4D Printing: Bridging the Gap between Fundamental Research and Real-World Applications

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Review

4D Printing: Bridging the Gap between Fundamental Research and Real-World Applications

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Abstract: The Special Issue "4D Printing: State-of-the-art, Recent Trends, and Applications" highlights the significant impact of scientific advancements on practical and innovative applications. It focuses on the interdisciplinary challenges of multi-material printability on a voxel basis and optimizing the actuation performance of composite structures with various stimuli. Key considerations, such as mechanical strength and potential adverse effects, shape the design methods suited to specific quantitative data limitations. Four-dimensional printing calls for creativity, interdisciplinary collaboration, and practical applications. While recognizing experience-based approaches in research, this review paper emphasizes integrating science and technology through alternative strategies; innovative approaches; and the exploration of engineering, design, and artificial intelligence.

Keywords: 4D printing; epistemology; innovation; artificial intelligence

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1. Introduction

Before the COVID-19 pandemic, our lifestyle was characterized by short-living trends, disposable goods, and a focus on convenience. This influenced many aspects of our daily lives, while science and business operations saw incremental changes due to risk aversion among stakeholders. In this context, the shift towards "factories of the future" has been driven by research across various technological domains. Zero-waste/defect manufacturing, particularly through additive manufacturing (AM), is crucial. The integration of new methods from academia and emerging technologies marks a significant breakthrough, aligning with Industry 4.0 and 5.0 principles. Four-dimensional printing, which combines AM with smart materials activated by energy, requires the integration of research findings that leverage the latest technologies and scientific innovations, including contributions from digital design and engineering sciences.

This need is emphasized by 4D printing, which prompts a reconsideration of mechanics and mechanisms. Achieving tangible economic success in a complex world requires moving beyond the current standards and methods. This involves proposing and evaluating detailed actions, adopting a holistic approach where the overall behavior is prioritized over individual relationships. Four-dimensional system thinking emphasizes the interconnectedness of elements and the importance of organizing principles within the entire system, including subsystems.

Introduced by Tibbits in 2013 and 2014, 4D printing builds on AM by adding a new dimension—time [1,2]. Using active materials, 4D printing creates objects that can change shape over time through energy stimulation. This method allows for digitally controlled deformation or changes in functionality. Successful 4D printing requires AM techniques and specific stimuli to alter the shape of objects made from active materials. Figure 1 illustrates this principle, while Figure 2 shows a 4D-printed object that changes shape when exposed to heat.

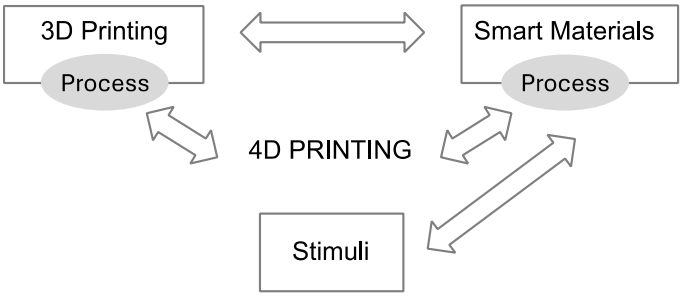

Figure 1. Interaction between additively manufactured smart materials and stimuli in 4D printing [3].

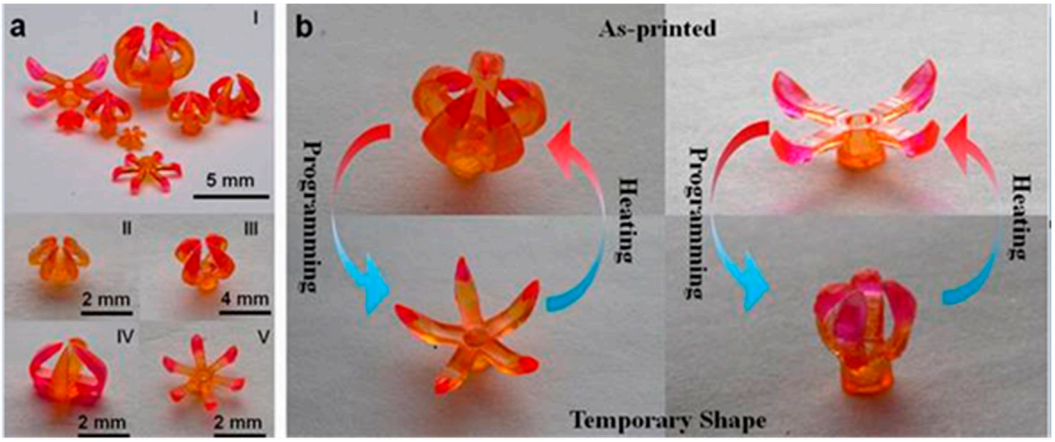

Figure 2. Example of a thermally stimulated shape memory polymer [4] (reproduced with permission from the authors). (**a**) 3D printed multi-material grippers with different designs (I–V). (**b**) Illustration of shape changes between as printed shapes and temporary shapes of multi-material grippers.

Figure 3 highlights the current state of scientific and technological progress in 4D printing, showing both strengths and weaknesses. Many areas lack clear, predictable prospects for practical applications, with only a few niches showing promise. The color intensity in Figure 3 (yellow: low exploration needed, orange: medium, and red: high) indicates the need for further exploration in areas such as AM, smart materials, design, and stimuli.

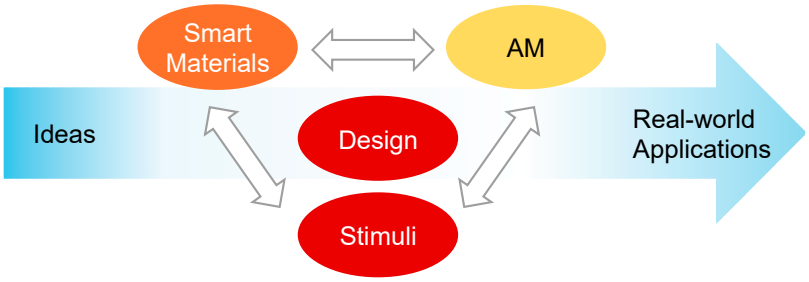

Figure 3. Research maturity in 4D printing (yellow: low exploration needed, orange: medium exploration needed, and red: high exploration needed).

Active materials, which are the focus of about 70% of scientific publications, are usually polymers that use macromolecular reptation to achieve shape changes [3]. However, there are several challenges beyond the intrinsic response time of the bulk material:

- The relationship between energy stimulation and material behavior, governed by Fick's and/or Fourier's laws, often leads to response times exceeding a minute for centimeter-sized objects;

- Limited mechanical performance, such as Young's modulus.

To address these challenges, objects need to be built using multi-material AM and specific structures that counteract Fick's and Fourier's laws. The shift from traditional manufacturing to 4D printing involves:

- Reassessing manufacturing strategies, moving from continuous to discrete approaches;
- Ensuring the printability of voxels with different materials using local and global methods;
- Refining the design of the AM process.

It is also essential to consider methods for stimulating active voxels. Viable methods for localized activations include light (with challenges like shadow effects and optical fiber integration), electricity (with concerns about thermal dissipation), and pneumatic methods. The literature often lacks substantial discussion on these practical aspects.

Moreover, it is crucial to understand the interaction between stimuli and voxelized 4D objects as the effects of successive or simultaneous stimulation with varying amplitudes over time and space. This understanding is vital for addressing the inverse design problem. Discussing these aspects in isolation risks oversimplification and limited analysis, as their deep interconnection often seen in the literature requires a comprehensive approach.

2. A Review of the Design of Complex Systems

2.1. Current Context

Knowledge about 4D printing is currently scattered across various disciplines and limited in terms of publications, but it is rapidly advancing at an annual rate of 44% [3]. This highlights the need for a comprehensive understanding and insightful perspectives to develop relevant concepts, convergences, and abstractions about 4D-printed systems. Despite the visionary outlook introduced by Boucher et al. [5], envisioning a conceptual breakthrough, such as replacing the digital electron with the atom or macromolecule in human activities, we currently operate using a singular medium, the electron. However, 4D printing still has a modest structure, resulting in a lack of widespread industrial applications. Overcoming these challenges is crucial for practical applications in technical, medical, or artistic fields. Therefore, this article reflects on the role of creativity in research and the emergence of disruptive innovations.

While Figure 1 illustrates four degrees of freedom in 4D printing, the actual number of parameters one can manipulate is far broader, including voxel size, material, printability, and energy stimulation strategies. This complexity implies that single-disciplinary approaches are insufficient for 4D printing. Therefore, a systemic approach involving numerous interrelated elements is essential, considering their overall characteristics and interactions (Figure 3). This systemic perspective also depends on the grouping of specific components, leading to the concept of opportunistic paths.

Exploring complexity, the study of dynamic systems aims to describe changes over time and space in the state of systems, focusing on the causes of these changes, particularly the interactions among the elements within the system. Modeling plays a crucial role in representing the evolution of dynamic systems using ordinary differential equations, where each variable's behavior is determined by its tendency at any given moment, influenced by other variables. A dynamic system is considered mathematically solved if one can trace the evolution of each variable over time.

This work stems from a specific situation where fabrication, behaviors, and stimulation are precisely defined, constituting a direct causal activity. However, from an applicative standpoint, the question is framed differently (inverse design problem): What active parts, object shapes (global), voxels (local), stimulations, etc. should be considered for a desired effect? Accuracy, cost, and efficiency considerations require defined selection rules to propose at least one admissible solution. With 4D printing, there is neither

proportionality of effects to their underlying causes nor additivity of causes on effects between voxels with different functionalities and inter-functionalities, except in singular situations. Addressing this inverse design problem after forward prediction poses a serious hurdle.

Research activity surrounding 4D printing and its industrial development face the risk of significant setbacks and deep disenchantments if admissible paths from underdeveloped concepts to applications are not identified. As Laruelle [6] aptly noted, science does not fully comprehend the objects it has enabled us to create; rather, it understands reality through these objects. Regarding the respective roles of startups and large enterprises in the emergence of disruptive innovations like 3D/4D printing [7], Bellit and Charlet [8] highlighted, through bibliometric analysis, that innovation dynamics do not follow the same routes. The dynamics are not merely an alternative between Schumpeterian archetypes ‘Mark I’ (disruptive innovations brought by risk-taking small entrants) and ‘Mark II’ (historical companies maintain technological advancement by leveraging prior knowledge) [9].

2.2. A Transition towards Engineering Sciences and Design

When an object comprises multiple elements and exhibits diverse behaviors when exposed to stimuli, it becomes a system, contributing to the concept of hyper-objects [10], which encompasses 4D-printed parts. Systems are collections of components interacting according to specific rules. Many research endeavors on 4D printing have focused on shaping objects using a single smart material, neglecting the complex role of stimuli. Therefore, all considerations related to 4D printing fall within the domain of systems thinking.

The design process involves bringing an artifact to life, shifting from human ideation to various shareable and intermediary descriptions before manufacturing [11]. This includes specifying and developing a set of functional, technical, aesthetic requirements, etc. typically outlined in a specification document. Design decisions are made by the product designer/architect using tools to represent the whole system. It is crucial to explore how designers make and validate their decisions based on various criteria and describe them in suitable formal expressions. Mental representations play a role in information and decision-making processes. As these elements involve all project stakeholders, standardized representations are relevant for comprehending all intentions, including heuristic and interdisciplinary expertise. This highlights a gap between strict scientific considerations and the criteria needed for the fabricating of a genuine 4D object for practical application.

However, it is important to understand the scientific, technical, and practical foundations of our research work, starting with the existing knowledge about active materials and their capabilities. Additionally, generic concepts from engineering sciences or design can serve as a conceptual support for 4D-focused initiatives.

A new technology may be considered groundbreaking because it transcends the existing paradigms. In the case of 4D printing, building on the success of its AM parent technology, the introduction of four parameters suggests significant changes in the printing and utilization of shape-changing objects. However, according to Siberzahn [12,13] and Siberzahn and Rousset [14], the focus on disruptive technologies has important consequences: an emphasis on technology itself rather than its practical applications and a tendency towards innovation for its own sake. True innovation lies not just in the technology but in how it is used to gain an advantage. It involves challenging existing models to create new ones, requiring an entrepreneurial mindset for disruptive creation. Therefore, the question arises: Can we truly discuss disruption when the 4D printing technology is in its infancy?

The remainder of this article will be divided into three sections, emphasizing the importance of engineering and design sciences in developing functional 4D-printed structures.

2.3. Systems and Their Representations

The term ‘system’ refers to a collection of interacting objects. According to von Bertalanffy [15,16], systems with dynamic interacting elements cannot be reduced to the sum of their parts; their properties depend on the perspective that determines the grouping of specific components. This study aims to describe changes over time and space based on their causes, using mathematics to model the evolution of dynamic systems with systems of ordinary differential equations. Nonlinearity implies that the interactions among system components do not result in proportional or additive effects (e.g., threshold effects) [17]. In the sciences of the artificial, it is necessary to integrate knowledge from natural sciences into more anthropocentric contexts to advance further. The goal is not just to innovate in a specific field but to gather a comprehensive range of facts for a general synthesis—an ambition for 4D printing.

The adoption of 4D printing into society involves humans and their perceptions, departing from singular propositions arising solely from natural sciences. This approach results from discussions seeking a robust relationship between thought and reality. It serves as a means of discovering and transcribing reality, with some viewing the object as a way of constructing reality and conceiving truth as coherence within our belief system. There is a distinction between a local approach (discovery/invention) and a global approach that harmoniously incorporates the object into a person’s system of understanding and values; the two are not mutually exclusive.

Methods for formalizing ill-defined problems aim to engage actors from various disciplines and provide methods and tools for interdisciplinary cooperation and invention [18,19]. This approach is based on the design research of Findeli [20], Vial [21], and Raîche-Savoie and Déméné [22]. The targeted domains were selected for their quality practices and supporting research. At the core of Chaiken’s model [23,24] is the principle of sufficiency, which seeks a balance between the effort in information processing and the satisfaction of specific, preferably conclusive, motivations.

2.4. A Modest Strategy

Our scientific endeavors generate ideas that shape entire worlds [25]. Since 2013, research on 4D printing has shifted towards thorough investigation rather than direct applications [3]. Researchers have focused on the process of conducting this research, examining how 4D-printed objects are designed, built, used, and adopted as systems. Influenced by pragmatist theories of engineering, this approach emphasizes technical artifacts like machines and devices, ideal for 4D printing-oriented practices. Rather than seeing 4D-printed objects as static assemblies, they should be viewed as evolving entities, undergoing continuous disassembly and reassembly [26,27]. This perspective allows for more intricate and realistic designs. Interdisciplinary research, which combines the design of 4D-printed objects for societal applications with scientific knowledge, faces inherent challenges. While sciences strive for theoretical foundations, true consensus remains elusive due to interdisciplinary demands. The dynamics create fertile ground for original interdisciplinary work and unique designs. Reevaluating and reconstructing research methods is essential, incorporating design tools and societal concepts to explore 4D printing processes. Researchers must analyze their evolving relationship with 4D-printed parts, considering the broader historical context.

Interdisciplinary efforts produce provisional theories that illuminate the unique attributes of each 4D-printed object. They position us in a space between the familiar and the unknown, creating a pivotal situation [28]. Despite skepticism from established disciplines, interdisciplinary approaches are gaining importance, particularly in realizing effective applications of 4D devices.

According to Conan [29], the approach is designed to be flexible and adaptable to various contexts, guided by several principles:

- Collaborative project breakdown, with decisions made by project management;

- The simultaneous consideration of technical, usage, and management dimensions in their socio-spatial implications;
- Organized consultation process involving decision makers, actors, and users;
- Production of a programmatic document, iteratively constructed, that presents admissible solutions without being normative;
- Approach to design through transaction spaces, identifying actors based on usage and management.

However, maintaining an iterative and generative process during 4D printing projects raises questions about the qualifications and competencies of the involved actors. Péna and Parshall [30] argued that programming and designing require distinct mental capacities—analytical and synthetic—that must be alternated by the same individual if possessed [30]. Scientific aspects can have both positive and negative outcomes. At their best, they challenge existing concepts, methodologies, and tools, fostering a renewed understanding. A theory is a venture into uncertainty, aiming to comprehend the complexity and transience of reality [31].

The study of artifacts raises the question of which 4D objects to monitor and manufacture and which actors to include [32]. By focusing solely on obvious objects from in-depth sciences, we may neglect important actors like materials, voxel relationships, and energy effects on 4D-printed objects. These factors influence and transform human networks and should be included in discussions on scientific, technological, and application opportunities. Including additional or alternative actors requires considering their varied manifestations and forms based on design and application criteria. Projects should be examined through material representations, exploring the multiple registers in which the 4D-printed device will be used. This calls for reevaluating the traditional dichotomies between designer and user, expert and layman, politics, and aesthetics.

A key consideration is whether enhanced descriptions of 4D-printed objects can foster better societal dissemination. Improved descriptions should enable redefining the field and generating a different world. By producing nuanced reports of 4D-printed parts, designers could provide subtle control mechanisms, potentially essential for the industrial development of 4D printing. However, this stage has yet to be reached.

3. The Sciences of "Admissible" Things

In 1828, Tredgold defined design as the art of directing natural resources for human use and convenience. Similarly, Asimow [33] characterized design engineering as a human-driven process supported by technical tools aimed at transforming needs into technical systems that meet human requirements. This process involves implementing novel or enhanced functions by identifying a system's specific function and transferring its principles to the technological realm [34]. Technological decisions driving innovation may be influenced by the initial idea and chosen direction, regardless of the field, including 4D printing. The journey typically starts with an initial idea, whether from a bottom-up or top-down approach [35,36].

Integrating the perspectives of scientists and engineers/designers aims to foster mutual understanding within an environment that tolerates mistakes and allows revisiting ideas from diverse viewpoints [37]. Considering the environment as a cognitive landscape tolerant of errors highlights the versatile resources available to 4D printing, which gain significance through interdisciplinary collaboration [38]. In rigid cultural frameworks, sophisticated problem-solving is confined within disciplinary boundaries, limiting exploration and adaptation, as described by Lévi-Strauss [39]. Creativity in designing and fabricating a 4D object, and its subsequent usage, is inherently associated with a broad mental freedom.

3.1. The Sciences of the Artificial

Expanding concepts from natural sciences to contexts like the sciences of the artificial, introduced by Simon [40], facilitates applying these ideas beyond traditional design realms. This transition from "absolute" truth to a rational but "satisficing" proposition does not seek to position science as the sole access to reality but aims for practical applications.

The critical point is the effective cooperation among various partners during the design process, making it challenging to pinpoint individual responsibilities, as reflections build upon one another. This fosters a "win–win" dynamic. Simon [40] showed that using design sciences in the innovation process offers a viable path from idea to practical realization. This article highlights the role of these sciences in 4D printing innovation.

Simon [40] posited that design is a scientific problem-solving approach and called for a science of design. However, to reach the public, design often needs to produce artifacts, where knowledge remains tacit [41]. Design has been associated with aesthetics due to its links to the arts, emphasizing cultural criteria while sometimes neglecting functionality. Nonetheless, the design domain advocates for a focus on functionality, technology, user-centered meaning, and societal transformation.

Avenier [42] stated that the sciences of the artificial provide an epistemic framework for understanding phenomena that embody human intentions and regulations. This foundational science differs from traditional natural sciences by focusing on practical applications and the concept of non-absoluteness. Key tenets of the sciences of the artificial include [40]:

- Bounded rationality, which differs from "pure" rationality;
- Satisficing solutions, which are practical rather than optimal;
- Design without a final purpose, allowing for evolving decision criteria;
- Quasi-decomposability, modeling complex phenomena, starting from manageable subsystems;
- The distinction between state and process description, valuable in delineating the realization and usage of an object.

Simon [40] argued that natural laws contribute to rationality and innovation but do not solely determine ideas and designs. Applied objectives drive design activities, involving multiple actors to facilitate innovation in the sciences of the artificial. The process includes:

- Initial idea: originates from nature and framed by scientific and technical knowledge;
- Proof-of-concept (POC): requires design practices, leveraging existing knowledge or conducting specific inquiries;
- Complex phenomena: addressed within the design process using heuristic and interdisciplinary expertise;
- Subsystem design: can be independent but not uniquely decomposed, focusing on aggregative properties and ignoring weak relations [43];
- Satisficing solutions: proposed to validate POC usability;
- Technical validation: further evaluation transforms technical knowledge into innovation, considering societal criteria and feedback [35].

Fundamental knowledge in the sciences of the artificial and design is expressed as propositions of intelligibility [42,44]. This involves multiple partners, even temporarily, in the innovation process and decomposes expertise into subsystems. Messerschmitt [45] outlined five key attributes of good modular design:

- Functionality: each module offers conceptually linked functions;
- Hierarchy: modules can be decomposed into submodules with hidden internal structures;
- Separation of concerns: modules are weakly coupled;
- Interoperability: modules interact easily;

- Reusability: modules can be reused in various systems.

These operations require in-depth work, focusing on the idea's applied interest, organizing resources, and reconciling different values. The state of the artifact during research can be described as follows [46]:

- Analysis phase: identifying the idea's applicable interest;
- Information gathering: clarifying the initial ideas for engineering;
- Proposal of solution: convincing stakeholders for support;
- Design: specifying initial objectives for creating the artifact;
- Analysis of barriers: reviewing the literature and consulting relevant sciences;
- Requirements: specifying the POC and artifact realization;
- PoC design: technical improvements and economic/societal considerations;
- Artifact design: representing the artifact in its final state;
- Evaluation: conducting feedback at each stage;
- Dissemination: preparing the artifact for dissemination upon success.

Lubart [47] outlined cognitive abilities involved in the innovation process, including:

- Identification and definition: relevance and trajectory of the idea;
- Selective encoding: searching for relevant information;
- Search for similarities: exploring analogies, metaphors, and comparisons;
- Motivation and risk-taking: personal drive and willingness to take risks;
- Selective combination: grouping information to evolve the idea using heuristic expertise;
- Divergent thinking: generating possibilities;
- Self-evaluation: assessing the progress;
- Collaboration: trust in colleagues and support from the hierarchy.

Simon's [40] science of design involves creation, POC design, expertise, and integrating diverse knowledge. Collaborative efforts aim for satisficing solutions, but technical satisfaction alone may not lead to innovation. Socioeconomic factors introduce additional requirements and may necessitate design revisions [35]. Shifting from idea to application involves leveraging science, technology, creativity, and expert problem-solving before realizing the POC. Socioeconomic perspectives then modify the POC to fulfill additional criteria, ensuring the object is user-accessible. Design considerations are evaluated from both conceptual and applicative perspectives, identifying criteria for technical POC realization and socioeconomics.

Shifting from idea to application involves leveraging science, technology, creativity, and expert problem-solving to create a POC. Socioeconomics factors then modify the POC to meet additional criteria, making it accessible to the public. Therefore, design considerations are assessed both conceptually and practically, identifying criteria for technical and socioeconomic feasibility.

3.2. The Design Process

Design is a problem-solving process for creating a system, device, or object. According to UVED [48], the International Council of Societies of Industrial Design (ICSID) defined industrial design in 1961 as a creative activity that determines the formal properties of industrial objects. These properties include external characteristics and functional and structural relationships that make an object or system a coherent unit, from both the manufacturer and consumer perspectives.

The design process is a structured sequence of activities that develop representations of the product at specific milestones. It starts from a material or immaterial need outlined in initial specifications and progresses toward creating a physical product. In artificial sciences, "design" can mean different things, from concepts and inventions to aesthetics and tinkering. Because of its many meanings, using the term "design" can lead to misunderstandings. It involves both organizing data and defining an operational path, often using analogies.

A critical aspect of design is the practical realization of the artifact. This requires not only established facts but also specific, sometimes esoteric or aesthetic, knowledge. Acquiring this knowledge can be random, prolonged, and constrained, making it a skill held by a group of designers, engineers, experts, or scientists. Transmitting this knowledge is difficult, and the success of the POC at various levels may depend on it.

To materialize the POC, skilled actors and appropriate instruments are essential. Laboratories may vary in resources and personnel, leading to slightly different proposals based on the same manufacturing protocol. Despite experiments, practices can be opaque. Describing all the necessary conditions for realization is challenging, although ad hoc applications may assist in ensuring manufacturing and usage success. Many designers may not fully appreciate the expertise and intuition of certain individuals contributing to the artifact's refinement.

The design process typically unfolds in several stages:

1. Clarification of needs and functional specifications;
2. Preliminary design;
3. Embodiment design;
4. Detail design and prototyping;
5. Mass production.

The process starts with a clear definition of the need, described in a specifications document. It explores potential concepts that meet the specifications, validated by at least a technical POC in one or more stages. Figure 4, adapted from Pahl and Beitz [49], illustrates this approach across four phases (the readers can also refer to [50–55]).

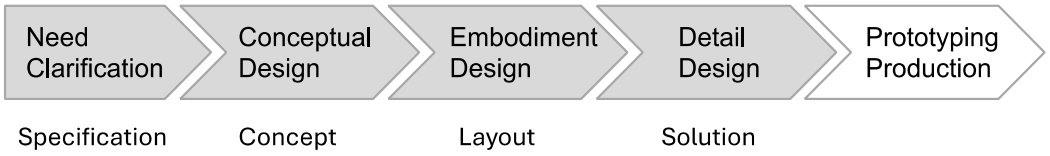

Figure 4. Design process adapted from [49].

Once an idea gains acceptance, understanding the relationships between structures and functions becomes crucial for technical design, as described by Cohen et al. [56]. In nature, various structures efficiently fulfill many functions at minimal cost. Using the TRIZ (theory of inventive problem solving) approach, researchers have compiled examples of recurring structure-function models. These models either facilitate or hinder system operations by harnessing or impeding energy sources, respectively. This collection of models serves as a repository of principles for investigating these relationships [57,58]. Other methods, such as the C-K method [59–61], the V-model revisited by Wöhr et al. [62], or multifunctional design [63–65], can also be considered. Additionally, Bono's Six Thinking Hats [66] and the Delphi method, which incorporate expert intuition and knowledge to predict the future, are noteworthy [67].

While these methods hold promise for expediting innovation and enhancing performance, the optimal pursuit of an idea remains a question. According to Parmentier et al. [68], it remains challenging to definitively assess the impact of these support methods on innovation. Ideas may spontaneously emerge to solve problems.

AM is digital, covering processes from online design to slicing tools and printing monitoring programs [8]. One can delineate how the initial POC can be realized, considering the machinery, tools, materials, etc. involved. This draft may prompt changes if the device's objectives are not met technologically. However, integrating and interoperating data from diverse sources remain challenging. Companies will reevaluate the POC to tailor it to industrial and commercial requirements (robustness, cost, aesthetics, ergonomics, etc.), potentially looping back to the initial POC. Efficiency depends on meticulous data gathering and integration, ensuring confidentiality and security. Digital agility must be incorporated to cope with the evolution and complexity of simulated systems. The design

part involves disinterested science, practical know-how, and expertise combined with external knowledge. It includes heuristic expertise to find satisficing solutions, propose a pathway for POC realization, and engage with society. This encompasses a wide range of skills.

The activity is constructed with clear goals in mind, focusing on what needs to be demonstrated or achieved. It is specific and unique, as it cannot be replicated exactly by different individuals or groups. The aim is to draw robust conclusions that advance 4D innovation, despite uncertainties and interdependencies. Managing complexity in the research involves using heuristic approaches from various disciplines to achieve credible conclusions in the field [35,69].

Reflecting on the design activity should include general knowledge, technology, economic and social contexts, environmental sustainability strategies, and ethics. These domains, with varying importance based on the chosen epistemological approach, should contribute to independent work on 4D printing innovation. This leads to what Simon [40] called "satisficing" solutions in artificial sciences. Researchers and designers must use specific, though sometimes vague, skills and integrate the impact of interfaces, linking different disciplines effectively. Artificial sciences help researchers navigate uncertain environments where agnotology (the study of ignorance) may prevail. These sciences do not provide absolute truths but solutions considered satisficing by Simon [40], requiring humility in researchers' conclusions. In technology, we often see the creation of appealing but imperfect devices that improve over time. This is the goal with 4D printing, starting from scratch and improving iteratively.

3.3. Heuristic Approaches

In a technological context, heuristics address specific needs, apply scientific principles, and use material technologies. A technological paradigm is a model for solving technoeconomic challenges, using principles from the natural sciences. It also includes rules for acquiring new knowledge and protecting it from competitors, as proposed by Dosi [70].

Traditional scientific frameworks may not always use paradigms based on experiments that rely on rational explanation and prediction. Instead, they may offer mathematical models and computer simulations. When variables interact in complex ways, these tools help create POCs that must align with real-world outcomes. These outcomes should lead to deterministic procedures that move from concept to industrial production.

Systemic uncertainties arise when dealing with complex realities. It can be helpful to identify and understand the dominant elements within these systems. New methods are needed to make use of our partial ignorance. Stakeholders must leverage established facts and knowledge while addressing uncertainty through heuristics to build expertise.

Engineering uses heuristics to bring about positive change in poorly understood situations with available resources. Engineering is action-oriented, working under time constraints and limited resources [71]. This makes interdisciplinary dialogue crucial during intense cognitive efforts. Reynaud [72] suggested heuristics are better for discovery than proof. The approach aims to find coherence and meaning among diverse design process partners.

Interdisciplinary practice involves sharing intelligence and reframing problems with concepts and methods from different disciplines. This requires patient dialogue and exploring unorthodox ideas until problems are resolved [73]. Innovation alters relationships between interacting elements, often needing an original convergence of different disciplines. Disruptive innovations involve complex interactions, uncertainty, unpredictability, and coevolution of the project and its context. These challenges may need evolutionary strategies or improvisation to overcome. This vision reevaluates disruptive innovations, emphasizing the convergence of different disciplines [7] (Figure 5).

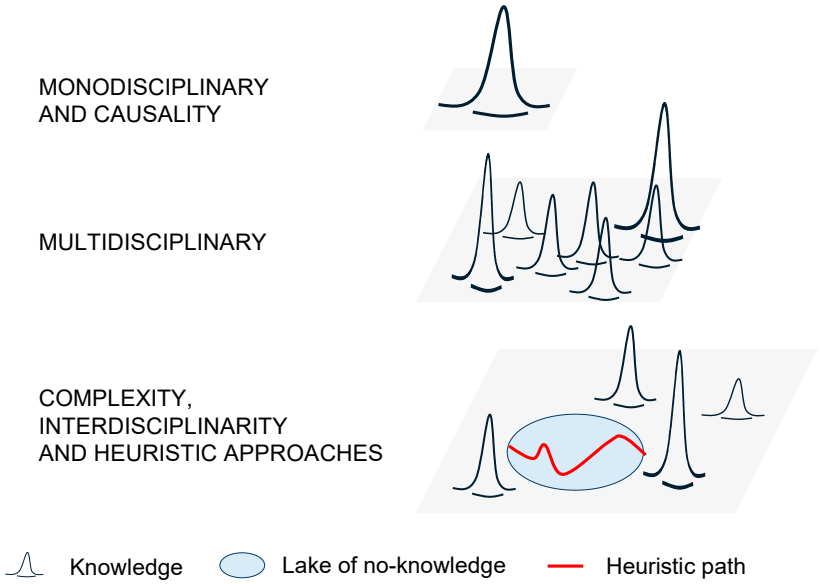

Figure 5. The heuristic approach—fields of expertise (Gaussian approximations represent scientific achievements from previous research work; depending on the expertise, the domain is either covered (causal or algorithmic) or partially covered (heuristic)).

The heuristic approach is an intuitive method to find solutions where knowledge is not fully established. It relies on common sense and quick decisions to solve problems, offering one admissible solution among many. Initially, ideas are mere hypotheses that may develop into viable solutions over time. A discipline is a body of knowledge with a specific object, method, and program [74]. It represents a division of labor in the social realm [75]. Legay [76] encouraged undisciplined reactions to stimulate debate. Interdisciplinarity involves collaboration among independent experts, fostering dialogue and recognizing the value of disagreements. It aims to produce precise and reliable conclusions by integrating diverse perspectives. Achieving interdisciplinary expertise requires selecting disciplines, experts, and organizational strategies carefully to clarify and synthesize goals [35]. While common in industry, interdisciplinary collaboration is challenging in academia due to barriers to cooperation. Sevtsuk et al. [77] showed that intentional campus design enhances interdisciplinary interaction by fostering physical proximity among researchers. Interdisciplinary collaboration raises several questions, including the number of disciplines involved, the selection of experts, organizational structures, time for expertise, and synthesis of diverse viewpoints. These elements are crucial for effective collaboration and will be discussed in the future [36]. A paradigm is a system of objective representations guiding new representations within its framework. However, familiarity with objects can lead to subjective biases. Malmiry [78] proposed a systematic modeling approach to manage uncertainty and complexity in manufacturing. This approach has two phases: model determination, including topology [79], and system analysis. It offers a modeling framework to facilitate the transition from functional to structural views, incorporating quantitative modeling. The second phase aids designers in decision-making during simultaneous design, considering both performance and costs. In AM, material parameters, defects, and deposition strategies affect the geometry and temperature fields of printed layers [80–82]. Numerical models analyze how the printing parameters affect various observables, optimizing 3D/4D printing strategies to ensure the part geometry, material integrity, and manufacturability [83,84].

Built upon these principles, design processes use scenarios to explore different perspectives and resolutions. These scenarios encompass strategic planning, engineering requirements, and human–machine interaction considerations relevant to 4D printing technology. Each scenario addresses specific technical or organizational objectives. However, it is crucial for the vocabulary used to be understandable to all stakeholders, including

planners, engineers, software developers, customer representatives, human–machine interaction designers, and end users (Figure 6 adapted from [85]). Establishing a common language is essential for effective communication and collaboration, promoting heuristic expertise in interdisciplinary contexts.

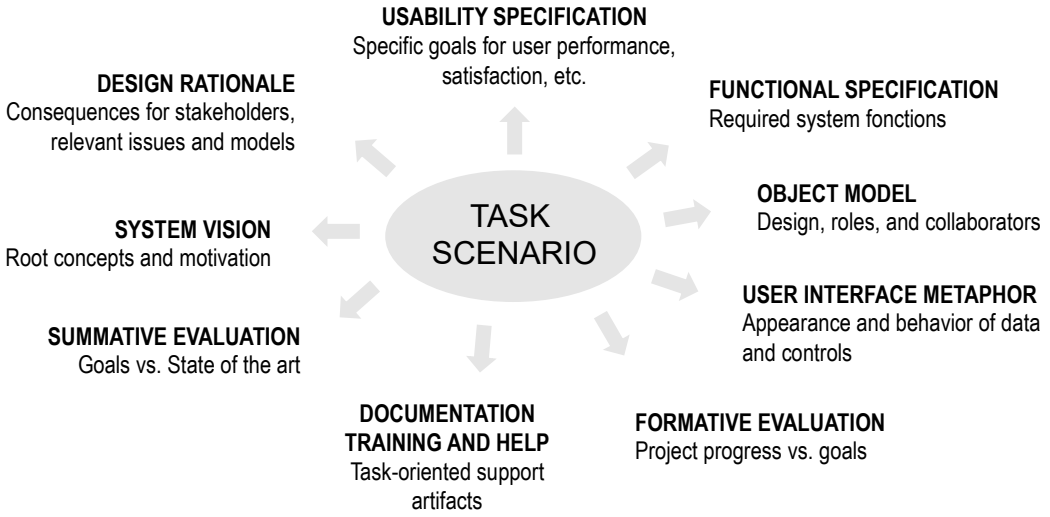

Figure 6. Common language for design (from upstream to downstream processes).

Disruptive innovations face many challenges due to their unique nature. Firstly, they cannot be forced; they emerge over time. Secondly, their significant impact on turnover takes a long time to appear. Thirdly, there is a risk of the disruptive entity becoming isolated within the organization [14]. Identifying disruptive ideas is complex and often non-intuitive. Companies may struggle to support potential developments systematically. Implementing disruptive inventions may require costly changes, making existing processes obsolete and incurring training costs for actors. Consequently, radical innovation ideas may be rejected [86]. Without the involvement of partners and traceability, promising ideas might be overlooked or forgotten. In universities, pursuing framed funding opportunities can hinder creative pursuits. To foster disruptive change, strong values are needed to challenge established traditions. However, this path is not straightforward. Embracing unconventional individuals can disrupt existing relationships and structures. Businesses and research institutions need new organizational priorities to drive decisive actions.

Emotional considerations also play a significant role. Emotional empathy fosters mutual identification and collective work, particularly in uncertain and turbulent environments. In such contexts, project teams need high motivation and autonomy in processes, organization, and objectives to manage risks effectively. However, delegating authority in risky situations may go against conventional instincts.

Shaping a scientific innovation team involves selecting a proficient facilitator who can lead independently while fostering collaboration. This shift emphasizes individual performance and excellence. Unlike standardized assembly line work, independent researchers require expertise and are not interchangeable. Success is equated with being in one's field, leaving little room for failure. This raises questions about engaging in interdisciplinary projects under such disciplinary evaluation norms.

Managing design projects is complex, requiring both the application and generation of knowledge. Intercultural expertise addresses challenges in language, perception, performance, and balancing debates among the involved actors. Various considerations come into play:

1. Disciplinary considerations: focus on new knowledge, innovation, wealth creation, technical progress, healthcare, well-being, risk management, and resource sustainability;
2. Ethical and moral considerations: emphasize prevention, ethics of life sciences, life preservation, intergenerational solidarity, sustainable development, and long-term effects;
3. Daily living environment: address issues like community well-being, pollution, hygiene, safety, health, stress, living conditions, and comfort;
4. Political and social framework: prioritize employment, social decision-making, civic engagement, democracy, community solidarity, policing, and security against terrorism;
5. Hierarchical considerations: can lead to silencing dissenting voices due to difficulties in verifying statements, fear of incompetence, or submission to authority.

The satisficing approach, proposed by Simon [40], aims to find satisfactory solutions iteratively, leading to reasonable outcomes. However, achieving convincing and robust solutions requires broadening the scope within design sciences. Design sciences bridge disciplinary knowledge, theoretical concepts, and practical applications. The key outcomes include:

- Empirical knowledge about object design;
- Specific concepts posing challenges in natural sciences related to function, intention, and creativity;
- Tools supporting designers' activities, such as computer-aided design and creativity methods.

In the later stages of idea realization, expertise in natural and engineering sciences is vital to articulate precise scientific inquiries and engage in debates about outcomes effectively. Heuristic approaches are valuable when scientific knowledge in the field of 4D printing is required, especially for creating a POC and a prototype.

According to Simon's framework [40], design science focuses on creating novel artifacts. Depending on the development stage of these artifacts, the required research approaches may vary. However, proposed methodologies often reflect a certain worldview, which may not always be purely scientific. The design aspect of artificial sciences is influenced by external factors and may be underpinned by specific ideologies. Gregor and Hevner [87] outlined four primary configurations within this domain: routine design (using established solutions for known problems), adapting known solutions for new problems, incrementally developing new solutions for known problems, and inventing entirely new solutions for novel problems.

3.4. Modeling and Design

Choosing a field of study involves a complex decision-making process influenced by personal interests, research opportunities, and the desire to tackle specific challenges. This choice requires identifying research questions that may not align with a single discipline or theory. Researchers make decisions based on their preferences and convictions, seeking coherence in their perspective rather than strict adherence to disciplinary boundaries or theoretical frameworks [88].

Figure 7 delineates the steps needed to create an operational and acceptable 4D-printed structure based on Simon concepts [40]. The design software predicts the behavior of active materials and addresses heuristic design challenges. To achieve this, sophisticated modeling techniques and topological transformations are used to address manufacturing and material constraints effectively.

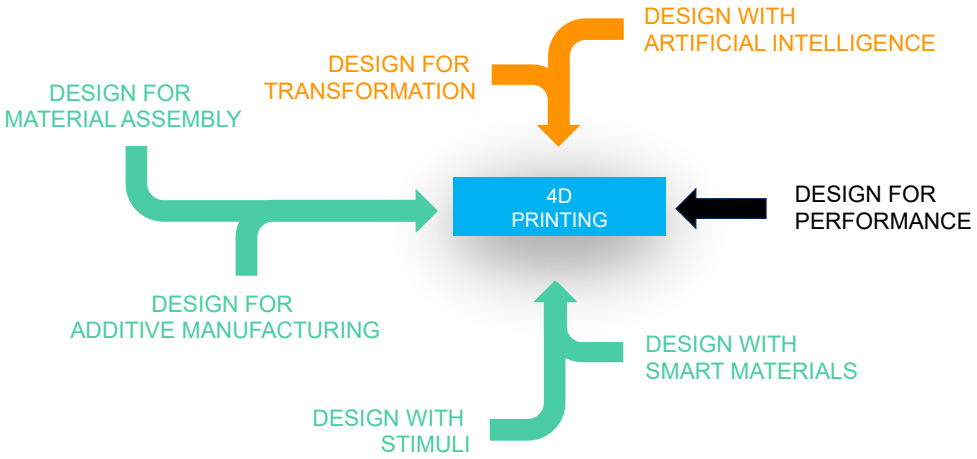

Figure 7. Design considerations for a successful 4D printing design.

Despite significant efforts, advancing 4D printing technology requires extensive research in design and engineering sciences to develop complex structures using smart materials and stimuli. These structures must adapt to various scenarios, particularly when dealing with materials that have intricate structures and limited control, such as voxel connections. Designers often lack expertise in both AM and active materials, so new design models, methodologies, and tools are needed, often starting with simpler structures.

In the realm of 4D printing, after selecting the material, printing approach, and programming method, the final critical step is modeling the original structure and predicting its behavior [89]. This step aims to formalize and reuse knowledge through a digital model. Initially, Dimassi [90] proposed a framework to build an ontology using both top-down (using multidimensional theories and basic formal ontology) and bottom-up (experience-based) approaches. The resulting ontology encapsulates knowledge about 4D printing, encompassing AM processes, active materials, stimuli, and transformation functions, serving as a comprehensive knowledge base for tasks like material process selection, transformation sequence planning, and material distribution recommendations.

This foundational work must culminate in the synthesis of the digital design of 4D objects, as it plays a crucial role before any physical realization, encompassing the functional, behavioral, and structural aspects. Furthermore, having a system, preferably automated, for making recommendations based on understanding the behaviors under various stimuli can be advantageous. This involves integrating conventional programming or finite element analysis (FEA) with physical fields, depending on the energy stimulus mechanism (linear and nonlinear behaviors induced by time resolved and amplitudes). Presently, only a limited number of tools employ analytical and numerical approaches to progress toward the desired design objectives in this domain. These systems should be informed by experimental results from the literature, ensuring robustness. These experiments serve as instances of the ontology and a foundation to feed a vector spatial model for proposing specific material distributions. Dimassi [91] and Dimassi et al. [92,93] developed a tool in the Rhinoceros3D/Grasshopper environment to demonstrate the applicability and relevance of these proposals.

3.4.1. Isolated Voxels

The fundamental mechanical considerations of 4D shape-changing structures produced through AM require modeling that incorporate measurements, the initial and final stress analyses, and complex modeling [94]. However, as shown in Figure 8, the characteristics of an isolated object are determined not only by its shape but also by other parameters, such as those associated with energy stimulation, which influence its steady or time-resolved deformation(s) and sometimes material transport inside a voxel.

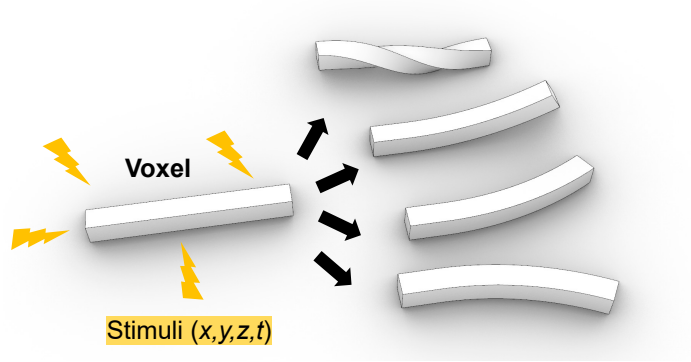

Figure 8. Shape changes of a voxel when exposed to stimuli.

Bhattacharyya et al. [95] developed a model for designing and synthesizing morphing mechanisms using materials capable of exhibiting preprogrammed complex changes. By integrating active and passive materials, their algorithm can encode the desired change into the material distribution of the mechanism. This approach paves the way for a new generation of material-driven machines that are lightweight, adaptive, damage-resistant, and easy to produce using AM. Currently, the modeling part of their work serves as a preliminary step towards advancement in this direction.

Similarly, Zolfagharian et al. [96] introduced a case study guiding the development of machine learning models to predict the behavior of nonlinear 4D printing scenarios. Developing a FE machine learning model to predict the bending angle of a flexible pneumatic actuator allows studying the influence of input variables on its bending. This initiative aims to run FE simulations to train data for machine learning.

In addition, Yue et al. [97] utilized multi-material printing capabilities to fabricate heterogeneous hinge modules. Different configurations can be encoded during AM due to the variable distribution and direction of modularly designed hinges. Following this experimental aspect, Zolfagharian et al. [98] developed a design strategy to use the desirable 4D morphing of multi-material composites. Composites with bilayer laminates composed of shape memory polymer and elastomer were made with variable thickness ratios to control the self-bending of the composite material. FE simulations were used to understand the underlying processes of the composite materials and to generate accurate predictions for the experimental results. Goo et al. [99] used similar foundations with simple thermoplastic structures.

However, leveraging the foundational principles of simplified systems, Choi et al. [100] capitalized on the understanding that the changes of active materials, when exposed to stimuli, exhibit nonlinear behaviors, which are challenging to characterize qualitatively and quantitatively, even with advanced numerical solvers. They propose:

1. Developing standardized kinetic components in smart materials that exhibit transformation primitives, such as bending and twisting, to be used as active components for mechanical assemblies with rigid parts;
2. Introducing an open kinetic library, accessible for downloading data on kinetic components to incorporate into designs, as well as enabling users to upload and share their own data;
3. Running simulations based on empirical methods using kinetic components within assemblies.

The authors have put forward two design proposals utilizing standardized kinetic components: an icosahedron and a mounting platform. Despite ongoing scientific exploration in this area, these elements delineate tangible constraints on the advancement of 4D printing applications. The abundance of possibilities poses a challenge in establishing a robust pathway forward. Until these barriers are adequately addressed, only a few specific and straightforward niches will be able to sustain activity. For instance, achieving the desired low response times by designers may necessitate producing very small objects or

employing optical or electromagnetic stimulations with well-defined temporal bases and simplified modeling. Nevertheless, these constraints underscore the importance of continuing research efforts along these modeling axes to facilitate the emergence of robust 4D printing technology as a viable industrial technology.

3.4.2. Voxel Assembly

In this context, bilayer actuators are highlighted as a notable example, as depicted in Figure 9, with researchers considering such devices as a potential foundation for complex modeling involving the assembly of two voxels exhibiting distinct behaviors. A bilayer actuator comprises two cohesive layers of materials with differing mechanical properties, typically characterized by distinct coefficients of expansion. It is the divergent properties of these materials that enable the bimorph to deform and execute mechanical actions. Bilayers can induce bending moments or form annular structures capable of generating displacement perpendicular to the element through shear forces [101]. A 4D printing model incorporating bimorphs was detailed in [102]. Furthermore, Baran et al. [103] proposed evolutionary systems involving multi-layer or multi-bimorph configurations. The deformation of a bilayer in response to applied loads can be readily understood using classical principles.

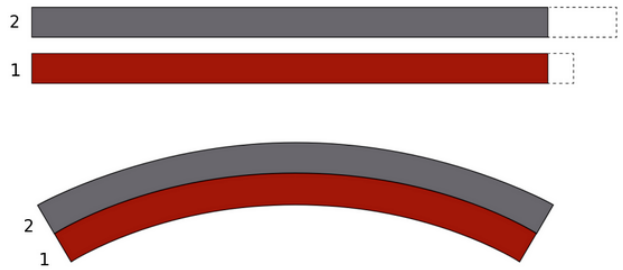

Figure 9. Deformation of a bilayer actuator ((1) active material and (2) passive material).

For instance, consider material 1, which initially has a length L_0 at temperature T_0. When its temperature changes from T_0 to T, it increases by following Equation (1):

$$\Delta L = L - L_0 = L_0 \cdot \alpha(T - T_0), \quad (1)$$

where α is the linear expansion coefficient of material 1. Young's modulus relates the normal stress σ experienced by the material to the resulting elastic deformation ϵ. In the material's elastic limit, Hooke's law is expressed in Equation (2):

$$\sigma = E\epsilon, \quad (2)$$

with ϵ representing the relative elongation. When two materials are bonded together, they deform under stress created by the temperature increase, which is proportional to the coefficient of thermal expansion (CTE) and Young's modulus of the material, as expressed in Equation (3):

$$\sigma = E \cdot \alpha(T - T_0). \quad (3)$$

With R_0 the initial radius of the curvature at temperature T_0, α_1 and α_2 representing the CTE of materials 1 and 2, respectively (with α_1 typically associated with the less expandable material), and E_1 and E_2 representing the Young's moduli of the two materials (usually close in value), the thicknesses of the two materials are denoted by s_1 and s_2, with $s = s_1 + s_2$ representing the total of the bimorph (typically, $s_1 = \frac{1}{2}s$). The simplified calculation for the curvature radius was expressed in [104] and via Equation (4):

$$\frac{1}{R} - \frac{1}{R_0} \approx \frac{3}{2}(\alpha_2 - \alpha_1)\frac{T - T_0}{2s} \quad (4)$$

From an experimental point of view, utilizing, for example, a multi-material 3D printer allows for the creation of such objects, and their deformation can be monitored based on the amplitude of the applied energy. However, the lack of complete parameter knowledge, including the interactions between bimorph components, presents challenges in further analysis, particularly given that a 4D-printed object typically comprises more than two voxels.

3.4.3. Wire-Like Structures

The mathematical control of deformations, which is considered highly challenging for solid materials, remains difficult to achieve, even with optimal design techniques, as highlighted in prior studies [105–107]. While certain trends may emerge, achieving numerical control over deformations remains elusive. Additionally, challenges persist in the 4D printing process and materials themselves, such as response times and local amplitudes of stimulations in active materials, as well as complexities in the production of stimuli within the system. Figure 10 depicts one of the hurdles encountered in leveraging 4D printing: understanding the properties of materials under stimulation, determining the optimal placement of active voxels within an inert supporting material, and considering local energy flows in both time and space to facilitate the shape-shifting of a 3D-printed object. Given the challenges associated with achieving uniform deformations in massive materials, it may be beneficial to mitigate interdependencies between voxels by designing the 4D-printed object with distinct active or passive lattices [104,108–110].

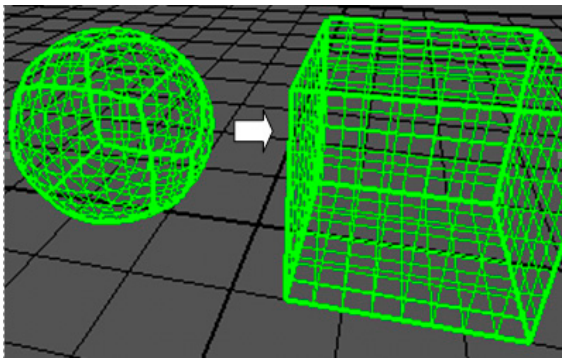

Figure 10. Modeling the shape change through stimulation—the possible case of a lattice structure changing from a spherical to cubic form.

Different structure and material combinations yield unique structural properties, such as stiffness, Poisson's ratio, and overall elasticity. Designing protective structures involves suggesting ideal distributions or configurations of input or output forces using various shapes, thicknesses, and auxiliary materials to mitigate the risk of damage. In comparison to single-material 4D printing, which is challenging to model, it is feasible to simulate changes based on the magnitude and directionality of the actuation [111–115].

Weeger et al. [113] optimized the cross-sectional properties of wire-like structures, particularly Young's modulus, to achieve a target shape under the given loading conditions capable of nonlinear geometric deformation. Subsequently, the structure could actively return to its original shape through the shape memory effect. This involved developing an algorithm for generating physical realizations derived from a computer-aided design model, facilitating direct fabrication through the printing of shape memory composites. While this approach was validated with POCs, it was limited to wire-like structures.

3.4.4. Toward More Complex Models

Several criteria, according to Zolfagharian and Bodaghi [89] and summarized in prior research [116], can frame the modeling of the realization and use of 4D-printed objects:

- General modeling principles stating that proportional expansion is a common self-morphing behavior for several materials;
- The four physical characteristics of mass diffusion, thermal expansion, molecular change, and organic development are differentiating elements;
- Most 4D-printed structures consist of an active layer/component and a passive layer/component.

However, the prediction and modeling of elementary behaviors require further investigation. This involves examining the deformation behavior of printed parts through numerical simulations, such as studies on beams and plates [99]. A fundamental difficulty is that mechanical stress anticipates actions, making it challenging for 4D-printed objects to release enough accumulated stress to be useful. Furthermore, for 4D printing technology to be more widely adopted, it would need to be simplified, especially in its design phase. Such simplifications could lower the entry barrier for companies and researchers, thereby accelerating progress [117–120].

In addition, more sophisticated models and topological transformations are emerging to address manufacturing and material restrictions (for example, full reversibility or residual deformations). These research efforts, developed by Frédéric Demoly's group at UTBM (Sevenans Campus) supported by CNRS, aims to overcome the experimental limitations by approaching multi-material 4D printing from the perspective of modular block assembly [121]. In Demoly and André [3], it was reminded that, apart from Nam and Pei's [122] initiative on a possible taxonomy of shape-changing behaviors, the interdisciplinary knowledge and inherent interdependencies of this technology need to be formalized and correlated. However, these data are rarely available, leading to simplifications in models.

Considering these restrictions, one approach assumes homogeneous material properties within a voxel. The use of a lattice enables simulating and obtaining a relevant qualitative response of the behavior associated with distribution under a specific stimulus. Integrating well-established techniques from the 3D graphics field, such as voxelization and skinning, allows to control object deformations using deformation primitives linked to the movement of skeletons, as successfully implemented in animating virtual characters [123,124]. To replace the springs—usually used to study the behaviors of mechanical systems—between adjacent voxels, beam elements have been used. They resist traction, biaxial bending, and torsion, being governed by the Euler–Bernoulli theory, neglecting the influence of shear. Figure 11 illustrates the steps of the approach.

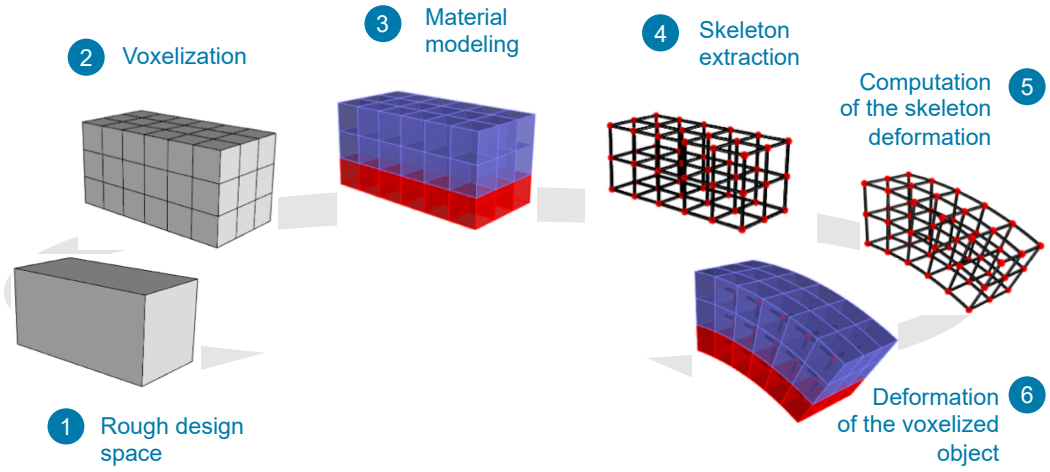

Figure 11. Voxel-based modeling and simulation of active materials [120,121].

Starting from simple initial shapes and behavior laws under energy stimulation, it becomes possible to simulate the shape changes of a 4D-printed object based on the scheme presented in Figure 12. Numerical results, as illustrated in Figures 13 and 14,

provide qualitative insights into this simulation, although cohesion between voxels of different natures is currently not considered [3,90,92,93,119,120,125,126].

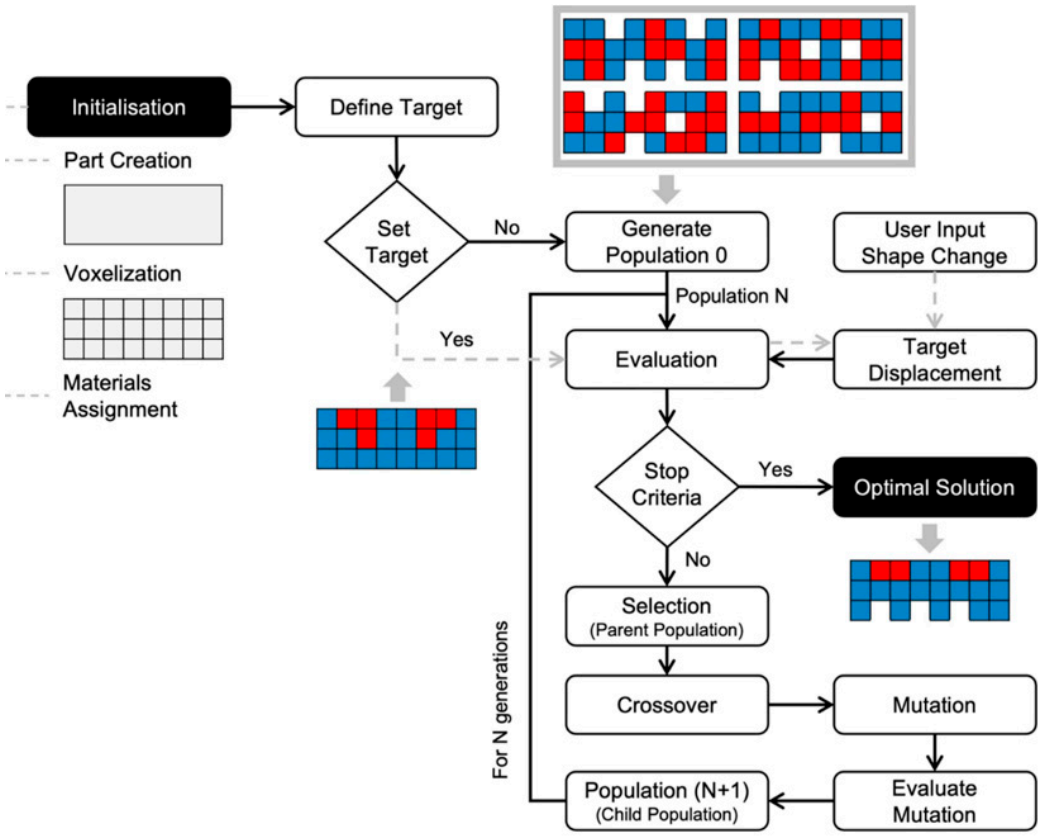

Figure 12. Schematic flowchart of the computational design of multi-material 4D-printed structures driven by an evolutionary algorithm [127].

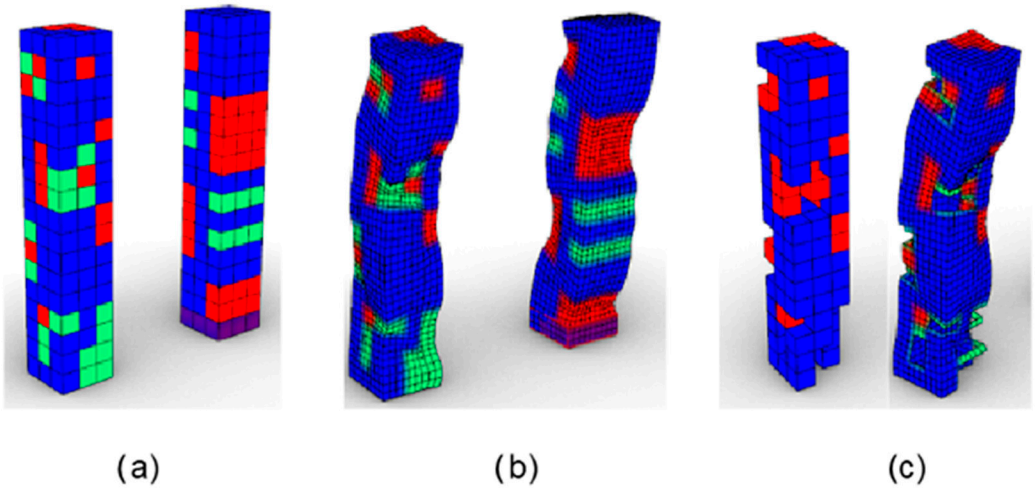

Figure 13. Determination of material distributions integrating void elements using the VoxSmart modeling tool and comparison with a patterned structure: (**a**) voxelized structures with 3 materials (active in red, passive in blue, and "extremely" passive in green) before stimulation, (**b**) stimulated structures, and (**c**) multi-material structures integrating void elements.

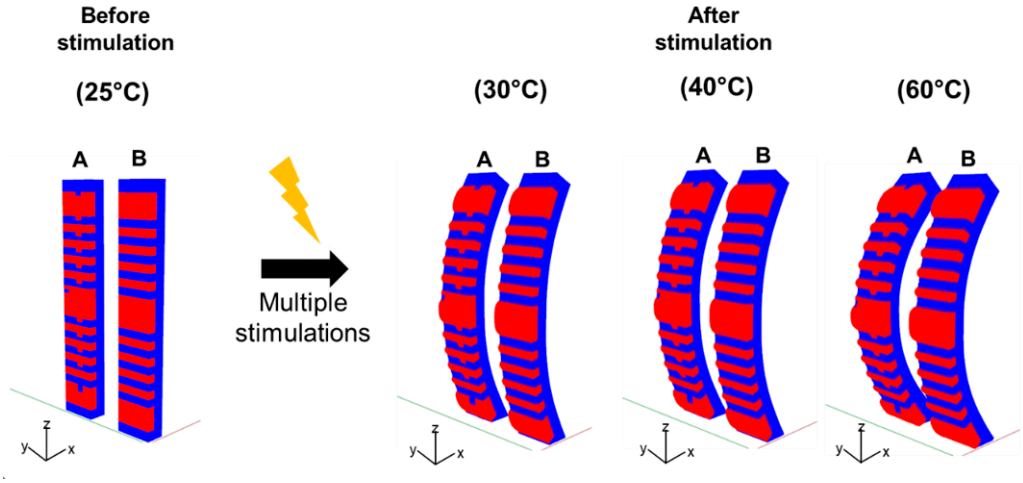

Figure 14. Simulation of an interlocked structure deformation (A) and a printed structure in a single operation (B) within the process flow of the VoxSmart modeling tool for voxelization, materials assignment, and simulation of the energy stimulation. (A,B) Before stimulation (at 25 °C) and after stimulation at 30 °C, 40 °C, and 60 °C [128]. Temperature sensitive hydrogel material is described is red color while the passive elastomer material is colored in blue.

Despite its evolving nature and incompleteness, the graduated presentation of this work offers perspectives and avenues for further research and development:

- Development of a multi-scale interlocking block generation algorithm to enhance the structural performance and control of multi-material distribution, considering voxel relationships and the homogeneous nature of each voxel before and during energy stimulation;
- Optimization of geometric deviations to address AM inaccuracies;
- Integration of mechanical behaviors at the interfaces of interlocking blocks to improve the modeling accuracy and predict functional fatigue;
- Calculation of shadow effects during stimulations induced by voxels located between the one of interest and its primary and secondary sources of stimulation;
- Enhancement of calculation procedures for determining interlocking blocks using artificial intelligence-based techniques;
- Consideration of additional conditions in the calculation of the assembly of interlocking blocks;
- Development of a robotic platform for the manipulation and assembly of blocks at different scales for physical demonstrations;
- Expansion of experiments to include various shape-changing configurations and other active materials activated by stimuli;
- Examination of the use of solid multi-active materials responding to various stimuli.

3.4.5. Synthesis

While the connection between natural sciences and the best practical applications is beginning to emerge through digital design, a robust methodology for designing 4D printing remains elusive. Additionally, attempting to address a wide spectrum of needs in this opinion article does not imply that everyone is expected to achieve practical 4D-printed objects. Alternative approaches, such as inventing subsystems, may also be considered.

Specific challenges related to the evolutionary nature of 4D-printed objects, such as complex interconnections between voxels, material fatigue caused by energy stimuli or using the 4D device, aging effects, and others, must be considered. Computer-aided design and FEA tools must also focus on understanding the spatiotemporal effects of stimuli. These challenges, among others discussed in this article, further complicate the proposed design methodologies.

3.5. Invention

As clarified, the existence of various possibilities does not imply the need to explore every potential subset during the transition from the 4D idea to its practical application. Figure 15 provides an example that does not require sophisticated calculations to increase the displacement of a humidity-sensitive bilayer 4D actuator. Instead of arranging these elements in a series, they could have been placed in parallel, potentially increasing the overall efficiency of the system. While the authors could have provided additional examples of admissible solutions, some documents remain confidential due to French national regulations, while others are publicly available.

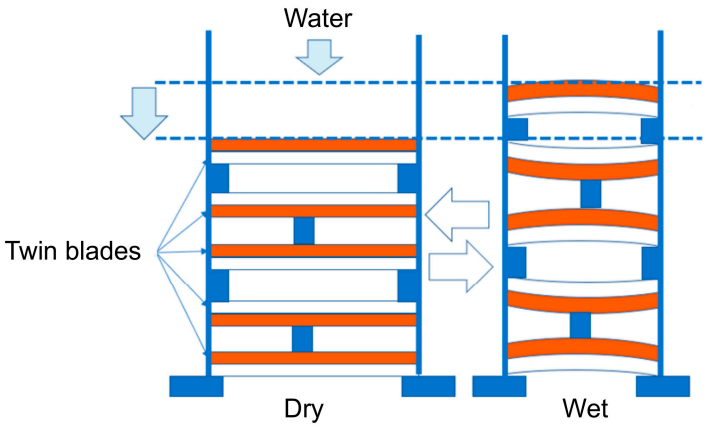

Figure 15. Combination of 4D bilayers to amplify the overall displacement of the structure. Actuators are illustrated in red color while passive structure is in blue color.

The demand for lightweight and active structures across various industrial sectors such as space, avionics, and automotive, alongside the medical field's need for devices like stents, drug delivery systems, and tissue engineering machinery, presents a significant impetus to address the challenges in design posed by 4D printing [118,129–131]. However, this must be done without causing excessive disruption to broader socioeconomic environments.

Given the complexity of creating multi-material objects using AM, it is crucial to develop assemblies that meet specific requirements for practical applications. This requires increasingly sophisticated computer applications capable of modeling and simulating complex assemblies. To mitigate the complexity associated with this deepening, alternative approaches such as interlocking assemblies and attachments are being explored [132–134]. These innovative approaches could potentially transform the design landscape and function within a different context, that of invention or at least innovation.

4. Conclusions

Expressing an idea requires thinking differently and considering alternative proposals beyond state-of-the-art technology. While some may attribute idea generation to chance, Mishima [135] suggested that chance itself operates within the framework of cause and effect, serving as the sole irrational element that free will can acknowledge. Horenstein [136] further explained that if a problem has only one response and merely requires assembling puzzle pieces, it is likely an analytical task, akin to the work of a handyman who gathers scientific and technical elements to maintain an overall idea, leveraging the ability to correlate various ideas and information from different domains. Through this process, the somewhat learned handyman cultivates a certain culture, organizing elements until clarity emerges, akin to the moment of realization famously associated with the exclamation "Eureka!" [137].

However, in more ambiguous and divergent situations, where the characteristics of an idea are not fully determined and the number of potential solutions or solution paths

is high, there are increased risks of failure. At this stage, insights from the artificial sciences can aid researchers and designers in their endeavor, supplementing other disciplines such as engineering and design. As an idea transitions from its initial conceptualization to the realization of a POC, its flexibility decreases, particularly when concrete steps are taken towards implementation. Following evaluation, the POC may undergo significant modifications based on robust results with validated credibility, which should be verified by the authors themselves. While scientists can provide decision makers with reflective scientific and technical works surrounding 4D printing devices, their role is rather assisting in making informed decisions. Even amidst uncertain analyses, engaged researchers must remain accountable.

The synthesis provided in Figure 16 encompasses various elements discussed in this article, serving as a guide for designers, either independently or in collaboration with partners from diverse backgrounds, as they navigate from a 4D design concept to its practical application. This responsibility entails complex design work, which encompasses expertise utilization, generic research, and heuristics derived from Simon's framework [40], as well as the consideration of ideological and/or commercial positions. Given the pivotal role of this domain in the success of 4D commercialization, it warrants dedicated attention. These factual elements should be considered during POC development and serve as a framework for reverse-questioning scientific assumptions, exploring alternative approaches to technical challenges, and more.

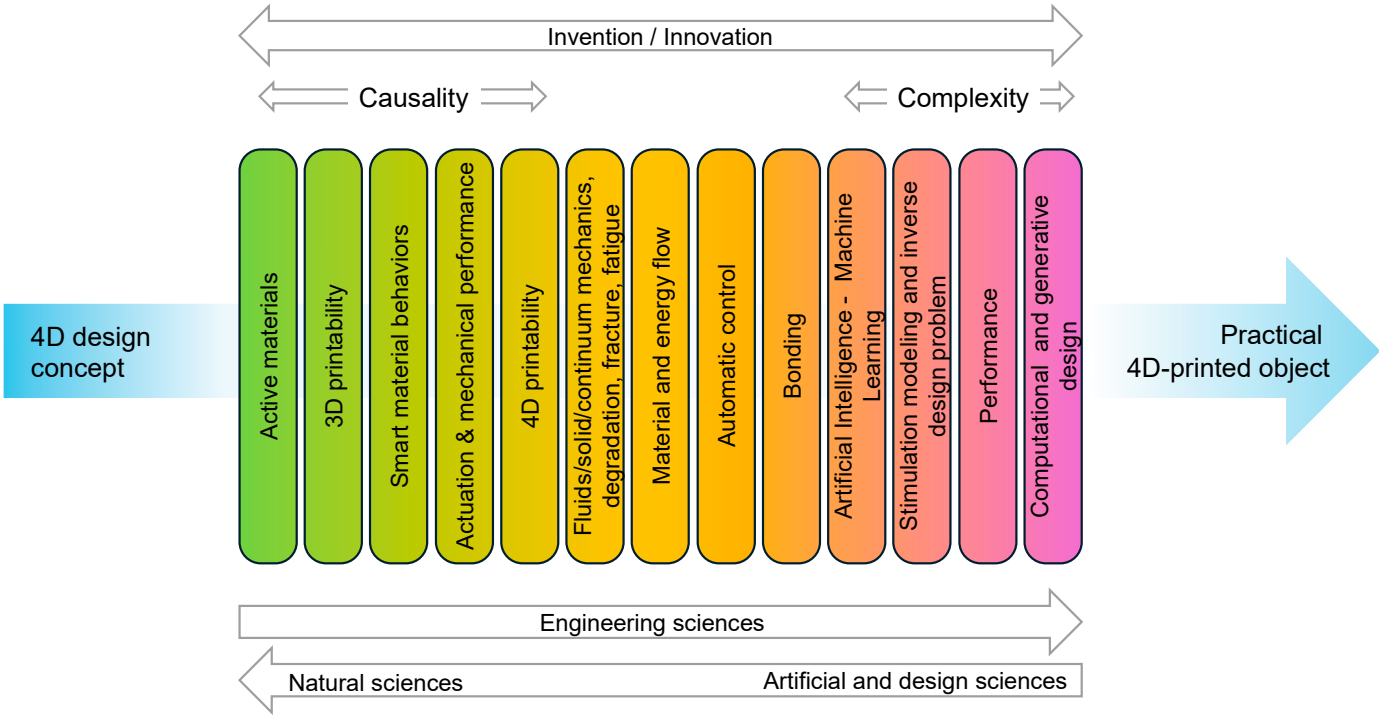

Figure 16. Design considerations to ensure the shift from a 4D-oriented design concept to its practical application. Each vertical bar requires thorough scientific elaboration. The horizontal progression of the vertical bars represents a paradigmatic expansion. A scientific hybridization coupled with an epistemological flexibility is necessary to achieve practical 4D printing solutions.

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