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Resilient city perspective: 4D printing in art, architecture and construction

Dalia Niazy [a,b], Mahmud Ashraf [a], Mahdi Bodaghi [c], Ali Zolfagharian [a,*]

[a] School of Engineering, Deakin University, Geelong 3216, Australia
[b] Architecture Department, Faculty of Engineering, Ain Shams University, Egypt
[c] Department of Engineering, School of Science and Technology, Nottingham Trent University, Nottingham NG11 8NS, UK

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ABSTRACT

Four-dimensional printing (4DP) improves material efficiency while enhancing the performance of the structure when subjected to external stimuli. Integrating stimulus-responsive materials with additive manufacturing offers a possible sustainable and environmental solution to mitigate current sustainability challenges. This perspective literature review comprehensively illustrates the research on 4DP conducted exclusively for art, architecture, and construction (4DPAAC). 3D printing responsive material research across buildings and construction is evaluated, resulting in the identification of seven research areas of 4DPAAC. They offer prospects for advanced building features, varying from façades to infrastructure, which are critically evaluated for their prospective contributions to reduce energy and material consumption and provide adaptability to climate change.

1. Introduction

The 2023 United Nations (UN) sustainable development goal (SDG) progress reports [1,2] indicated a continuous rise in global temperature and consequent natural disasters, renewable energy powering only 30% of the electricity sector, and an increase in fossil fuel usage in the past decade. Global domestic material consumption increased by 66% between 2000 and 2019, and hence, material footprint consumption per capita rose to 95.1 billion metric tons. The expected greenhouse gas (GHG) reduction by 2023 is 0.3%, which falls short of the planned 43% reduction in the 2015 Paris Agreement. In 2023, the International Energy Agency (IEA) reports [3], the buildings and construction sector accounted for more than one-third of the 2022 global energy-related emissions. Records and reports mentioned show unprecedented peaks, declaring the 2050 plan for decarbonization will not be achieved.

The material aspect is considered to play a core role in decarbonization [4]. Material science and engineering disciplines' research advancements presented higher control over material performance and utilization through material programming. Material programming is identified as composites designed with programmed new behaviours in the material system (MS), lamination being the most common method. The material lamination technique was used to produce composites actuating to diverse stimuli [5,6]. Static and adaptive building components were investigated [7,8]. The lamination of composites governed the material programming of responsive façades and building components, varying from magnetic bistable flaps [9], bimetal [10], bamboo veneer [11], and plywood sheets. Lamination was used to produce a hygroscopic adaptive unit [12], a bistable wood veneer laminate actuator [13], and a merge between wooden veneer and metal foil [14]. Shape memory alloys (SMA) were also investigated for adaptive façades [15,16]. Static materially programmed composites were also investigated for buildings and construction. The Urbach tower's curved walls were programmed with water content control to modify the curvature of cross-laminated timber (CLT) [17,18].

A common feature of material programming, through lamination [19] and SMA composites [20], is that they are highly constrained by the dimensional features of the active (actuators) and passive (struts or panels) parts. Utilizing 3D printing opened the spectrum for advanced material deposition control, and an opportunity to overcome delamination through advanced material distribution in the material systems like weaving of different paths [21]. Material programming evolved smart materiality from composite lamination to a higher level of material distribution control through 4DP [22–24]. The fourth dimension in 4DP is identified as time [25], where the 3D-printed specimen has a programmed behaviour upon stimuli application. Computational analysis and prediction models for 4DP material distribution design were developed [26–29]. 4DP research is found in different disciplines, like medicine [30–32], robotics [33–35], and dampers [36] like boat fender design [37]. Being conscious of the SDGs – identified by the UN to conserve Earth for future generations – specifically, five of them with direct relation to the built environment (BE) – which are SDGs 7, 9, 11,

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* Corresponding author.
E-mail address: a.zolfagharian@deakin.edu.au (A. Zolfagharian).

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Abbreviations

Acronym	*Name*
SDG	Sustainable development goal
SDG 7	affordable and clean energy
SDG 9	industry innovation and infrastructure
SDG 11	sustainable cities and communities
SDG 12	Responsible production and consumption
SDG 13	Climate action
UN	United Nations
4DP	4D printing
3DP	3D printing
RLP	Rapid liquid printing
RH	Relative humidity
SMA	Shape memory alloy
SMP	Shape memory polymer
PLA	Polylactic acetate
ABS	Acrylonitrile butadiene styrene
WPC	Wood polymer composite
PK	Polyketone
FDM	Fused deposition manufacturing
LDM	Liquid deposition manufacturing
SLA	stereolithography

12, and 13 –, 4D-printed BE components can be presented as viable strategy methods to address them all, as shown in Fig. 1. 4DP can help enhance BE sustainability through energy savings, adaptability, and material consumption rationalization. 4DP research [13,21,38–42] proved efficiency in enhanced utilization of material properties, optimization of performances through aware material distribution, reducing material consumption, utilizing environmental stimuli (natural clean "renewable" energy resources), and increasing material biodegradation, which results in reduced or eliminated energy consumption during the operation of adaptive shading elements. A graphical representation of the material programming transition from conventional lamination of discrete sheets to 4D-printed material in architecture and construction is shown in Fig. 2.

The environmental loads affecting buildings vary from relative humidity, rain, solar radiation, over- or under-heating, wind, and seismic loads. All loads are changing in diverse geographic locations and over time for the same location. 4DPAAC research investigated mitigating diverse loads as the stimulus for motion or change to reduce electromechanical building loads, but gaps in wind and seismic loads 4DP were identified. A critical point of research is the energy consumption of buildings during the operation phase and efforts to mitigate energy use in buildings [46]. Considering the life cycle assessment (LCA) of 4DP building components, lower material and energy consumption of parts are evident during pre-operation and manufacturing while decreasing the environmental loads affecting the rise in energy consumption is being investigated. Le Duigou and Baley [47] have identified enhancements in the LCA of products when incorporating natural fibres in the pre-fabrication phase. Thus, the prospect of an environmental end-of-life cycle of 4DP components utilizing sustainable printing materials [48–50] is presented. Consequently, 4D-printed building components present a sustainable approach with a better building life cycle through all phases.

This paper discusses current 4DP research work in art, architecture, construction, and any related 4DP built environment investigations. 4DP discussed in this paper is the human-controlled mesoscale behaviour of the structure across time using 3DP, programming non-inherit/expected behaviour. The change over time is found in shape, growth, bioreactivity, and properties like colour, vibrations, and sound damping.

2. Methods

A systematic review is conducted as part of the current research. Initial literature screening to formulate a general dataset is done using the following keywords: Boolean ("4D printing" OR "3D printing") AND ("architecture" OR "construction" OR "building") AND ("shapeshift" OR "self-morph" OR "shape change" OR "living" OR "material programming" OR "interactive" OR "responsive") NOT ("Nano" OR "micro" OR "medical" or "medicine"). Web of Science, Deakin Library, and Elsevier ScienceDirect search engines are used, with a custom year range of 2013–2023. 214, 3307, and 1003 publications were identified by each engine, respectively. Upon screening exclusion, identified publications were reduced to 186, 2675, and 735, respectively. It should be noted that due to the word limit in ScienceDirect, search keywords are reduced to ("4D printing" OR "3D printing") AND ("Shape shift" OR "self-morph" OR "living" OR "material programming" OR "responsive") NOT ("Nano" OR "medical").

The resultant publication databases are reordered separately using a machine learning ML tool identified as ASReview Lab, which is verified in Ref. [51]. Each dataset for each website was inserted separately and reviewed. Five relevant and five irrelevant papers were identified with each dataset entry. The ML tool reorganized the literature from most relevant to irrelevant. The literature relevance criteria were direct relevance to 4DP in Arts, Architecture, and Construction (AAC) or future possible integration possibilities. The total relevant publications of all databases were 95, with 56 most relevant to 4D printing of art, architecture, and construction 4DPAAC after removing repeated relevant publications among the three databases, which amounted to 9 publications. The full screening statistics are presented in Fig. 3. It is noted that, upon publication analysis and analysis of the research groups' previous work, another 10 publications were added to the most relevant database. Thus, the total most relevant publications to 4DPAAC are narrowed to 66 (see Fig. 4).

AAC research work-specific structuring and classifying areas is conducted about motion mechanisms. According to Ref. [58], there are four dimensions of mechanism definition deployed in science. The mechanism classification dimension used in this paper is defined as the organizational system between entities (component parts) and their respective operations for more generation of a phenomenon. This was first defined in Ref. [59] and further detailed in the minimal mechanism [60]. The entities in this paper are identified as the material distribution, while the operations are the stresses and forces among the 3D-printed material system. The phenomenon is the physical change of the material system over time.

Based on their mechanisms, the research that has been found on 4DPAAC evolution has been put into seven categories: printing on flat surfaces, 4DP shell structures, 4DP line structures, 4DP lattice structures, lightweight 4DP joint structures, heterogeneous 4DP systems, and living 4DP structures. **Section 3** goes into more detail on each of these categories. A categorization of materials feedstock and printing methods is identified in **Section 4**, along with an overview of the current printers' feedstock sustainability research.

3. 4D printing in architecture and construction (4DPAC)

3.1. Print on planar surfaces (layers/sheets/textiles)

Two subcategories are identified, as shown in Fig. 5a. The first is printing actuating material on a passive substrate, while the latter is printing passive/constraining material on the active stretching/shrinking substrate. This research area builds on Timoshenko's [19] and classical laminate [61] theories. The theories' equations were used to evaluate and predict the bending behaviour of 4DP layers of multi-materials upon stimuli application.

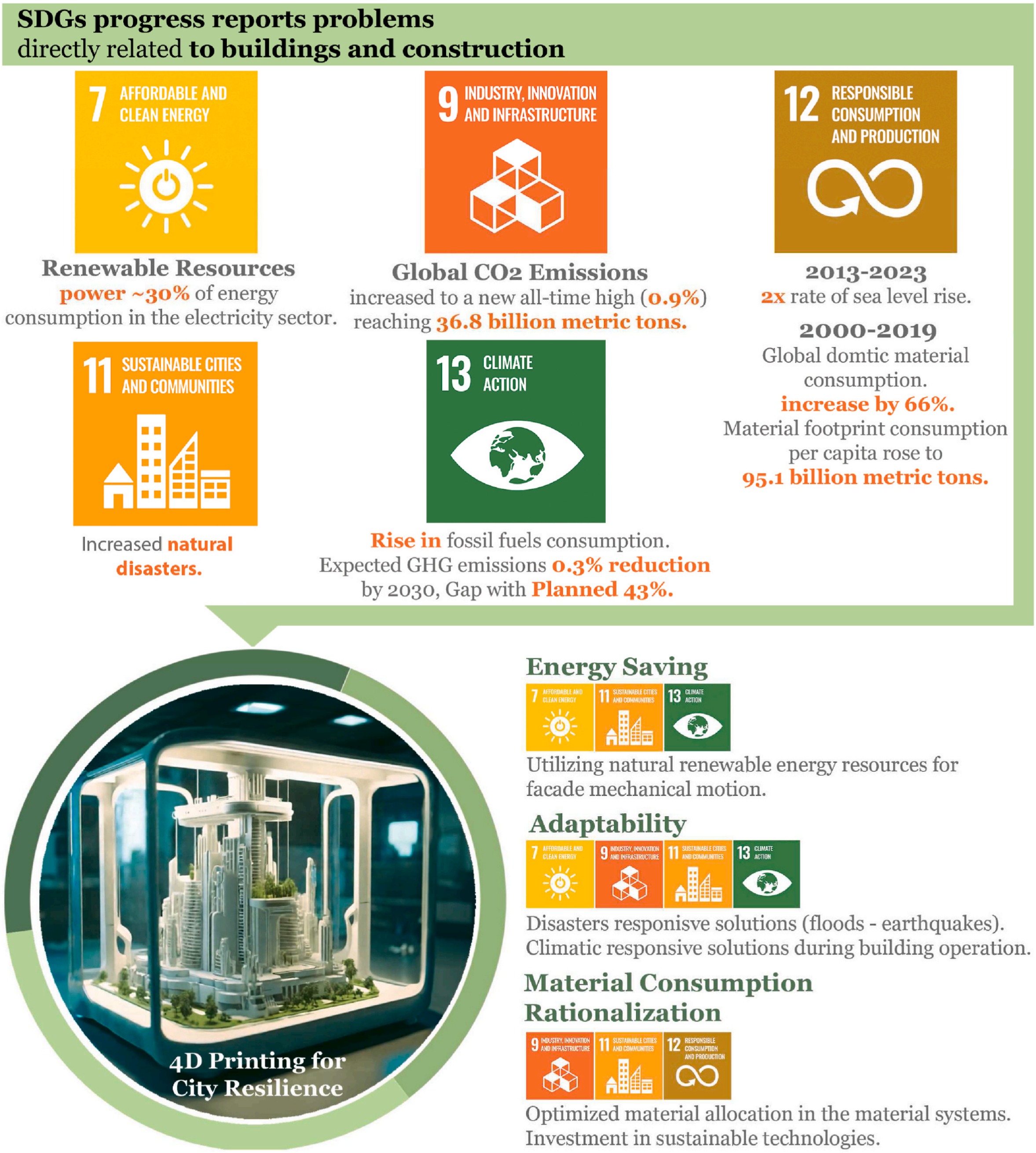

Fig. 1. Current global challenges and possible 4D printing integration as a possible strategy to mitigate climate change. SDGs statistics, data, and logos are adapted from Refs. [1,2].

3.1.1. *4D printing actuating matter on passive substrate*

This research builds on 3DP of active matter on the passive actuating layer(s). The parameters affecting actuation are the elasticity of the passive sheet, print path, active material properties, and investigated stimuli for actuation.

Yao et al. [65] presented bioprinting natural hydromorphic material on a flexible substrate. Material distribution on the substrate was varied to control bending and folding. Correa et al. and Poppinga et al. [21,38] investigated the biomimicry of pinecone's seed scale hygroscopic motion through 4DP bilayered material system. Discrete lamination and weaving of two filaments were used. The discrete lamination consisted of 3D-printed ABS as the stiffening laminate, while the print path control of the wood polymer composite was the hygroscopic motion driver laminate. Correa et al. investigated different alignments of active material in relation to motion acquired. Poppinga et al. illustrated modular façade apertures. All prints show delamination during continuous actuation cycles except when the two materials were interwoven together by Correa et al., forming a shell/shallow lattice structure.

A crease folding method was developed for 4D printing origami structures [66]. The method differs from regular origami joint motion drivers to curved joint and face motion drivers. The crease line induced the folding of discrete surfaces and the bending of one or two surfaces. Three materials were introduced into the system: wood filament for the actuating layer, acrylonitrile butadiene styrene (ABS) for the restrictive layer, and thermoplastic urethane (TPU) as the hinge. The results showed that the larger the crease curvature, the smaller the folding angle. A relative humidity (RH)–actuated adaptive façade prototype was achieved.

A 4D-printed fan product design enhancement was introduced, showing potential success for application by Zouboulis et al. [67].

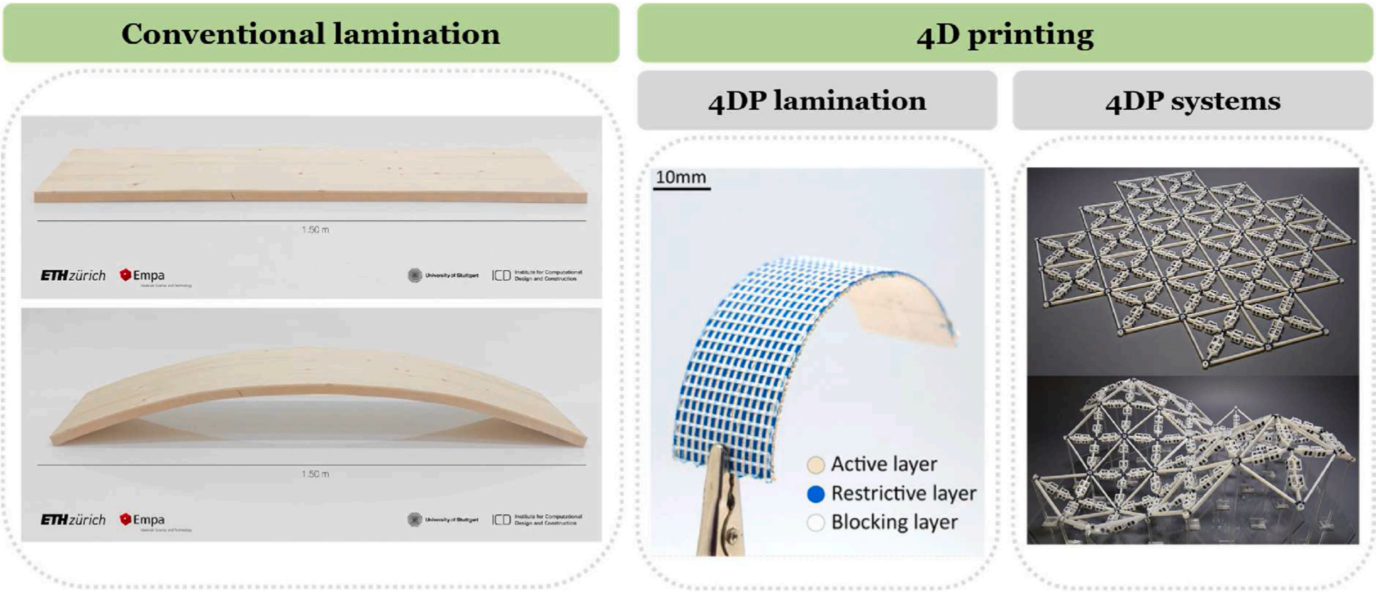

Fig. 2. The material programming transition in Architecture and construction from conventional lamination [43] to 4D material programming. 4D programming started with lamination (adapted from Ref. [44]) reaching larger deformable advanced 4DP systems merging different mechanisms (adapted from Ref. [45]).

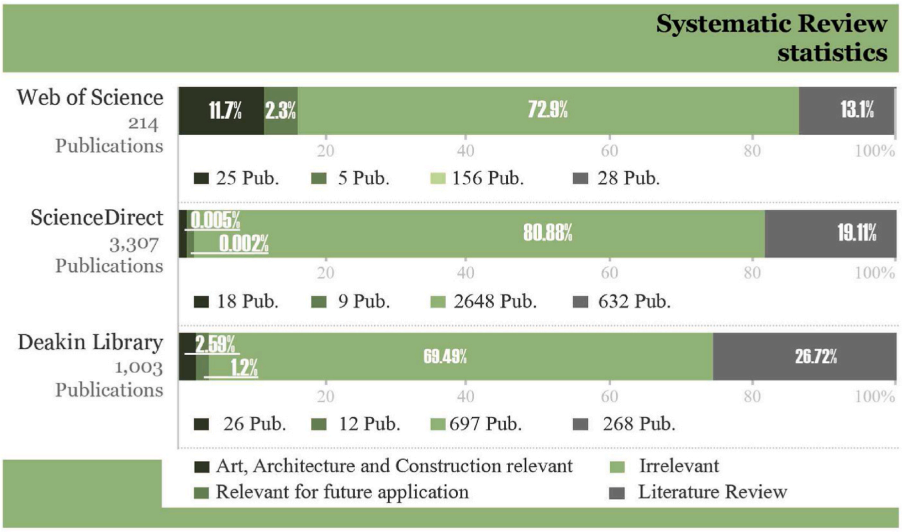

Fig. 3. Graphical representation of systematic review papers filtering statistics.

Different active material fibre print patterns were investigated to produce a target curved state of the fan blade at lower temperatures and a flat state at higher temperatures for cooling energy-saving considerations. In Ref. [68], graphene conductive polylactic acetate (PLA) – as the actuator – was 3D-printed on paper to produce shape-changing iterations of paper. Printing patterns and paper patterns/shapes were investigated to test the morphability.

3.1.2. *4D printing passive/constraining matter on the actuating substrate*

Three sub-research areas categorized in this work for the actuating substrate include 4D textiles, shrinkable substrates, and different materials on active substrates. The 3DP of the passive matter acts as the constraining element, which is a vital parameter to control shape retention iterations upon stress release or stress application. Stress release is found in 4D textiles, while stress application is found in the other active substrates.

The 4D textiles area has been largely investigated, with the first product presented in Ref. [69]. The 4D textile substrate concept relies on programming the geometrical allocation of reinforcement material on a prestressed stretchable surface. Upon surface prestress release, specified 4D parabolic shapes are achieved by transforming the energy from the substrate to the reinforcement. The 4D geometry is affected by printed 2D/3D geometry and the extent of the prestressing effect [70], where diverse material deposition patterns as a voxel element were investigated to achieve 4D textile iterations for soft joint control. Schmelzeisen et al. [71] discussed 4D textiles by experimenting with different materials and introducing a corresponding design to the product pipeline. In Ref. [72], a conceptual parametric pattern printing on textiles to induce tailored sound-absorbing panels was illustrated. Preliminary 4DPAAC prototyping investigations started in Ref. [73] to evaluate a single pattern for form finding upon stress release. The single pattern was used as the base, and diverse proportions (specific height and width of pattern in a single print) were investigated to evaluate the 4D structures' form and shape retention. Another test was executed to investigate diversifying the height and width across the pattern in a single print. Results indicated a new affecting parameter, which was the time to cut the print

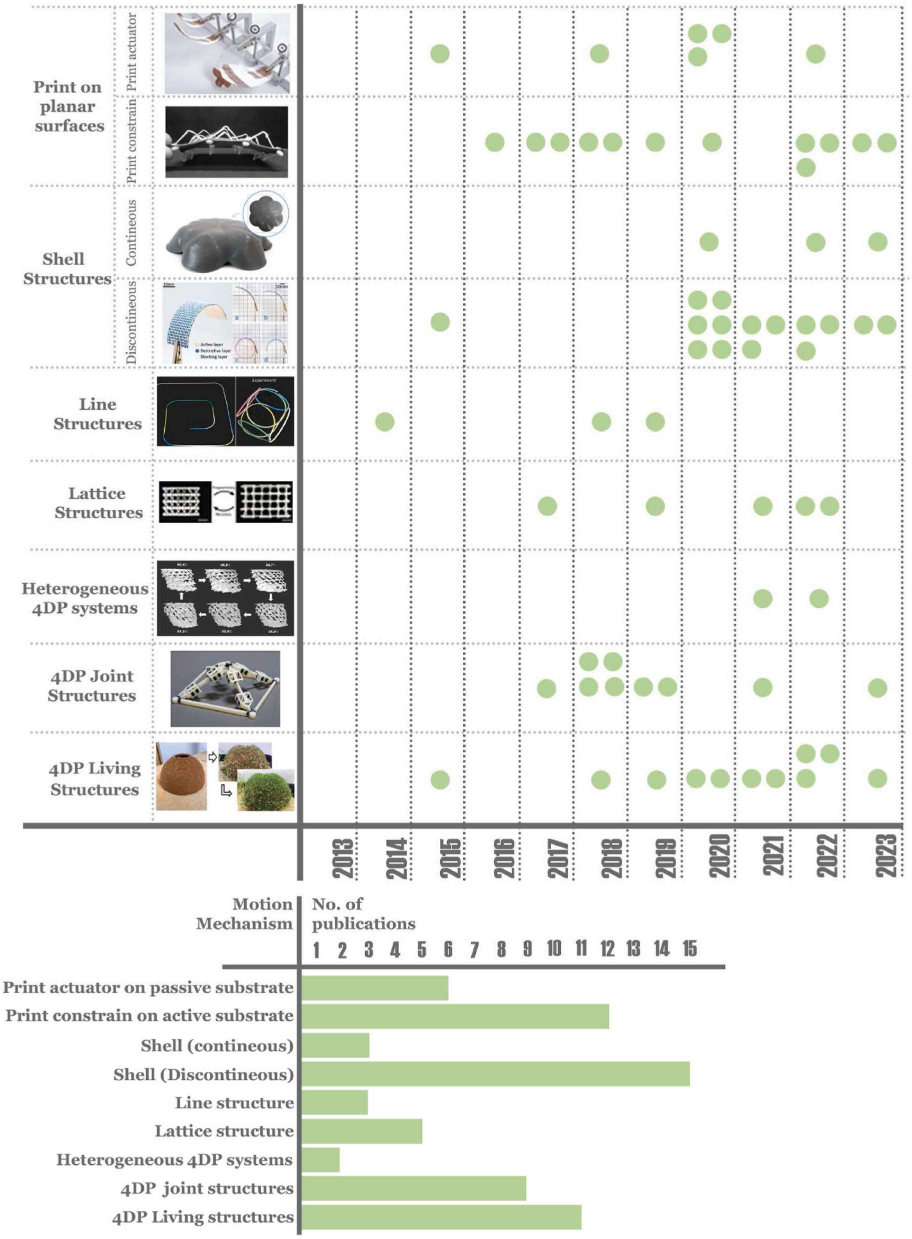

Fig. 4. The 4D printing research areas progress timeline (Architecture & construction only). Print actuator [21], Print constraint [52], Continuous shell structure (adapted from Ref. [53]), Discontinuous shell structure [44], 4DP line structures [54], 4DP lattice structures [55]. Heterogeneous 4DP systems [56], 4DP joint structures [45], and 4DP living structures (adapted from Ref. [57].

when taken off the print bed and its impact on delamination after a while.

Agkathidis et al. [74] researched print pattern optimization on pre-stressed Lycra sheets and their corresponding 3D forms. Karamaba in Grasshopper plugin was used to simulate the expected stress analysis, thus aiding in the selection of the print path topological arrangements. Utilizing the stress lines as a guide, several 2D patterns and corresponding 3D structures were investigated. The 3D-printed patterns were glued to the prestressed Lycra. Other print pattern investigations while 3D printing on prestressed are discussed in Ref. [62] Fig. 5b. A different printing on fabric method was investigated by Christie et al. [52], with the concept of defining 3D-printed material points of contact and others of non-contact with the pre-stressed substrate. This was achieved through printing on fabric at specific points while moving the print head up and down during the print paths, as shown in Fig. 5c. This method differs from the most common method of XY plane layers to XZ or YZ print paths. Upon substrate stress release, synclastic and anticlastic surfaces were achieved. An apparent limitation that can be observed from this research is that the material printed – of the non-contact part – must be able to attain shape and remain in the air in its designed position during printing, which requires further material exploration.

The shrinkable substrate field explained in Ref. [75], produced tessellated 3D structures from 2D sheets using inkjet 4D printing. The method utilized ink jetting on both sides of heat-shrinkable sheets. Upon heat stimulation, the 3D origami-tessellated 3D structure is produced. The researchers stated that it is 1200 times faster, has higher printing resolution with a subsequent effect on printed tessellation facets resolution, and has a higher colour diversity in a single print.

The final area is identified which controls the print pattern of constraining 3D-printed material to fulfil the required shape morphing. In Ref. [76], 3D-printed pattern height, the density of the grid's XY print paths, and wavy wall geometry were investigated to produce an

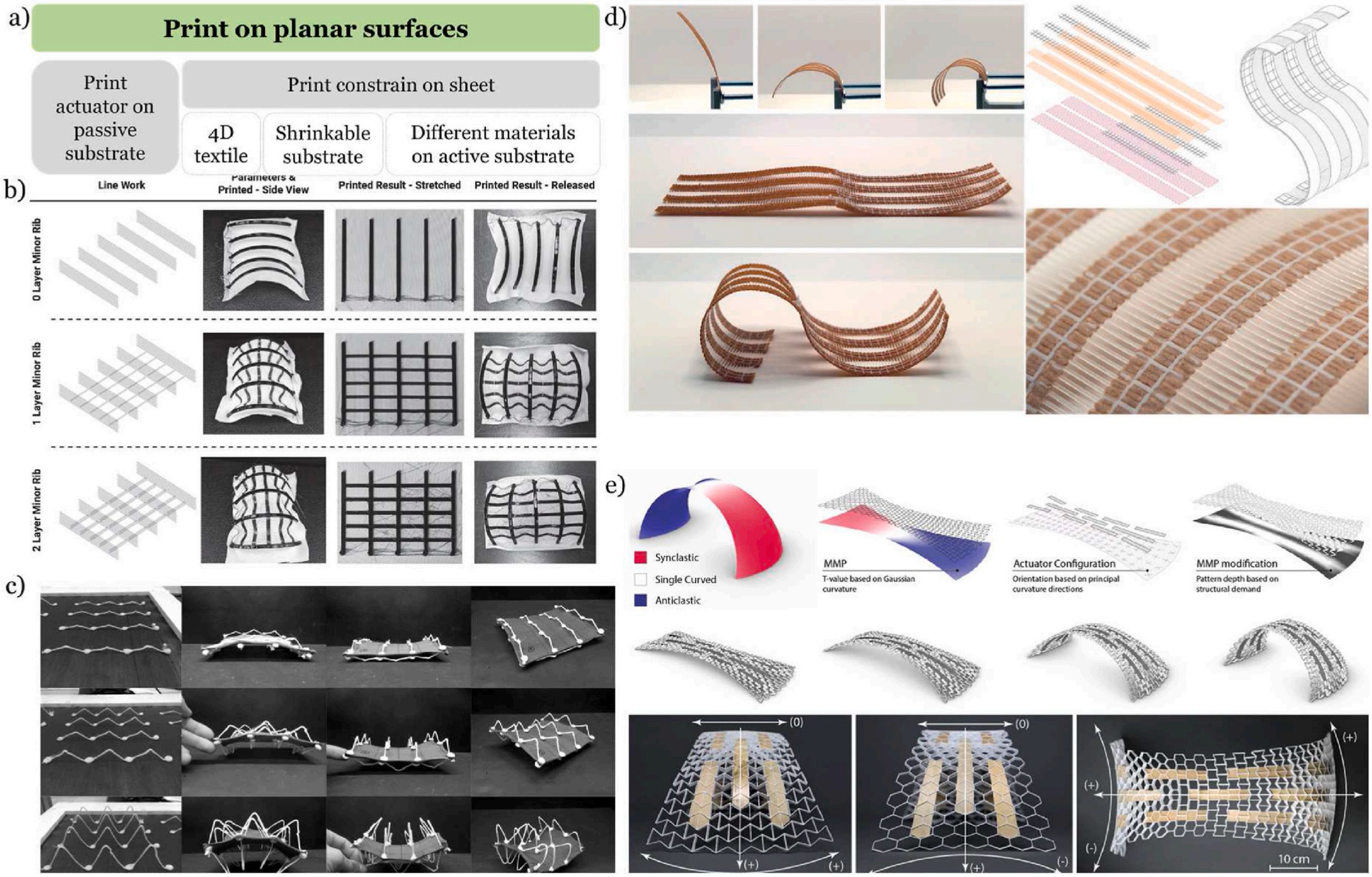

Fig. 5. Print on planar surfaces. a) Classification of subfields of printing on planar surfaces. b) Patterning of constraining material on pre-stretched textile, adapted from Ref. [62]. c) Textile 4DP through the varying point of contact during printing of the constraining material on the pre-stretched substrate [52]. d) 4DP patterning investigations for variable shape change [63]. e) Patterning of passive material for controlling actuation direction and attaining higher stiffness for shape fixity [64].

armature. Using this armature, the impact of varying stiff material patterning on retention and direction during system deformation with varying RH was investigated. The parameters were proven to control the intensity and stiffness of actuation, specifically because of the stretching and compressions induced by wavy walls. The 3D-printed material system included pockets to insert the wooden bilayer actuators and the 3DP was continued after. The problem was that the armature caused increased stress at some points, which reduced the actuator's impact. Other investigations of print path patterns in 4DP bilayered systems for adaptive façade elements were done in Ref. [63], as shown in Fig. 5d.

Another example that investigates the patterning of the passive layer as a factor for directional motion control was presented in Ref. [64], which presented a conceptual large-scale 4D printed roof prototype with a proof of concept. The research investigated merging 3D-printed auxetic layers with bilayered wood actuators. The surface curvature using this method was evaluated through simulation and evaluation of the physical prototype in parallel, to identify the relation between the 3D-printed pattern and the bilayered wood. The 4D material system incorporated a hybrid fabrication workflow where base layers were 3D-printed leaving pockets for computational numerical control (CNC) cut actuators to be inserted, and then the final layers were 3D printed on top, as shown in Fig. 5e. The researchers used support for the large-scale prototype during shape change from the centre of gravity to overcome the self-weight issue. Constraining the corners/ends of the 4D structure after self-shaping is discussed to achieve higher structural stability.

3.2. *4DP shell structures*

This approach utilizes print paths and the corresponding impact on shape morphology upon stimuli application. Timoshenko's bilayer [19] and classical laminate theory [61] were used. The print path parameters investigated in the literature were meso- and macro-level geometries. The meso included layer height, thickness, and single and multi-materials. The latter investigated larger material orders and their consequent impacts on allowing and restricting motion for directional motion control. The materials' properties were investigated. Single- and multi-material systems were studied. The shells are classified here into continuous and discontinuous surfaces.

3.2.1. *Continuous surfaces*

A thermo-deformable shelter [53] prototype was developed using 4DP of a single material. PLA was investigated to achieve 3D structure from 2D printed surfaces. Circular 2D surface planes overlap during 3DP, resulting in a higher net surface's core height uplift when heated. Also, polyurethane-based shape memory polymer (SMP) was investigated to validate using the shape memory effect (SME) for facilitating prototype transportation. The previous research depended on assuming geometric print paths for shape transformation exploration, while in Riely et al. [77], the pre-stain during printing aligned with the SME, which induced the material spatial allocation for the print path. Researchers 4D designed a multi-stable, recoverable concept for a snap-shut prototype. They also investigated possible remote control by 4DP PLA and iron on a specific part of the surface.

A 4D-printed bistable shell structure [78] was explored, utilizing the pre-strain induced in the direction of the print path of the material. The difference in the method from previous research is in the parameters investigating the pre-strain magnitude for design. The varying parameters were nozzle temperature, layer height, and print speed, which was their first set of investigations. The second set was about changing the print path direction in a certain way. This was like previous research, but seams were added at the triangular connections of the tessellated geometry to make it easier for flat unit cells to change shape. Lastly, all samples were tested to identify the morphed shape's mechanical properties and subsequent bistability. The researchers stated that the larger the print speed, the lower the temperature, and the lower the layer height resulted in a larger prestrain and consequent shape change.

3.2.2. Discontinuous surfaces

Poppinga et al. [38] illustrated biomimicry for compliant motions using 4DP. Four design iterations of the hygroscopic structure actuation mechanism mimic the geometrical motion of four plants: bending of lily petal, bending of pinecone, modular aperture, snap buckling instability, and snap-trap with kinematic amplification. The bending of the pinecone design was previously explained in Ref. [21] and illustrated in Ref. [79]. The modular aperture used bilayering mechanism as well. The other two design iterations 3D-printed an actuating edge and passive middle part for each 4D-printed petal mimicking petal bending and ringlike flytrap as shown in Fig. 6b [79]. Correa further explained 4DP through the weaving of active and passive material distribution in Ref. [79], as shown in Fig. 6c.

Zupan et al. [81] presented a smart pneumatic façade responsive unit. The alternating vertical and horizontal print pattern resulted in isotropic behaviour under air pressure. Heating above glass temperature (Tg) helped achieve a maximum morphing state. Vazquez et al. [82] explained the iteration work cycle of designing with 4D self-morphing materials as a framework and applied it to 4D-printed kirigami geometries to amplify the hygroscopic shape morph for architecture scale requirements. The use of bilayer patterning as a shape grammar was investigated. In Ref. [44], the thickness of layers was investigated to achieve variable curvature angles, resulting in prototyping an adaptive prototype with tailored variable apertures as shown in Fig. 6d.

Sossou et al. [83] introduced the VoxSmart simulation tool design based on [27]. The tool is the first to be custom-made for designers to visualize non-uniform material distribution expressed as a voxel for shape change research investigations. A detailed voxelization workflow is illustrated. The workflow starts with converting the full object/material system to entities described as a voxel. The conversion is done by comparing initial and final shapes and identifying nodes of degrees of motion that produce the number of voxels and their respective nodes, which defines the resolution. It can be stated that the tool tackles spatial 3D material distribution.

A development in modelling the mesostructure of surfaces for fused filament fabrication (FFF) for controlled spatial behaviour was explained in the mesostructures framework by Cheng et al. [84]. The material structure discretization differed from voxel modelling for 3D material distribution [27] to 2D planar functional region modelling. Three regions - passive, active, and external-are identified. A non-uniform rational basis SP-line (NURBS) workflow was used. Each

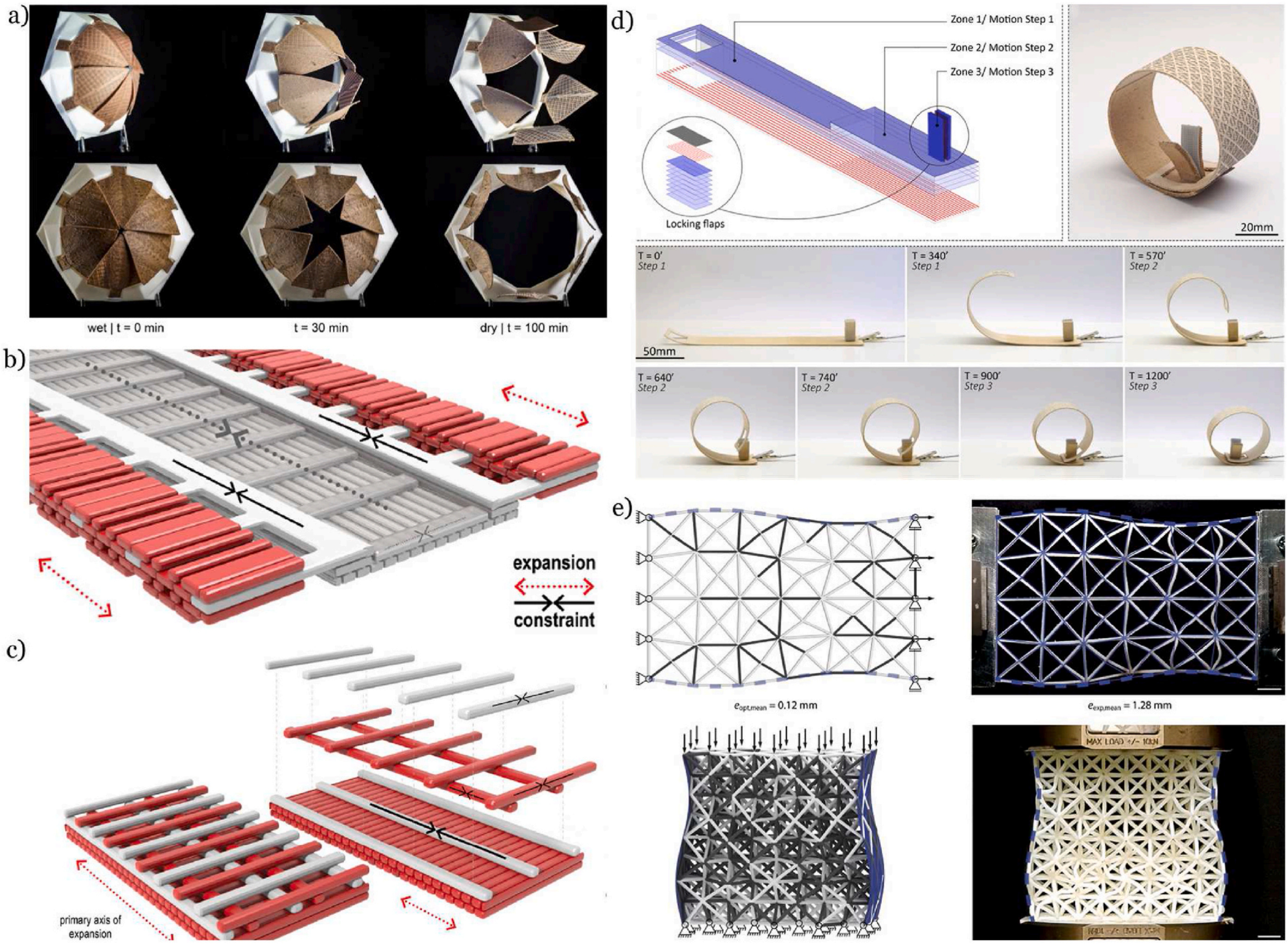

Fig. 6. Shell structures. a) Adaptive façade aperture module [79]. b) Periphery and internal section material system for programming actuation behaviour [79]. c) Weaving of print paths (adapted from Ref. [79]). d) Patterning of passive material for controlling actuation direction and attaining higher stiffness for shape fixity [44]. E) Reversible 4DP lattice load tests [80].

region was modelled as a NURBS planar surface with panels, which is different from 3D voxel modelling. The active layer is identified by bilayered materials for bending actuation. NURBS control points were used to encode mechanical properties to each region's plane in an object. Thus, corresponding bending, directional control, stiffness, and actuation speeds were predicted. Consequently, a pattern of grid selection was achieved. The researchers then achieved an anticlastic surface and a dome-like structure using the mentioned framework. The porosity and thickness of the passive planar region were varied to investigate the resultant double curvature from a single flat surface. The passive plane mesh pattern density variance allowed constraining and motion freedom; thus, when the active region actuates, the motion direction is controlled. The functional patterns presented were further investigated in Ref. [85] at a larger scale by incorporating a bilayer hygroscopic wood actuator inside a diverse print patterned structure as a programmed stiffener base.

Tahouni et al. developed the RH-actuated hygroscopic bi-folds façade unit [86], through biodegradable filament development and higher complexity of material distribution of 4DP multi-materials [66]. Cellulose powder was mixed with each of the TPU and PK-based matrices separately for filament production [86]. The filament performance was tested to produce prototypes using the mesostructure design model [84]. Short-term and long-term cyclic evaluation showed that the higher the cellulose percentage in filament the higher the transformation, TPU-based filament samples showed higher curvature than PK-based ones in bilayered module sample, Pk-based samples of the bifold showed higher curvature than TPU-based one. Thus, it can be concluded that the more complex the compliant system generation, material stiffness is needed to uphold the motion mechanism. Also, it didn't require water immersion for actuation.

An experimental work [87] for directional motion control for the mesostructure of surfaces investigated the single/mono-materials and patterning. Off-the-shelf filaments validity for 4D adaptive façade was investigated, utilizing the mesostructure of a standard rectangular flat object using infill printing parameters, infill density and pattern, and corresponding bending upon heat stimulus application. Sahin et al. [40] expanded the layer patterning for mono-material 4D printing moving the prototype cross-section from XZ or YZ to the XY plane. Using this concept, they introduced a higher level of control over cross-sectional patterns. The printing geometrical pattern's two parameters were the cell resolution (size and shape) and wall (geometry and thickness), which were evaluated for shrinkage and swelling behaviours. Voxel-based model simulations morphing data were input from the physical model shape change upon actuation. The wall geometry variation showed a trend for shape change while the cell resolution variation didn't, except that the smallest cell resolution showed the highest shrinkage and consequent shape change. Self-morphing biomimetic prototypes were produced utilizing shrinkage and swelling behaviours of print pattern parameters.

Li et al. [88] investigated the printing speed impact on prestrain and consequently the shape changes like what was demonstrated in Ref. [78]. The two differences from previous work are the presence of gaps between print paths – a selected concentric circle print pattern inside each circular unit – and varying print speed during the single print. The experiments proved that the larger the number of circles in a single print, the larger the load-bearing capacity and energy-absorbing capabilities. Also, diversifying the circular unit paths in a single print reduced the energy-absorbing capacities.

3.3. 4DP line structure

This research area is considered a special case of shell structures. The material system aligns across a longitudinal direction, where the material voxel positioning in the material system is controlled to actuate motion upon stimuli application. Raviv et al. [89] presented a mathematical model and a physical proof of concept for the first 4D-printed line structures. The material system was constructed with two passive and active materials. The passive material allocation around and at the two sides of the active material joint allowed the constrained directional angle of bending control.

Ding et al. [54] explained using residual compressive strain found due to polyjet 3D-printed elastomers to produce 4D-printed line structures. The line bending method depends on the mismatch strain – the dominant factor – and thermal coefficient difference between the elastomer and glassy polymer found in the composite line upon heat stimuli. Bending and helical twisting were exhibited by manipulating the material positioning across the cross-section. The radial, equal-spaced distribution of elastomer along the rod axis helped produce twisted 3D structures. The ratio of elastomer to glassy polymers was the key investigation parameter. A realized cubic frame was introduced with a possible application to be used in a humanitarian shelter. The cubic frame is achieved from a self-assembled line structure through regular bending through layering and bending in differing directions through radial material distributions.

A-line project [90] utilized a single material PLA non-uniform cross-section design of a FDM printed line. The 4D-printed line is segmented to show diverse bending joints to achieve deployable 3D structures. Directional bending was first investigated through physical material experiments, and then the results were input into the computational system for simulations.

3.4. 4DP lattice structures

Lattice differs from shell structures, as its' programming through 4DP utilizes the 2D/3D unit cell as the voxel for change iterations. Lattices were investigated to achieve different levels of change control. The research investigated the interplay of stresses and strains among the material distribution for programmed behaviours. Results presented prospects for integration in lightweight structures and adaptive systems. The research investigated change through two methods.

The first method is a uniform material distribution across all unit cells, while the geometry of the cell directs the motion change upon stimuli [91]. The latter is a multi-material distribution across the whole system, with a uniform single-material distribution in each unit cell. The second method can be explained in the research done for 4D-printed multi-material lattices [92], which investigated the effect of stresses generated between lattice cells due to thermal actuation. Complex iterations of patterning the material distribution design in the lattice were investigated for predicting morphological behaviour prediction. Another printed geometry investigation was conducted to achieve a large deforming auxetic structure, "eth letter" [93]. A reduced beam model was introduced to reduce computational simulation time and expenses. The origami 2D mesh auxetic meta-material discussed in Ref. [93] achieved a deployable 3D structure with a 200% area change. Relying on the shape memory cycle of the material, the pattern geometry's negative Poisson's ratio, and variable stiffness, the structure deploys to the programmed 3D system upon stimuli application and recovers when removed. A finite element simulation was conducted, where the simulation predicted physical shape change with marginal errors.

Active 4D-printed lattices utilize Poisson's ratio effect pattern to drive directional motion control in irreversible structures [55]. Then, Lump and Shea [80] investigated reversible active lattices for mechanical load-bearing structures as shown in Fig. 6e. The work utilized two materials that have different T_g, which cause gradient stiffness differences at higher temperatures. Subsequently, shape morph is controlled through the material's higher stiffness due to higher T_g. A programming deformation step can be added to fix the shape morph in place, followed by cooling. Discrepancies between predicted behaviour and printed lattices were possible warping in the out-of-plane direction and local buckling of bars of the material of less T_g. A custom gradient-based optimization framework was developed by the authors to allocate the stiffer matter paths to the softer matter in the rest of the lattice.

3.5. Lightweight 4DP joint structures

This section explains the change over time due to active joints. The joints were programmed through 4DP to produce the required behaviour, which is the key distinguishing factor from previous work.

3.5.1. 4D multi-material joint

Beites [94] introduced one of the pioneering works of using SMP joints for shade unit proof of concept. In his work, the stimulus of motion was the surrounding temperature. The researcher utilized discrete assembly to attach the passive and active parts of the shaded module. He achieved up to 90° of motion actuation. In Ref. [95] the development of the same adaptive shade unit is investigated using 4D printing. Both utilized discrete assembly to achieve a larger deployable system incorporating active joints and passive shade units. The 4D thermo-responsive façade unit hinge was programmed through a material distribution of zigzag infill varying from 30 to 100%. The joints had issues being motion-constrained by the non-active tiles and had weak recovery rates.

Thermorph [96] was introduced as a self-folding 4D-printed structure methodology from 2D sheets. The researchers introduced an actuator made of 3 layers of PLA and one layer of TPU. The actuation is controlled by controlling passive and active layers, where the structure motion status is generated from the print path direction. Through print speed and print path direction of PLA, which is the active layer, folding control was achieved. Then, the motion iterations were input into the designed tool using Rhinoceros software and a grasshopper plug-in. A design to fabricate a user-friendly tool was introduced.

4D mesh [97] investigated the Thermorph [96] methodology, but with single material PLA filament printing. The active material was allocated to specific parts of the system to produce motion iterations. Two methods of shrinkage and bending upon heat stimuli were investigated. The shrinkage method achieved one-directional motion shown in Fig. 7a, while the latter achieved 3D form iteration. 4D mesh produced 4D-printed lamps, chairs, and others.

A 4D-printed solar radiation-actuated adaptive façade module with a 4D-printed SMP joint concept was presented in Ref. [99]. A SMP filament was chemically synthesized using boron nitride (H-BN), hydroxylated BN nanosheets (OH-BNNS), and PLA. The 2D BN nanosheets have a large aspect ratio of length to thickness, which contributes to anisotropic behaviour when thermally stimulated. The shear stress induced during FDM 3DP is the governing parameter in aligning the nanosheets in the conductive filament printed layers. Also, the PLA polymer chains were aligned and stretched during 3DP, which stored energy memory in the printed layers. The conductive filament was used to present a self-bending joint for window installations.

Serode et al. [100] discussed applying smart 4D textiles to façades and their positive impact on energy efficiency. Their research included textile usage, including two work levels. The first was to investigate the visual perception of users and the façade textiles, while the second was to explore diverse design and material iterations. The HEXA façade SMP joint module produced was tested and showed one-way deformation due to a lack of sufficient force to retrieve its initial position. While the bimetal 4D textile façade module was revisable, it was thus recommended for 4D textiles.

Deployable solar panel [98] was presented as a self-deployable

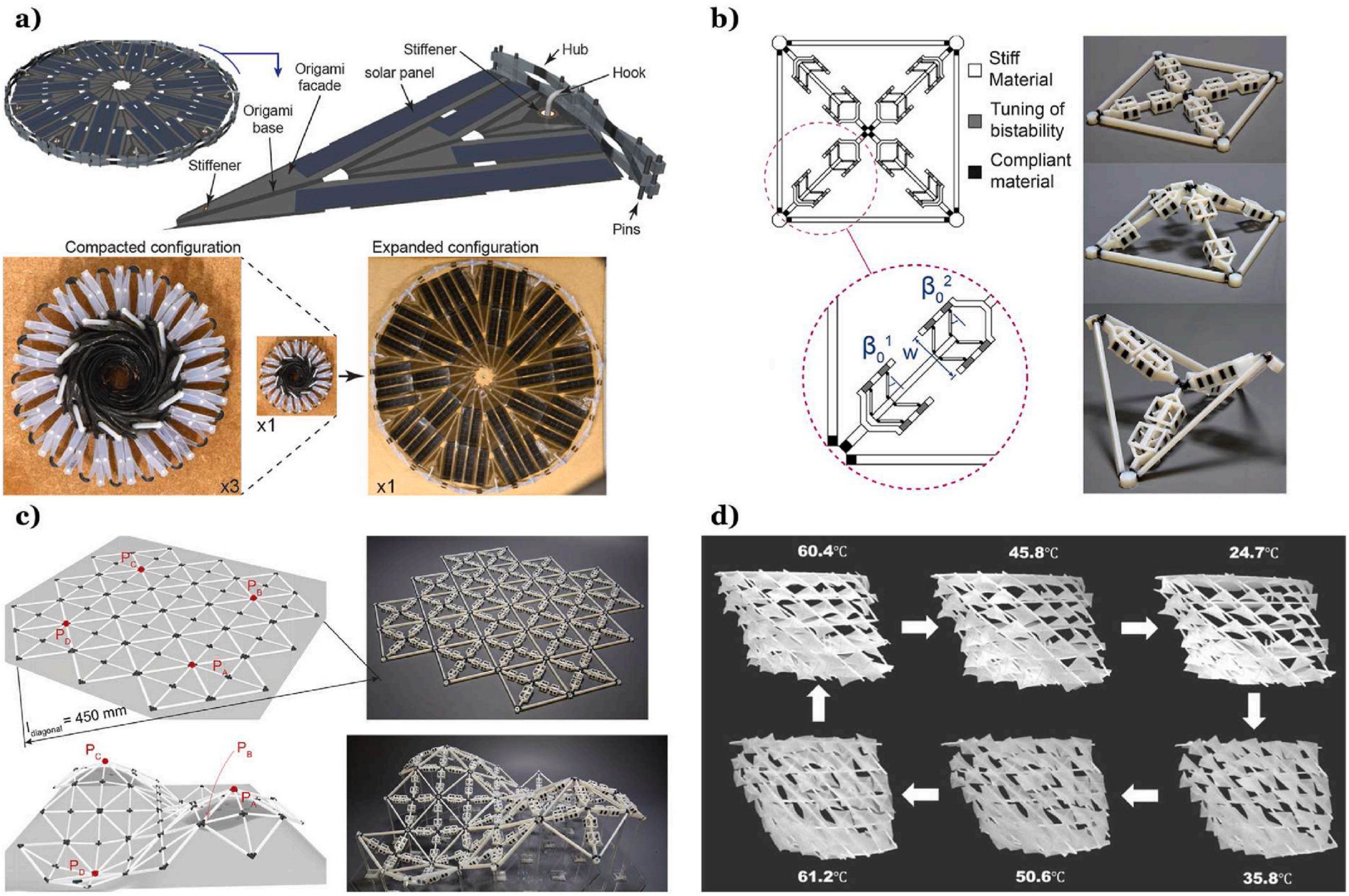

Fig. 7. 4DP Lightweight joint systems. a) Deployable solar cells [98]. b) Assembly of the bistable units into a modular 4D joint [45]. c) Achieving anticlastic and synclastic surfaces from bistable 4D joints [45]. d) Adaptive façade prototype thermal actuation [56].

mechanical system for space solar panels. The proposed idea could be applied in architectural façade mechanical systems. The system consists of a Hoberman ring (which consists of scissors joints and extra SMP joints) and an origami substrate (which has SMP at crease lines) where the solar panels are mounted. The complexity of the system comes from integrating three mechanisms of motion for the deployment: the flasher origami, the scissor, and the thermally actuated SMP joint/crease fold. Each part is printed discretely and then assembled as shown in Fig. 7a. The assembled structure is rotated from the middle, deploying in origami folds. Then, the structure is fixed in place in a specific container. Upon removing the container and water bathing the system, the system is primarily deployed by the origami folds, which have SMP parts, and then locks in its final shape by the Hoberman scissors motion actuated by the SMP joints. The SMP transits from a glassy to a rubbery state upon exceeding the T_g.

3.5.2. Bistable load-bearing

In hierarchal structures with bistable mechanisms, Chen et al. [101] investigated 4D deployable monolithic structures with load-bearing capacities. The work constructed a diverse hierarchal framework of material systems, a single 3D ink jetting print of the rigid elements, and the bistable actuator controls the shape change using the Von Mises Truss (VMT) [102]. The hierarchal system is characterized by several equilibrium states when evolved from a flat to a 3D structure, where the stimuli are needed to evoke change but not to maintain it. The prototypes presented consisted of a module of a set of actuators and rigid elements When tiling the modules, spatial structures are produced and evaluated using a modified dynamic relaxation method.

In [103], Chen et al. studied module tiling as shown in Fig. 7b from their previous work using SMP material for the actuator, which is stimulated by the surrounding temperature (environment condition) as the motion driving force. Their work used a bistable mechanism for actuation and amplifying the forces. In Ref. [45], researchers investigated the modules tiling for complex geometries realization, achieving paraboloid surface discretization using Chebyshev nets as shown in Fig. 7c. The global surface reconfiguration was achieved by modifying the internal angles of each module. Further efforts [55] to produce lightweight load-bearing structures using lattice 4D printing were made by the same researchers, but the load-bearing capacity of the lattice was less than that of the bistable deployable structure.

3.6. Heterogeneous 4DP systems

These systems refer to the 4DP of SMA and SMP. Yi et al. [56,104] investigated a two-way shape memory composite (TMSC) façade unit as shown in Fig. 7d. Researchers utilized parametric design to investigate both interwoven patterns and biomimicry of the stomatal shape of the Mexican pincushion cactus. Composites were formulated by embedding SMA wires in 3D-printed SMP matrices. Thermo-responsivity has been evaluated across the enthalpy of SMA Fiber and the entropy levels of different SMPs in the matrix. SME simulation was carried out for SMA and SMP theoretical constitutive models separately. Followed by shape memory composite (SMC) using a constitutive model (ANSYS FEM software) to parametrically identify the volumetric ratios of SMP and SMA. The interwoven pattern and biomimetic composites showed ~8 and 5–8 mm 2-way displacement on a 1:20 scale model, respectively.

3.7. Living 4DP structures

Evolving structural elements, either during the construction or operation phases of buildings, can be considered 4D-printed structural elements. The materials studied show human-controlled programmed material transformation over time, which complies with the 4D printing principles described by Ref. [105]. In this section, evolving structure studies are discussed, although they were not classified as using 4DP by their respective authors. The currently identified research areas are biologically growing (4D bio-growth), bio-illuminating (4D illuminance), and self-healing (4D heal) structures.

The 4D bio-growth research provided structures with living cells that continuously interact with their environment through photosynthesis and sometimes additional biological processes. A 3D-printed living soil structure wall [57] is classified in this paper as a 4D-printed soil wall. The biological growth of the wall from implanted seeds transcends the structure to the 4th dimension, as shown in Fig. 8a. The seed implantation in the wall was done through embedding in the mixture and spreading on the wall surface after printing; seed embedding was done in a small ratio for extrudability considerations. The fourth dimension was achieved in a controlled environment for germination and growth phases.

In [109], several studies, investigated 3DP-specific geometrical structure patterns and the control of slime mould or mycelium growth on them. The mycelium-based module was presented as a building wall unit. The presented self-growing wall structures can be classified as 4DP living structures because of the ability of human directional geometry to control living cell system growth. Jauk et al. [106] investigated growth paths of mycelium as a structural joint as shown in Fig. 8b, while Colmo and Ayres [107] investigated 4DP living walls as a non-load-bearing remedy landscape wall for contaminated sites shown in Fig. 8c. A 4D-printed acoustic material is proposed through guided paths design of bacterial cellulose growth form [110]. The growth programming in a moulded silicone vessel environment was achieved through a 3D-printed mould of special design. The 3D-printed mould controlled the growth programming, achieving 4DP principles.

3DP Living building construction material was investigated in Ref. [111] through bioprinting. Bioprinting of bio-inks and hydrogels with embedded microorganisms (living cells) was conducted to produce non-load-bearing biocement. The aid of 4D in this material investigation was to design the porosity for cell survival and allow higher growth rates for living cells. The 4D-printed bio-cement proved to be of higher strength, but further investigation is needed about porosity design to control the strength and consequently the wall's structural integrity.

4D-printed luminous structures [108] were investigated by printing light-emitting bacteria as shown in Fig. 8d. The medium containing the bacteria is spatially designed to maximize print path exposure to oxygen through large surfaces and cavities. Thus, the 4DP design of paths controls bacterial perception and illumination, while considering the wall structural stability. Other studies investigated 4DP illumination with textile substrates, like in Ref. [112], and expansion for smart actuators using protein-based hydrogel that can react to heat, PH, and enzymes [113].

4D heal is identified in this review as the ability of the material system to heal when critical material disturbances such as cracks occur. Healing is found as the programmed material distribution of healing agents to overcome any disturbance at any local point of the structure, thus preserving the structural integrity and increasing the life span of the material system. Self-healing 3D-printed concrete is found in this paper as 4D-printed concrete walls. In Ref. [114], researchers introduced 3D-printed tetrahedral mini-vascular networks, which correspond to cracks in the concrete, to fuse a healing agent that fixes the cracks and maintains the structure integrity with external interference. In Ref. [115], a self-healing polymeric composite structure was produced, which has important potential for lightweight building structures or future applications in fibre-reinforced polymers (FRP) structural columns.

3.8. Mechanisms summary

A summary of 4D printed products' motion mechanisms is presented here, which were mainly used for architecture and construction applications in Table 1. Twelve different mechanisms were investigated in the literature. Some research work utilized two mechanisms in parallel. The mechanisms identified from 4DPAAC research are non-uniform voxels

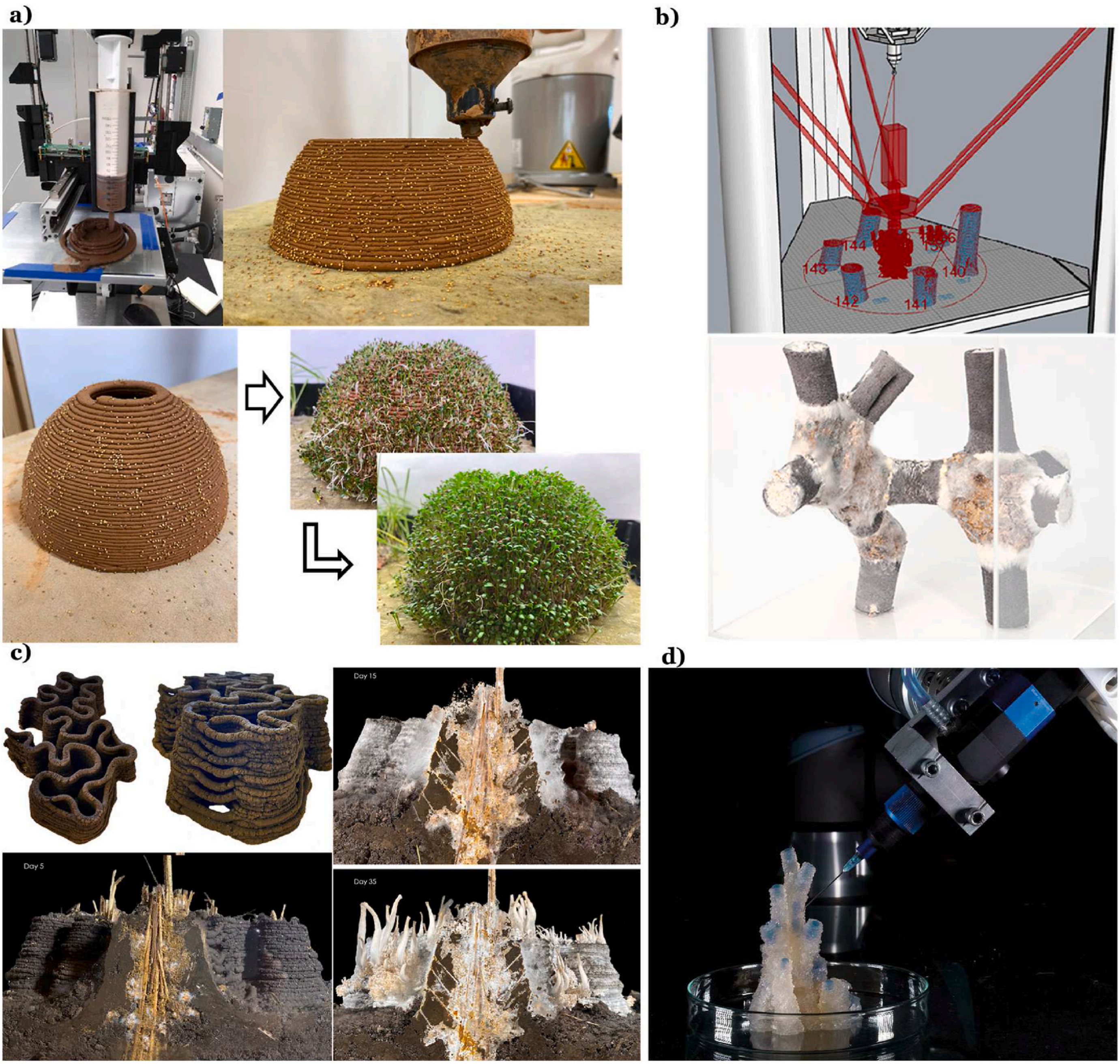

Fig. 8. 4DP Living structures. a) 4DP growth in earthen walls [57]. b) Structural living joint made by mycelium growth (adapted from Ref. [106]). c) 4DP growth walls for soil remedy (adapted from Ref. [107]). d) 4DP illuminating wall [108].

(lines/meshes/Origami), non-uniform voxels (Lattice structure), Uniform voxels (Shell structures), Uniform voxel (Lattice structure), Bistable joint, Bilayer/Lamination, Shrinkable Substrates Lamination, Embedded fibre/stiffer material in matrix, SMP joint, Tensegrity, Biological growth, Bio-interaction.

Matter voxel is the building unit/cell that constructs a structure, or it is the building block of a programmed structure [121]. The material distribution of voxels in the investigated structure varied between uniform and non-uniform distributions. As deduced from the literature, the uniform voxel material distribution mechanism was investigated in shell and lattice structures research areas, while the non-uniform was investigated in lines/meshes/origami and lattice structures. The bistability mechanism is the actuation of a joint with two rest stable states [122]. The bilayering mechanism is the deposition of the two distinct material paths over each other especially using Timoshinko's bilayer [19] and classical laminate theory [61]. The shrinkable substrate mechanism is identified as the utilization of matter's shrinkage factor which differs from bilayering which depends on the expansion factor for actuation. Fibre in flexible matrices mechanism utilizes the fibres as motion directors [123]. SMP joints mechanism utilizes the shape memory effect of mostly digital materials of SME. The tensegrity mechanism utilizes wires connection among strut elements which constrain motion upon actuation. The biological growth mechanism is the programming of a medium to be a hub for natural man-controlled bio-growth. Bio-interaction mechanism is the programming of a medium inducing illumination/healing upon stimuli application.

4. 4DP materials between 4PAAC and other disciplines

Materials used throughout the 4DPAAC identified papers are

Table 1
Mechanisms classification.

4DAC research	References
Non-uniform voxel (lines/meshes/ Origami)	[40,53,54,76,78,79,83–86,90,97,99,98]
Non- Uniform voxel (Lattice structure)	[80,92]
Uniform Voxel (Shell structures)	[21,64,81,82,87,93,116–118]
Uniform voxel (Lattice structure)	[91,119]
Bistable joint	[45,55,101,103]
Bilayer/Lamination	[21,52,54,65,66,68,70–73,62,63,64,76,82, 84–86,88,120]
Shrinkable Substrates Lamination	[75]
Embedded fibre/stiffer material in the matrix	[56,104]
SMP joint	[95,100,98]
Tensegrity	[70]
Biological growth	[57,106,110,111]
Bio-interaction	[108,112,113]

classified – shown in Table 2 – into three states of the actuator, constraint, or a medium for reaction. Curing and extra processes were sometimes found and needed as the final fabrication step.

As evident from Table 2, FDM 3D printing dominates the 4DP research in 4DPAAC for scalability (prospect ability to achieve products for buildings scale), availability of materials, higher fabrication speed than other printing methods, less curing post-printing is needed, and printers' modification applicability to experiment different materials. Enhancing the environmental impact of filaments for FDM printing has been widely investigated, either through recycled plastics [48,125] or natural materials-based filaments [126–128]. The natural material's swelling has been considered a constraint so far in manufacturing, but recently is considered an opportunity to produce stimuli-responsive bio-composites [129]. The biodegradability and environmental compatibility of natural materials exhibit a pivotal road to advance printing materials for 4DP while sustaining a favourable environmental impact, thus achieving sustainable morphing and 4D-printed components. Exploiting natural materials like fibres has been investigated to produce sustainable composites for 3D/4D printing-related materials, although not a specific discipline related. The natural fibre filament composite investigations varied from short to long fibres.

Short fibre research investigated the extrusion of granules/pulverized (natural fibre and polymer) feedstock composites with their respective additives and binders when needed. Agricultural waste-based composite filaments [130] (mixing granulated hemp fibres and weed powder, each with PLA) showed anisotropic behaviour upon stimuli application, with increased mechanical performance than their pristine components. Recycled wood from crushed wooden blocks [131] was printed with pulverized PLA to produce sustainable composite filaments with no binders used. A natural material-based commercially available filament – a mix of PLA and polyhydroxyalkanoate (PHA) matrix – has been investigated by Le Duigou et al. [132] for their hygroscopic response and consequent 4DP applicability.

On the other hand, long fibres impregnation in a polymeric matrix has been evolving for sustainable filaments' production, while investigations of their thermo-mechanical and hygroscopic response show promising results in increased strength than their counter pristine materials [129,133,134]. Twisted yarns of natural jute fibre yarn [135], continuous twisted ramie yarns [133], and continuous flax fibre yarns [50] impregnation in a PLA matrix were investigated to produce sustainable composite filaments. The jute fibre and ramie yarns-based composites were coextruded, while the flax fibre-based composite was extrusion coated achieving higher impregnation in the polymeric matrix. The continuous flax fibre yarns in PLA (CFF/PLA) filament's humidity responses were investigated in Ref. [134], and a 4DP prototype was studied in Ref. [136].

5. Discussions

The 4DPAAC presents a possible strategy to alleviate material consumption, decrease buildings' energy consumption, and provide viable solutions to control natural disaster damage. This technique could potentially be used to complement achieving the decarbonization plan of the 2015 Paris Agreement and to provide a strategy for buildings to comply with SDGs priority actions. The literature explained the controlled allocation of materials inside the system, which helps in optimizing the material used. The 4D-printed adaptive façade units were designed to utilize renewable environmental stimuli of heat and humidity for motion actuation; in turn, they minimize motors and non-renewable electric energy consumption. Also, recent research investigated the possible integration of conductors for remote human-material intervention in 4D applications. 4DP allows complex material systems, which can correspond to natural disasters caused by Earth's global temperature rise, in the form of inflatable resilient infrastructure for floods, seismic dampers, or even wind diffusing cladding. 4DP research holds a promising future for other 4DPAAC investigations such as acoustic dampers, self-healing of structural elements, self-illuminating façade, and adaptive façade units.

In reference to building components, identified research areas are classified into façade/building envelope, indoor products/furniture/artwork, and structural elements, as shown in Fig. 9a. 4DP façade/building envelope research presented static and adaptive approaches. The 4D-printed static research targeted achieving complex non-reversible form iterations with minimum manufacturing steps and providing ease of transport for the complex-shape products. The 4D-printed adaptive research approach achieved reversible units for solar shading [56,79,86,104]. The 4D-printed indoor products varied from furniture to artwork, lamps, and acoustic damping installations. The 4D-printed structural research included walls, joints, and lightweight structures like shelters. Adaptive façades dominated 4DP research, followed by lightweight structures and then indoor products, with percentages of 49.2%, 20%, and 13.8%, respectively as shown in Fig. 9b. It is observed that shape morph in 4DPAAC is found in either mechanical shapeshift or bio-growth. Shape morphing dominated 4DPAAC research by securing 90.6% of total research above others, as shown in Fig. 9b.

6. Research outlook and conclusion

It is evident from the literature that the 3DP challenges (e.g., warping-shape deformation) are becoming opportunities for 4DP. The 4DPAAC could be practised through either the interplay of stress in the material system or a human-controlled material interaction level of the material system. The interplay of stress among the material system due to stimulus application is found in single and multi-material systems, which is done through print path control. The programmed interaction is achieved through the control of the interaction surface (programming the print paths) between the bi-matter and stimuli for variable controlled iterations. The scale of shape morph varied [80], reaching a macro-scale reversible shape-change of large-scale 4D-printed lattices, but due to self-weight, self-actuation wasn't possible, and an external lift of weight was needed. The bio-growth achieved fits buildings' requirements, and thus upon further development, can be adapted to buildings.

Some building components were not 4DP investigated, although integration of 4DP holds an opportunity for possible progress, like wind diffusing panels, structural columns, joints, and foundations. Upon exploring the recent advances of 4DP in other disciplines, such as robotics, apparent 4DP research investigations and reorientation towards 4DPAAC can be done to provide environmental solutions. Sugahara [124] presented programming 3D-printed acoustic tiles. The tiles consisted of a unit cell matrix. Each unit cell contains a hole with a geometrical material system inside. The results indicated that the larger the hole, the less the sound damping, while the denser the grid-like

Table 2
Materials identification for all 4DPAAC research discussed.

Materials			Printing method			
Actuators	Constraints	Curing/extras/medium	FDM	LDM	Inkjet/ polyjet	SLA
PLA		–	[53,78,87,90,97]			
Nylon (PA6)		–	[87]			
TPU/PU		–	[81,87,88]			
SMA-SMP		–	[56,104]			
WPC: Laywoo-D3 (40% wood flour and PLA polymer matrix)		–	[63]			
LAywood meta5: Cardboard/polymer filament		–	[40]			
PLA/Proto-Pasta Magnetic Iron PLA (PLA + iron)		–	[77]			
H-BN + OH-BNNS + PLA		–	[99]			
MM5520 SMP		–	[95]			
Carbon fibre impregnated with PLA		–	[91]			
VeroWhitePlus RGD835 (VW+)		–			[93]	
Protein-based hydrogel (Temperature-Ink, pH-Ink, and Enzyme-Ink using methacrylate bovine serum albumin (MA–BSA) as a building block		–			[113]	
Ceramic blended resin (Therma 294)		–				[124]
Conductive Graphene PLA	NP: Paper	–	[68]			
NP: bilayered beech-maple wood veneer	PLA/cellulose-filled plastic bio-composite (UPM Formi 3D 20/19 - UPM)	–	[64]			
Laywood filament	PLA	–	[82]			
Laywoo-D3	PLA/ABS	–	[63]			
Laywood Meta5 (40% cardboard and polymer	ABS	–	[66]			
WPC	ABS	–	[21,84,86]			
Undetermined copolyester	ABS	TPU hinge	[38]			
WPC	TPU	–	[38,79]			
PLA	TPU	–	[96]			
Glass/Carbon fibres	PLA/PLA composite with 1% magnetic nanoparticles MNPs	–	[67]			
Cellulose-TPU_PK filament	PLA	–	[86]			
VeroWhite+ (VW)	High temperature (HT)	–			[80]	
FLX9895 VeroWhitePlu,	–	Agilus30, and SUP760 a chemically dissolvable			[45,101,103]	
Hakko Shrink Film 841-02 + Vilene Iron Shrink Sheet OR-30 N	Mimaki LUS-150 (CMYK + White)	LH-100 (clear) + PR-200 (primer) as UV curable inks			[75]	
Tango+	Vero family	–			[54]	
Polytek PlatSil Gel-25 silicone	Smooth-On Sorta Clear silicone	–				[120]
NP: Polyamide lycra	PLA-TPE	–	[70]			
NP: Polyester fabric	PLA	–				
Fabric (Polyamid (80%) + Spandex (20%))	PLA/TPU 95A	–	[73]			
Ko-BO (SMP)	NP: Elastic fabric	–	[100]			
NP: Lycra fabric	TPU 95/Polypropylene/PA	–	[74]			
NP: Spandex fabric	TPU/PLA	–	[62]			
NP: polyester/Lycra jersey knit	TPU/PLA	–	[71]			
Jersey fabric	HS-ABS	–	[52]			
NP: Maple and spruce veneer layer	Flexifil thermo plastic composite TPC	–	[76]			
Bacillus subtilis spore	Flexible inert film (0.2-mm-thick latex, 0.3 mil Kapton, and 0.3 mil polyethene terephthalate)	–	[65]			
NP: bilayered wood composite	Cellulose-filled bio-based polylactic acid compound (UPM Formi 3D 20/19, UPM Biocomposites)	–	[85]			
Modified polyethylene terephthalate (PET)	Polycarbonate (PC)	–	[92]			
White clover (Trifolium repens) seeds	Mosser Lee ML1110 Desert Sand, red clay fill dirt from Barboursville, VA, and the silt from Nephi, UT with water content 30–35%	–		[57]		
Cyanobacterium Synechococcus sp. strain PCC 7002	–	Bioink (alginate + methylcellulose + sea sand)	[111]			
Mycelium (clay and water, and organic parts)	–	Substrates (sawdust/bleached cellulose/ unbleached cellulose)		[106]		
10% mycelium spawns	–	60% soil, 0.4 % xanthan gum, 0.2% guar gum, 20% water, 2% wet hay, 1% glycerol, 1.4% molasses, and 5% perlite.		[107]		
Bacterial cellulose biofilm	–	Silicone resin	[110]			
Bacteria	–	Agar, Gelatin, Glycerin, Nutritive media, and water	[108]			

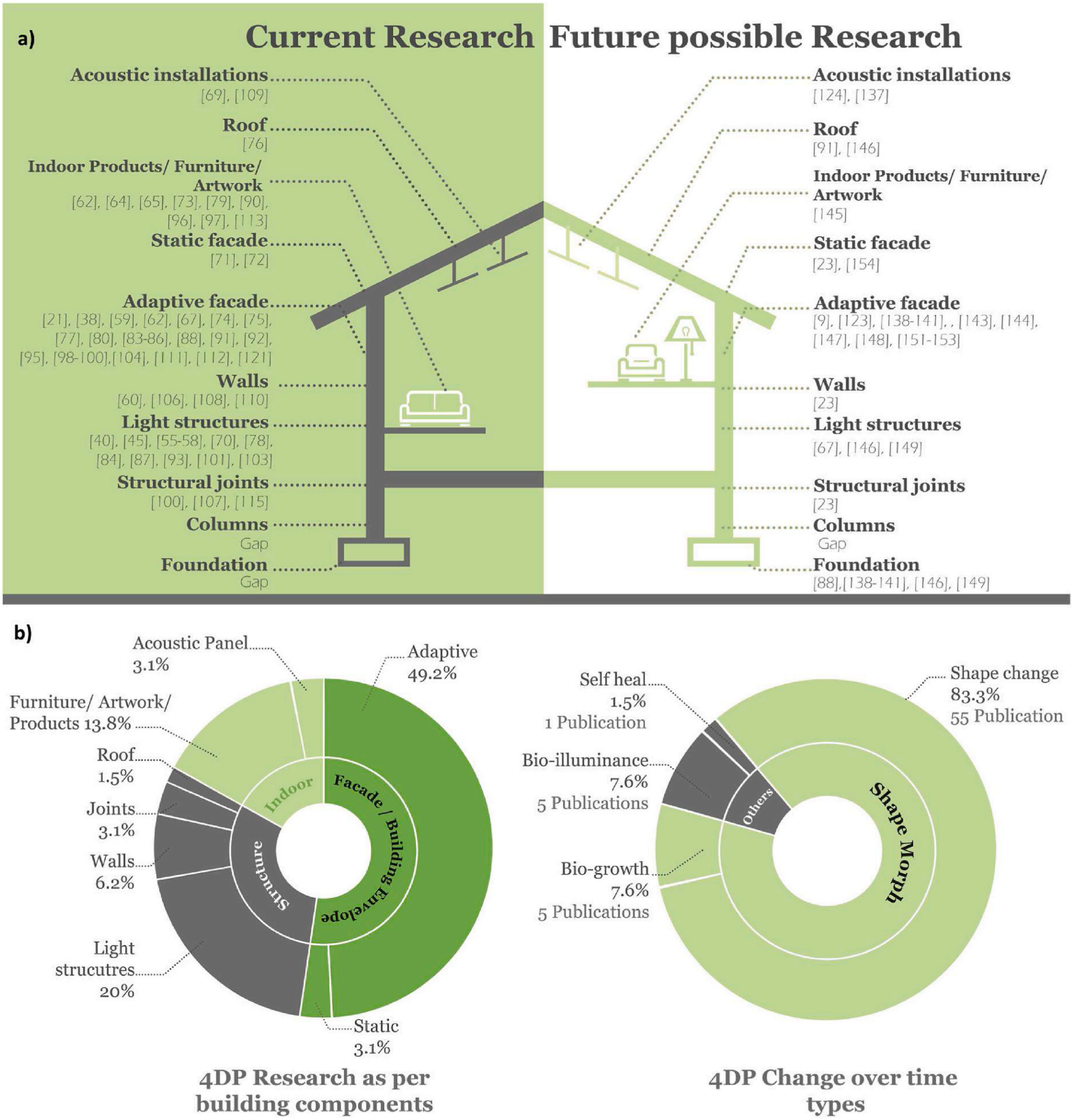

Fig. 9. 4DPAAC literature classification. A) Classification of current and possible future investigations for 4DPAAC. B) Statistics of 4DP research done on each building component and 4DP change over time.

material system inside the hole, the larger the damping. Mixing both could help tailor the required performance. This approach can help tailor sound absorption globally over diverse panels, or locally over the same acoustic panel. 4D-printed thermally excited membranes, single and multi-material, with subsequent frequency variation, were introduced in Ref. [137], which can present future 4D-printed acoustic panel control if merged with Sugahara's unit cell 3DP explorations. The 4D programming proposed will be the result of the material print pattern and its impact on sound resonance control for damping applications.

Previous research work utilized SMA as an energy-dissipating material for seismic energy control [138–141]. Damping through 4DP was investigated in Refs. [37,88,142], which, if investigated with seismic vibrations, can present future seismic energy-absorbing solutions. Finding a replacement for metal wire programming with other 4DP will help boost a higher level of control over the dampers' design. Overcoming the self-weight challenge of 4D-printed adaptive façades can be done by amplifying the load capacity of joint systems through complex 4DP like in Ref. [143], which, upon further development, can allow soft actuation of façade joints or expandable roofs. Modular joint stacking for force amplification [101] and integrating an actuating surface along with a truss system with hinges [144] could provide a viable prospective solution to enhance the applicability of 4DP in the building sector. Also, multi-actuation mechanisms stacking in a single system, like in Ref. [98], can provide a solution to amplify forces to fit the building's load-bearing scale requirements.

Another observed possible application is 4DP smart textiles for home applications, which can build on previously investigated non-4D-printed smart textile products for homes [145]. 4DP inflatables during flooding could be investigated by building upon inflatable dome patterns [146], 4D pneumatic soft robots [147,148], and 4D-printed self-healing structures [149]. Bridging such research investigations into the building and construction sector, especially structural elements research, can help increase the life span of the structure system and minimize waste due to demolition.

Among the challenges in 4DP for architectural applications is considering the sustainability dimension of the materials used in parallel to the required mechanical properties. In Ref. [125], recycling and self-healing of plastics through 4DP to minimize waste were investigated. Natural fibre integration into the 4DP for shape morphology is considered to have a great sustainable and green impact, where the opportunity arises from the fibre hygroscopic properties [49]. It is worth noting the current advances in 4DP methods, although non-4DPAAC, such as higher fibre impregnation in the print path through rotational printing [150], achieved a higher level of sub-voxel control.

Extra features investigated, like remote actuation and faster actuation, enhance the 4DP practicality, which can help in achieving an upscale building-suitable product. Remote actuation [151,152] through integrating electroactive materials during 4D printing, which provides dual actuation, allows human intervention of architecture components when needed [153]. 4DP construction moulds for concrete and other possible materials can help produce diverse complex shapes, and the moulds would return to their initial flat position afterwards. An example of this was presented in Ref. [23], where a 4D-printed SMP precursor was used to achieve diverse, complex ceramic products. Another interesting future irreversible façade product with good insulating capabilities can be achieved by utilizing the 4DP of ceramic introduced in Ref. [154].

Using 4DP techniques to further develop art, architecture, and construction may, in the future, help close research gaps, provide viable solutions, align with decarbonization goals, and offer a resilient, sustainable city perspective.

CRediT authorship contribution statement

Dalia Niazy: Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Mahmud Ashraf:** Writing – review & editing, Supervision, Resources, Project administration, Methodology. **Mahdi Bodaghi:** Writing – review & editing, Methodology, Conceptualization. **Ali Zolfagharian:** Writing – review & editing, Supervision, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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