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RESEARCH ARTICLE

Generative design for additive manufacturing using a biological development analogy

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Abstract

The transformation in manufacturing capability being driven by new processes, such as additive manufacturing, offers huge potential for product innovation and opportunity to create bespoke designs tailored to individual specifications or needs. However, current design systems and tools are not yet capable of fully capitalizing on these new technologies and new approaches are needed. Many current methodologies are top-down and sequential, offering limited flexibility and an overly constrained design space. Post-processing is needed to ensure that a design can be manufactured. This work presents a novel bottom-up methodology to generate designs that can be tightly integrated with the additive manufacturing environment and that can respond flexibly to changes in that environment. Focusing on overhang as an exemplar manufacturing constraint, the method engenders changes in the design either by locally adjusting the geometry to stay within limits or by adding an appropriate support structure. The method is bio-inspired, based on strategies observed in natural systems, particularly in biological growth and development. The design geometry is *grown* in a computer-aided design-based, bio-inspired generative design system called 'Biohaviour'. This process is similar to plant growth, and the design's final configuration, shape, and size are informed by both the manufacturing capability and internal design stresses. The approach is demonstrated for overhang limit and build orientation and is extensible to any general situation.

Keywords: generative design; design for additive manufacturing; bio-inspired design; plant development; engineering design; innovation

1. Introduction

1.1. The challenge of design for additive manufacturing (AM)

The AM field has developed at an extraordinary pace and is now used for producing mainstream production parts, as well as to manufacture bespoke products and to support the rapid realization of concept components (Thompson *et al.*, 2016). The rate of growth of AM is expected to increase. However, while it offers an abundance of advantages, it is well recognized that AM is not cost effective for every part, and that not all parts can or should be made by AM. Thomson *et al.* use the design of a manifold to show how current design approaches, which address the problem top-down, cannot fully exploit AM. This is because the

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top-down approach is reductionist, gradually breaking the problem down into smaller segments until each is tractable, but in doing so introduces constraints that then often prevent alternative manufacturing solutions from being used. The understanding of when and where to use technologies such as AM in designing a product remains immature, and design for AM is only in its formative stage. According to Thomson *et al.*, bottom-up thinking, i.e. building the concept in steps, produces a solution much more suited to AM than the typical top-down approach.

This issue is not unique to AM, rather it reflects the general difficulty in achieving full integration of design and manufacturing models and processes. Fundamentally, the goal is to maintain design intent so that the operational product functions in service as intended from the outset (Price *et al.*, 2013). Achieving this requires a systematic approach to modelling and parametrization of the design. However, this is not easy. If the parametrization is too flexible, then the design may be difficult to manufacture, and it may not be possible to ever converge on a solution. If it is too inflexible, then the design may not account for the versatility of the manufacturing process, meaning that the resulting product has increased cost and suboptimal performance. Further, when the parametrization is then applied to a B-rep computer-aided design (CAD) model, as the standard form of geometry representation in all mainstream CAD packages, it is difficult to grasp how to relate the way the shape can be updated to integrate with any manufacturing system. In recognizing this, Price *et al.* (2013) recommended that the parametrization of the geometric model is tailored to the capability of the manufacturing process to ensure there is a set of parameters available in the design model that represent the manufacturing process.

1.2. Methods supporting design innovation

Mass production of consumer products (such as smart phones and white goods) and the development of complex systems (such as aircraft) have become common place, with a corresponding need for better design and manufacturing systems to ensure continued innovation and improvement. The diversity and sheer number of products have resulted in a corresponding range of design systems and frameworks, allowing rapid and consistent product development. In large corporations, the design process for complex products is exemplified by the system engineering process (NASA, 1995), which is an overarching top-down framework that utilizes technology such as CAD systems and simulation tools at various stages in the design development. In recent years, these tools have advanced the capability and speed of design exploration at the concept stage. Leading examples of these include TRIZ (Altshuller, 2005), set-based design (Ström *et al.*, 2016), axiomatic design (Su, 1990), and generative design systems (Krish, 2011).

Generative design (Krish, 2011) is emerging as a highly functional tool for rapidly generating design concepts and generating geometric representations of those concepts. It can be used to generate many solutions that meet the key design constraints, offering the designer a much larger range of options to choose from. Several commercial generative design systems (e.g. Fusion 360 AutoGen, CATIA xGenerative Design, and nTopology) have appeared and provide impressive functionality for generating concepts and geometry representations. Coupled with L system technology, this has recently been used to generate exciting support structures for AM components (Zhang *et al.*, 2020) that can reduce material usage. Recent practical applications of topology optimization include additive manufacture of composite structures (Goh *et al.*, 2021) and the design of heat exchangers (Haertel & Nellis, 2017). Generative design has much potential but is not without challenges. Zhang *et al.* (2020) note challenges with computational cost and the need for post-processing at various steps in the process.

Examples of generative design technology include Shape/Spatial grammars (Stiny, 1976; McKay *et al.*, 2012), where a rule-based approach is used to generate a 'language' of designs, and topology optimization (Bendsoe, 2004) that optimizes the material layout within a given space. Both produce organic looking structures, although while shape grammars are usually defined based on operators on shape primitives, topology optimization is based on simulation technology. One limitation of topology optimization is that it is largely confined to structural problems and is unsuitable for complex multidisciplinary challenges. Also, as the method works by removing elements from the domain, the resulting geometry is not a traditional B-rep, and so requires post-processing to be converted to a format more suited for use later in the design process. This issue also hampers shape grammar approaches.

In practice, a combination of these powerful tools is often used to more fully explore the design space and derive enough information to progress with the design, and to support decision making at various stages in the design process. More generally however, none of these approaches fundamentally change how design is executed. Most are focused on enabling the exploration of designs at the concept phase with manufacturing planning and execution as a separate activity. The major question remains as to how to go beyond the concept phase, with a toolset flexible enough to allow wide exploration at the beginning and be capable of adapting and embedding detail as the design progresses.

1.3. Problem summary

The preceding two sections each identifies two major issues that guide potential solutions, namely:

1. Bottom-up thinking, building the concept in steps, produces a solution much more suited to AM.
2. The parametrization of the geometric model should be tailored to the capability of the manufacturing process.
3. Generative design systems have much potential for developing bottom-up solutions.
4. The geometry of the design needs to be usable at all stages of design without significant post-processing and which can adapt and embed detail as the design progresses.

This work proposes an approach that addresses these questions by using bio-inspired metaphors to create a bottom-up generative design system that has its parameters more tightly integrated with the manufacturing environment.

2. Bottom-Up Generative Design

Bottom-up approaches take a building block approach where systems or solutions are assembled to allow the required functionality or solution to emerge. Each building block is studied in detail and notably takes account of all the relevant voices for that building block without constraints having been proposed from above, allowing a focus on the capability and knowledge available to the design team at any given point in the process. In the case of design for manufacturing, this implies that the manufacturing process capability is accounted for from concept

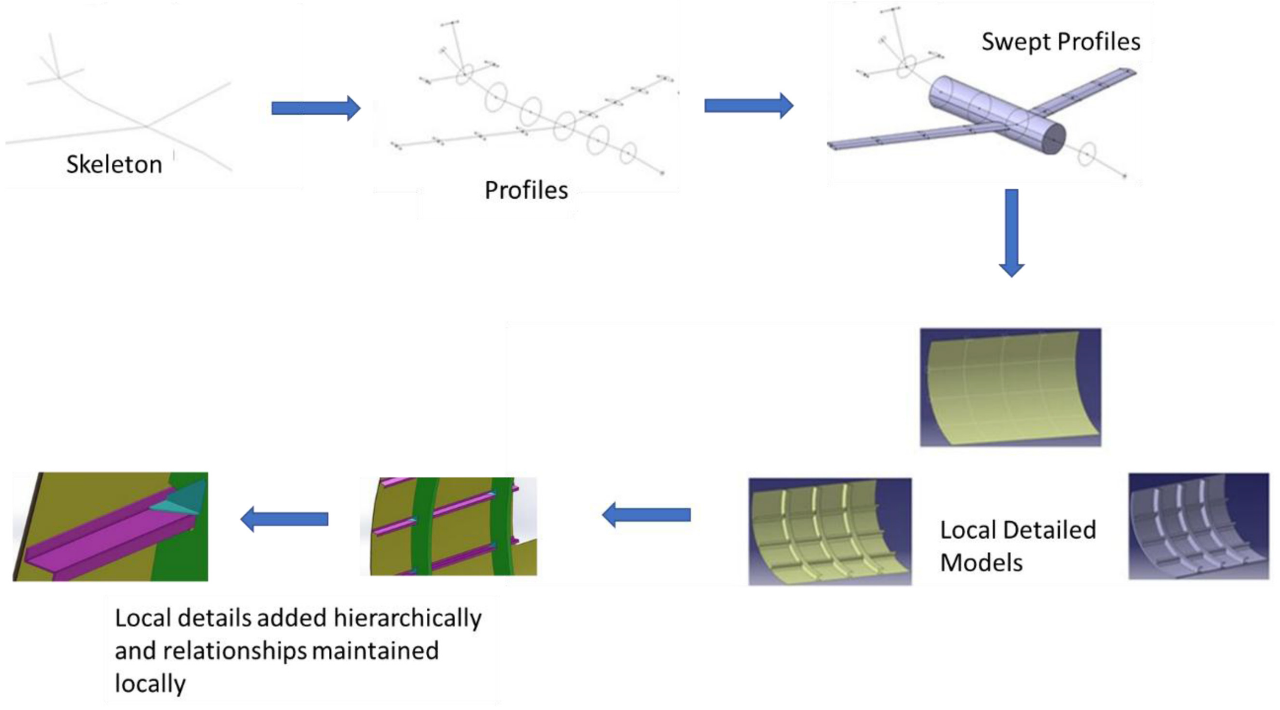


Figure 1: DADI can generate complex CAD models helping to maintain relationships between parameters and sub-structures.

development on, rather than once the concept is well defined. One critical advantage of this approach is that design parameters influencing, or influenced by, the manufacturing process are visible from the start and can play an active part in the formation of the solution. This mitigates against the issue highlighted in maintaining design intent right through to manufacture (Price *et al.*, 2013). In practical terms, the set of parameters describing the design is gradually expanded as knowledge of the design grows and this is particularly suited to a generative approach, with the geometry of the product for manufacture tightly integrated.

2.1. Dimensional addition and detail insertion

Whereas traditional approaches to using geometry models for simulation start with a fully featured CAD model and break it down into features for analysis (Robinson *et al.*, 2006), often represented by elements of reduced dimension (Nolan *et al.*, 2014) the concept of ‘dimensional addition and detail insertion’ (DADI) has shown how a CAD model can accommodate an evolving design and enable robust linkage between the simulation models representing a design (Price *et al.*, 2006). In this, the CAD and simulation representations are automatically generated from lower dimensional entities (e.g. sweeping points to generate lines, which can be swept to generate surfaces and similarly then surfaces to solids) and the parametrization expanded to provide better resolution at each step, with parametric relationships naturally evolving and remaining consistent as the design develops (Robinson *et al.*, 2006). A number of different approaches that demonstrate the DADI philosophy exist (Nolan *et al.*, 2015; Agarwal *et al.*, 2019), with applications on sophisticated assembly and simulation models (Fig. 1).

DADI provides the mechanism to reverse the traditional process by modelling the transition from the lines and surfaces, as the underlying skeleton, eventually creating the solid bodies. These mechanisms exploit simple geometric operators such as extrudes, sweeps, and thickenings that are themselves analogues for growth.

Creating a design model by adding dimensions and then layering on detail can be analogous to the natural world of plant systems. For example, the underlying structures of a tree and an aircraft can be idealized using the same assumptions such as aspect ratio, where elements that are very long and thin (e.g. a branch or a beam stiffener) are idealized as beams or where wide areas that are very thin (such as leaves or aircraft skin) are idealized as plates or shells.

2.2. Bio-inspired analogies

Fu *et al.* (2014) provide a comprehensive review of bio-inspired design (BID) systems and document key findings and contributions. The review highlights that the fields of bionics, biomimetics, and BID have resulted in many successful products and systems and importantly have enormous potential to transform how design is conducted today. Two basic questions raised relate to visualization, simulation, and manufacturing:

1. How could BID methods assist designers in attempting to perform the steps beyond concept generation?
2. How could BID methods be enhanced, expanded, or integrated with modelling approaches, visualization, simulation, experimentation, and production processes?

Building on the DADI capability as shown in Fig. 1, highly detailed geometry is possible and in combination with a bio-inspired growth analogy (e.g. plant development) this geometry can be continually informed by its manufacturing process to ensure what is generated can be made.

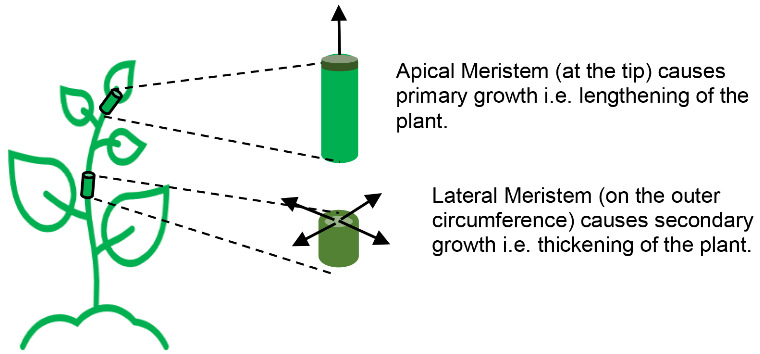


Figure 2: Primary and secondary growth mechanisms in plants. Longitudinal growth drives from the apical meristem at the stem tip, while thickening comes from the lateral meristem around the circumference of the stem.

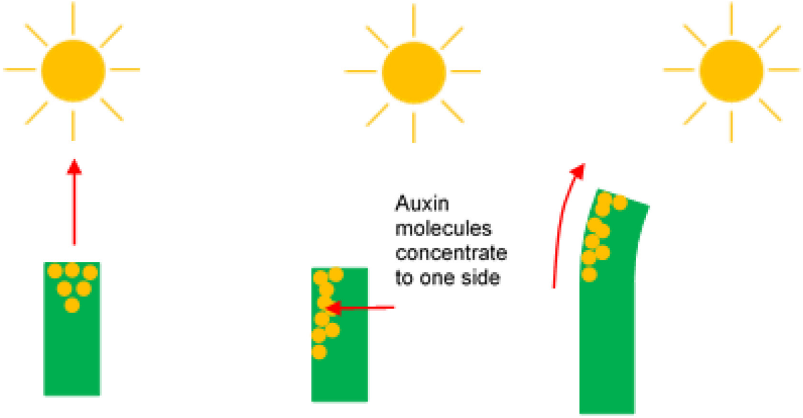


Figure 3: Phototropism caused by the accumulation of auxin on shaded side of plant resulting in more elongation on that side and hence the stem bends.

3. Plant Development Metaphors for Bottom-Up Design

3.1. Metaphors in development processes

Plant development provides an excellent metaphor complementing the DADI paradigm. The detailed mechanisms in plant development are extremely complex and still a subject of research, but the general principles are sufficiently simple to extract ideas and processes from.

Meristems are cells in the plant that divide. The meristem enables the plant to grow in two major ways: primary growth and secondary growth. Primary growth (lengthening of the main shoot) occurs at the apical meristem. Secondary growth (widening) occurs at the lateral meristem (Fig. 2). Primary growth is a metaphor for geometric shape, and secondary growth is a metaphor for geometric sizing. All growth is controlled by a plant hormone called auxin. Concentrations of auxin encourage cell growth and typically where there is more auxin there is more growth. Leyser (1998) sums up plant hormone as being comparable to animal nervous systems 'that collect information from a variety of sources, process it, and direct appropriate responses'.

The distribution and concentration of auxin are affected by environmental stimuli, including gravity, light, moisture, and touch. These cause responses in the plant's development referred to as geotropism, phototropism, hydrotropism, and thigmotropism, respectively. In phototropism, the plant bends towards the light. This happens because the side of the plant with less light has more auxin and therefore the cells grow and divide more, causing that side of the plant to be longer than the other (Fig. 3).

At a more fundamental level, the plant's genes determine all its characteristics. This ranges from simple expressions such as flower colour to controlling cell types and their resulting shape or form. In nature, visible traits are normally a complex combination of these underlying genes. They control the formation of the structures inside a cell and hence directly influence the response of a cell to any changes in the system. The final form, or phenotype, of a plant is therefore determined by these three key concepts: development, hormones, and genes.

This general description of the metaphor now needs to be translated into the geometric modelling domain to explore how it can form the core of a design system.

3.2. Metaphors in data and representations of form

There are capabilities in geometric modelling systems that have strong alignment with the plant development metaphors embedded within the CAD concepts of cellular modelling (Bidarra *et al.*, 1998, 2005). Use of this more specialised capability of CAD systems is more prevalent for mainstream engineering in simulation technology (e.g. finite element analysis), but the key functionality to enable it is available in the geometry kernels of most CAD systems (e.g. ACIS). In most mainstream mechanical CAD systems (Dassault Systemes, 2013a, b; Siemens, 2020), each body has its own topological definition (usually defined around the B-rep) and is defined to be manufactured as a separate component. However, as simulation capability improved and as ambitions outweighed the computational resources available, the simulation communities' needs developed around having bodies of different dimensions connected to each other, e.g. connected beam, shell, and solid regions (Thakur *et al.*, 2009; Nolan *et al.*, 2015). Such non-manifold representations (i.e. where a face can bound more or less than one body or an edge can bound more or less than two faces) required different data structures and consequently new representations emerged (Weiler, 1986, 1988), driven by the need to integrate CAD and computer-aided engineering (CAE) systems.

Cellular modelling emerged from this as an alternative approach in geometric modelling for analysis, where spatial subregions are represented as individual bodies, rather than having a single body to represent the whole. In this, space is partitioned into 'cells' that have individual significance for the geometry or simulation. The representation is non-manifold and the ambition is that cells should represent all of the different solid, fluid, or even void regions of space.

Together, cellular modelling and non-manifold representations provide a powerful paradigm to enable plant-growth metaphors in engineering design. Cellular modelling provides an analogue to the fact that a single plant is composed of many sub-cells, each with their own significance in the life of the plant. This leads to the requirement for understanding the equivalence between the different representations of a design, and the different decompositions within it, whether they indicate a change of material or function in the design. The biological analogy is the ability to view the plant as being equivalent to the superset of the roots, the stems, the branches, the leaves, and the flowers, with each cell having further decompositions possible (viewing a simple leaf demonstrates a complex biological entity with multiple materials and functions).

Non-manifold modelling provides the analogue to the fact that while the cells in a plant are all separate entities, they are all connected, and so when a plant moves in the wind it moves as a whole. Also, nutrients and chemical messages pass from cell to cell because each cell is attached to the cells beside it. In the design process, non-manifold modelling ensures that the connectivity of the cells in the geometry model is known and provides a means to ensure that design edits in one cell can be propagated throughout the structure. This is a key element of a bottom-up design process. Having a geometry modeller that manages the proximity of the entities in the design, as opposed to relying on the designer to supply such information, is essential for generative design processes where the emergence of interfaces between cells needs to be free rather than constrained.

Geometric parameters are an excellent metaphor for cell genes as the low-level entities that dictate the final form of the geometry. The notion of genes to represent a cell is not new. Gero (2017), Gero and Ding (1997), and Gero and Sarkar (2006) proposed the use of gene representations in architectural design and showed how characteristics of typical architectures could be incorporated into design systems and new design created using generative systems. Gero's fundamental elements were already grouped into sets, referred to as plans, so particular facades could be extracted, and they were able to show architectural styles emerging and complex facades generated from populations of alternative designs. The semantics supporting model generation revolved around spatial location and orientation of the plans and did not include complex multiple representations for simulation or interaction with the surrounding environment.

Sophisticated functionality has grown around cellular modelling, particularly in the simulation world, which supports capability to automate many analysis tasks and enabling a tight link between CAD and CAE systems. Enquiries can be made of the cell data and the parameters relevant for a particular simulation type returned. Nolan *et al.* (2015) illustrate this concept with a cylinder and show how the analysis model and geometric parameters are linked. Additionally, it is shown that the inherent presence of cell interface information enables the automated creation of simulation models where manual pre-processing is traditionally required.

Therefore, cellular modelling and associated parameters provide the basis for the first two metaphors as noted in the previous section, and Gero's early work has demonstrated that the metaphor for genes can work in a design scenario. The remaining element is how such models can interact with an external environment to influence design development.

3.3. Metaphors in interaction with the environment

As noted in Section 3.1, plant development is influenced by external factors such as pressure, heat, light, and gravity. These external factors cause internal physical responses in the plant cells, resulting in growth. In engineering terms, these are analogous to the operational or in-service conditions. These are typically applied when preparing a CAD model for simulation. For example, a wind load is studied through applying a pressure to the component and the stresses resulting will inform the design choices for size and material. In this sense, the designer represents the environment and interacts with the product via simulation models, by imposing loads and constraints as necessary to represent the in-service conditions. Similarly, in terms of the manufacturing environment, engineers interact with the CAD/computer-aided manufacturing models through features and parameters to affect changes as needed to ensure manufacturability.

In plant development, the separate external environmental issues are aggregated and influence growth through hormones, as noted previously. In the engineering design domain, this metaphor has not yet been extensively explored, but recently Wilson *et al.* (2019) demonstrated the viability of using a virtual hormone system to control swarm behaviour in robots. In this, a collection of virtual hormones aggregated behaviour to respond to changes in the surrounding environment.

4. The Biohaviour System

The analogies described earlier provide the key elements needed in a CAD/CAE-based system for design. Building from a geometric 'cell', the concepts in cellular modelling allow for parameters to be used as representations of design characteristics and hormones to co-ordinate external influences on the geometric cell. This is enabled by the fact that the interfaces between cells are known in a non-manifold model and are considered cells themselves. In this section, the system, its data structures, and operation are explained. The system is based around the rudiments of the plant development process.

4.1. Data structures

The fundamental component of the Biohaviour system is a 'cell'. Cells divide and grow with the resulting collection called an organism, and the final form of this organism is the design output from the system. All cells contain the same data structures: geometry, genome, hormone, and sensors.

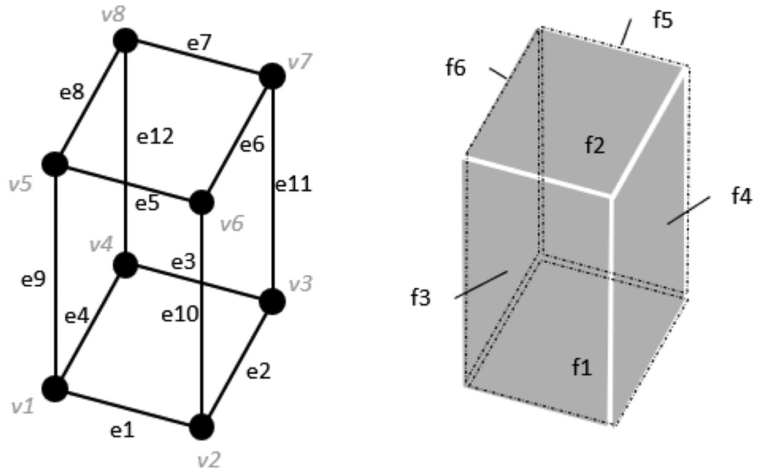
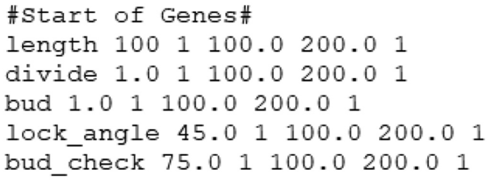


Figure 4: Cell geometry structure showing vertices (v), edges (e), and faces (f) of a cell of square cross-section.



```
#Start of Genes#
length 100 1 100.0 200.0 1
divide 1.0 1 100.0 200.0 1
bud 1.0 1 100.0 200.0 1
lock_angle 45.0 1 100.0 200.0 1
bud_check 75.0 1 100.0 200.0 1
```

Figure 5: Sample genome showing gene structure.

4.1.1. *Geometry*

The geometry data structure holds information on the shape and form of the cell, namely how it appears in 3D space. While the generic definition of a cell in a cellular model is simply a representation of a region of 3D space, the DADI approach allows a more typical B-rep structure of faces, edges, and vertices, Fig. 4, providing an effective implementation format that is easily encoded and can link directly with a commercial CAD system.

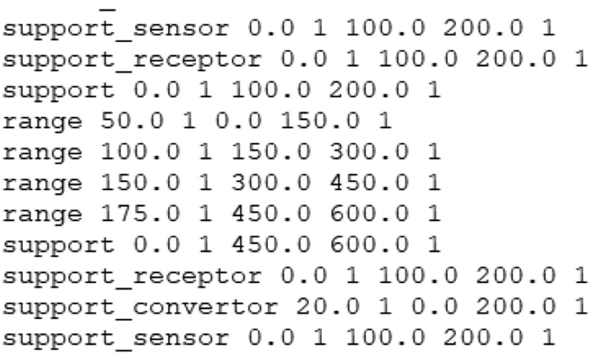
4.1.2. *Genome*

The genome structure (genotype) contains all the parameters that define the shape and form of the cell. Zhang *et al*. (2020) introduce the concept of the design gene and genome in this system and the principles under which they operate. A design gene dictates how the cell will express a given characteristic, which in this case includes typical design characteristics such as size, shape, material type, or failure stress. The gene is structured as an array of six elements.

$$\text{Gene}: [\text{attribute}, \text{delta}, \text{activestatus}, \text{start}, \text{stop}, \text{priority}]$$

Attribute is the characteristic represented by the gene, delta is the value that the attribute may change by in the presence of hormone, active controls whether the gene will be expressed (active) or not (dormant), start and stop are the lower and upper hormone levels, respectively, at which the gene is expressed, and priority is the priority of one gene over another with the same attribute.

A sample of genome is shown in Figs 5 and 6. In circumstances where complex characteristics require more than one gene to accurately represent them (e.g. cell sensors; see Section 4.1.4), non-coding genes (ncGenes) are used to bound regions of the genotype that should be grouped together as illustrated in Fig. 6.



```
support_sensor 0.0 1 100.0 200.0 1
support_receptor 0.0 1 100.0 200.0 1
support 0.0 1 100.0 200.0 1
range 50.0 1 0.0 150.0 1
range 100.0 1 150.0 300.0 1
range 150.0 1 300.0 450.0 1
range 175.0 1 450.0 600.0 1
support 0.0 1 450.0 600.0 1
support_receptor 0.0 1 100.0 200.0 1
support_convertor 20.0 1 0.0 200.0 1
support_sensor 0.0 1 100.0 200.0 1
```

Figure 6: Example of ncGene for sensors.

4.1.3. *Hormone*

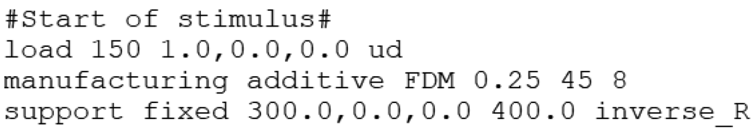
The hormone data structure holds the data that determine the expression of a certain gene. For example, the delta value of the gene is multiplied by the concentration of hormone to determine the actual magnitude (delta) of the change of length (attribute) of a cell. For these purposes, it is a real number that excites the gene into action if it is within the lower and upper bounds as defined by the start and stop conditions for the gene.

4.1.4. *Sensors*

Sensors are the interface between the cell and the environment that convert the external stimulus into development change. The sensors have two components, namely a receptor and a convertor. The receptor scans the environment for a complementary stimulus and when it identifies one it sends a message to the converter that generates a hormone concentration for the cell to use in development, e.g. to grow in length. Both components are controlled by ncGenes, Fig. 6, which allow the organisms to have different sensitivities and different responses to a given stimulus in the environment.

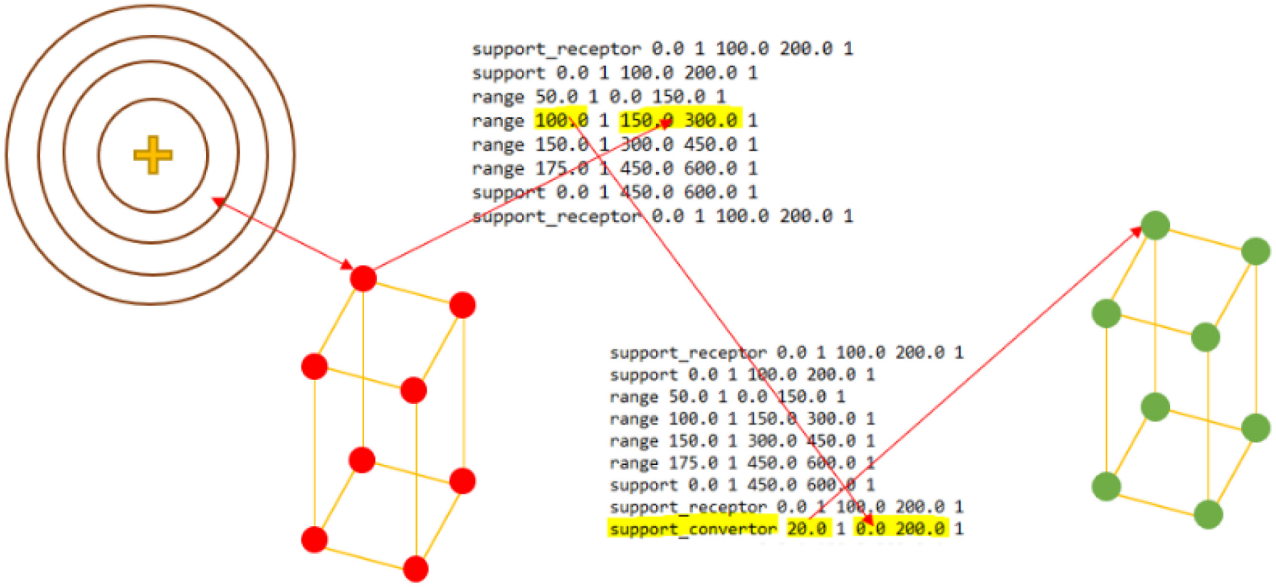
4.2. Environment

The environment represents everything outside the organism that influences its development. The primary response in plants is observed in the various tropisms that display gross changes in shape or form. These gross changes in turn influence internal



```
#Start of stimulus#
load 150 1.0,0.0,0.0 ud
manufacturing additive FDM 0.25 45 8
support fixed 300.0,0.0,0.0 400.0 inverse_R
```

Figure 7: Examples of environment stimuli.



```
support_receptor 0.0 1 100.0 200.0 1
support 0.0 1 100.0 200.0 1
range 50.0 1 0.0 150.0 1
range 100.0 1 150.0 300.0 1
range 150.0 1 300.0 450.0 1
range 175.0 1 450.0 600.0 1
support 0.0 1 450.0 600.0 1
support_receptor 0.0 1 100.0 200.0 1
```

```
support_receptor 0.0 1 100.0 200.0 1
support 0.0 1 100.0 200.0 1
range 50.0 1 0.0 150.0 1
range 100.0 1 150.0 300.0 1
range 150.0 1 300.0 450.0 1
range 175.0 1 450.0 600.0 1
support 0.0 1 450.0 600.0 1
support_receptor 0.0 1 100.0 200.0 1
support_convertor 20.0 1 0.0 200.0 1
```

Figure 8: Sensor action showing receptors (red) read proximity data and the convertor (green) response.

states such as stress or temperature. These secondary effects cause local changes in shape or form as needed. This provides a neat metaphor for the engineering environment. In this context 'Primary Stimuli' are those that directly influence the overall shape and form of the organism, such as target attractors, repellers or exclusion zones in the 'space' of the developing organism, or manufacturing processes such as additive or subtractive, with their specific constraints. Traditional boundary conditions such as loads and constraints can be represented as 'Secondary Stimuli' invoking changes in the internal state of the organism, the magnitude of which can be determined through simulation and analysis.

Stimuli are represented in a similar format to design genes (Fig. 5), with parameters that identify and define characteristics within the system, although the parameter types are not specific and can vary for each stimulus type. For example, in Fig. 7, a load stimulus has a magnitude, direction, and type, whereas a manufacturing stimulus has a type, such as additive, a specific process type with relevant constraints such as wall thickness, overhang limit, and maximum aspect ratio. Parametrization of the stimuli allows definition of multiple different stimulus types in the same environment, with their complementary sensors defined by ncGenes, Fig. 6, meaning that the organism can interact with each stimulus resulting in an aggregated effect on the organism.

4.3. Organism–environment interaction

Development functionality is embedded in the system to allow the organism cells to interact and respond to the environment, as it is this that triggers and controls organism development. The mechanism for this interaction is through triggers from stimuli in the environment. Figure 8 shows a schematic of this functionality. Each attractor support has a field strength represented by a function such as an inverse-r relationship. Each cell vertex, Fig. 4, has a suite of sensors, with the complementary sensor using its receptor to locate the stimulus in the environment deriving the field strength at the sensor location. The converter then uses this field strength value to release a corresponding level of hormone that the cell will use for growth at that location in the cell. A response is performed for each of the complementary sensor-stimuli at the cell vertices, whether related to growth or any appropriate attribute. In effect, this process is converting multiple inputs of different types into geometry and local attribute changes. In some circumstances, the stimulus may trigger a rule-based response explicitly defined in the system based on pre-requisite knowledge, e.g. in the case of manufacturing-based constraints or rules that may directly or indirectly affect the organism's geometry. An example of this is included in Section 6.

5. The Development Process

In this initial implementation, development is limited to branching plant-like structures; however, the process is completely general and can apply to shell or solid structures. In branching structures, cells are long and thin and grow along their main axis as the primary growth direction, with secondary growth in response to stresses tending to increase their cross-section. In these structures, two main types of activity occur. The first is cell growth where the cell gets longer and/or thicker. The sec-

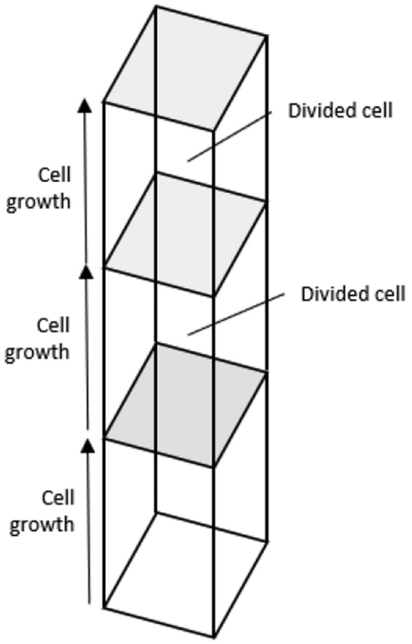


Figure 9: Primary growth by cell growth and cell division.

ond is cell division. Cell division occurs in two forms. One is the creation of a new cell at the apical meristem location, Fig. 2, i.e. driving growth in the primary direction. The second is the creation of a lateral bud cell on the long faces of the cell to grow in a direction different to the primary direction.

5.1. Primary growth

In the system, the first cell, a ‘seedling’, will grow along its face normal, from its starting point, ‘seed location’, based on an initial growth direction variable used to set the orientation of the system. Cells grow by converting hormone into a movement of the cell vertices to change the volume and shape of the cell. Cell division creates new cells that grow, resulting in an overall change in the organism, Fig. 9.

The growth process works in a loop as shown in Fig. 10. The organism interacts with the environment stimuli, through its sensors, to aggregate their effects through hormonal responses in each cell.

This hormonal change affects the expression of the gene attributes, Fig. 5, causing geometric changes in the cell at each vertex. Each vertex moves independently of the others, allowing unconstrained shape development. At any point in time, each vertex location is defined by the series of transformations it has undergone from the creation of the cell.

5.2. Cell division

In mimicking plant development at a macro-scale, the concept of the apical meristem is a useful guide. In plants, this region is at the tip of the plant and it is here that primary growth occurs rather than in parts further away from the tip, where secondary growth mainly occurs. This can be reflected in the system by the creation of a cell at the end of the parent cell, Fig. 11, with the child cell inheriting its parent’s genome. This cell will originally have two end faces that are coincident and therefore have no volume, but will grow rapidly. Practically, this involves the creation of (i) n vertices, where n is the number of edges bounding the face at the tip, with each vertex corresponding to and located at the same position as the vertices bounding the edges of that face, (ii) $2n$ new edges. There will be one duplicate of each of the edges bounding the tip face, and one edge between each vertex of the tip face, and the new vertex at the same position, and (iii) $n + 1$ new faces. One face will have the same geometry and topology as the tip face, and n faces represent the cell’s side faces.

The new volume cell will be bound by the faces created in step 3. While the original cell will have no volume as its end bounding faces are coincident, this cell can now grow using the same mechanism as described in Section 6.1. There are many options for how division can occur, but this is an expedient starting point.

5.3. Branching

More complex structures can be created by branching. In this process, a bud (which is a starting branch) is created on the centre of a face in a cell. Like the new cell created at the meristem, the bud cell is a volume cell, which will initially have no volume but can then grow in subsequent steps in the same way as every cell grows, Fig. 12a. Growth in the branches occurs in the same manner as that described for the main cells, through the application of transformations to the positions of the vertices defining its end face. Buds are triggered if the developing organism is passing an attractor stimulus and the main growth direction is such that it will move past the stimulus. A bud therefore would create growth that can head towards that stimulus, Fig. 12b.

6. Examples and Demonstration

6.1. Beam geometry in-plane in various environments

Figure 13 shows simple examples demonstrating the key functionality of the system. All organisms begin growth in the positive z direction. From top left, (a) an organism developed to a single attractor directly above the seed – primary growth, (b) an organism developed to an off-centre attractor target due to hormone distribution in the vertices from the sensor-based organism–environment interaction, representative of the analogy made with phototropism in plants, Fig. 3, (c) an organism developed to an attractor target in the presence of a repeller causing more pronounced curvature of the organism due to an increased hormonal response at the vertices, aggregated from both stimuli, (d) a multi-attractor target environment where the organism traverses the space based on proximity to and strength of the targets using its sensors, (e) an organism developing by constant directional changes between field ranges in a mixed multitarget environment, and (f) an organism developing infinitely in the presence of two equally spaced attractors of equal strength resulting in no curvature. Note that for this demonstration branching has been turned off.

6.2. Functional geometries

Figure 14 demonstrates branched organisms. In scenarios such as that in Fig. 13f, an organism with genetic information to trigger budding will ensure that attractor targets are reached. Depending on this genetic information, the bud may appear before (a) or after (b) the organism has passed the target’s location and will happen in the presence of multiple targets as it develops (c).

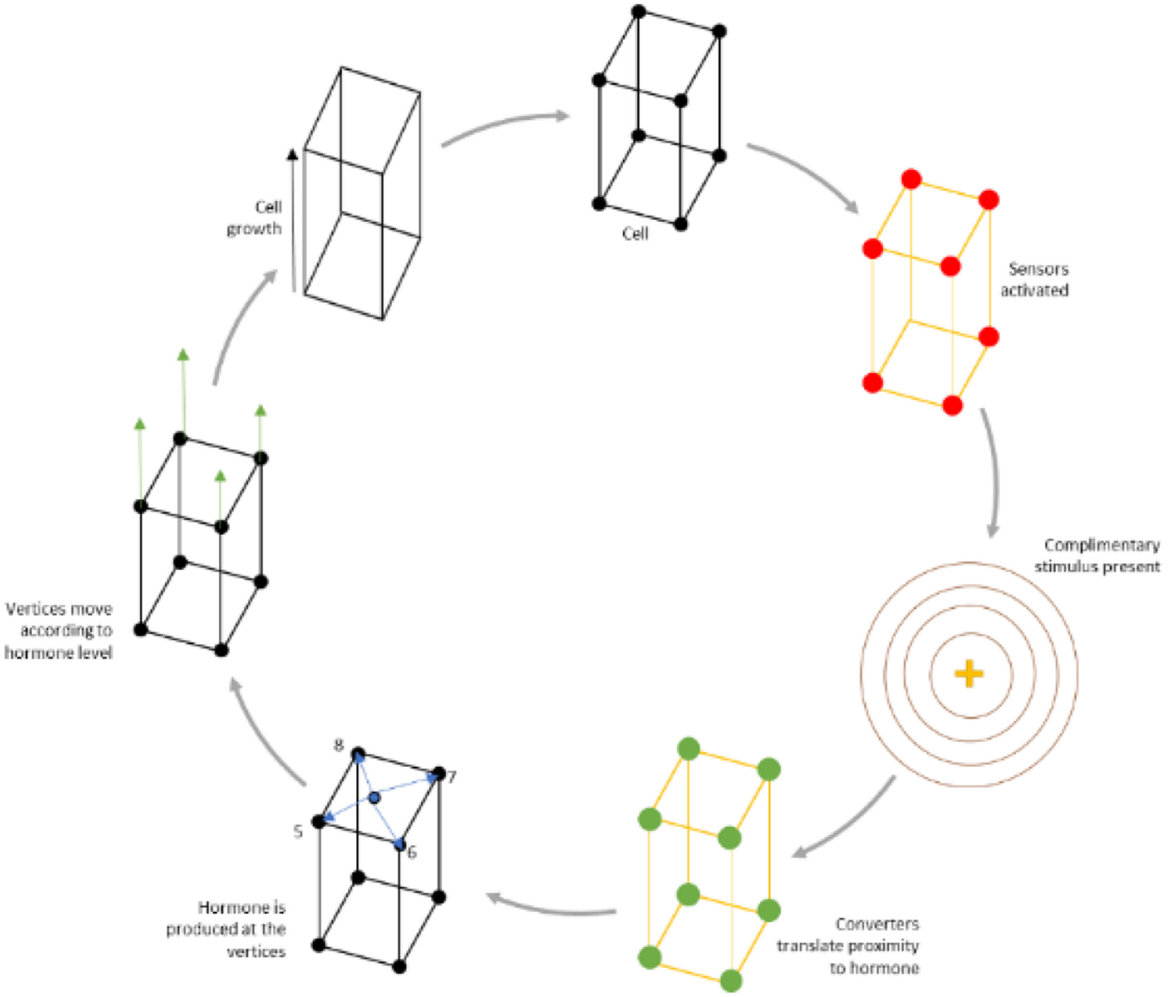


Figure 10: Process of cell growth by sensor activation and hormone response.

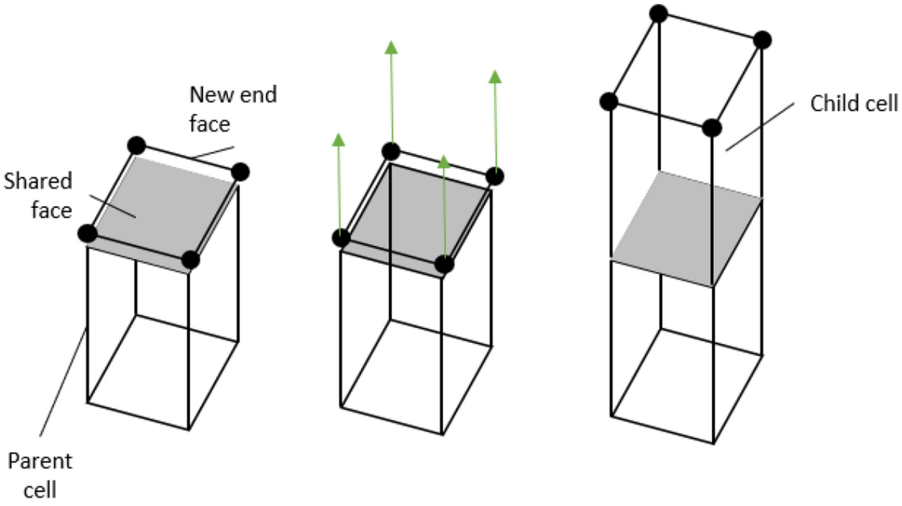


Figure 11: Cell division creating a child cell from a parent cell with a shared face.

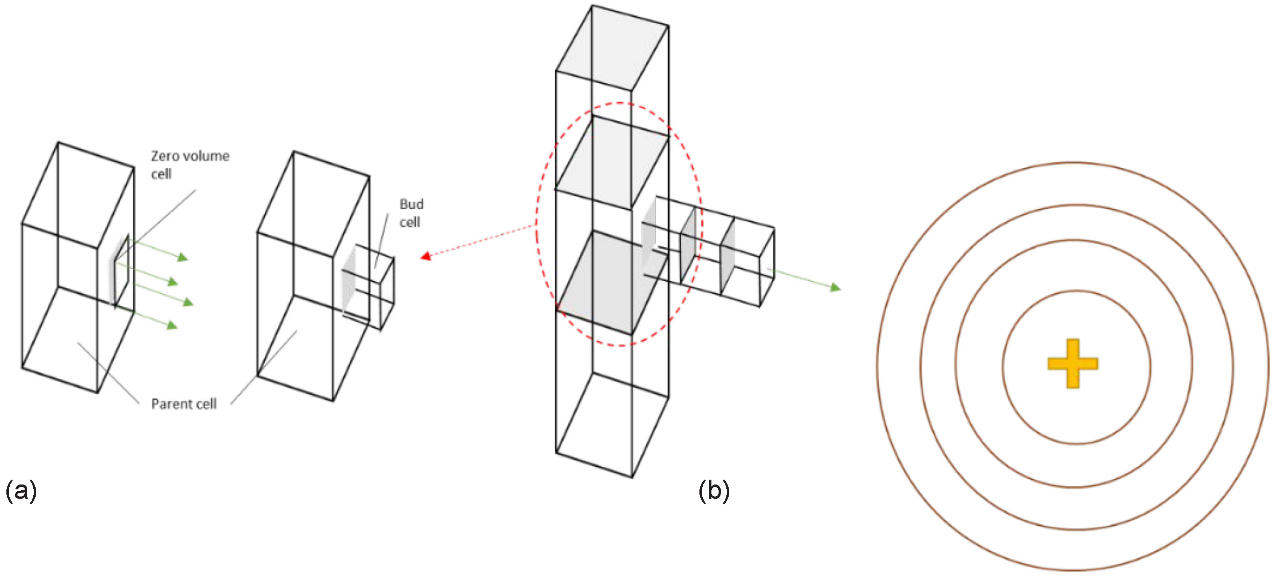


Figure 12: (a) Bud cell creation from a parent cell. (b) A bud cell triggered and developing towards an attractor stimulus.

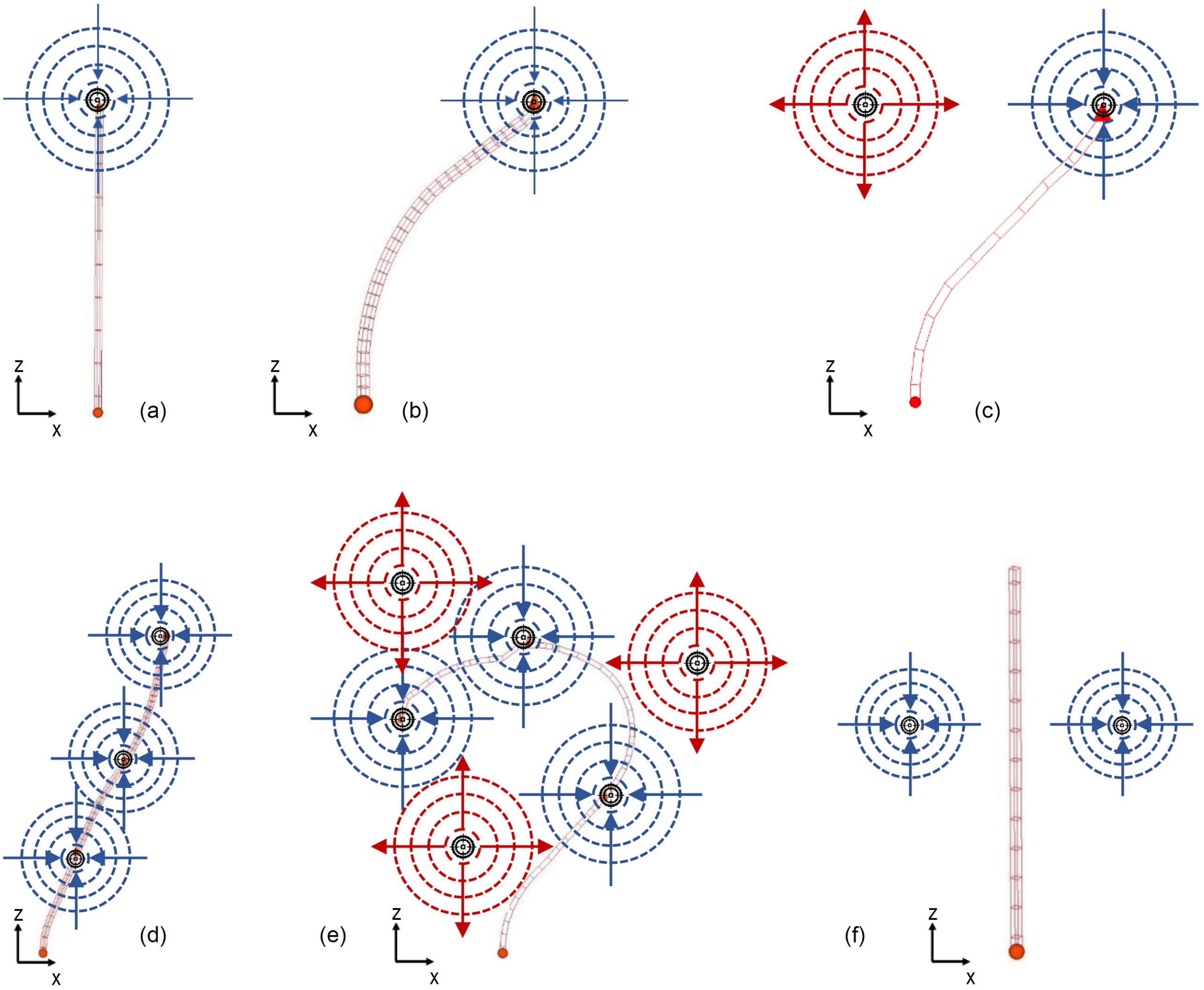


Figure 13: Demonstrations of organism development in different environments.

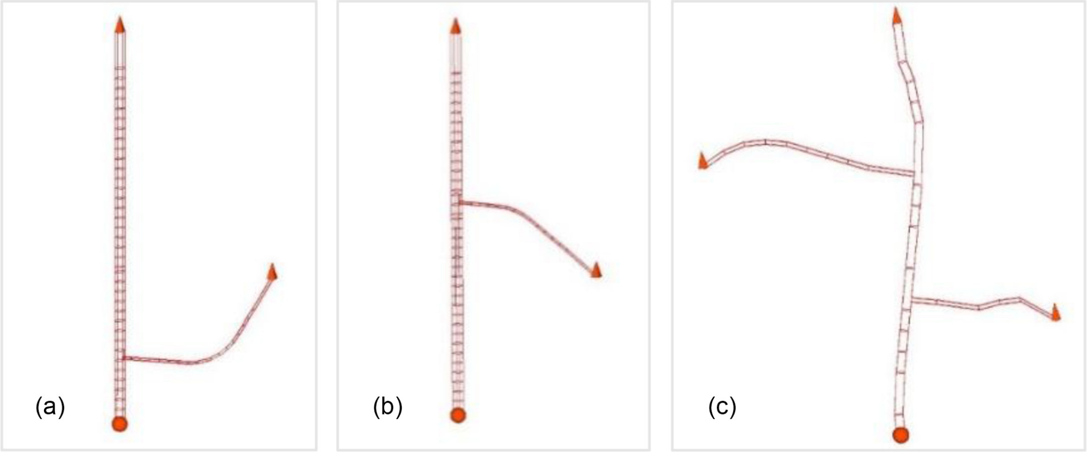


Figure 14: Developing organism branching towards different target stimuli.

Figure 15 demonstrates the development of an organism in an environment that includes stress analysis. The analysis is set up on the organism (a) from the environment stimuli, load (pink) and support types (blue), visualized on the FE model in (b) and the organism's genome (material data). The organism–environment interaction via sensors means that the stress results in each cell (c) directly affect the geometry in the next development step, secondary growth, Section 5.

The mechanism of secondary growth involves the distribution of strain energy density (SED), Fig. 15c, across the organism triggering a hormonal response via complementary sensors at each cell vertex, which convert the SED results to a vertex displacement relative to the magnitude of SED near it. In areas of high SED (red/orange elements), a displacement of the vertices results in an increase in the 'depth' of the organism relative to the loading direction, *x*, Fig. 15b. The resulting geometry change can be seen in Fig. 16, a superimposed image of two organisms, one that has not experienced secondary growth (black wireframe) and one that has (red wireframe).

6.3. Designing for additive manufacturing

This example demonstrates how the system incorporates a manufacturing stimulus, specifically for fused deposition modelling that the organism will interact with during development. This interaction directly affects the final form of the organism. The system itself will respond to the stimulus in one of two ways; by triggering support structures on the part or by constraining the development of the organism in such a way that support structures are not required. It is generally recognized that support structures are required if any part of the model exceeds an overhang limit of 45 degrees from the build direction or likewise, within 45 degrees of the base plate (Klahn *et al.*, 2015; Al-Ketan & Abu Al-Rub, 2019; ZHU *et al.*, 2021). In this system, following this manufacturing rule, the organism will 'develop' support cells if any cell is growing at an angle greater than 45 degrees from the build direction or the system will constrain the cells of the organism to grow at 45 degrees from the build direction and therefore no support cells will be generated on the organism. The examples demonstrate how the inclusion of manufacturing constraints and different DfAM rules based on this constraint results in different final products. This is demonstrated on a simple shelf bracket. The operational environment of the bracket is shown in Fig. 17a, with the equivalent system representation shown in Fig. 17b. The seed is located at an origin, acting as one support, with two more supports located where the bracket is to be supported at the wall, and at the end of the shelf to be supported. These supports are represented by target attractors in this example, with loading on the bracket shown in the positive *x* direction.

6.3.1. *Development with support structures*

Figure 18 shows the developed organism in its environment when the build direction is specified to be in the +*z* direction. Support structures (cells) are shown in blue and each cell on the branch has a support cell associated with it. It is clear that these organism cells are growing in a direction greater than 45 degrees from the build direction. The support cells span from the cell to the *x*–*y* plane, i.e. the base plate of the machine given a build direction of +*z*.

6.3.2. *Orientation*

It is understood that model orientation has a direct effect on the support structures needed for AM of the part (Mirzendehdel & Suresh, 2016). Model orientation aligns with the build direction of the organism in the system. As a parameter, this can be changed to investigate its effect during organism development. The shelf bracket has been developed in the same environment with the same genome as in Section 6.3.1, but the build direction is now +*x*. Figure 19 shows the developed organism with support structures, however, at this orientation, in lesser numbers. It is understood that for this example, the optimum build direction may not be +*z* or +*x*; however, at the outset of development, this is unknown. These examples show how the system parametrization, and the organism–environment interaction, can directly aid the identification of 'optimums'.

6.3.3. *Development with restriction*

In this example, the system response to the manufacturing stimulus and its overhang angle limit is to restrict the organism development so that no cell exceeds the overhang limit and thus no support structures are required. In effect, no cell growth direction will exceed 45 degrees from the build direction. Figure 19 shows developed organisms at (a) +*z* build direction and (b) +*x* build direction. Two different organisms develop, with (b) reaching all target supports, but (a) will not reach the bottom target due to this manufacturing constraint. In this system configura-

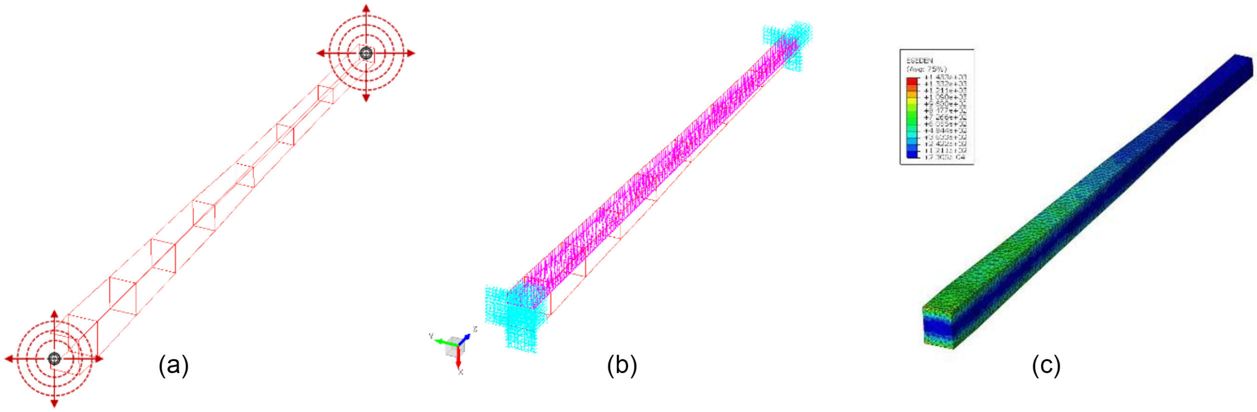


Figure 15: Stress analysis can provide additional input to hormone distribution to drive secondary growth.

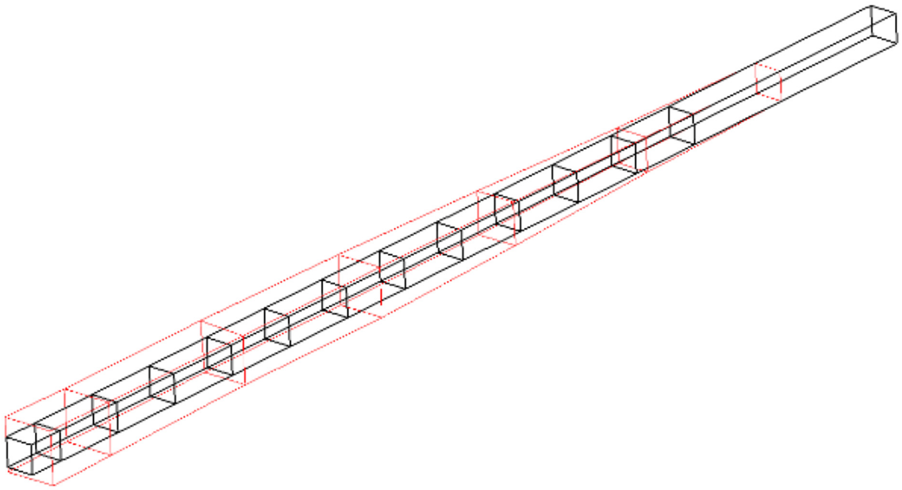
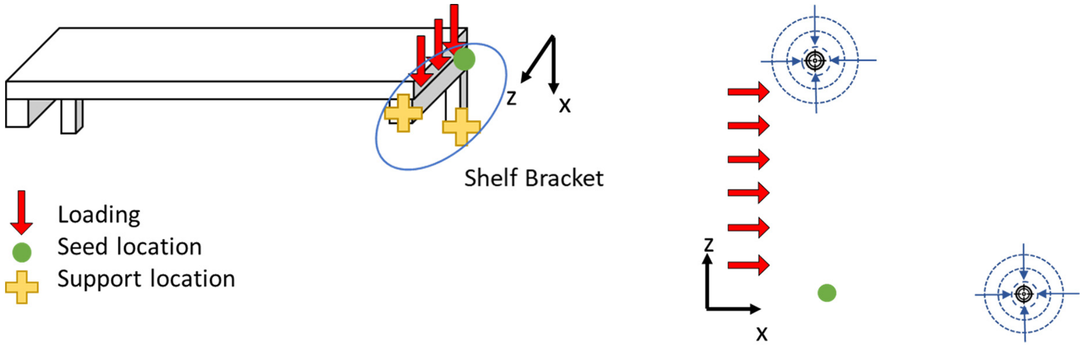


Figure 16: Superimposed images of organism with (red) and without (black) secondary growth.



(a) Operational environment

(b) system representation of the shelf bracket.

Figure 17: (a) Operational environment and (b) system representation of the shelf bracket.

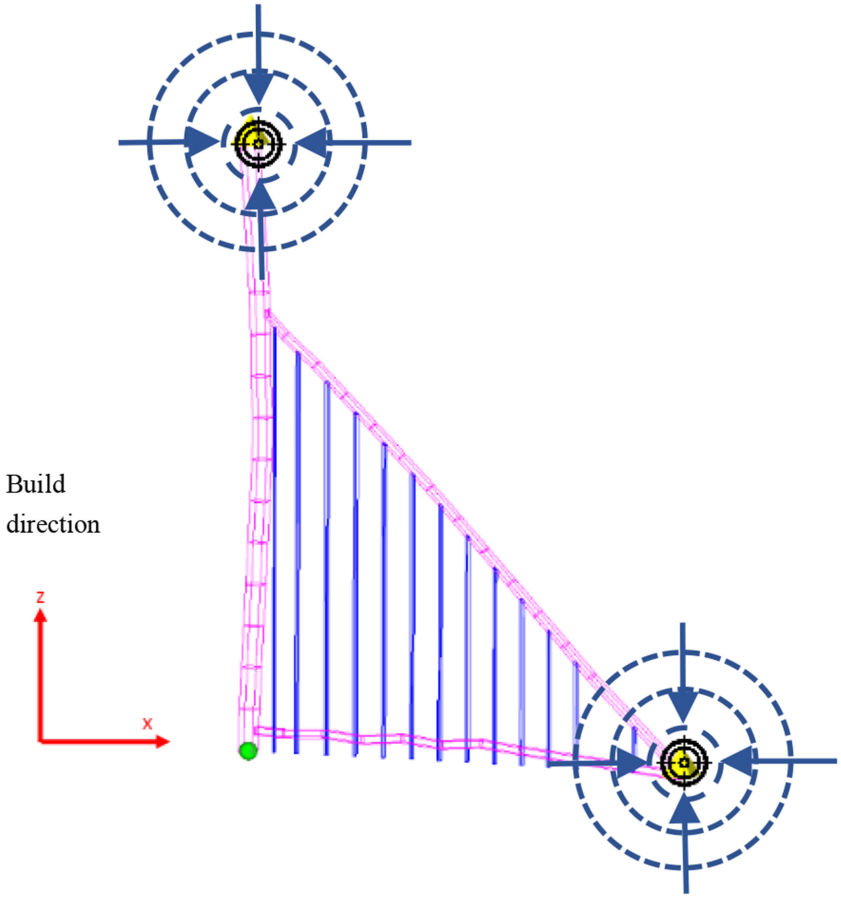


Figure 18: Developed shelf bracket in the system with support structures.

tion, manufacturing is driving design, making the part manufacturable without structures, but this organism will not meet requirements for functional design. With the parametrization of the Biohaviour system, these configurations can be seen and understood during the design stage.

Although the shape of the organisms developed in the +*x* direction, Figs 19 and 20b look the same, when overlayed, Fig. 21, it can be seen that without restriction (blue organism) the cells grow at an angle greater than 45 degrees from the build direction (+*x*) and therefore support structures (cells) are generated in response, Fig. 19.

7. Discussion

The goal of this work was to address a fundamental need in design systems for new approaches that can take advantage of novel manufacturing systems such as AM. The literature in the field identified a need for bottom-up thinking, building the concept in steps, to produce a solution more suited to AM and that the parametrization of the geometric model should be tailored to the capability of the manufacturing process. Of the different methodologies available, generative design systems have shown much potential for developing bottom-up solutions. As design becomes ever more tightly integrated with manufacturing, new approaches to geometry creation and management are needed to ensure that it is usable at all stages of design without significant post-processing and which can adapt and embed detail as the design progresses.

The examples in the preceding section present a bio-inspired metaphor for growing a design, adding complexity, and responding to the manufacturing environment as the product develops. There are three key outcomes from this approach. First, the geometry is changing in response to both environment (i.e. manufacturing constraints) and performance (i.e. simulation); hence, the system is dynamic and agile. Secondly, the environment can influence product location, orientation, shape, and manufacturing capability; hence, the range of interactions and facets of a design that can be explored from inception to detailed design is potentially very rich. Lastly, changing underlying genes can create a vast array of possible phenotypes, or individual solutions, giving significant potential in innovation and alternative solutions.

In addition, the work addresses a number of the supplementary questions posed by Fu *et al.* (2014) regarding BID systems. The core functionality provided by this approach naturally and seamlessly integrates the external environment with the product as it develops. This ability to represent aspects of the environment right from the inception of the idea allows a designer to interact with the developing design across all aspects that influence the product. This environment therefore can develop in complexity in concert with the designer's level of experience. The designer can add elements to the environment and the code responds to this element so that the developing product changes or adapts as the designer wishes at that point. This ability also naturally creates a more dynamic and adaptable environment, within which the philosophies of a designer may be encoded. By

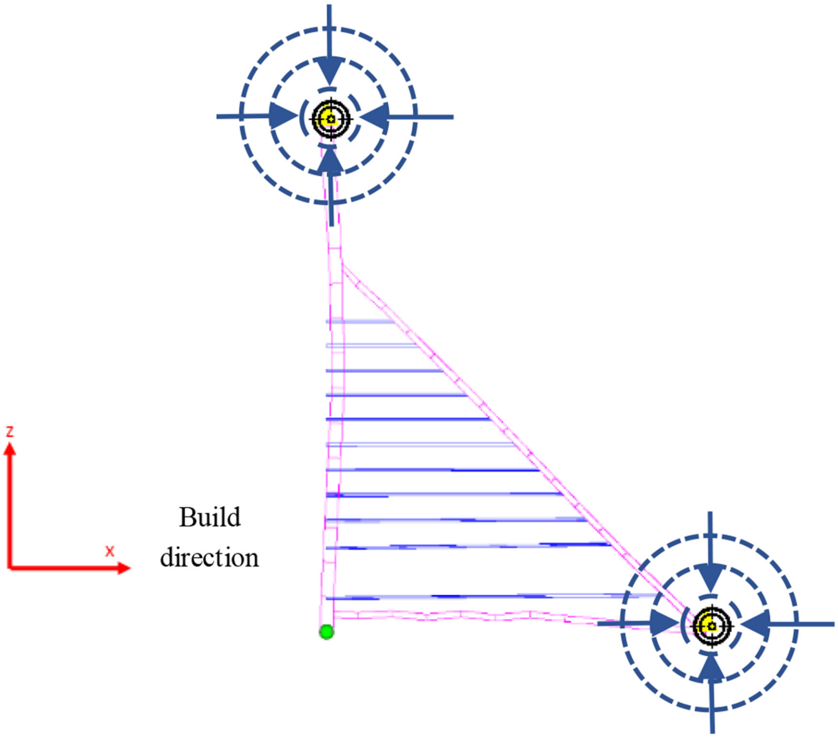
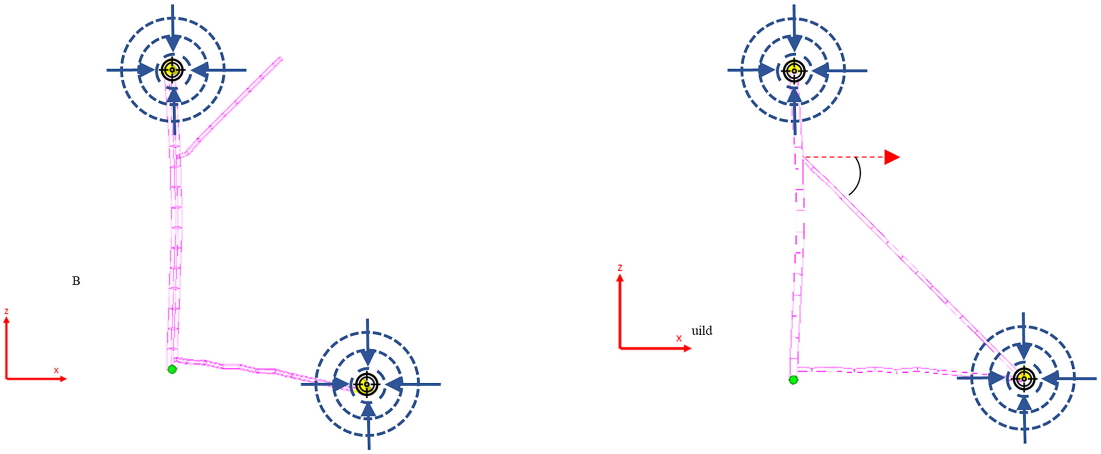


Figure 19: Developed shelf bracket at +*x* build direction with support structures.



(a) +z build direction

(b) +x build direction

Figure 20: Shelf bracket developed under a restriction constraint at (a) +*z* build direction and (b) +*x* build direction.

using a mechanism such as a hormone analogy between the geometry of the product and stimuli, either external as in forces or internal as in stresses, a naturally integrated approach emerges that allows different drivers to be incorporated into geometry (or any other) design change. In this early work, two hormones drive geometry changes. A primary hormone drives growth in length towards the goal, where a secondary hormone for stress drives cross-sectional changes to maintain acceptable stress levels. The approach here therefore provides the linkage with simulation and visualization as a by-product of the process.

It is interesting to note that this work has focused on the development of the product and that the interaction with the environment is unidirectional. It is very easy to see how a bidirectional interaction would allow elements in the environment to respond as the product develops, creating potential for a metaphor for symbiosis and competition. The development of this implies the potential for the manufacturing system to grow and develop itself, as the product currently does in this system.

An interesting aspect of this approach is that the hormone analogy provides an aspect for dealing with multiple types of

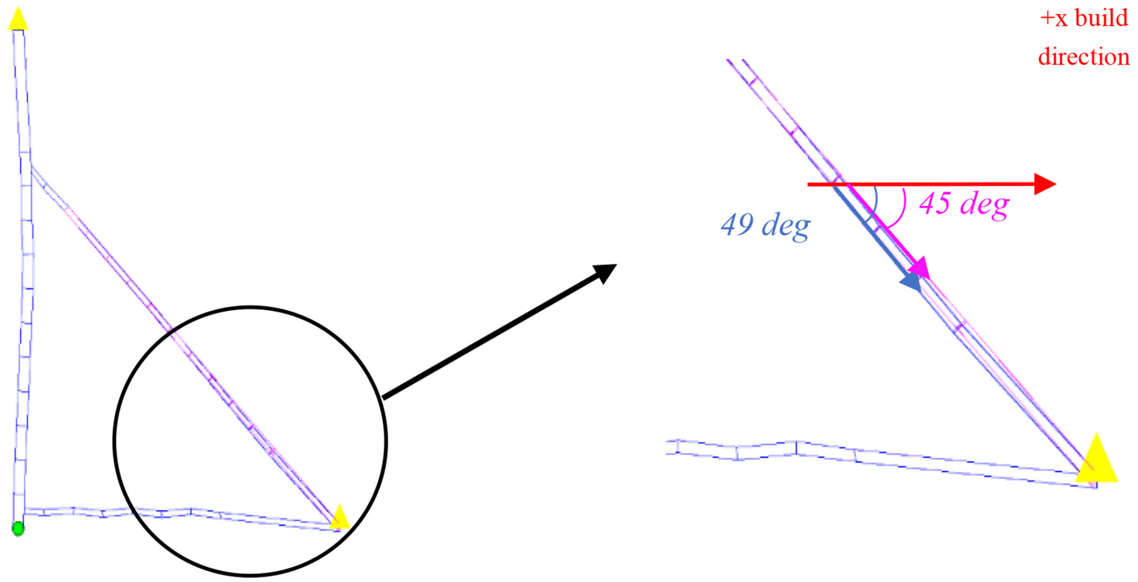


Figure 21: Growth angle difference that triggers support structures.

input to the design. In this way, the interoperability challenge is dealt with naturally by aggregating inputs to drive design changes and hence eliminating, or at least reducing, the need to link the myriad of models that represent the design, as per the current more typical approach to interoperability. It is recognized that, in reality, constraints and other external inputs will conflict. In the current implementation, the net impacts of such external constraints are aggregated via the hormone and sensor mechanisms, the sensitivities of which can be investigated through an evolutionary algorithm where large populations can be evolved based on their fitness in the environment. This aspect requires significant investigation to explore the best approaches for dealing with conflicting requirements and constraints.

The system has been implemented using Python and model creation is fully automated based on standard CAD functionality using sweeps and Boolean operations. The core data held in the model are therefore highly simplified and are efficient in terms of memory storage. Any relevant models (e.g. simulation, CAD) are created on the spot when needed and for memory efficiency are deleted when completed, although as the system creates CAD-ready geometry models the transfer of these models between design systems is trivial. As the system capability increases so too will the need for computational efficiency. Numerous opportunities exist to increase the efficiency of the system. The most obvious one is to execute any disciplinary simulations (e.g. FEA and CFD) in parallel, and then to explore individual organisms (components being designed) in parallel, enabling significant speed-up for studying large populations over many generations in artificial evolution. However, there are also opportunities in efficient modelling by using the cellular modelling structures from this work to generate highly idealized or simplified models that will speed up simulation times. This is the subject of ongoing work.

A particular aspect of the cellular modelling approach adopted here is that since all models derive from the same core data many interoperability challenges no longer pose a problem. For example, a cell representing a cylinder can allow from a beam/line model to be extracted and built from the end points of the cylinder axis or a solid model can be built from the same core information. Both design and simulation intent are maintained.

One of the technical and efficiency aspects of this approach is that the geometry and component configuration are changing continuously and hence the need for simulation to drive growth decisions results in a computationally intensive process. This challenge will need to be dealt with in future developments. Another is that the solutions are not necessarily optimal, rather the solutions provide a starting point for a more focused optimization study on the configuration chosen from the population.

It is clear from the studies, however, that the method can rapidly generate a range of unexpected solutions and could therefore be a powerful support tool in seeking innovative solutions, and solutions that are more tailored to the manufacturing environment. The use of artificial evolution overlayed on this will allow very large solution spaces to be explored and identification of the best traits in the given design.

This approach is radically different to current reasoning in geometric design tools that are typically applied to go from a manufacturable design down to geometric cells that can be used in simulations. This work is now investigating different geometric reasoning to construct and combine cells to create a manufacturable design. The design approach is intuitive, allowing the designer to focus on the key characteristics of the design needed rather than the details allowing their skills to be applied in this more creative zone than in building and interpreting very detailed simulation models.

8. Conclusions

A novel BID approach has been presented that offers potential to radically change how design and manufacturing are enacted. The method takes a starting point from previous well-founded research in CAD systems for automating design that can direct the set of design parameters and how the innovative design is emerged. Observation that this approach has parallels with the world of plants has opened an avenue to build a BID system that uses metaphors from plant growth. The methodology developed here uses a gene analogy to represent the product characteristics and hormone analogies to influence the growth of the product, allowing functional designs to be grown within a given environment. The approach presented is bottom-up and has been demonstrated herein to generate designs that are tightly integrated with the AM environment and that can respond flexibly to changes in that environment.

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Conflict of interest statement

None declared.

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