

Jun 8th, 9:00 AM - Jun 12th, 5:00 PM

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Qin, J., Pei, E., and Cifter, A.S. (2026) A hierarchical and ontology-based taxonomy of stimuli–smart materials–transformation effects in 4D printing as a new interactive modality, in Simeone, L., Gray, C. M., Verhoeven, A., de Götzen, A., Bakırlıoğlu, Y., Zohar, H., Stead, M., and Buwert, P. (eds.), *DRS2026: Edinburgh*, 8–12 June, Edinburgh, United Kingdom. <https://doi.org/10.21606/drs.2026.1046>

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A hierarchical and ontology-based taxonomy of stimuli–smart materials–transformation effects in 4D printing as a new interactive modality

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doi.org/10.21606/drs.2026.1046

Abstract: 4D printing functions not merely as a smart manufacturing technique but as an interactive material technology: materials respond to human or environmental stimuli and generate a direct feedback loop. This study proposes a taxonomy that links Stimuli, Smart Materials, and Transformation Effects, developed through a combined Hierarchical Classification and Ontology-Based Classification approach grounded in a systematic literature review and ontology mapping. By organising complex stimulus–material–effect relationships into a designer-accessible structure, the taxonomy supports non-technical designers in identifying feasible pathways from intended interactions to material outcomes. It also provides a structured data foundation for developing 4D printing design guidelines and toolkits, enabling more direct translation of 4D printing concepts into real projects. Positioned as an interface between human intent and material expression, the proposed framework highlights how 4D printing can enable new forms of interaction design and fluid, responsive artefacts across design domains.

Keywords: 4D printing 1, Design Technologies 2, Human–Material Interaction 3, Ontology-based Taxonomy 4

1. Introduction

Additive manufacturing (3D printing) creates objects layer by layer from digital models, offering greater design flexibility and material efficiency than traditional methods (Nam & Pei, 2019). Despite these benefits, conventional 3D printed parts remain static, limiting their adaptability and functionality (Pei, 2014). The emergence of 4D printing (4DP) addresses these limitations by integrating smart materials capable of responding dynamically to external stimuli, enabling structures to be programmed for transformations (Joshi et al., 2020; G. H. Loh et al., 2018).

The concept of 4DP was first introduced by Tibbits (2014) as an evolution of 3D printing that adds time as a design dimension. In practice, this time dimension is enabled by printing with smart materials, whose programmed responses can be activated by external stimuli such as



heat, moisture, light, chemical conditions (e.g., pH), electric or magnetic fields, and mechanical loading, so that the printed object can change over time (Joshi et al., 2020; G. H. Loh et al., 2018; Pei, 2014). From a design perspective, the stimulus-driven behaviour of smart materials becomes a design variable in 4DP, allowing designers to specify not only the printed form but also how it responds and changes under defined stimuli. Table 1 highlights how 4D printing extends conventional 3D printing by replacing static material behaviour with stimuli-responsive smart materials, enabling intrinsic capabilities such as stimulus-triggered actuation, time-dependent reconfiguration, and damage recovery (when self-healing chemistries or architectures are used).

Table 1 Selected common capabilities enabled by 4D printing systems (dependent on smart material choice and design/programming strategy), compared with conventional 3D printing.

Capabilities	4D printing	3D printing
Stimulus-triggered shape change	Printed smart materials can change geometry when stimulated, enabling programmed shape transformations (Joshi et al., 2020; Pei, 2014).	Printed parts are typically static and do not transform in response to stimuli without additional mechanisms.
Programmable time-dependent behaviour (shape memory / multi-stability / self-deployment)	Time-dependent behaviours can be designed through material selection and structural programming, allowing reconfiguration after printing (Ahmed et al., 2021; G. H. Loh et al., 2018).	Geometry is fixed after fabrication; reconfiguration usually requires assembly or external actuators.
Functional feedback via property modulation (e.g., colour / stiffness / conductivity)	In some material systems, stimuli can modulate properties (e.g., optical or mechanical) and provide perceivable feedback useful for interaction and adaptive functions (Ahmed et al., 2021).	Property change is not typically stimulus-responsive; feedback requires embedded components or post-processing.
Compact fabrication-to-deployment strategies (flat-pack / self-assembly in specific approaches)	Certain self-assembly or flat pack approaches can transform from simple printed states to more complex forms when triggered, reducing assembly steps in those cases (Ahmed et al., 2021).	Similar deployment usually requires manual assembly or additional mechanisms.
Self-healing	Some 4DP material systems can recover damage through intrinsic or extrinsic self-healing mechanisms, enabling partial restoration of function or geometry under suitable conditions (J. Wang et al., 2023; B. Zhang et al., 2019).	Typical 3D-printed parts are passive after fabrication and do not self-repair without specialised self-healing material systems or external repair steps.

From a fabrication perspective, 4DP does not require a completely new manufacturing category, it is typically realised through established additive manufacturing processes. The 4DP literature most commonly reports four process families: (1) material extrusion, including fused deposition modelling and direct ink writing, which is widely used for thermoplastic shape memory polymer (SMP) filaments and printable hydrogel/functional inks; (2) vat photopolymerisation, such as stereolithography and digital light processing, which supports high-resolution printing of photocurable SMP-based systems; (3) powder bed fusion, including selective laser sintering/melting, which is frequently associated with powder-based polymers and shape-memory alloys; and (4) material jetting (e.g., inkjet/PolyJet-type approaches), which is often used for multi-material deposition and programmable composites (Ahmed et al., 2021; Antezana et al., 2023; Rastogi & Kandasubramanian, 2019).

Beyond manufacturing, we position 4DP as a novel interactive technology. Interaction is not confined to screens or conventional interfaces, but enacted through human–material interaction, where users or environments provide stimuli and materials respond through perceivable changes in shape or properties. In this view, 4D-printed artefacts function as interfaces that translate human intent or environmental signals into material expression, creating a direct feedback loop between stimulus and response that aligns with core definitions of interaction design (Kolko, 2010). Recent human–computer interaction research similarly frames smart materials as shape-changing interfaces, where inputs such as humidity, pH, heat, or light are converted into visible changes in form or colour, making the material itself the site of interaction. For example, xPrint links printing parameters and material chemistry to define interactive outcomes (G. Wang et al., 2016). This perspective is increasingly reflected in fashion and textile research, where 4DP is discussed as an enabling approach for adaptive wearables and smart textiles (Li, 2023; Manaia et al., 2023). Experimental studies demonstrate textile–polymer composite routes that translate stimulus-responsive behaviours into design-relevant transformations, such as depositing polylactic acid based structures onto nylon fabrics to realise thermally triggered shape recovery within textile forms (Leist et al., 2017), and developing thermo-responsive polymer–textile composites whose deformation behaviours can be tuned through material and fabrication parameters for shape-changing textile applications (H. H. Loh, 2021). This opens opportunities in fashion, product design and architecture, where material dynamic transformations can enhance user experience, functionality, and aesthetic value (Li, 2023; Manaia et al., 2023).

Nevertheless, compared with its wide adoption in technical fields such as soft robotics, biomedical devices, and aerospace engineering, 4DP remains relatively underdeveloped in the creative industry, partly because it requires the integration of materials science, physics, and design aesthetics. Notably, translation from material behaviour to design intent requires effective cross-disciplinary communication and representation (Azhar & Pei, 2019). A persistent barrier is that designers and engineers often lack a shared way to specify and predict time-based transformations, which limits practical decision-making in stimulus selection, material choice, and expected transformation effects (Azhar & Pei, 2019, 2023). This motivates the need for an accessible taxonomy that explicitly links Stimuli, Smart Materials, and Transformation Effects to support creative design application.

Hence, this research aims to bridge the gap between technical 4DP innovation and creative practice by establishing a designer-accessible framework that links Stimuli, Smart Materials, and Transformation Effects. This paper focuses on showing how these relationships can be systematically categorised through combined hierarchical and ontology-based classification to support design application. A brief questionnaire study was conducted and reported in the final section to provide preliminary support for the taxonomy’s relevance and clarity.

2. Research methods

To build a systematic and designer-readable taxonomy of Stimuli, Smart Materials, and Transformation Effects in 4DP, this study combined a Systematic Literature Review with an Integrative Review to ensure both comprehensive coverage and consistent terminology (Whittemore & Knafelz, 2005). Based on the resulting data base, the taxonomy was

constructed through a hybrid qualitative classification strategy: Hierarchical Classification structures each domain into layered categories, while Ontology-Based Classification links the domains by mapping evidence-supported relationships among Stimuli, Smart Materials, and Transformation Effects (Hoehndorf et al., 2011; Wessel et al., 2018). In addition, a small questionnaire-based user study was included to (i) capture designer needs that motivate the taxonomy and (ii) collect expert feedback as preliminary validation.

2.1 Systematic Literature Review

A systematic literature review (SLR) was conducted to build an evidence base for categorising the relationships between Stimuli, Smart Materials, and Transformation Effects in 4DP. A PRISMA-style screening workflow was used to document study identification, screening, eligibility assessment, and inclusion. PRISMA is a reporting guideline for systematic reviews that uses a structured checklist and flow diagram to improve transparency and completeness in documenting study identification, screening, eligibility, and inclusion (Moher et al., 2009; Page et al., 2021). It was adopted in this study because relevant 4DP evidence is dispersed across disciplines and databases, making the screening pathway difficult to audit without a structured record. Following PRISMA, we recorded the number of records and key exclusion decisions at each stage and reported the full selection flow, ensuring traceability from the initial search to the final corpus used for coding and classification (Page et al., 2021). To strengthen reproducibility of the search reporting, database-specific search strings and related details were documented following PRISMA-S principles (Rethlefsen et al., 2021). The search focused on English-language, peer-reviewed journal and conference publications published between 2013 and 2024. Searches were carried out across Scopus, Web of Science, ScienceDirect, Taylor & Francis Online, and Google Scholar. Database-specific search strings were constructed using Boolean logic by combining four keyword blocks: (i) 4D printing terms (e.g., “4D print*”, “four-dimensional print*”), (ii) stimulus terms (e.g., thermal, humidity/moisture, light/photoresponsive, pH/chemical, electric, magnetic, mechanical), (iii) smart material terms (e.g., shape memory polymer, hydrogel, liquid crystal elastomer), and (iv) transformation effect terms (e.g., shape change, shape memory, multi-stability, self-assembly, self-healing, colour change, stiffness/conductivity change). The full database-specific strings and initial record counts are provided in Appendix I (Table I-1).

Records retrieved from all databases were merged and deduplicated, resulting in 5,043 unique records. Titles and abstracts were screened against predefined eligibility criteria, followed by full-text assessment. Eligibility and quality criteria were defined to ensure that included studies explicitly addressed 4DP and reported a stimulus-triggered response mechanism. Studies were included only if they clearly described (i) an external stimulus, (ii) a stimuli-responsive smart material, and (iii) an observable transformation effect. Studies were excluded if they focused on static 3D printing without time-based or stimulus-responsive transformation, did not explicitly identify a stimulus, did not employ stimuli-responsive materials, or did not report transformation effects. Only peer-reviewed sources with sufficient methodological transparency to interpret stimulus–material–effect relationships were retained. A detailed list of inclusion, exclusion, and quality criteria is provided in Appendix II. The screening flow and the number of records retained at each stage are

reported in Figure 1. After full-text screening, 230 publications were retained for subsequent coding and taxonomy construction.

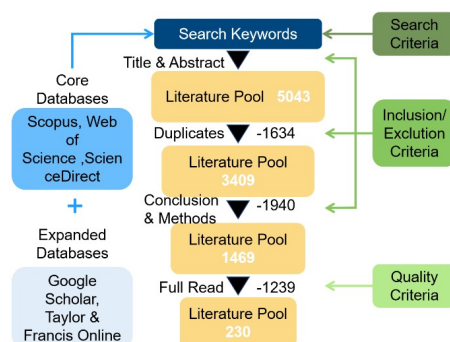


Figure 1 PRISMA-style screening workflow for the systematic literature search and study selection.

2.2 Integrative Review and terminology normalisation

Because 4DP research is reported across materials science, engineering, robotics, biomedical studies, and design, similar concepts are frequently expressed using different terms. Therefore, an Integrative Review (IR) step was conducted to normalise terminology before coding and taxonomy construction, so that equivalent concepts were treated consistently across the dataset (Torraco, 2005; Whittemore & Knaf, 2005). Terms and near synonyms were extracted from the final included corpus and cross-checked against highly cited review papers to establish a controlled vocabulary. For example, stimulus variants (e.g., thermal/heating/temperature; humidity/moisture; light/UV/photoresponsive) were consolidated, material naming was standardised into common families (e.g., SMPs, hydrogels, LCEs), and outcome wording (e.g., behaviour/response/effect) was normalised under the unified label Transformation Effects, with common effect variants grouped to avoid duplicate nodes. Mapping decisions prioritised consistent usage across multiple studies and alignment with baseline review definitions (Torraco, 2005). The resulting controlled vocabulary was applied in the subsequent coding, ensuring consistent labels in the hierarchical taxonomy and reducing fragmentation in the ontology-based mapping.

2.3 Combined Classification Methods

This study combines Hierarchical Classification (HC) and Ontology-Based Classification (OBC) to organise relationships among Stimuli, Smart Materials, and Transformation Effects in a way that is both designer-readable and semantically explicit. HC provides a clear tree structure and consistent category labels for each domain (Wessel et al., 2018), while OBC captures cross-domain dependencies and supports multi-directional navigation across stimulus–material–effect links (Sanya & Shehab, 2014). Using OBC alone can fragment information because relational networks do not inherently impose hierarchy (Hoehndorf et al., 2011), whereas HC alone can be overly rigid and does not represent many-to-many cross-domain relationships.

In practice, the final screened corpus was coded by extracting, for each study, the stimulus applied, the stimuli-responsive material used, and the observable transformation effect reported. Terminology consistency was supported by the normalised terminology table produced through the Integrative Review, so that near synonyms across disciplines were

mapped to a single label during extraction. Where descriptions were ambiguous, the original source was revisited, and brief coding notes were recorded to maintain traceability and improve consistency across the dataset. HC was then applied to organise the extracted codes into three parallel hierarchies (Stimuli, Smart Materials, and Transformation Effects), which define the controlled category labels used throughout the paper (Fig.2).

In this paper, the ontology-based component is implemented as a lightweight knowledge graph rather than a fully axiomatized ontology. It uses three top-level classes (Stimulus, Smart Material, Transformation Effect) and a minimal set of relation types to represent (i) a stimulus activating a material response and (ii) the material producing an observable effect. Each edge is retained only when the source explicitly reports the stimulus–material–effect triad, and relationships are stored with bibliographic provenance so that every link can be traced back to the supporting publications. No inferred links were added beyond what was explicitly reported in the included papers. Because the corpus selection is PRISMA-documented and each edge is stored with bibliographic provenance, the mapping can be independently reconstructed and checked for reproducibility. This combined approach enables both systematic exploration within each domain (via HC) and multi-directional navigation across domains (via OBC), allowing designers to flexibly tailor their search to different needs and workflows by starting from a stimulus, a material, or a desired transformation effect.

3. Taxonomy of Stimulus, Smart Material, and Transformation Effect

Within existing attempts to organise and review 4DP knowledge, some studies focus on the properties of individual stimulus (Chu et al., 2020), while others explore stimulus-responsive materials (Ahmed et al., 2021; Joharji et al., 2022; Joshi et al., 2020). However, there is a lack of a systematic framework that connects these three key elements (Stimuli, Smart Materials, and Transformation Effects). This gap limits designers' ability to fully understand the potential of 4DP technology, making it challenging to consider Stimulus, Smart Materials, and desired Transformation Effects holistically when developing design solutions. Specifically, a HC was applied to further categorise the three key elements into a tree structure. Based on this tree structure, an OBC was then used to map the interrelationships among the subcategories. This process led to the development of a systematic taxonomy designed to support flexible design-oriented queries.

3.1 Hierarchical classification of Stimuli, Smart Materials and Transformation Effects

Hierarchical Classification (HC) is used to organise the 4DP literature into an accessible, multi-level structure, enabling consistent naming and navigation across the three core domains: Smart Materials, Stimuli, and Transformation Effects. The following overview introduces these domains in a sequence that reflects a typical design workflow, moving from material choices to activation conditions and then to observable outcomes.

Most designers face the choice of materials first in their redesign workflow. Smart Materials have been widely classified in the 4DP literature based on their stimulus-responsiveness and

dominant actuation mechanisms. Three material families are most frequently reported: Shape Memory Materials (SMMs), Hydrogels, and Liquid Crystal Elastomers (LCEs) (Chu et al., 2020; Momeni et al., 2017). SMMs include SMPs, Shape Memory Alloys, Shape Memory Ceramics, Shape Memory Hydrogels, and Shape Memory Gels. They are valued for large, programmable shape recovery, most commonly triggered by heat and, in some systems, by light or other inputs (Chu et al., 2020; Momeni et al., 2017). Hydrogels are hydrophilic polymer networks that undergo reversible swelling/shrinkage and can respond to multiple environmental cues such as temperature, pH/ionic conditions, light, and electric fields, making them widely used in biomedical and biomimetic contexts (Jiang et al., 2020; Zhao et al., 2022). LCEs exhibit programmable anisotropic deformation (e.g., contraction, bending, twisting, curling) under heat or light due to mesogen alignment, supporting fast and reversible actuation behaviours (White & Broer, 2015). Beyond these dominant families, the literature also reports other functional material classes—such as electroactive/conductive polymers, magneto-responsive materials, piezoelectric composites, and chromic systems—which extend 4DP capabilities toward sensing, remote actuation, and optical feedback (Kouka et al., 2023). Table 2 summarises major smart material families, typical activation routes, and the dominant transformation effect families commonly associated with each material class.

Table 2 Compact classification of major Smart Material families used in 4D printing (synthesised from (Chu et al., 2020; Joharji et al., 2022; Kouka et al., 2023; Momeni et al., 2017; Zhao et al., 2022)).

Smart material family	Response stimuli	Dominant transformation effects	Commonly application contexts
Shape Memory Materials	Thermal; Light; Electric; Humidity	Shape recovery; Shape change (folding/bending/curling/twisting etc.); Expansion/ Contraction; Property modulation (conductivity/stiffness/optics/ colour-change etc.); Self-healing	Deployable products, adaptive structures, soft actuation
Hydrogels	Thermal; Light; Electric; Humidity; pH	Swelling/shrinkage; differential swelling (bending/curling/folding etc.); Property modulation (stiffness/optics/ colour-change etc.); Self-healing	Biomedical/bio-inspired design, soft interfaces, responsive textiles
Liquid Crystal Elastomers	Thermal; Light; Electric; Humidity; pH	Reversible anisotropic actuation (contraction/bending/twisting/curling etc.); Property modulation (stiffness/optics/ colour-change etc.)	Soft actuation, artificial muscle-like behaviours, responsive surfaces
Other functional smart materials (electroactive/conductive, magneto-responsive, piezoelectric, chromic)	Electric; Magnetic; Mechanical stress; Thermal; Light	Property modulation (conductivity/stiffness/optics/ colour-change etc.); Shape change (folding/bending etc.)	Self-sensing structures, untethered actuation, visual feedback in products/textiles

4DP relies on the Stimuli, which serve directly to influence material behaviour and permit dynamic transformations. In most literature reviews on 4DP, Stimuli have already been classified and described in detail. Based on their intrinsic properties, these Stimuli include physical (e.g., thermal, humidity, light, electric, magnetic and mechanical stress), chemical (e.g., pH and solvents), and biological (e.g., enzymes) triggers (Chu et al., 2020; Rastogi &

Kandasubramanian, 2019). In Table 3, the reviewed literature outlines the property-based classification of 4DP Stimuli and provides a brief overview.

Table 3 Stimuli used in 4D printing: designer-facing definitions, typical compatible Smart Material families, and design considerations (synthesised from Ahmed et al., 2021; Antezana et al., 2023; Chu et al., 2020; Joharji et al., 2022; Joshi et al., 2020; Kantaros et al., 2023; Momeni et al., 2017; Rastogi & Kandasubramanian, 2019; Yang et al., 2017).

Stimulus	Definition	Typical compatible smart materials	Design considerations
Thermal	Heating input to activate internal stress inequalities, leading to controlled shape changes.	SMPs, SMAs, LCEs, Hydrogels, Thermochromic composites	Activation temperature & safety; power/heat source; reversibility; cycle durability
Humidity	Water uptake/loss drives swelling or differential strain	Hydrogels, SMPs, LCEs, Hygromorphic composites	Environment dependence; response speed; hysteresis; long-term stability in wear
Light	Illumination triggers photochemical/photothermal response	Photo-SMPs, photo-LCEs, Photothermal composites, Chromic composites	Illumination conditions; penetration depth; ageing; safety (UV)
Chemical	Chemical variations like pH shifts drive solubility or swelling changes	pH/ionic-responsive hydrogels	Medium availability; reversibility; contamination/biocompatibility constraints
Electric	Electric input drives actuation or property change	Electroactive/conductive polymers; Conductive composites	Power supply & electrodes; insulation; heat generation; material fatigue
Magnetic	Magnetic field enables remote actuation (often via particles)	Magneto-responsive elastomers/composites	Field equipment; particle alignment; controllability; scalability
Mechanical stress	External force/strain triggers response or feedback	Piezoelectric / mechanochromic composites	Force control; fatigue; calibration; repeatability

Transformation effects refer to observable functional or structural changes in 3D-printed objects under stimuli. Currently, Transformation Effects have not been systematically classified or discussed in literature. Most technical papers focus on individual Transformation Effects such as bending, while review articles rarely offer a structured overview. Notably, Nam and Pei (2019) systematically categorised shape-change behaviours from a geometric perspective based on observable deformation outcomes, identifying modes such as bending, folding and twisting etc. However, they did not further classify these transformations based on the underlying mechanisms involved in achieving each specific geometric change. To address this gap, Transformation Effects are organised here into three outcome families, grouped by what primarily changes in the artefact during activation to support consistent terminology and effect-led interpretation. Self-adaptive effects refer to stimulus-triggered adjustments that primarily alter a material's optical, mechanical, or surface state rather than reconfiguring overall geometry; in the literature these are commonly reported as colour-change behaviours, material property modulation (e.g., stiffness, conductivity, transparency, magnetic or piezoelectric responses), and surface morphology modifications such as texture or optical surface adjustments (Tran et al., 2022; Wu et al., 2020). Shape-changing effects capture visible geometric transformations and can be described either by the underlying mechanism (e.g., shape-memory recovery, multi-stability switching, self-assembly) or by the resulting deformation outcome (e.g., folding, rolling, bending, twisting, buckling, curling, and

expansion/contraction) (G. H. Loh et al., 2018; Nam & Pei, 2019). Self-healing effects represent autonomous restoration after damage and are distinguished as intrinsic (arising from dynamic reversible bonding or chain diffusion within the matrix) or extrinsic (enabled by embedded healing agents or delivery networks such as capsules or microvascular systems) (Abdullah & Okay, 2023; B. Zhang et al., 2019). Table 4 summarises this outcome-based classification with representative examples to support consistent terminology and effect-led interpretation in subsequent mapping. As summarised in Fig 3., HC provided an accessible, multi-layered breakdown of each element, allowing designers to understand the internal categories of Stimulus types, Smart Materials classes, and Transformation Effects behaviours.

Table 4 Transformation Effects taxonomy for 4D printing, organised into self-adaptive, shape-change, and self-healing effect families (synthesised from (Ahmed et al., 2021; Antezana et al., 2023; Chen et al., 2021; Chu et al., 2020; Joshi et al., 2020; Kouka et al., 2023; Li, 2023; G. H. Loh et al., 2018; Momeni et al., 2017; Zhu et al., 2018).

Category	Sub-category	Representative Examples
Self-Adaptive Effects It describes a material's ability to adjust continuously and reversibly its optical, mechanical, or surface properties under external stimuli, without mechanical intervention or shape alteration.	Colour-change Effects Stimuli-triggered change in material optical properties (brightness or transparency) using pigments, liquid crystals, or chromic materials for camouflage, encryption, smart textiles, and interactive food.	Thermochromism; Electrochromism; Photochromism; pH-responsive Chromium; Mechanochromism
	Material Property Modulation Stimuli-induced changes in material properties (stiffness, conductivity, transparency, magnetism) affecting physical and functional behaviour rather than geometry.	Stiffness Change; Transparency Modulation; Conductivity Change; Magnetic Property Modulation; Piezoelectric Modulation
	Surface Morphology Modifications Stimuli-induced surface changes (texture, topology) affecting wettability, adhesion, roughness, and optics for biomedical, optical, and soft robotics applications.	Texture Change; Optical Surface Adjustments
Shape-Change Effects Observable geometric transformation of printed structures under stimuli.	Mechanism-based Classification Classification by how shape transformation occurs or the process of shape changes	Shape Memory Effects Shape recovery to a pre-programmed form after prior deformation and stimulus activation.
		Multi-Stability Reversible switching between two or more stable shapes without continuous energy input.
	Self-Assembly Autonomous transformation from simple to complex shape driven by internal encoding, without prior programming.	
Self-Healing Effects Autonomous restoration of structural integrity after damage.	Geometry-based Classification Classification by the resulting geometric deformation.	Folding, Rolling, Bending, Twisting, Helixing, Waving, Buckling, Curving, Curling, Topographical Change, Expansion/Contraction
	Intrinsic Self-Healing Effect Repair via dynamic reversible bonding within the material matrix.	Dynamic-bond/self-healing SMP systems (e.g., UV-curable double-network SH-SMP with thermal healing + shape-memory retained)
	Extrinsic Self-Healing Effect Repair via release of healing agents from capsules or vascular networks.	Microcapsule-embedded systems releasing healing agents; micro-vascular network-enabled healing delivery

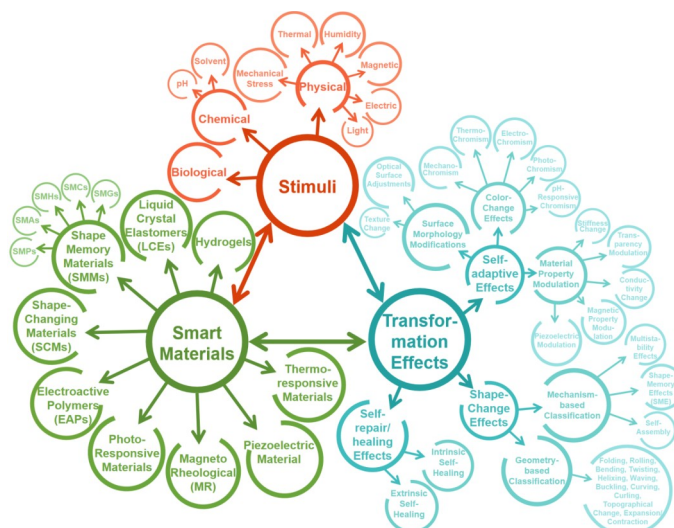


Figure 2 Hierarchical Classification of Stimuli, Smart Materials and Transformation Effects

3.2 Ontology-Based Classification of Stimuli → Smart Materials → Transformation Effects

An ontology is a formal model that defines entities, properties, and relationships in a domain (Gruber, 1993). Unlike a simple taxonomy, it can capture complex, bidirectional links, and support semantic queries. In 4DP, ontology enables designers to explore relationships between stimuli, materials, and effects from multiple entry points, complementing the hierarchical structure with richer semantic connections. To construct a comprehensive ontology linking Stimuli, Smart Materials, and Transformation Effects, this study first established one-way mappings based on the HC results and literature synthesis.

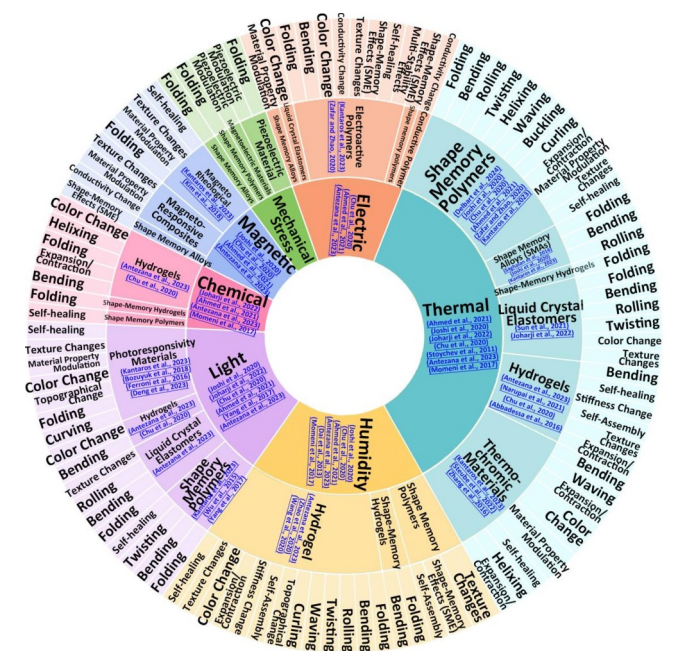


Figure 3 Stimuli-based taxonomy: Stimuli → Smart Materials → Transformation Effects. High-resolution version is available via an anonymised supplementary repository (https://osf.io/c6e4t/overview?view_only=afee977bad044ca0bfea699ca7d9ebc0).

This research linked seven stimulus types to responsive materials and their transformation effects based on the hierarchical results and literature synthesis, then cross-validated links by multi-source triangulation to support forward and backward queries. Fig. 3 visualises this as a network, revealing that one stimulus may activate multiple Smart Materials and lead to a range of Transformation Effects, while one Transformation Effect can also result from various combinations of Stimuli and Smart Materials. For example, thermal may activate polylactic acid- or Polyurethane-based SMPs to produce bending, curling, or contraction, depending on structure and programming (Ahmed et al., 2021). This model reflects the multi-directional logic of real 4DP systems and lays the foundation for flexible design toolkits.

3.3 Ontology-Based Classification of Transformation Effects → Stimuli → Smart Materials

Building on the initial ontology linking Stimuli, Smart Materials, and Transformation Effects, the second stage of classification reverses the logic by starting from specific Transformation Effects and tracing them back to the materials and stimulus that enable them. This reverse mapping helps designers explore feasible pathways for achieving a desired functional or aesthetic outcome. Specific effects induced by different types of stimuli include geometric transformations, colour shifts, property modulation, texture change, and self-healing. For instance, shape-change effects such as bending-, curling-, rolling-, and twisting-type deformations are among the most frequently reported Transformation Effects in 4DP and can be realised through different stimulus–material pathways (Ahmed et al., 2021; Nam & Pei, 2019). Specifically, bending/curling in hydrogels is commonly achieved via humidity-induced differential swelling, which is widely explored in soft robotic and wearable-textile contexts (Joharji et al., 2022). In LCEs, light stimuli (especially UV) can trigger bending/rolling through molecular realignment, enabling fast, programmable actuation behaviours (Yang et al., 2017). Similarly, magnetic fields can drive rolling/bending in magneto-active elastomers, supporting untethered actuation concepts in soft robotics (Kantaros et al., 2023). Beyond geometry change, self-adaptive effects are often reported as colour-change (e.g., thermochromic polymers responding to temperature) or property modulation (e.g., conductivity, stiffness, or transparency changes in conductive/piezoelectric systems), which provide functional or perceptual feedback under thermal or electrical activation (Chen et al., 2021; Kouka et al., 2023).

Self-healing effects further extend outcomes toward damage recovery, with reported high recovery efficiency under suitable thermal or chemical triggering conditions (Tran et al., 2022; Z. Zhang et al., 2019). Integrated into the network shown in Fig. 4, this classification supports designers in starting from an intended effect and tracing back plausible stimulus–material combinations.

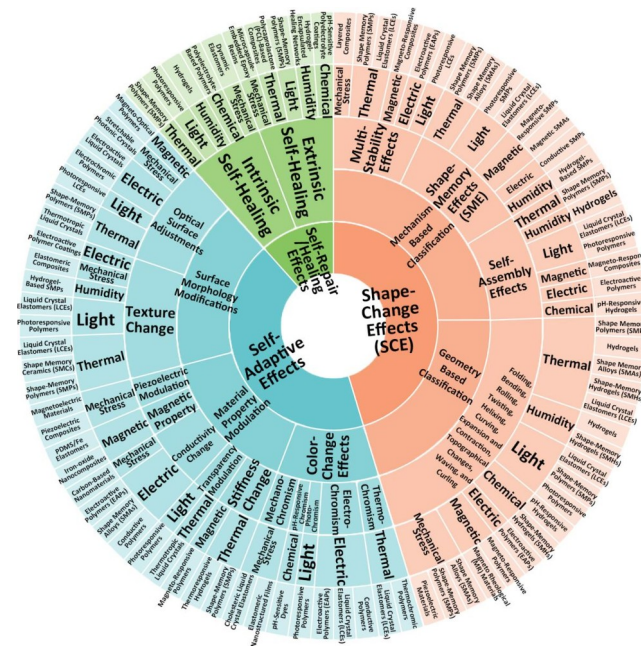


Figure 4 Transformation Effect-based taxonomy: Transformation Effects → Stimuli → Smart Materials. High-resolution version is available via an anonymised supplementary repository (https://osf.io/c6e4t/overview?view_only=afee977bad044ca0bfea699ca7d9ebc0).

3.4 Ontology-Based Classification of Smart Materials → Stimuli → Transformation Effects

The material-centric ontology mirrors design workflows that start from a specific material and its responsive behaviour. This classification bridges theoretical developments in stimuli-responsive materials with real-world applications by mapping each Smart Material to its corresponding Stimuli and resulting Transformation Effects. SMMs —especially polylactic acid and polyurethane-based polymers—respond to heat or light to produce bending, folding, or expansion (Momeni et al., 2017). LCEs, with their anisotropic molecular structure, exhibit reversible deformation such as curling or twisting under thermal or optical stimuli (Chu et al., 2020). Hydrogels respond to humidity, temperature, or pH through swelling-based changes and are ideal for soft biomedical or wearable applications. Functional materials like piezoelectric composites, conductive polymers, and thermochromic compounds further expand 4DP’s adaptability in areas such as sensing, flexible electronics, and smart textiles (Ahmed et al., 2021; Kantaros et al., 2023). Fig 5. visualises this Smart Materials → Stimuli → Transformation Effects ontology, supporting forward exploration of material capabilities and enabling multifunctional, adaptive designs tailored to diverse engineering and design goals.

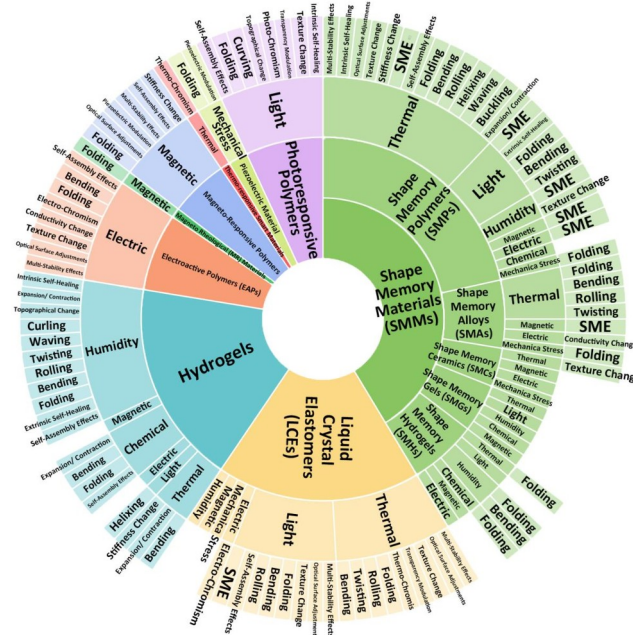


Figure 5 Smart Material-based taxonomy: Smart Materials → Stimuli → Transformation Effects. High-resolution version is available via an anonymised supplementary repository (https://osf.io/c6e4t/overview?view_only=afee977bad044ca0bfea699ca7d9ebc0).

3.5 The Systematic Taxonomy

In summary, this research establishes a structured classification framework for the three-core design-relevant components of 4D printing: Stimuli, Smart Materials, and Transformation Effects. A dual strategy combining HC and OBC was adopted: HC provides an accessible, multi-layered breakdown of each domain, while OBC captures evidence-supported semantic links showing how a given stimulus activates a specific material to produce an observable transformation effect.

Fig. 6 illustrates how the taxonomy can support early-stage design reasoning through worked examples. For instance, when aiming to achieve a folding transformation under thermal activation, a designer can start from the “Thermal” pathway (Fig. 4), identify commonly linked material families such as shape memory polymers (SMPs), and then trace the associated transformation mechanisms and representative application contexts. This helps narrow down feasible stimulus–material–effect combinations during concept generation without requiring extensive engineering background.

To support future design use, the taxonomy is intended to be operationalised as a designer-facing search and navigation aid built on the controlled vocabulary and the mapped cross-domain links. However, practical 4DP decisions also depend on feasibility constraints that are not fully captured by a triadic mapping alone, including response time/kinetics, reversibility, fatigue under cycling, achievable scale, safety, and environmental conditions. In the broader doctoral programme, targeted experiments will parameterise representative stimulus–material combinations and quantify how these operational constraints influence observed transformation effects, enabling designers to move from “possible in principle” to “feasible under specific constraints”.

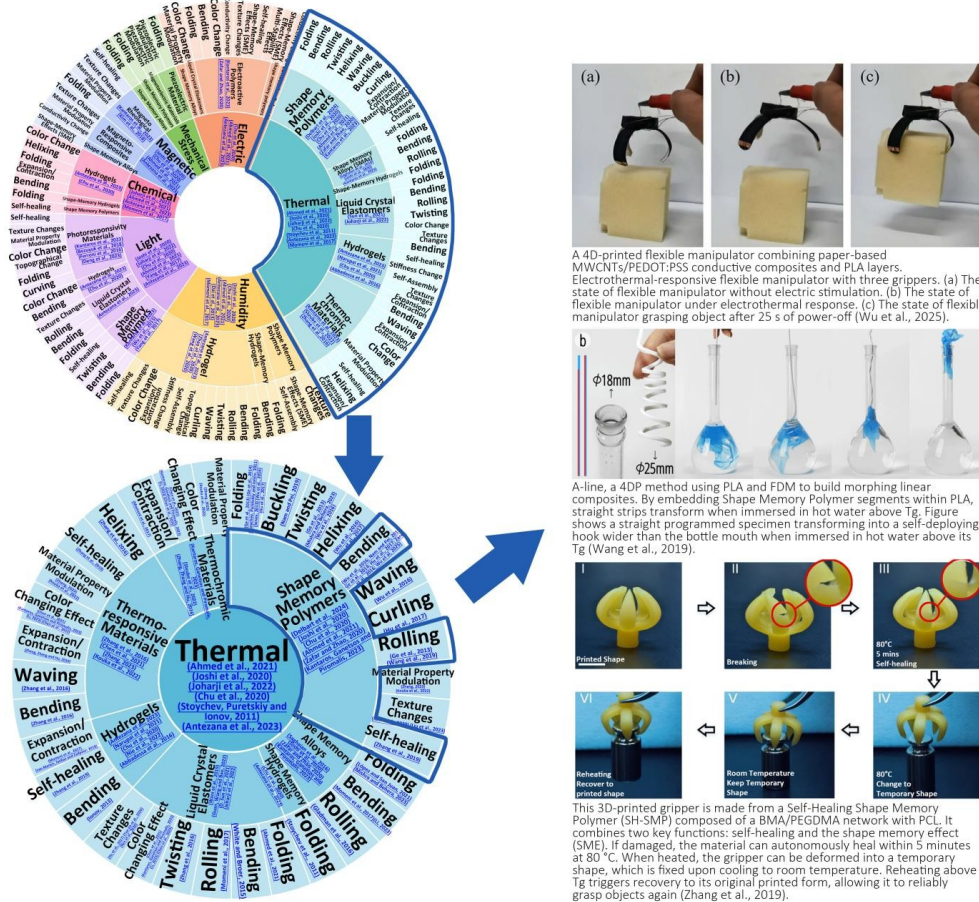


Figure 6 Smart material-based taxonomy: pathway from Smart Materials to Stimulus and Transformation Effects (illustrative case examples)

3.6 Questionnaire Study: Needs Identification and Validation

Two complementary questionnaire studies were conducted to capture both user needs and expert evaluation of the proposed taxonomy. Survey 1 examined designers' awareness, perceived challenges, and preferred knowledge-access formats for 4D printing, providing user-side justification for a taxonomy linking stimuli, smart materials, and transformation effects. Survey 2 served as an expert validation stage to assess the taxonomy's clarity, scientific accuracy, and completeness.

Survey 1 targeted designers from product, fashion, textile, and interaction design. It asked about familiarity with 3D/4D printing, experience with adaptive design, barriers to accessing material knowledge and visualising transformations, and preferences for decision-support tools (e.g., databases or AI assistants). The survey gathered 72 valid responses, mainly from industrial, fashion, and interaction designers with over three years of experience. Most respondents had used 3D printing; 89% had heard of 4DP and 17% had tried it. As shown in Fig. 7, respondents reported transformation unpredictability, limited smart-material knowledge, and lack of simulation tools as key barriers, and expressed demand for clearer guidelines, easier material access, and more practical support for linking materials, stimuli, and transformation outcomes.

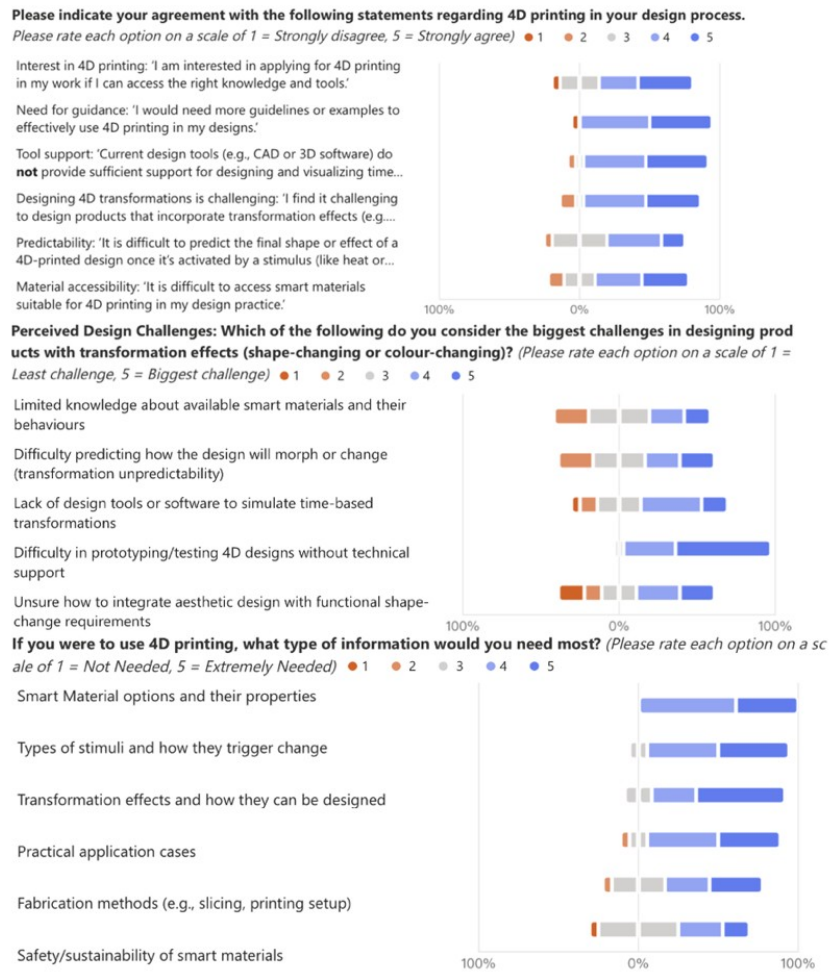


Figure 7 Designers' perceptions of 4D printing: key attitudes and challenges (Survey 1).

Survey 2 targeted experts in materials science, applied physics, and design engineering to evaluate the taxonomy's logical structure and terminology across three relationship paths. Ten valid responses were received (40% smart materials; 60% design engineering). As shown in Fig. 8, experts agreed or strongly agreed that the taxonomy is clear, uses appropriate terminology, and is scientifically accurate across stimuli, smart materials, and transformation effects, and considered it useful for interdisciplinary communication. A minority (20%) noted that biological and chemical stimuli were under-represented, and several respondents emphasised that additional experimental validation will be required, which will be addressed in subsequent work.

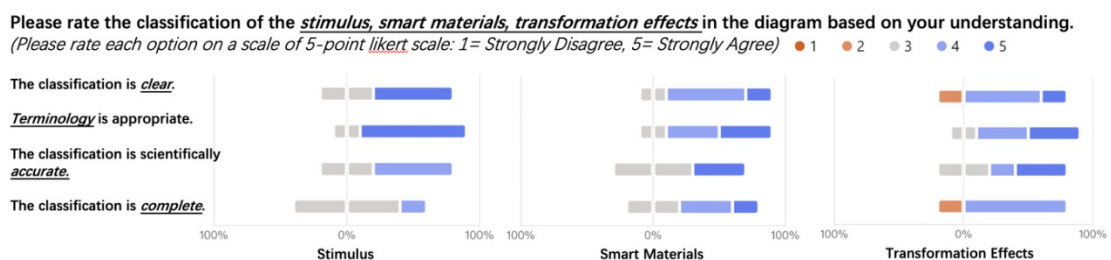


Figure 8 Expert evaluation of clarity, terminology, scientific accuracy, and completeness across stimuli, smart materials, and transformation effects. (Survey 2 results)

4. Conclusions

This research positions 4DP as an interactive material technology that reshapes the relationship between users, materials, and environments. Unlike interface-based systems, 4DP enables direct human–material interaction with perceivable feedback, where 4D-printed artefacts not only perform functions but also participate in interactions. This study delivers a designer-oriented classification that links Stimuli, Smart Materials, and Transformation Effects through hierarchical structure and semantic relations. The triadic mappings and visual summaries (Figs. 2-5) make pathway options explicit and support both forward and backward reasoning, helping non-engineering designers narrow down feasible stimulus–material candidates and anticipate transformation outcomes in creative workflows. This paper reports one stage of a wider PhD framework, focusing on a designer-accessible representation of Stimuli-Smart Materials-Transformation Effects relationships. The next stage will experimentally validate and parameterise selected stimulus–material combinations using an electrothermal SMP platform, where heating-film pattern design and coupling conditions (e.g., placement, interface/contact mode, and coverage) are systematically varied and linked to intermediate thermal uniformity metrics and final recovery outcomes (e.g., recovery time and shape recovery grade). Based on these experimentally grounded constraints, the taxonomy will be extended into a designer-facing toolkit or guideline that supports material selection and effect specification under feasibility limits. Finally, the toolkit will be evaluated through task-based studies with target designer groups, comparing performance against a baseline literature-search approach using decision time, agreement with an expert-defined answer key, and usability ratings (e.g., System Usability Scale).

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6. Appendix I. Systematic search details and eligibility criteria

Table I-1 Database-specific search strings and search results.

Database	Specific Database Search String	Search Results
Scopus	(TITLE-ABS-KEY (("4D print*" OR "four-dimensional print*")) AND TITLE-ABS-KEY (("stimuli" OR "stimulus-responsive" OR "external trigger" OR "thermal" OR "temperature" OR "heat" OR "humidity" OR "moisture" OR "light" OR "photoresponsive" OR "pH" OR "chemical" OR "electric" OR "magnetic" OR "mechanical")) OR TITLE-ABS-KEY (("smart material" OR "responsive material" OR "shape memory polymer" OR "hydrogel" OR "liquid crystal elastomer")) OR TITLE-ABS-KEY (("transformation effect" OR "shape change" OR "shape memory" OR "multi-stability" OR "self-assembly" OR "self-healing" OR "colour change" OR "stiffness change" OR "conductivity change" OR "magnetic property modulation"))))	Article:1310 Conference paper:207 Review:487 Book chapter:184 Book:25 Conference review: 14 Total (Title-Abstract-Keywords) : 2227
ScienceDirect	("4D print" OR "four-dimensional print") AND ("stimuli" OR "smart material" OR "shape memory polymer" OR "hydrogel" OR "transformation effect" OR "shape change" OR "shape memory")	Review Article: 329 Research Article: 504 Book chapter: 167 Encyclopedia: 33 Total: 1033
Taylor & Francis Online	("4D printing" OR "four-dimensional printing" OR "4D printed") AND ("stimuli" OR "thermal" OR "temperature" OR "humidity" OR "moisture" OR "light" OR "pH" OR "electric" OR "magnetic") AND ("smart material" OR "responsive material" OR "shape memory polymer" OR "hydrogel" OR "liquid crystal elastomer") OR ("transformation effect" OR "shape change" OR "shape memory" OR "multi-stability" OR "self-assembly" OR "self-healing")	Article: 800 Review Article: 37 Review: 21 Report: 7 Total (Title Only and Open Access) : 865
Google Scholar	("4D print*" OR "four-dimensional print*") AND (("stimuli" OR "stimulus-responsive" OR "external trigger" OR "thermal" OR "temperature" OR "heat" OR "humidity" OR "moisture" OR "light" OR "photoresponsive" OR "pH" OR "chemical" OR "electric" OR "magnetic" OR "mechanical") OR ("smart material" OR "responsive material" OR "shape memory polymer" OR "hydrogel" OR "liquid crystal elastomer") OR ("transformation effect" OR "shape change" OR "shape memory" OR "multi-stability" OR "self-assembly" OR "self-healing" OR "colour change" OR "stiffness change" OR "conductivity change" OR "magnetic property modulation"))	Total: 531
Web of Science	TI=(("4D print*" OR "four-dimensional print*") AND ("stimuli" OR "stimulus-responsive" OR "thermal" OR "temperature" OR "humidity" OR "moisture" OR "light" OR "pH" OR "chemical" OR "electric" OR "magnetic" OR "mechanical") OR ("smart material" OR "responsive material" OR "shape memory polymer" OR "hydrogel" OR "liquid crystal elastomer")) AND ("transformation effect" OR "shape change" OR "shape memory" OR "multi-stability" OR "self-assembly" OR "self-healing" OR "colour change"))	Review Article:78 Research Article:1374 Book chapter:2 Total: 1454
Total: 5043 (duplicates are removed)		

7. Appendix II. Eligibility, exclusion, and quality criteria

Search Criteria:

Language: Only publications written in English were included to ensure consistency and accessibility.

Access (data extraction preference): When multiple versions were available, open-access versions were prioritised for data extraction and verification. Lack of open access was not used as an exclusion criterion.

Temporal Scope: Studies published between 2013 and 2024 (the period of major growth in 4D printing research) were considered.

Inclusion Criteria:

Technological Relevance: Studies must explicitly involve 4D printing.

Stimuli Responsiveness: Papers must address external stimuli as part of the transformation mechanism.

Smart Materials: Studies must include or analyse stimuli-responsive materials, such as shape memory polymers (SMPs), hydrogels, or liquid crystal elastomers (LCEs).

Transformation Effects (TEs): Included studies must discuss or demonstrate observable transformation behaviours, such as shape change, colour change, self-healing, or multi-stability.

Exclusion Criteria:

Lack of 4D printing focus: Studies that only discuss 3D printing without time-based or stimuli-responsive transformation.

No stimuli: The study only discusses 4D printing technology, such as 4D printing equipment, but does not explicitly identify any external stimuli.

No smart materials: Papers dealing with general materials or mere composites that do not respond to stimuli do not employ a 4D printing process.

No transformation effects: Studies lack discussion of any transformation effect, for example, only discussing the preparation of materials.

Quality Criteria:

Peer-reviewed source: The study must be published in a peer-reviewed journal or conference, ensuring it has undergone expert academic evaluation.

Methodological transparency: The paper should clearly describe experimental methods, materials, or modelling procedures, allowing reproducibility or accurate interpretation of stimuli–material–transformation relationships.