage from a design perspective, it can lead to significant increases in performance (Goidea et al., 2022).

To address this, the project developed a dual design environment which constituted the particle-spring network on the one hand, and the volumetric model on the other. These respond to a scalar difference in requirements, where the particle-spring network easily incorporates large length scales and global connectivity, and the volumetric model allows for high resolution manipulation without global repercussions.

The particle-spring network can address simultaneously a large and variable scalar range, spanning pipe networks at scales up to tens of meters, all the way to the centimeter to millimeter scales found in the transient network. Every network in the particle spring system has its own, internally defined force balance and reach, capable of reacting to external particles as well as internal, allowing for scalar variability and efficient, self-organizing computing.

In the volumetric model, the full model space can be understood as a 3-dimensional array of points, each designated as a solid or void. This allows for a high resolution of geometric features, but the trade-off is that the global model can become incredibly large. While this can be addressed to some extent by variable voxel resolution, the main feature is that the model is defined independently for each voxel. Any value in the voxel array can be read or written without any consequence for the other values in the array, and while the total size of the database is vast, operations that read or write to the array can be locally contained and very efficient. Therefore every algorithm that operates in this design environment can interact efficiently and independently with the virtual material. However, this environment may also be altered by other algorithms acting on the same array of values. At first glance this appears to be problematic as the actions of one algorithm can be interfered with by other algorithms. However, if algorithms that act on the volumetric model do so though iterative processes that incorporate continuous reading as well as writing, it can provide a method for negotiating seemingly conflicting requirements in a manner similar to what is found in biology (Turner, 2012).

3.2 Stigmergic modelling

This model of interaction between multiple functionally driven processes (or algorithms) which takes place indirectly through a medium (digital materiality in this case) is fundamental in biological organisms, where it is termed *stigmergy*. This term is sometimes understood to have a very narrow definition, relating to the use of pheromones in social insects, but it refers more broadly to any indirect coordination between actions or agents through the environment rather than directly between the agents or actions themselves (Grassé, 1959; Marsh & Onof, 2008).

The different algorithms operating on the model space can be understood as agents operating individually on the digital environment, and their coordination is indirect through the simulated materiality of the model space. Every algorithm or agent is defined internally according to its own logic and with its own mode of sensing and manipulating the environment. The environment in this case refers to the discrete voxel-space, or in some cases the continuous space of particle-spring systems. The stigmergic mode of operation allows for the interaction of an arbitrary number of algorithms or agents in the same model, without the nature of these agents being known in advance, and it is equally possible to add new agents (and their associated functions) further down the line without adjusting previous algorithms.

In the case of the Meristem Wall, there was a sequential relationship between some of the different algorithms that were used to achieve the desired outcome, and some of the algorithms took the form of direct manipulations by the designers. We would argue that this is not a shortcoming of the overall design approach, but rather a testament of the adaptability and flexibility of the stigmergic approach. With further development, these direct manipulations can be codified as independent algorithms that can operate in a broader context than was the case for this demonstrator.

Similarly, the mostly linear relationship between the particle-spring network and the volumetric model (the particle-spring network predates the volumetric model with a mostly one-way translation between the two), and between the volumetric model and the textile generation, is not an imperative of the design model, but something that further iterations could develop to a fully parallel process with constant feedback in both directions.

3.3 Industrial application and further work

The technologies that enable the fabrication of the Meristem Wall as well as its design are not currently adapted for the construction industry, not least in terms of durability and sustainability of the materials and fabrication process. Nevertheless, they evolve quickly, with recent examples such as *Breuer X AM* (Briels et al., 2023), and are likely to represent a real possibility for use in building components in the near future. The Meristem Wall was divided into almost two dozen sub-components which was necessitated by its transport and assembly, but for a full-scale implementation it is likely that much larger components are necessary and/or beneficial. This is likely to rely on a significant implementation of robotics and automation at construction sites, capable of managing the size and precision necessary for the installation of such components.

We believe that the functional integration enabled by high-resolution additive manufacturing can generate significant added value in the built environment, and that this value is a necessary component of a sustainable business model based on 3D printing in the construction industry. A key element of this integration is the ability to, in a single monolithic component, create continuous spatial logic that ties together the component and neighboring parts of the building and environment. Lacking standardized modularization, the only way this can be resolved is through a design environment that can integrate many distinct and variable design algorithms and considerations. As is illustrated through the integration of electricity hardware in the prototype, the volumetric model provides an effective interface for junctions between a digitally standardized component and conventional hardware that relies on set geometries, and the particle bed printing process can meet the necessary resolutions.

The work presented here outlines how a design environment capable of organizing such integrated functionality may be structured, or at least under what principles it may operate. If similar systems are implemented, this would potentially lead to radical changes in the industry, not just in terms of design but within the whole value chain ranging from design, through fabrication and construction, to building management. Not least regulation and certification would be heavily impacted, and legal considerations and changes are warranted besides technological ones. Meristem wall and its design environment is not a near-market product, but an attempt to demonstrate potential, challenges, and possibly solutions for emerging 3D printing technologies in architectural design. We hope and intend that further research from both the community and our own lab will continue to explore this paradigm across multiple disciplines, academic and industrial.

4 Conclusions

The Meristem Wall demonstrates how a continuous and functionally graded building element can be made through additive fabrication from a monolithic material, and how it may interface with other building elements and components, physically and in the design phase. To take full advantage of such a structure, functions need to overlap in space, resulting in interdependencies across scale, material, and form. Furthermore, the fabricated structures should respond to their specific local and micro context, which includes not only the surroundings and building, but the structure itself.

This results in transcalar interdependencies, where functional geometries interact with each other, potentially leading to synergies and conflicts. To design such structures, design models must incorporate mechanisms for 2-way feedback, allowing for iterative and gradual conversion of design objectives. Furthermore, different functional requirements and dependencies may be expressed in fundamentally different languages or notations, preventing direct analytical optimization as an exclusive method of coordinating such functionalities.

To resolve this conundrum, we propose a design model based on principles of stigmergy modelled on the process-based functional coordination mechanisms found in biology. We conclude that a volumetric model can provide an efficient base for a multi-agent design model, using a digitally coded environment acting as an intermediate link between different agents or algorithms.

Supplementary Information

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Supplementary Material 1.

Supplementary Material 2.

Supplementary Material 3.

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Authors' contributions

Ana Goidea : Conceptualization, Methodology, Software, Investigation, Writing, Visualization. Mariana Popescu : Methodology, Writing, Visualization, Resources. Anton Tetov Johansson : Software, Investigation. David Andréen : Conceptualization, Methodology, Investigation, Writing, Visualization, Supervision, Project administration, Funding acquisition.

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Availability of data and materials

The research presented is based on specific designs and custom-built code. Some of the code is available at https://www.github.com/biodigitalmatter, but most relevant data is provided in the article itself.

Declarations

Competing interests

The authors have no competing interests to declare that are relevant to the content of this article.

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