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Research on Interdisciplinary Design Thinking and Methods Based on Programmable Mechanical Metamaterials

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Abstract: Interdisciplinary design thinking and methods are developed based on interdisciplinary research backgrounds. Through cross-integration with other disciplines, it can realize the design's interdisciplinary collaborative innovation and development. At the same time, with the increasing interdisciplinary research interest in programmable mechanical metamaterials, design urgently needs to produce an interdisciplinary design thinking and method model to guide the development of related design research activities. Based on this, this research uses interdisciplinary research methods (mainly grafts method) to transplant the construction methods and related contents of programmable mechanical metamaterials into the research of design thinking and methods to propose a set of interdisciplinary design thinking based on programmable mechanical metamaterials (IDTPMMs). At the same time, under the guidance of IDTPMM, an interdisciplinary design method based on programmable mechanical metamaterials (IDMPMMs) is proposed. The thinking and method take the IDTPMM and IDMPMM process models as the concrete manifestation forms. Subsequently, this study selected two architecture design cases to analyze the rationality of IDTPMM and IDMPMM. This study believes that the proposal of IDTPMM and IDMPMM can narrow the focus of design research from the traditional macro scale to the micro scale of material research and development, which can drive design innovation with material innovation. Meanwhile, it can also change the design research from passive use of existing material mechanical properties to active programming control of material mechanical properties according to demand, which will greatly enhance the programmability, adjustability, controllability, and flexibility of design research with materials as carriers and objects. Additionally, this will have an essential impact on broadening the field of design interdisciplinary research and innovating design thinking and methods. In addition, IDTPMM and IDMPMM will also provide systematic theoretical guidance for designers to conduct interdisciplinary research on design and material science. Its scientific features will also make design research more rigorous, solid, and reliable.

Keywords: design thinking and methods; design thinking process model; design method process model; interdisciplinary research; programmable mechanical metamaterials; architecture design applications

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1. Introduction

In the face of increasingly complex social, scientific, and technological challenges, design has developed from a study of art and architecture to a comprehensive discipline with interdisciplinary characteristics [1,2]. According to the nature and purpose of design projects, design science can involve many fields, such as natural sciences, humanities, social sciences, technology and engineering sciences, creativity, and art [3,4]. At the same time, design is increasingly concerned with the interactions at the intersection of natural, human, networked, and artificial systems [5]. It is fuses different concepts, methods, and theories in an interdisciplinary manner to cover a broader range of activities and practices [6].

The interdisciplinary research between design science and material science is an extremely critical ring of design interdisciplinary research [7,8]. Materials have always been the material basis for the survival and development of design science, and material properties have always been an inseparable part of the design process [9]. However, for a long time, the method of using materials in design has always been: passively recognizing, learning, and selecting the existing materials to complete design activities according to their characteristics [10–16], which greatly limits the potential of design innovation. In order to progress from this state, design began to mix and link scientific thinking and methods with design thinking and methods and started from emerging design demand to establish a beneficial and full-process design closed loop from material research and development to design applications [8], so as to promote design innovation with new material research and development and innovation [17,18]. For example, designers design buildings by calculating and controlling the stimulus–response properties of smart materials rather than according to the original finite state of traditional materials [19]; designers explore design by interacting with materials rather than simply cognition and simulation [20]; by cooperating with living tissues, bacteria, living organisms, and life processes in the material synthesis process, designers develop new biocomposites to achieve innovative creation of architectural installations or artworks [21–23]; designers realize the innovative design of building components by computationally controlling the regeneration and renewable of bio-based materials [24].

At the same time, with the emergence of smart materials and computational matter [25], designers' attention has begun to focus on the programmable research of materials [19]. At present, the interdisciplinary research of design and programmable materials has produced many design achievements [26–31] and design methods [32–38];. for example, digital material design and manufacturing method [39], fiber composite material computational design method for architecture design research [40], bio-based material computational design method [23,24,41,42], data-driven material modeling method [22], and material-based digital design method [43]. These achievements have shown that by transplanting the construction method and the new material development process of materials into the design thinking and method and design process, design research can directly sink from the macro scale to the micro scale and stage of material research and development [44], which can achieve drive design innovation with the material innovation. In addition, design can alter from the passive use of materials to programmable control of materials and their physical properties based on human demands [45], thereby generating design innovations [46,47]. This dramatically broadens the scope of design research and improves the controllability of design.

Along with the development of interdisciplinary research on design and programmable materials, materials science has proposed a new class of materials with excellent properties, that is, programmable mechanical metamaterials [48]. Compared with ordinary programmable materials, it has programmable, controllable, adjustable, and extraordinary mechanical properties [49–51]. Therefore, interdisciplinary design thinking and methods based on programmable mechanical metamaterials will be more promising than those based on programmable materials [52–54]. Although there currently have been some research results on interdisciplinary design thinking and methods based on programmable materials (different from the extraordinary properties of metamaterials, it only focuses on conventional mechanical properties) [31,45,55–57], there is still an extreme lack of the systematical description of the interdisciplinary design thinking and method based on programming mechanical metamaterials. Therefore, it will be a very forward-looking and innovative topic to propose a set of interdisciplinary design thinking and design methods based on programmable mechanical metamaterials to guide new interdisciplinary design research activities.

This study will refer to the interdisciplinary research methods of design research and programmable materials(e.g., according to the design demands, learning material construction methods and knowledge to develop design research) [32–38] and design interdisciplinary research methods (see Section 2.4), and use the method of proposing new methods based on theory, grafting method, the assistance of the analogy knowledge transfer method, combinatorial evolutionary thinking to develop IDTPMM and IDMPMM. By grafting the construction method of programmable mechanical metamaterials and related content into design thinking and methods, this research will propose a set of interdisciplinary design thinking (IDTPMMs) based on programmable mechanical metamaterials. Meanwhile, under the guidance of IDTPMM, a set of interdisciplinary design methods based on programmable mechanical metamaterials (IDMPMMs) will be proposed. IDTPMM and IDMPMM will take the thinking and method process model as the specific forms of expression, respectively. Specifically, Section 2 will review related theories to provide a theoretical basis for the construction of the IDTPMM and IDMPMM process model. Section 3 will introduce the research methodology of this study. Section 4 will propose a set of IDTPMM process models. At the same time, a complete set of IDMPMM process model will be proposed under the guidance of the IDTPMM process models. In addition, Section 4 also will select two architecture design cases to verify the rationality of the IDTPMM process models and the IDMPMM process models, respectively. Section 5 will discuss the advantages and disadvantages of the IDTPMM and IDMPMM process model. Section 6 will summarize the full text and propose a vision for future development.

2. Literature Review

2.1. Design Thinking

The definition of design thinking is not single. It refers to the human-centered and systematic creative strategies used by designers in the design process [58–61], internal situational logic [62], and the way of thinking when solving problems [63]. It can also be understood as a non-linear process [62,64–66] or framework [67–69] of exploration and innovation strategies in design activities.

Design thinking has typical interdisciplinary features [70]. Not only in the field of design, but it is also popular in the field of management science [71], often as a loosely structured organizational process that stimulates innovation [65]. At the same time, design thinking is considered to bridge the gap between the designer's problem-oriented creative approach and the engineer's problem-solving-oriented analytical approach. It is considered to be a kind of thinking between "artistic creative thinking" and "rational analytical thinking" [72]. Therefore, design thinking supports people from different disciplines and backgrounds to achieve certain goals in a collaborative way.

Design thinking emphasizes the value of people, and human-centeredness is its core feature. Firstly, it starts from human behavior, desires, and needs and puts this as the beginning point to seek breakthrough innovations [71]. Human-centered is not simply user-centered but considers the harmonious unity of humans and nature, which can embody human goals and natural laws at the same time [60]. Secondly, active and experiential design thinking can better analyze and deal with the real needs of users and then find out the conditions that need to be met to meet these needs [73]. It will simultaneously involve three specific aspects: cognition, affective expression, and interpersonal activity [74]. Thirdly, design thinking relies heavily on the ability that people to construct ideas to achieve emotional resonance and practical functions by using Intuition and discernment [75]. Strong personal motivations are the design thinking's characterization in a wide range of design disciplines, so designers with different backgrounds may have different ways of thinking [6].

Design thinking is the key to design innovation [6,75]. It is considered to be a powerful, effective, and widely accepted creative thinking process that can achieve innovation [63] and can be applied to all fields of various disciplines and even the whole of society [76]. Design thinking requires designers need to maintain curiosity and openness in the face of things they do not understand, to accept new things, not to be afraid of risks, and to dare to try [77]. This is an essential factor for design thinking that it can continuously achieve innovation [78,79]. At the same time, the innovation generated by design thinking is not achieved by relying on a certain professional field, and the critical link of the innovative solution must be the result of cross-field cooperation [80].

Design thinking in practical use is presented through a design thinking process model [81]; f For example, the "Say-Do-Make" model [82], the "Three Gears of Design" non-linear model [83], the design thinking process with four questions and ten design tools as the main content (Figure 1) [81], and design thinking process with three stages of inspiration, ideation, and implementation as the main content [71]. Meanwhile, design thinking also has some separate processes; for example, observation [84], field investigation [85], interpretation [86], and analogy [87]. In addition, the Design Thinking process proposed by Stanford University and IDEO Corporation, respectively, has the most extensive influence. The non-linear iterative design thinking process of Stanford University is very good at solving poorly defined or unknown complex problems, which can help designers better understand the human needs involved and can redefine the problem in a human-centered way [88]. It has five stages (Figure 2): Empathy, Define, Ideate, Phototype, and Test [88]. Based on this, some improved design thinking processes have also emerged. For example, Waidelich divides "Empathy" into "Understanding" and "Observation" phases [89]; Lugmayr et al. modified it according to the context of knowledge in the field of media management (Figure 3) [70]; Henriksen et al. used it in the field of educational practice and updated it [90]. IDEO's design thinking process has six stages (Figure 4): Observation, Ideation, Rapid prototyping, User feedback, Iteration, and Implementation [91]. Here, the Stanford and IEDO design thinking process model will provide the main references for this study.

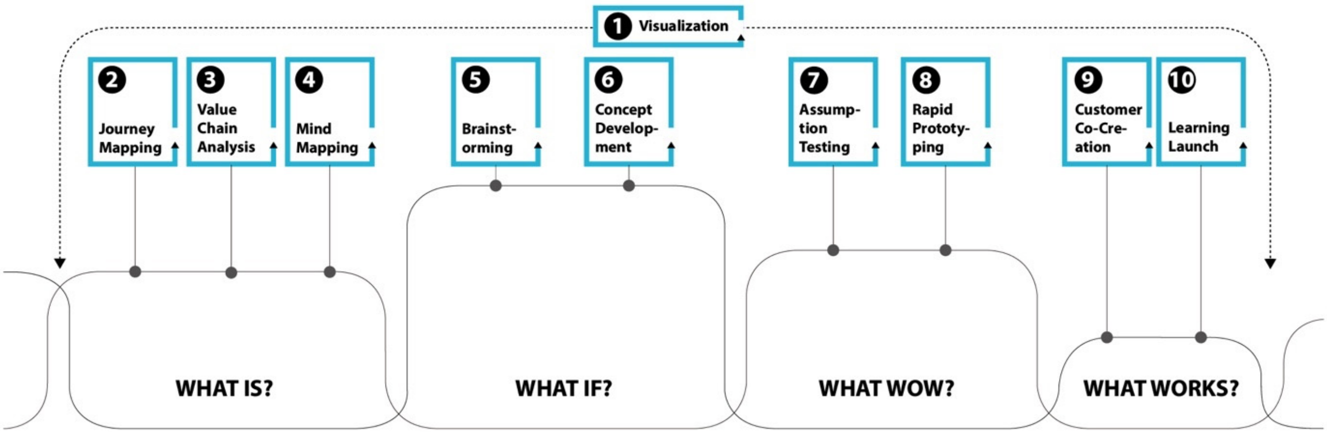

Figure 1. The design thinking process model with four questions and ten design tools as the main content. (According to ref. [81], this figure is painted by this article).

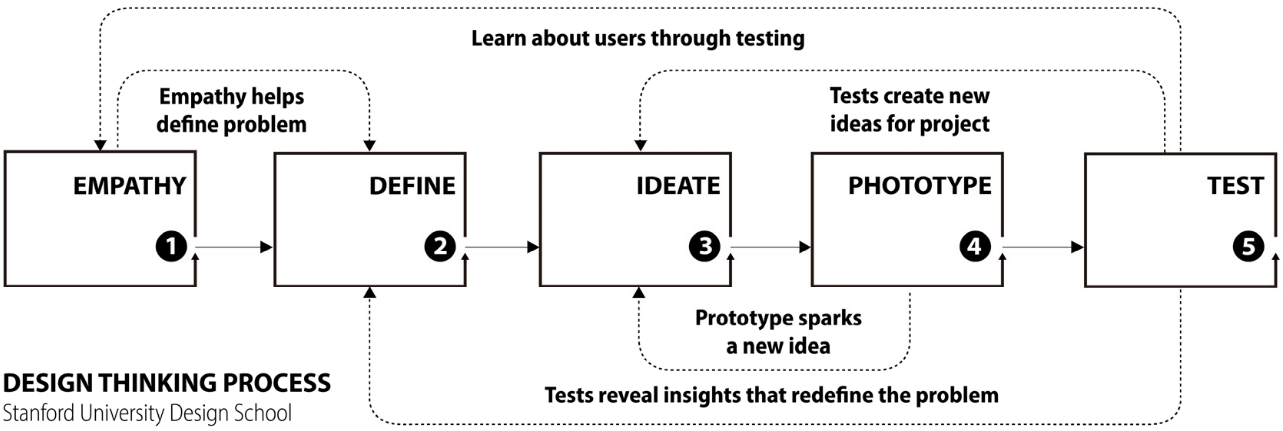

Figure 2. The Design Thinking Process model of Stanford University. (According to ref. [88], this figure is painted by this article).

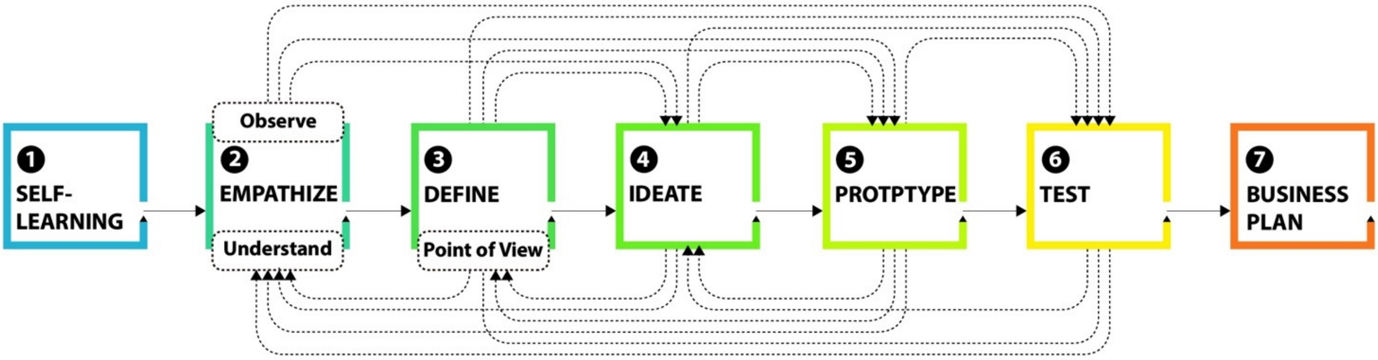

Figure 3. The design thinking process model modified according to the knowledge of media management. (According to ref. [70], this figure is painted by this article).

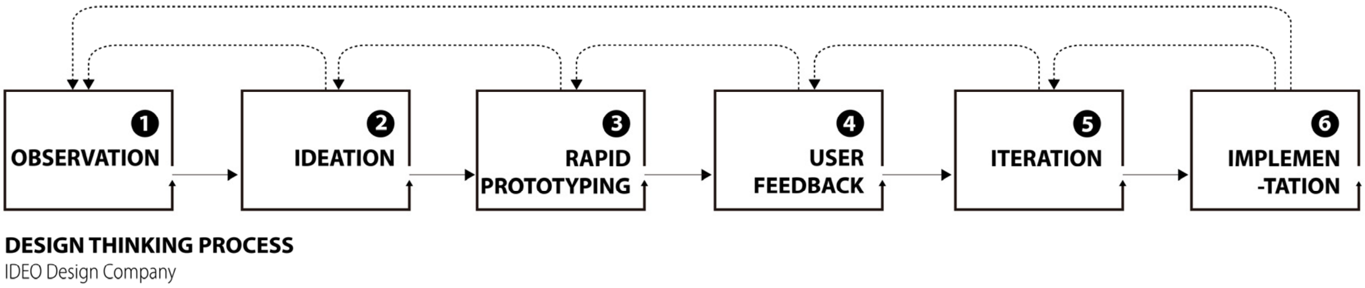

Figure 4. Design Thinking Process model of IDEO. (According to ref. [91], this figure is painted by this article).

2.2. Design Methods

Design methods are the formalized expression of design activity, and it articulates how to conduct design practice [92]. It is a collection of tools, techniques, means, and methods for designers to achieve design goals [93]. Design methods can serve as information carriers, expressing how users perform specific practice activities designed by designers through processing, interpretation, and subsequent behavioral changes [94]. Since the design method was proposed by the British Conference on Design Methods in 1962, its importance has been continuously increasing, and now it has become one of the core topics of design research [95].

According to different design and subject scenarios, a series of systematic design methods have been produced around solving a specific problem. For example, architectural and planning design methods, graphic design methods, interior design methods, general design methods [96], industrial and product design methods [97], design history research methods [98], engineering design methods [99], design methods for guiding teaching works [100]. In addition, there are also many unitary-specific methods in the design methods. Examples are shown in Table 1. First, according to nature, design methods can be divided into two categories. One category is controlled, experimental, and quantitative methods [101]. One category is the naturalistic, qualitative methods [101]. Most of this broad category belongs to general-purpose design methods. Designers are less influenced by the theme or purpose of the design when choosing such a method. Second, according to the design stage or detailed demands, design methods can also be divided into general heuristic methods (Table 1), systematic research and analysis methods (Table 1), and details and delivery methods of design presentation (Table 1). The heuristic method mainly plays the role of diverging and inspiring design ideas and generally appears in the early stage of the design stage. Systematic research and analysis methods are more rational, formalized, framed, and complicated, like algorithms. The details and delivery methods of design presentation are more inclined to the application level, mainly focusing on better exploration of the design process and display of design results.

Table 1. Examples of unitary specific Design methods.

Classification		Examples of Different Methods
Classified by nature	Controlled, experimental, quantitative methods	Quantitative Research Methods [101,102], Experimental Methods [101]
	Naturalistic, qualitative methods	Interviews and Field Observations [97,103], Participatory Observation Method [104], Phenomenological method [105], Practice-generated Method [97], Design Ethnography [106]
Classified by design stage or detailed demand	General heuristic methods	Conjecture Analysis [106], Creativity Methods [107], Concept Sketching [97], Cognitive Heuristics [108]
	Systematic research and analysis methods	Spatial Syntax [109], Creative Search Methods [110], Ergonomic Approach [111], Protocol Analysis Method [112], Triangulation method [113], Iteration and Reflection [114], Morphological Analysis [115], Analogical Reasoning [116], 101 Design Methods [97], Semantic Discontinuity Detection Method [117]
	Details and delivery methods of design presentation	Visualization Maps [118,119], Visual Reasoning Models [120]

The centrality, prescriptive presentation mode of the design method is the design method process model [121]. It is not composed of one method but a main method as the main line, supplemented by other methods or a mixture of methods [122]. There are many types of design methods programs, covering architectural design, industrial and product design, engineering design, and other fields; for example, the normative design process [122,123], the computer-based design process model [121], the process of design solutions [124], the new product development process [125], the goal-directed design process [126], walking process [127], and engineering design process [128]. Among them, the relatively systematic, rigorous, and complete method process is the Morris Asimow design method process (Figure 5). It transforms the design process into a series of decisions, including three levels the feasibility study, preliminary design, and detailed design [124,129]. It informs the development of most new design method processes and, at the same time, will provide the core reference for the design method process model of this study.

2.3. Design Thinking and Methods

Design thinking serves as a conceptual framework that can allow designers to better understand the use of design methods [130]. Meanwhile, it can also connect various design methods in series or in parallel to solve design problems [105]. Additionally, design thinking can guide the design methods [131]. Designers can use design thinking as a guide to using different methods to solve design problems according to needs. For example, IDEO adds many methods, techniques, and tools to each step of the design thinking process model to solve design problems [124]. Parametric architectural design is also realized by using various design methods and information process models under the guidance of parametric design thinking [132]. At the same time, from the perspective of design methods, design methods are a means to concretize the designer's thinking process model [131]. Design methods require tandem design thinking, and a single design method is not enough to solve complex design problems [132]. Therefore, design thinking and methods are complementary and indispensable.

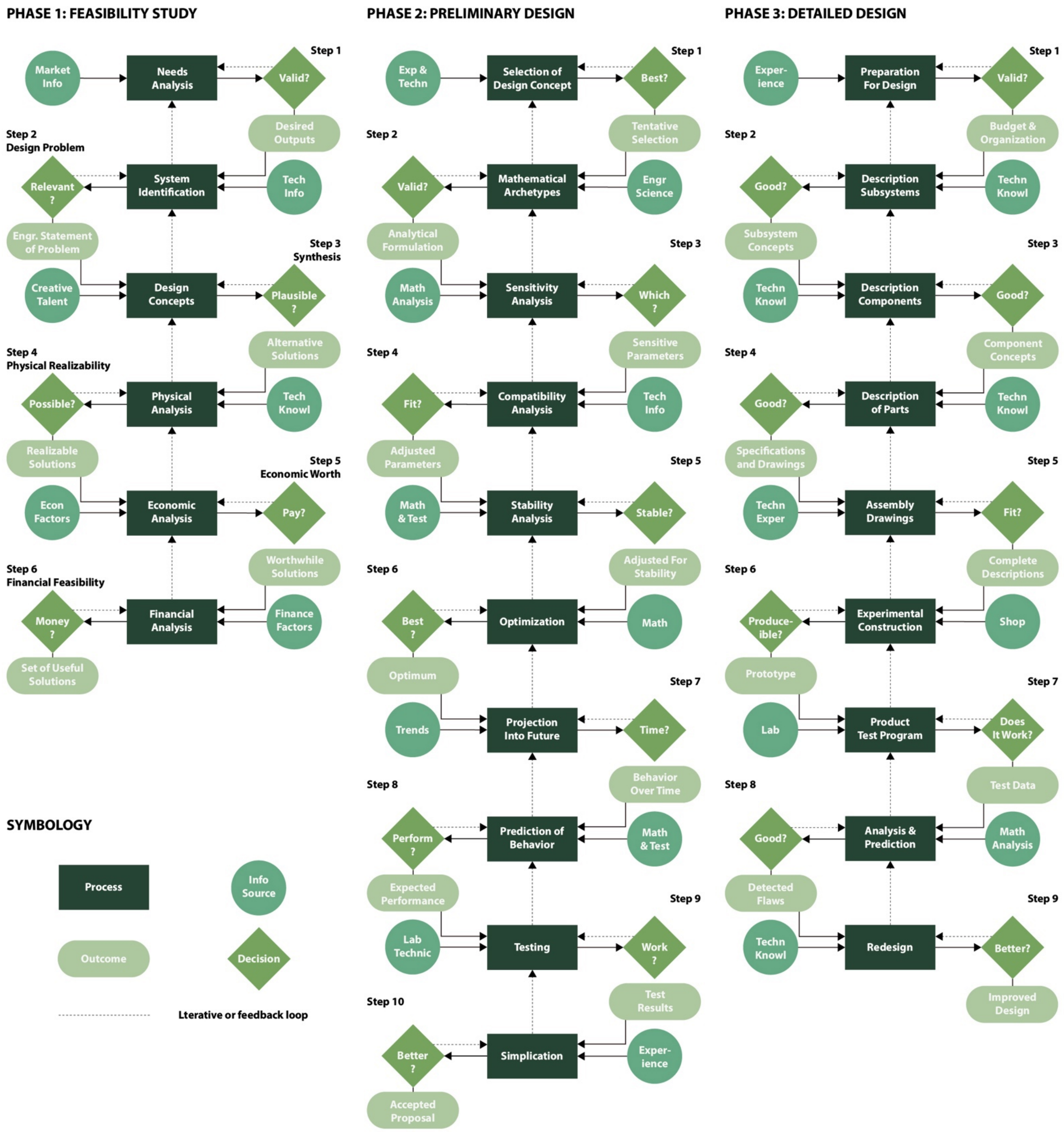

Figure 5. Morris Asimow's design method process model. (According to ref. [124,129], this figure is painted by this article).

2.4. Interdisciplinary Design Thinking and Method Research

As early as 1979, Archer demonstrated that the interdisciplinary effect of design research was enormous by incorporating operations research and management techniques into design methods [61]. In recent years, with the continuous development of design disciplines, more and more natural and engineering scientific thinking and methods have been incorporated into design research, resulting in many new interdisciplinary design thinking and methods [133]. Interdisciplinary design thinking and methods have been identified as fundamental keys to generating innovation [134,135].

The origin of the design method is in the "scientific" method [136]. For example, Hubka and Eder believe that an important part of the design method contains knowledge of many natural and human sciences [137]. Oxman proposed a Krebs Cycle of Creativity framework, which believes that the discipline boundaries of science, engineering, design, and art are no longer obvious, and the mutual conversion of knowledge and methods is the main development trend [138]. As a result, design has become increasingly interested in science [8,139]. As Table 2 shows as examples, it has been through drawing extensively on scientific methods, knowledge, and theories, from which a variety of systematic design thinking and methods have been derived, mixed, and generated [8,102]. At the same time, as shown in the example in Table 2, in addition to systemic thinking and methods, drawing multidisciplinary approaches, a number of single interdisciplinary design thinking and methods have emerged, which are often used to solve specific problems arising from a particular step in the design process model.

Table 2. Examples of interdisciplinary design thinking or methods.

Classification	Examples
Systematic interdisciplinary design thinking or methods	Behavioral design methods [139,140]; Parametric design thinking (PDT) and methods [132,141]; Intelligent building automation methods [19]; Design optimization methods and tools [111]; Computational design methods [19]; Artificial intelligence design methods [142]; Architectural generative design methods [142]; Social design thinking and methods [139,143]; Service design methods [139]; Sustainable design thinking and methods [139,144,145]; Biologically inspired design (Bio-inspired design) method [21]; Co-evolutionary design model [146]; Design research teaching method based on philosophical method [147].
Single, specific interdisciplinary design thinking or methods	Shape grammar [148]; Product 3D shape generation method [149]; Think Maps based on ICF model [150]; Automatic space and structure interaction design method [151]; In-Between Area Design method [152]; Evolutionary structural optimization method [153]; Strategic design concept [154]; life cycle thinking [155].

In addition, interdisciplinary design research also involves the study of new method-generating strategies. It generally adopts the strategy of mixing, introducing, borrowing, and bridging. For example, Dubberly advocates the introduction of the scientific problem-solving process into design thinking and methods to ensure that human environmental problems are solved in a systematic and precise way [124]. Love expounded the research method of interdisciplinary design theory system from the perspective of philosophical issues [156]; Pinxit believes that a key direction for future design is the integration of multidisciplinary knowledge [157]. Alkire et al. generated a new service design method using an interdisciplinary framework bridging transformative service research (TSR), social entrepreneurship, and service design [158]. Tobi and Kampen, on the other hand, proposed an interdisciplinary research framework (MIR) for designing research that allows for the combination and mixing of a range of methods [159]. Malcolm and others believe that interdisciplinary design activities are the cooperation of two or more disciplines [160]. By combining skills together, solutions to complex systems can be achieved [161]. These studies will provide a lot of references for the cross-disciplinary research methods of this study.

2.5. Programmable Materials and Programmable Mechanical Metamaterials

The concept of programmable materials is relatively broad at present, and there is no extremely clear definition yet. Deformable materials, programmable matter, digital materials, bio-based computing materials, smart materials, and 4D materials all belong to the research category of programmable materials. Programmable materials can be roughly summarized as follows: Under the guidance of computer programming thinking, materials with physical properties (such as deformation, color, and refractive index) that can be adjusted on demand are constructed through "information parameter" programming [45].

Among them, "information parameters" can be divided into two parts: structure and external driving force. The structure mainly refers to the programmed control of material structure, for example, the control of material anisotropy [46]. Extrinsic driving forces mainly refer to the control of forces that affect material changes, for example, computational forces, manual forces, and environmental forces [47].

Programmable mechanical metamaterials are developed on the basis of Programmable electromagnetic metamaterials, programmable materials, smart materials, 4D materials, and mechanical metamaterials [162]. Mechanical metamaterials, also known as structural metamaterials, refer to certain materials with special mechanical properties, which are determined by their structure rather than their original material properties [162]. Mechanical metamaterials have numerous extraordinary properties, for example, ultrahigh stretchability [163], negative compressibility [164], negative stiffness [165], superstrength [166], auxetic (negative Poisson's ratio) [167], and adjustable stiffness [162].Thanks to the extraordinary performance of mechanical metamaterials and the programming thinking exploration of programmable materials and programmable electromagnetic metamaterials, programmable mechanical metamaterials can be roughly described as follows: using programming thinking to construct metamaterials with controllable [168,169], adjustable [170] and programmable [171] supernormal mechanical properties through computational control of "information parameters". Specifically, on the one hand, it is built from unit cells with the same or different "geometric parameters". These unit cells can be dynamically distributed, arranged, and assembled in different computing networks, arrays, spaces, and subdivisions through the programming system, so as to achieve the purpose of controlling the propagation of mechanical signals [172–174]. Unit cells can interact and drive each other. On the other hand, it can also combine external driving forces and use logic operations to control mechanical properties [175]. Here, the knowledge of programmable mechanical metamaterials will provide rich interdisciplinary knowledge for the research of IDTPPM and IDMPPM.

Interdisciplinary research on design and programmable materials has yielded many achievements in interdisciplinary design thinking and methods. However, interdisciplinary research results on design and programmable mechanical metamaterials (especially interdisciplinary design thinking and methods based on programmable mechanical metamaterials) are still very scarce. As shown in Table 3, this study uses examples to sort out the situation of interdisciplinary research on programmable materials and programmable mechanical metamaterials and design. This will provide a reference for the proposal of IDTPMM and IDMPMM.

Table 3. Examples of current state of interdisciplinary research on design and programmable materials and programmable mechanical metamaterials.

Classification	Examples
Design thinking and methods based on programmable materials, design results	Deformation interface design methods based on soft composite materials (pneumatic drive) [26,46]; Design methods based on synthetic multi-material 3D printing (programming model dominant) [28]; Architectural design thinking and methods based on material self-assembly [29]; Building assembly and automation design methods based on programmable materials [30]; Introduction to design methods based on programmable materials [31,38,43]; Design of deformable components based on stimulus-responsive materials [32]; Shape change interface design based on programmable materials [33,45]; The concept of programmable materials in design research [35,55]; Building component design methods based on 4D materials [36,37,56,57]; Digital Material Design Method [39]; Collaborative design method for architectural computing based on fiber materials [40]; Computational design methods based on biological materials [41,42,47]; Design methods based on deformable materials [43].
Interdisciplinary design thinking and methods based on programmable mechanical metamaterials	There is no systematic description of design thinking and methods, only a few designs practice results. For example, energy-saving architectural design based on programmable kirigami mechanical metamaterials [168].

3. Methods

3.1. Research Method Framework

The main research method adopted in this study is shown in Figure 6. Firstly, based on existing academic theories, various knowledge and theories required for the development of new thinking and methods are provided through the literature review. Secondly, they use interdisciplinary research methods (mainly the grafting method) to transplant the programmable mechanical metamaterial construction method and related knowledge into the design thinking and method, resulting in IDTPMM and IDMPMM. At the same time, IDTPMM and IDMPMM are systematically presented using the thinking process model and method process model, which is convenient for designers and users to learn, understand and use.

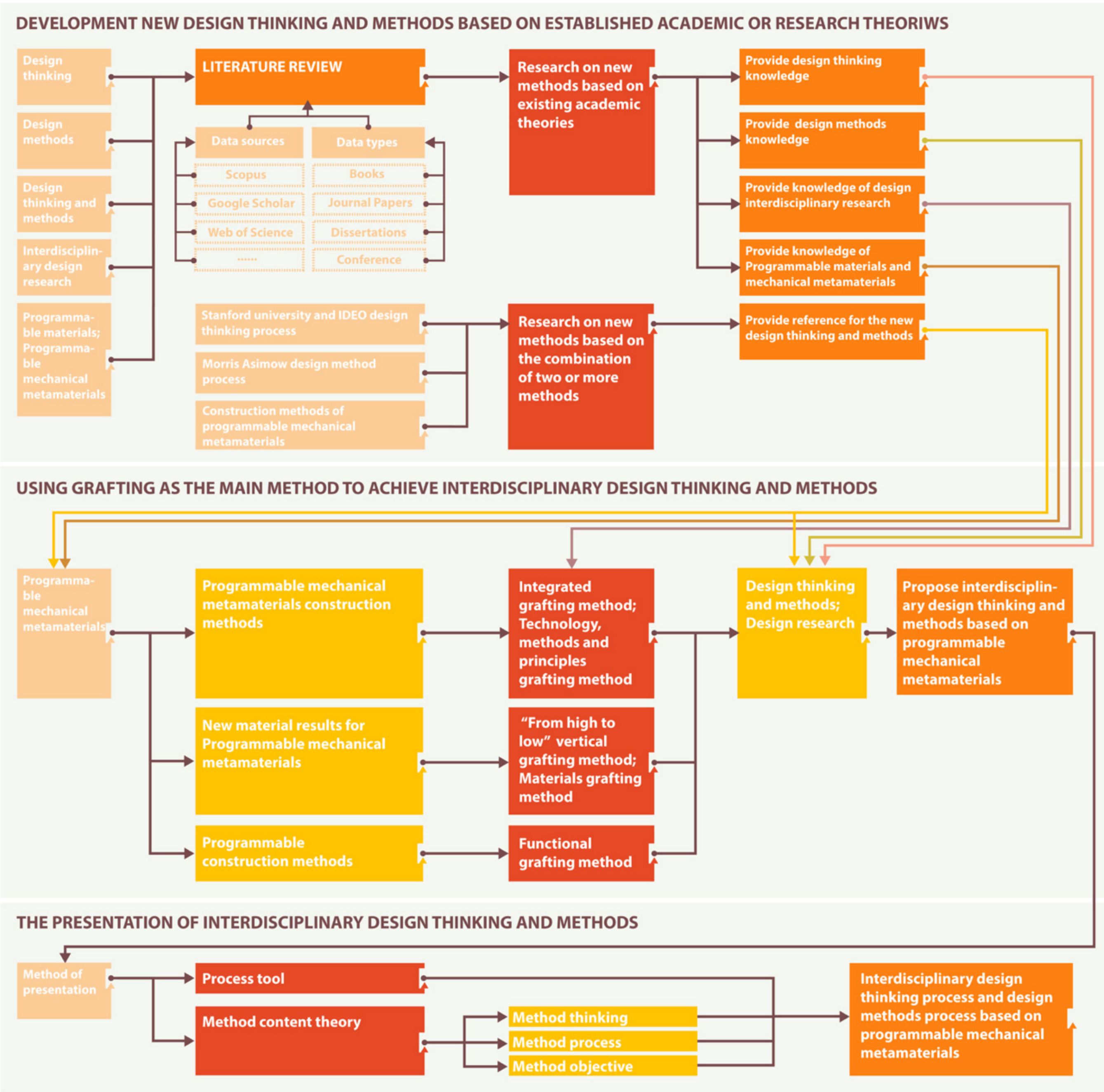

Figure 6. The framework of research methods.

3.2. Conduct Research Based on Existing Scholarship or Theory (Provide a Theoretical Basis)

The proposal of new design thinking and methods is generally divided into two approaches: proposing new methods based on the research and summary of existing design practices and proposing new methods based on the support of existing academic or research backgrounds [97]. Proposing new methods based on practice refers to the development of design methods in creative professional design practice activities. The method is not directly influenced by academia or theoretical research and pays more attention to the understanding of real-world environments [104]. In contrast, proposing new methods based on academic and research backgrounds relies on more comprehensive existing methods and literature systems to summarize, describe, and generate new design methods to support design practice [93,96,97]. This method can be roughly summarized into three development directions: building a new thinking and method based on a theoretical framework [176], using two or more thinking and methods to build a new thinking and method [177], and adjusting and developing existing thinking and methods [178].

This study will use the method of "proposing new methods based on existing academic or research theoretical research" to provide theoretical knowledge for the development of this study. Specifically, this study will adopt a research path combining two modes: "based on a theoretical framework and a combination of two or more methods":

- Above all, according to the concepts, methods, and theories that are involved and need to be clarified, this research will systematically use the method of literature review to provide the required theoretical basis for the research. Relevant knowledge comes from Scopus, Google Scholar, and Web of Science databases, involving monographs, scientific articles, dissertations, and conference papers. Specifically, firstly, by sorting out the knowledge of design thinking and design methods, the definitions, concepts, and interrelationships of specific research objects are clarified. Secondly, by sorting out the research situation of interdisciplinary design thinking and methods, clarify the current mode of interdisciplinary design and multidisciplinary cooperation, and provide ideas and models for interdisciplinary design research for this study. At the same time, these cases can also demonstrate the necessity and rationality of this research. Thirdly, by combing the cooperation status of programmable materials and design to provide more specific research ideas and model references for this study. Fourthly, by combing the relevant situation of programmable materials and mechanical metamaterials to provide the definition, concept, and methods of interdisciplinary research objects for this study.
- Additionally, the design thinking process model of Stanford University and IDEO, Morris Asimow's design process model, and the existing programmable mechanical metamaterial construction methods are selected as the main source of reference for new design thinking and methods.

3.3. Taking Grafting Method as the Main Method to Propose the New Interdisciplinary Design Thinking and Methods

The grafting method is the core research method of this study. The grafting method is a method for obtaining results by transplanting the principles, techniques, and methods in a certain discipline into the other discipline [179]. According to the scope of research, the grafting method can be divided into vertical, horizontal, and integrative grafting methods [179]. Among them, the vertical grafting method of "from low to high" refers to the following: transplanting the concept and methods of the disciplines having low forms of movement into the discipline field possessing the high forms of movement [180,181]. The "high to low" grafting method is a way of thinking and a key solution to trigger the understanding of lower forms of movement by referring to the results of disciplines that study higher forms of movement [180,181]. The integrative grafting method is the transfer of concepts, principles, and methods from multiple disciplines to an object of study in a particular field of research to examine the particular nature and laws of that object of study in an integrated manner [180,181]. In addition, according to the research object, the grafting method can also be divided into [182]:technology, method, and principle grafting method (apply technology, method, and scientific principle in a certain discipline to solve problems in other disciplines), function grafting method (apply a certain function of a certain thing to solve problems in other things), Material grafting method (transfer the material to a new carrier to produce new effects).

This study uses three categories of the grafting method to carry out the study (Figure 6):

- Using integrative grafting method and technology, method and principle grafting method, the construction method of programmable mechanical metamaterials and the principles of multidisciplinary knowledge (such as mechanics, material science and engineering, and mathematical principles) are transplanted to design thinking and methods, a set of Interdisciplinary design thinking and methods covering from basic research to applied research is formed.
- Using the "high to low" vertical grafting method and material grafting method, the subject knowledge and new material achievements involved in programmable mechanical metamaterials are applied to design research. The obtained results are used to complement interdisciplinary design thinking and methods based on programmable mechanical metamaterials.
- Using the functional grafting method, the programmable construction method is transplanted into the design thinking and method. The obtained results are used to complement interdisciplinary design thinking and methods based on programmable mechanical metamaterials.

In addition, it should be noted that, in addition to the grafting method as the main research method, this study also needs the assistance of the analogy knowledge transfer method and combinatorial evolutionary thinking.

The analogical knowledge transfer method refers to the transfer of knowledge from one context to another through mapping between different knowledge systems [183]. This method has a core feature: it is not copying knowledge, but based on the background of the original discipline, borrowing or transforming the knowledge or tools of other disciplines for my own use [184]. Therefore, this study is not to completely copy the construction method of programmable mechanical metamaterials into design thinking and methods, but to transform its concept and apply it to design research according to the research background of design science and the usual description methods. This is convenient for linking with the original design thinking and methods, and it is also easy for designers or engineers to understand and apply. However, although the construction methods of programmable mechanical metamaterials have been transformed according to the design method, their core advantages remain unchanged.

Combinatorial evolutionary thinking refers to the ability to combine elements that no one else thought matched and arrive at a new perspective [185]. It is a synthesis process, the process of discovering connections between seemingly unrelated domains [186]. Simple transplantation and knowledge transfer cannot make the resulting design thinking and methods more systematic. Therefore, this study will assist in the use of combinatorial evolutionary thinking to connect and reorganize the elements to optimize the research results of IDTPMM and IDMPMM.

3.4. Specific Presentation Methods of IDTPMM and IDMPMM

Design usually adopts a graphic-based expression method, which can better convey creating ideas to others while assisting thinking [187]. Therefore, in terms of IDTPMM presentation, this study mainly takes the design thinking process model as the specific form. The design thinking process model is a good tool for expressing design concepts and communicating among designers [188]. It can be seen as a kind of Think Map [150]. Through the frame model, it can combine abstract text with symbols and signs to better show the reasoning relationship of thinking [150].

In terms of design method presentation, this study mainly uses method content theory for presentation. The elements of method content theory are mainly method procedures, method goals, and method thinking [92]. The method process model is the specific guidance on how to achieve the goal of the method and the specific presentation form of the method tools. It is defined as follows: the structural activities described in the method and their relative temporal and logical order [92]. Method goals refer to the purpose, scope, and degree of flexibility of the method [92]. Method thinking is defined as follows: the values, principles, fundamental beliefs, and logic of methods [92]. At the same time, it is known from literature reviews that the main means of presentation and expression of most current design methods is the design method process model [97,131,156,189,190]. Therefore, the presentation of the IDMPMM will mainly revolve around the method process model. Additionally the method of thinking is the same as IDTPMM, and therefore, the study is not repeated in the method presentation phase.

4. Results

4.1. Interdisciplinary Design Thinking Based on Programmable Mechanical Metamaterials (IDTPMM)

4.1.1. Basic Logic Description

The main logic of IDTPMM is divided into two aspects: a. Introduce the programmable control thinking of programmable mechanical metamaterials into design thinking so that design research can no longer passively use existing material mechanical properties but can be programmed and controlled according to human needs or social needs. b. Innovative research-driven design innovation research based on programmable mechanical metamaterials.

4.1.2. Introduction of IDTPMM Process Model

The IDTPMM process model is mainly divided into two main parts: design basic research and design application innovation. Design basic research mainly focuses on factual, theoretical, and experimental research on programmable mechanical metamaterials. Its main purpose is to reveal the essential laws and principles of the research object. Design-applied research mainly revolves around basic research results. It is mainly based on the laws and principles of basic research and is demand-oriented to conduct divergent and innovative research. It puts the satisfaction of a need, the solution of a specific problem, or the achievement of a specific goal as a result. Therefore, as shown in Figure 7, the IDTPMM process model can be described as follows:

- **Geometric or structural unit cells design (①):** Geometric or structural unit cells are the basic building blocks of programmable mechanical metamaterials. At the same time, it is also the basic unit for design thinking to intervene in material research. Designers can provide basic elements for building metamaterials through unit cell design.
- **Programmable design or construction (②):** Programmable design or construction refers to the construction of materials based on unit cells and using programmable design methods.
- **Realization of programmable mechanical metamaterials (③) (with controllable, adjustable, programmable mechanical properties of novel materials):** Realization of programmable mechanical metamaterials refers to the actual fabrication of metamaterials based on programming construction schemes.
- **Demands (④):** Designers need to start design application research by investigating how well human needs match with programmable novel mechanical properties. At the same time, determine which demands can be achieved through innovative thinking that sinks the design into the material research and development stage or through programmable material mechanical properties. In addition, demands can also be pre-empted, as the first step in the entire design thinking process model, to meet people's needs as the main goal of unit cells design and metamaterial construction, and then design innovation. Solving the demands of people is the origin of design research, the inducement of design, and the value and significance of design.

- **Ideates (⑤):** Propose creative solutions according to needs.
- **Prototype (⑥):** Realize the design prototype according to the creative plan.
- **Test or user feedback (⑦):** Propose revisions based on tests or user feedback.
- **Iteration (⑧):** Iterate according to the revision comments.
- **Implementation (⑨):** Final design output.

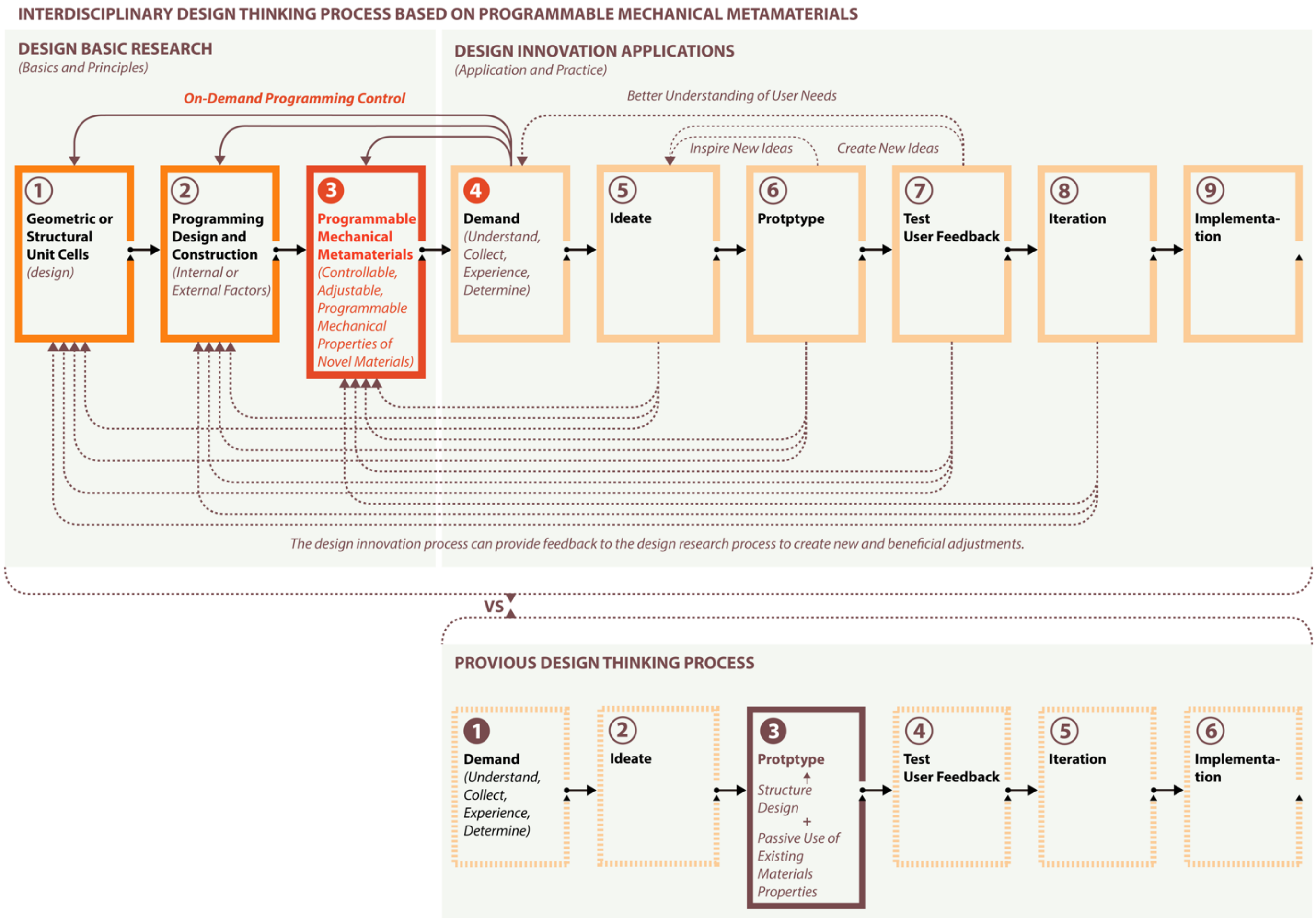

Figure 7. Interdisciplinary Design Thinking Process Model based on Programmable Mechanical Metamaterials.

4.1.3. Non-Linear Characteristics of IDTPMM Process Model

The IDTPMM process model has typical non-linear characteristics. Here, the non-linear process of the IDTPMM process model is described in terms of on-demand programming control, design application innovation, and design fundamental research and design application innovation, respectively. The description is given by way of examples.

In terms of demand-based programable control, first, from the perspective of design research-design innovation thinking logic, "demand (④)" is the fifth step in the IDTPMM process model. However, since "demand (④)" is the core step and element of the IDTPMM process model, it can appear as the first step in most application cases, that is, on-demand programming to control the mechanical properties of metamaterials for design innovation. The process model can be expressed as ④-①-②-③-⑤-⑥-⑦-⑧-⑨ (Figure 8a). Among them, ①, ②, ③ can be adjusted and modified separately or in association according to ④. Second, in the IDTPMM process model, the direct use of existing metamaterials with programmable mechanical properties developed by materials science can also achieve design innovation development. The process model can be expressed as ④-③-⑤-⑥-⑦-⑧-⑨ (Figure 8b). In addition, the IDTPMM process model can also delete the step of the construction and realization of programmable mechanical metamaterials and only use programmable thinking to realize design research and design innovation. The process model can be expressed as ④-①-②-⑤-⑥-⑦-⑧-⑨ (Figure 8c) or ④-②-⑤-⑥-⑦-⑧-⑨ (Figure 8d).

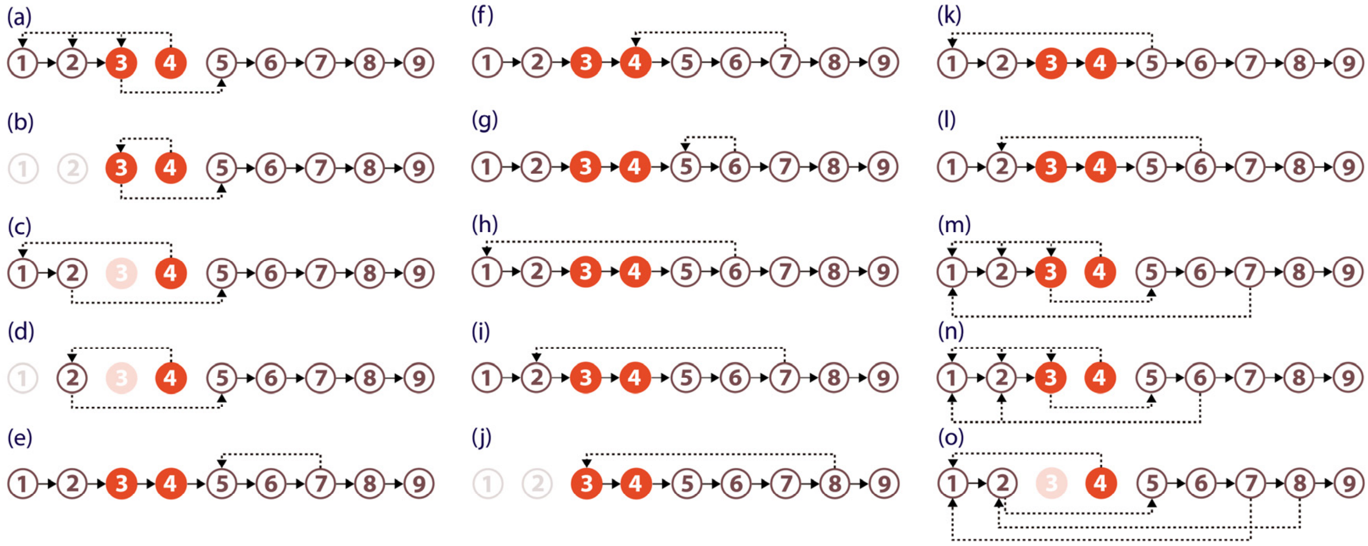

Figure 8. Examples of IDTPMM nonlinear process model (①–⑨ represent the 9 steps of IDTPMM process model; Red indicates core steps; light colors indicate steps not involved in the process; other colors indicate routine steps). (**a**–**d**) The Non-linear thinking processes with programmed control as the main purpose.(**e**–**l**) The non-linear thinking processes with the main purpose of designing application innovation.(**m**–**o**) The non-linear thinking processes that includes both design fundamental research and design applied research.

From the perspective of design application innovation research, first, "testing or user feedback (⑦)" is helpful for the development of new design ideas. At the same time, it can also help designers understand "user needs" better and more accurately. The process model can be expressed as ⑦-⑤ (Figure 8e), ⑦-④ (Figure 8f). Second, the exploration and research of prototypes can also better promote the generation of new ideas. The process model can be expressed as follows: ⑥-⑤ (Figure 8g). Third, during the "Ideate (⑤)", "Prototype (⑥)", "Testing and user feedback (⑦)", and "Iteration (⑧)", if any temporary need for material construction arises, regardless of where the design step is, it is possible at any time to modify or adjust the "geometric or structural unit cell design (①)", "programmable design or construction (②)", and "Programmable mechanical metamaterials (③)". This can be used to improve problems that arise during the design process model or to meet new ideas that arise during the design process model. For example, "prototype (⑥)" can propose new requirements to make designers adjust and modify "geometric or structural design (①)" (①-②-③-④-⑤-⑥-①-②-③-④-⑤-⑥-⑦-⑧-⑨) (Figure 8h); "Testing and user feedback (⑦)" can require changing programmable thinking (①-②-③-④-⑤-⑥-⑦-②-③-④-⑤-⑥-⑦-⑧-⑨) (Figure 8i); In the implementation of the step "iteration (⑧)", the designer found that it would be more beneficial to the design to choose a programmable mechanical metamaterial with different properties (③-④-⑤-⑥-⑦-⑧-③-④-⑤-⑥-⑦-⑧-⑨) (Figure 8j). At the same time, ⑤, ⑥, ⑦, ⑧ can also generate new thinking and ideas to promote the innovation of ①, ②, ③. For example, new geometric or structural designs (Figure 8k) will be generated through the stimulation of "Ideate (⑤)"; new programmable thinking will be discovered through "Prototype (⑥)" (Figure 8l).

The non-linear thinking process is not a single one, and it may also be a state in which two or more thought processes co-exist. Specifically, in the IDTPMM process model, two or more non-linear thinking processes can exist at the intersection of design research and design innovation. For example, when designing materials with required mechanical properties based on geometrical or structural unit cells according to requirements and applying them to design innovations, “testing or user feedback (⑦)” can also provide useful insights for “geometrical or structural unit cell design (①)”(Figure 8m). Meanwhile, “Ideate (⑤)” can also provide useful insights for “geometric or structural unit cell design (①)” and “programmable design or construction (②)”, respectively(Figure 8m); When using programmable thinking to achieve design innovation on demand, “testing or user feedback (⑦)” and “iteration (⑧)” can also provide useful insights for “geometric or structural unit cell design (①)” and “programmable design or construction (②)”, respectively(Figure 8n).

The above is just an example description of the non-linear process of the IDTPMM process model, not exhaustive. Generally speaking, in the specific use of the IDTPMM process model, its thinking process is not a single one, but two or more non-linear processes exist simultaneously. It can be seen that no matter what kind of non-linear thinking, it is related to new ideas, opinions, or needs generated in specific steps. Therefore, the complexity of the non-linear process depends on people’s overall needs for design and sudden, beneficial, or temporary needs in different processes of design thinking. Designers need to choose the complexity of the non-linear process according to the needs and actual conditions when using it.

4.2. Interdisciplinary Design Methods Based on Programmable Mechanical Metamaterials (IDMPMM)

4.2.1. Objectives of IDMPMM

IDMPMM was produced under the guidance of IDTPMM. Each step in the design thinking process model requires a design method to realize and implement it. Therefore, under the guidance of the IDTPMM process model, the IDMPMM process model is a specific tool and way for designers to realize and complete design thinking. The IDMPMM process model mainly describes in detail the implementation method of each step of the design thinking process model without expressing too much about the non-linear thinking process. The designer has the flexibility to use the methods and steps in the design method process model according to the actual requirements of the non-linear process.

4.2.2. IDMPMM Process Model

The IDMPMM process model is divided into two parts: design basic research methods and design applied research methods. The design basis research is divided into four parts: construction of unit cells, testing of mechanical properties and tunable parameters of unit cells, construction of programmable mechanical metamaterials based on unit cells, and testing of mechanical properties of programmable mechanical metamaterials. In different parts, this study introduces the commonly used methods for each step. It should be noted that when engaged in specific design activities, designers do not have to strictly follow the steps and methods of this study but flexibly select them according to the actual situation and needs.

Section 1. Unit cells construction

This part is mainly divided into five steps (Figure 9):

- **Step 1: Nature or artificial structure inspiration.** Nature or artificial structures are rich in types. It is the most important source of inspiration for geometric or structural unit cell design, which can provide a wealth of reference for the design of the unit cell. Origami geometry or structures [191], kirigami geometry or structures [168], lattice geometry or structures [192], tensioned monolithic structures [193], and layered structures are common sources of geometry or structures. Typical origami geometry or structures, for example, Miura Origami Structure (Figure 10a) and Eggbox Origami Structure (Figure 10b); Typical kirigami structures, for example, stretched kirigami structures (Figure 10c); Typical lattice structures, for example, Triangular 2D lattice structures with sinusoidally curved beams (Figure 10d), Cuboctahedron lattice structures (Figure 10e), and Body-centered cubic(bcc) lattice structures (Figure 10f).

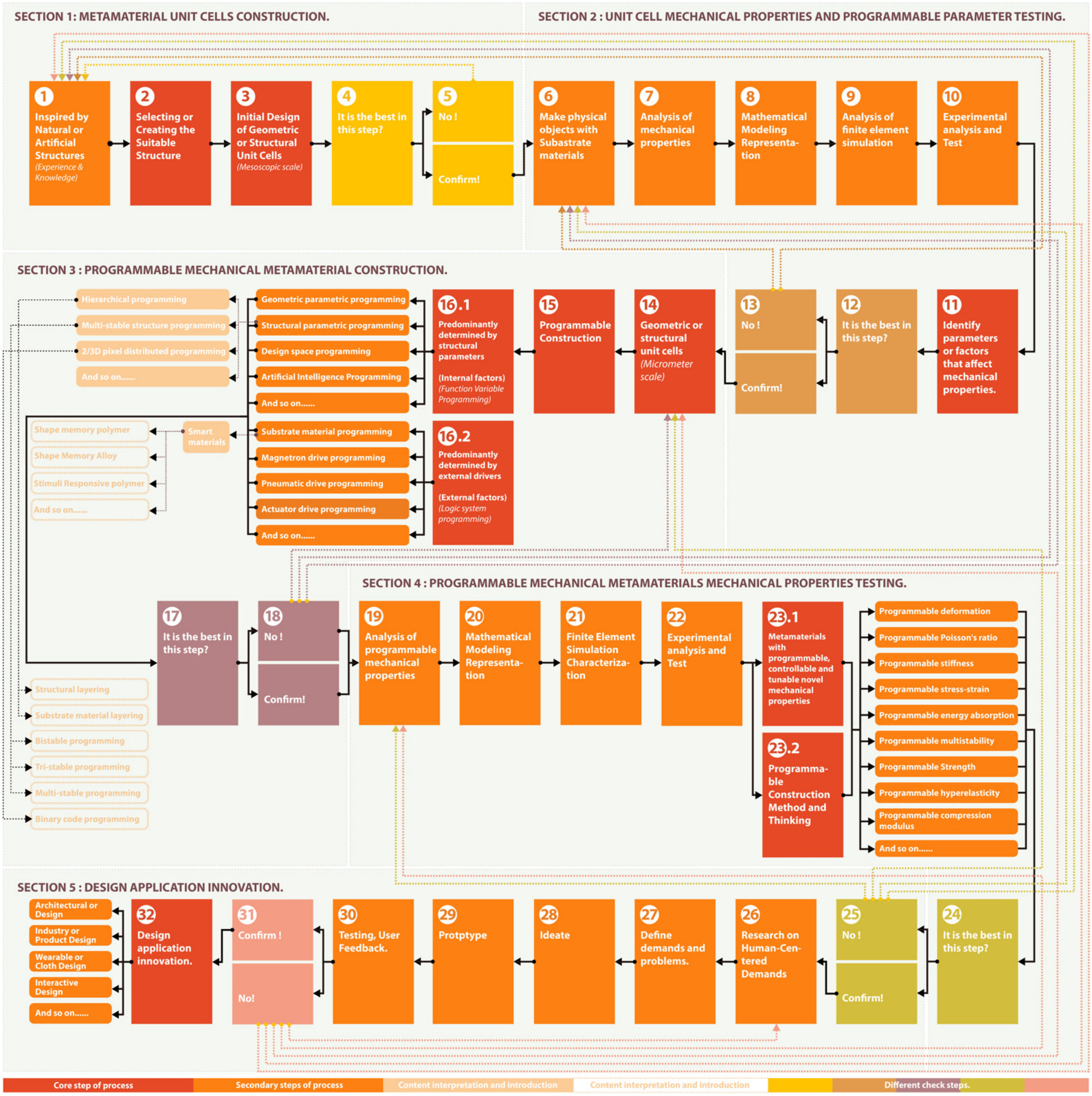

Figure 9. IDMPMM process model.

- **Steps 2–3: Geometric or structural unit cells design.** Inspired by natural or man-made structures, designers can use appropriate methods to design programmable mechanical metamaterial unit cells. Currently, geometric design [194], topology optimization design [195], and artificial intelligence algorithm design are the main design tools. Geometric design is a method of constructing structures using points, lines, planes, planes, distances, angles, curves, and surfaces based on mathematical principles [194]. Among them, Euclidean Geometry is the main research object [196]. Artificial intelligence design refers to the method of generating unit cells geometry or structure by means of computer calculation [197]. Taking machine learning (ML) as an example, first, the designer selects a certain number of unit cell structures to generate a database. Then, let the computer use the Convolutional Neural Network (CNN) or Generative Adversarial Networks (GAN) to learn and automatically analyze and obtain the structural rules of the unit cells. Finally, new unit cell structures are generated using rules (Figure 11). Topology optimization is a mathematical calculation method. It can optimize the material distribution in the fixed area through calculation iterations according to the given load conditions, constraints, and performance indicators until the optimal solution for the structural design in the fixed area is obtained [195]. Its general topology optimization problem can be described as follows: find the material distribution that minimizes an objective function $\mathcal{F}$, subject to a volume constraint $G_0 \leq 0$ and possibly M other constraints $G_0 \leq 0,\ i = 1, \ldots, M$ [198]. The material distribution is described by the density variable $\rho(\mathrm{x})$, which can take the value 0 (void) or 1 (solid material) at any point in the design domain Ω [198]. This optimization problem can be expressed in mathematical form as follows [198]:

$$\left.\begin{array}{r} \underset{\rho}{min} : \mathcal{F} = \mathcal{F}(\mathrm{u}(\rho), \rho) = \int_{\Omega} f(\mathrm{u}(\rho), \rho) dV \\ s.t. : G_0(\rho) = \int_{\Omega} \rho(\mathrm{x}) dV - V_0 \leq 0 \\ : G_i(\mathrm{u}(\rho), \rho) \leq 0,\ j = 1, \ldots, M \\ : \rho(\mathrm{x}) = 0\ or\ 1,\ \forall x \in \Omega \end{array}\right\} \tag{1}$$

Here, the state field u satisfies a linear or nonlinear state equation [198]. Geometric design is currently the most common metamaterial unit cells design method. Artificial intelligence design and topology optimization are relatively new design methods. These two methods can sometimes produce some structures with excellent mechanical properties, which are important means for the innovation of structures. In addition, in Steps 1–3, under the guidance of nonlinear design thinking, designers can also choose natural or man-made structures according to the design purpose or demand and then carry out more purposeful metamaterial unit cell design activities.

- **Step 4–5: Check.** After the unit cell design, the designer needs to check whether the unit cell obtained so far is optimal in the current state based on his own experience. If yes, continue the process. If not, return to Step 1 to rethink and design. At the same time, under the guidance of nonlinear design thinking, this step can also check whether the design demands are met according to the final design demands. This step is an empirical, subjective check.

Section 2. Unit cells mechanical properties and adjustable parameter tests.

This part is mainly divided into eight steps (Figure 9):

- **Step 6: Use the substrate materials to make the unit cell physical model.** After the unit cell design is completed, in order to facilitate the subsequent mechanical performance test of the unit cell and better observe the design results of the unit cell, the designer needs to use the substrate materials to make a physical model of the unit cell. Substrate materials fall into two categories: ordinary materials or smart materials (Table 4). When using ordinary materials, the properties of the material itself will not affect the mechanical properties of the metamaterial unit cells. Mechanical properties are determined by geometry or structural design. Therefore, ordinary materials are the preferred materials. When smart materials are used, they can affect the mechanical properties of metamaterial unit cells due to their stimuli-responsive properties. Therefore, such materials will only be chosen when using smart materials for the programmable construction of metamaterials. See Section 3 for the detailed method of programmable construction. In addition, there are various manufacturing methods, as shown in Table 4.

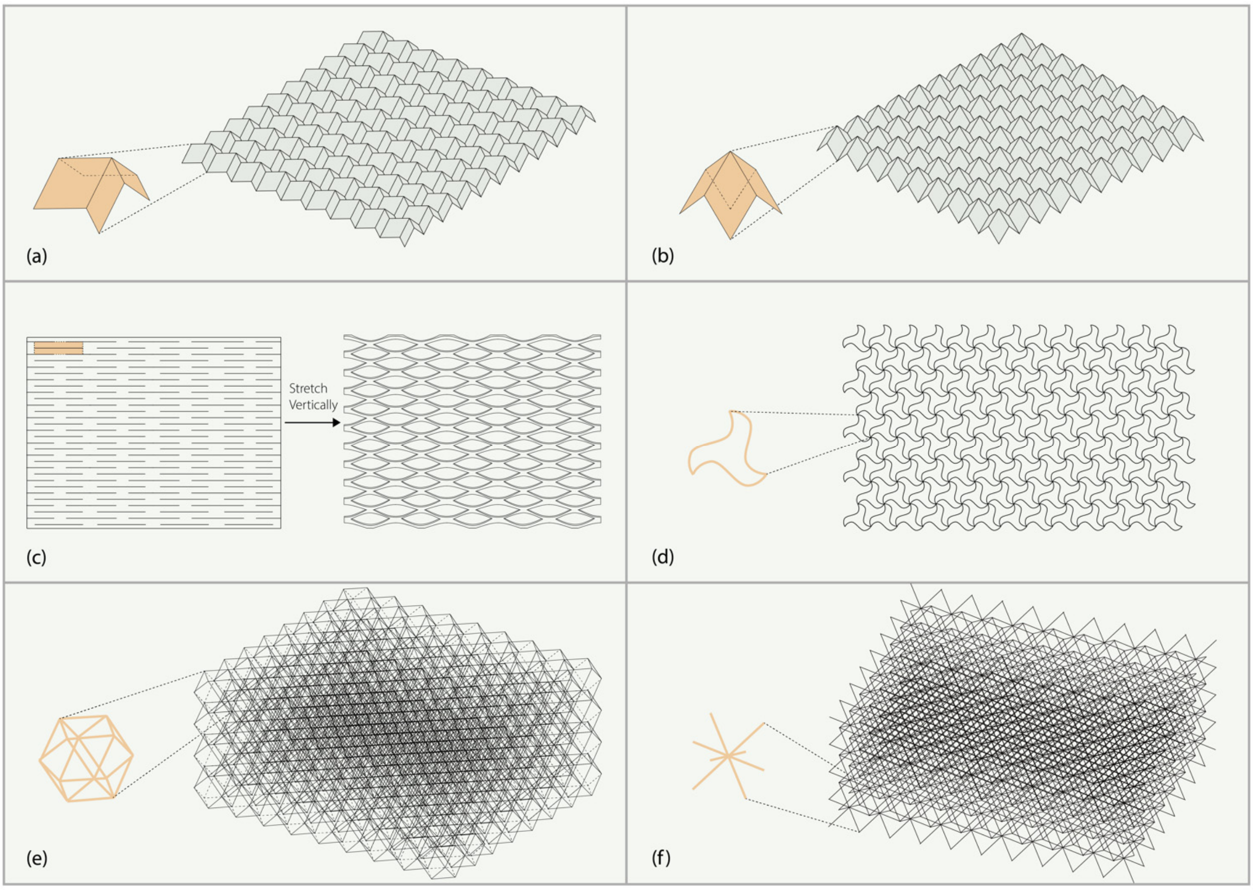

Figure 10. Example of a typical geometry or structure (Unit cells and its Tessellation). (**a**) Miura Origami Structure; (**b**) Eggbox Origami Structure; (**c**) stretched kirigami structures; (**d**) Triangular 2D lattice structures with sinusoidally curved beams; (**e**) Cuboctahedron lattice structures, (**f**) Body centered cubic (bcc) lattice structure.

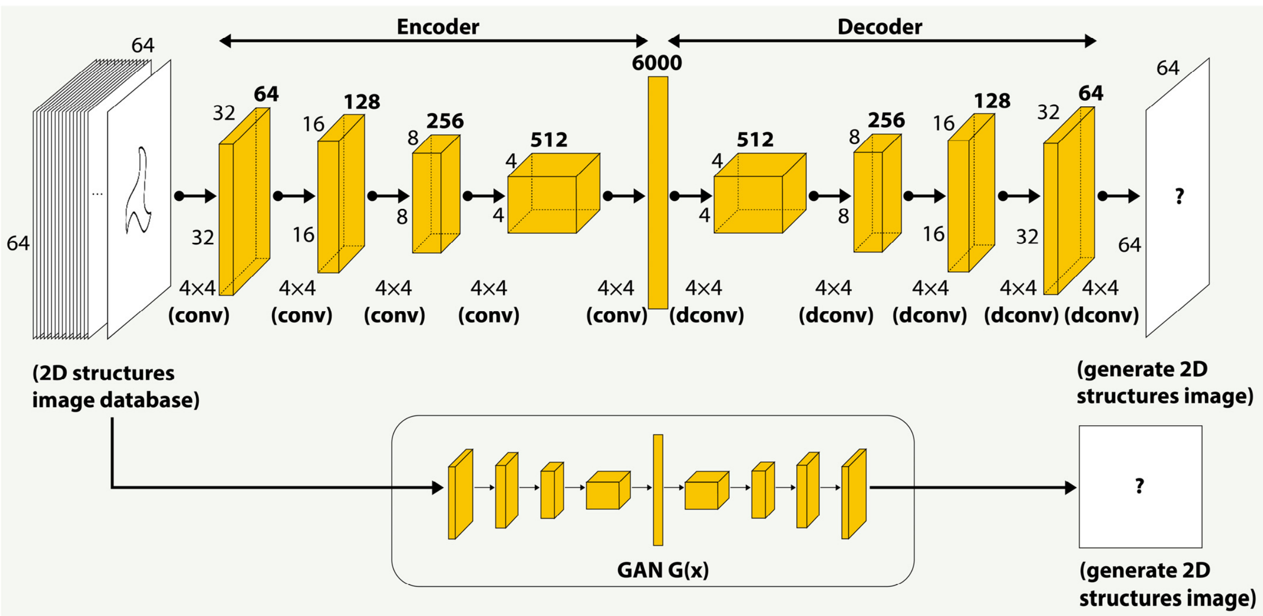

Figure 11. Schematic diagram of generating adversarial network (GAN) model (using 2D structural unit cells database to generate 2D structure as an example).

Table 4. Unit cells manufacturing elements.

	Examples
Smart materials	Shape Memory Polymer (SMP); Shape memory alloys (SMAs); Stimuli-responsive materials;
Ordinary material	Flexible photoreactive resin (FPR) [199], Flexible photocurable polymers [200], Elasto plastic (EP) [199], Brass (CuZn40) [201], Polyethylene terephthalate (PET) [202], Aluminium 1060 sheet [203]; Silicone-based rubber (TangoPlus) [204], Flexible material (FLX9795-DM) [205], PolyvinylSiloxane [206], Acrylonitrile butadiene styrene (ABS) [207], PA 2200 nylon plastic [208], Thermoplastic polyurethane (TPU) [209]
Manufacturing	3D printing [199], Soft lithography technique [199], Stamping manufacturing [201], laser-cutting technique [202].

- **Step 7–10: Analysis of the mechanical properties of unit cells.** After the unit cell is manufactured, the designer needs to analyze the mechanical performance of the unit cell. This step is mainly used to analyze the relationship between geometric or structural parameters and mechanical properties. There are two types of mechanical performance analysis of unit cells: mechanical analysis of a single unit cell, using tiling or tessellation to construct unit cells into simple materials for mechanical analysis (Figure 10). Mathematical modeling analysis of material mechanics, finite element visualization simulation analysis, and experimental testing are the main means of mechanical performance analysis of unit cells. Mathematical modeling is a fundamental means of mechanical analysis of materials, for example, refs. [200,203,206]. Finite element visual analysis is a means of mathematical simulation. It is usually realized by computer visualization software calculation, and the basic steps are shown in Figure 12. Common software, such as follows: FE software LS-DYNA(R13, Livermore Software Technology Corporation, Berkeley, CA, USA) [203], FE package ABAQUS/Standard (2022 HF4, ABAQUS Inc., Palo Alto, CA, USA) [205]. In addition, experimental testing methods are also diverse, for example, uniaxial tensile tests (e.g., testing stress–strain curves, Poisson's ratio) [200,205,206,209], quasi-static crushing tests (e.g., testing load–displacement curves) [203]; quasi-static uniaxial compression tests (e.g., testing Poisson's ratio-strain curves) [204,210]; and quasi-static and impact mechanical tests [208]. It should be noted that the testing of the mechanical properties of unit cells is not a necessary step in the construction steps of programmable mechanical metamaterials. Some metamaterials will skip this step when building. Additionally, after the metamaterial programming design is completed, its mechanical properties are tested.

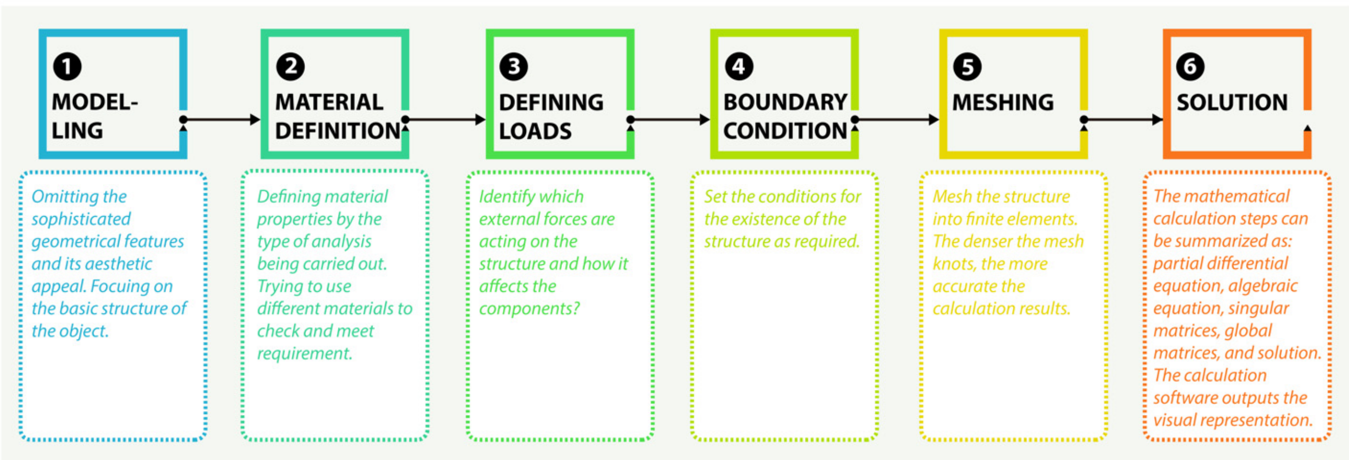

Figure 12. Basic steps of finite element analysis.

- **Step 11: Analysis of the relationship between unit cells' geometric or structural parameters and mechanical properties.** According to the test of steps 7–10, determine the geometric parameter (for example, length, —L;, diameter, —D;, radius, —R;, width, —B;, height, —H;, area or cross-sectional area, —t;, thickness, —δ;, coefficient of stiffness or slenderness ratio, —λ) and the relationship between mechanical properties. This can provide programmable elements for the construction of subsequent metamaterials. In addition, the response of smart materials to external stimuli can also be used as one of the elements of programmable construction. If the smart material is selected as the substrate material in Step 6, it is also necessary to determine the relationship between the smart material and the mechanical properties according to the tests of Steps 7–10 in this step. **Step 12–13: Check.** According to the test and analysis results of steps 7–11, the designer needs to objectively check whether the work at this stage is optimal or meets the demands. If yes, then continue. Otherwise, return to step 6 for modification. At the same time, according to nonlinear design thinking, it is also possible to return to any step that has been performed. This step is a check of objectivity.

Section 3. Construction of Programmable Mechanical Metamaterials.

This part is divided into five steps (Figure 9):

- **Steps 14–15: Implement programmable construction based on unit cells.** Based on unit cells, unit cells tessellation (results from Section 1), relationships between unit cell geometry or structural parameters and mechanical properties of materials, or relationships between smart materials and mechanical properties of materials (results from Section 2), designers can achieve the programmable construction of metamaterials. The construction method consists of construction elements and construction strategies.

Construction elements:

Programmable thinking: guide logic. First, it can be considered as code (unit cells) + operation (distribution rule), which can be processed programmatically by regulating related "information parameters (internal geometric or structural parameters)" ($\varepsilon_y = f(\varepsilon_x)$) [211]. Secondly, it can also be considered a controllable mechanical operation system with logical flow characteristics ($if - then - else$) [211].

Information parameters: manipulate objects. It is mainly divided into three parts: a. Unit cells geometric parameters, which mainly refer to various geometric parameters of different geometric types, for example, geometric parameter variables of kirigami, origami, and lattice; b. Structural parameters, mainly refer to the parameters related to the structure formed by the spatial arrangement of unit cells, such as hierarchical structure and voxel structure. c. External driving force, mainly referring to the force exerted by the outside on the material, such as manual, humidity-driven, light-driven, thermal-driven, electric-driven, magnetic-driven, pneumatic, etc.

Construction strategies:

Two scenarios for the use of programmable thinking [212,213]: a. Mechanical properties are a function of geometric or structural parameters. That is, endogenous factors determination: after the metamaterial is manufactured, the mechanical properties are fixed, and different metamaterials have different mechanical properties, which depend on their respective micro geometric or microstructural parameters. b. Mechanical properties are a function of exogenous factors. That is, determined by external factors: after fabricating a specific metamaterial micro-geometry or micro-structure, the mechanical properties can be programmed and modulated according to some external controllable factors, such as stimulus-response control.

According to the two situations, the main programmable strategies can be divided into: a. Endogenous factors programming: design and construct metamaterials with controllable mechanical properties through the programming and regulation of geometric or structural parameters. b. Exogenous factors programming: that is, to construct metamaterials with real-time adjustable mechanical behavior by controlling external driving force programming.

- **Step 16.1: Endogenous factors programming method.** As shown in Figure 13, Endogenous factor programming is mainly composed of geometric parameter programming and structural parameter programming. Geometric parameter programming refers to controlling the mechanical properties of metamaterials through the programming of geometric parameters [214]. For example, Overvelde et al. proposed a metamaterial constructed based on complex geometric extruded polyhedra unit cells, which can achieve programmable deformation properties through geometric parameters programming [202]. Equations (2)–(4) and Equation (5) quantify the geometric deformation of this metamaterial with vector $\mathbf{P}_1$ and internal volume v_{int}, respectively [202]:

$$\mathbf{P}_1 = [L, 0, 0] \tag{2}$$

$$\mathbf{P}_2 = [L\cos(\gamma_3), L\sin(\gamma_3), 0] \tag{3}$$

$$\mathbf{P}_3 = \left[L\cos(\gamma_2), L\delta, L\sqrt{1-\cos^2(\gamma_2)-\delta^2}\right] \tag{4}$$

$$v_{int} = |\mathbf{P}_3 \cdot (\mathbf{P}_1 \times \mathbf{P}_2)| + 2L(\|\mathbf{P}_3 \times \mathbf{P}_1\| + \|\mathbf{P}_1 \times \mathbf{P}_2\| + \|\mathbf{P}_2 \times \mathbf{P}_3\|) \tag{5}$$

Here, $\delta = [\cos(\gamma_1) - \cos(\gamma_2)\cos(\gamma_3)] / \sin(\gamma_3)$, therefore, changing the angles $\gamma_1, \gamma_2, \gamma_3$ can programmatically control its deformation state [202].

Structural parameter programming is mainly based on hierarchical structure programming and pixel or voxel structure programming. Among them, hierarchical programming is further divided into geometric hierarchical programming and substrate material hierarchical programming. Geometric hierarchical programming refers to the programming control of the mechanical properties of metamaterials through the heterogeneous hierarchical arrangement of unit cells. For example, Jiao proposed a metamaterial that is constructed of a layered structure consisting of postboxed elements [215]. It can adjust the deformation configuration state of the beam (length L, width W, thickness t, and constraints gap g) by adjusting the geometric ratio $R_{gt} = g/t$ and $R_{lw} = L/W$, which can increase or decrease the tensile and compressive stiffness (K_T and K_C) [215]. In particular, when the values of the geometric parameters t and W are fixed, increasing the geometric parameters L and g decreases the stiffness, while decreasing L increases the stiffness [215]. Material hierarchical structure programming refers to the use of hierarchical construction of different materials to achieve programming control of the mechanical properties of metamaterials. For example, Peng et al. proposed a metamaterial constructed by two layers of substrate materials with different thermal expansion coefficients (such as Ceramal (4 J33) and Aluminum alloy (5A02)) and a pyramid housetop geometry [209]. By controlling the thermal expansion coefficient ratio α_1/α_2 of the two-layer substrate material to increase from 0.2 to 10, the thermal expansion coefficient ΔS of the metamaterial can be controlled from positive to negative [209]. At the same time, on the basis of α_1/α_2 regulation, combined with the angle φ_1 and the height ratio S_1/S_2, a wider range of positive and negative adjustments to the thermal expansion coefficient can be achieved [209]. Pixel or voxel structure programming refers to programming and building metamaterials by spatially arranging pixels (2D) or voxels (3D) with different mechanical properties (lattice arrangement). For example, Pan et al. proposed a 3D metamaterial constructed by multistable voxels (bistable units connected in series), called a mechanical pixel (MP) [216]. In this metamaterial, a multistable voxel with n bistable units have 2^n stable states and $n+1$ stable lengths, which can generate $n+1$ different force-displacement curves [216]. Thus, by arranging these voxels to form predefined gradients, programmable force-displacement curves (The number can reach $2^{m \cdot n+1}$) can be obtained [216].In addition, there are multi-stable structure programming methods for structure programming. Based on bistable or multi-stable structures, programming with logical thinking can make metamaterials switch between two or more states on demand, thereby achieving a variety of programmable mechanical properties. For example, programmable energy absorption properties [217].

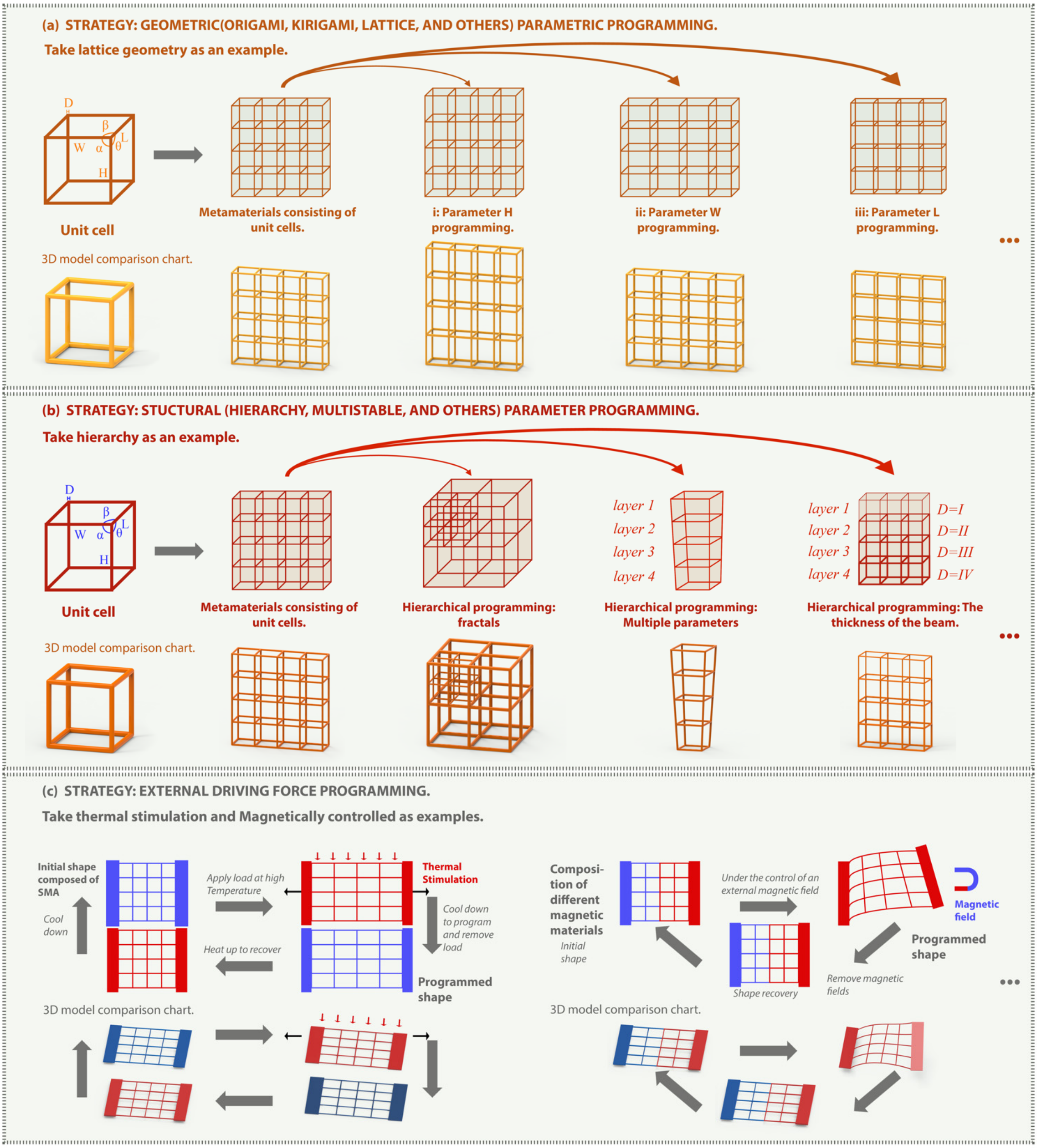

Figure 13. Examples of the programmable construction strategy based on cubic unit cells. (**a**) Programming of the geometrical parameters of the unit cell (e.g., forming a structure with different parameters by changing the length, width, and height, respectively, thus controlling the changing of the mechanical properties of the material). (**b**) Structural parameter programming (e.g., modulation of the mechanical properties of materials by means of fractal, hierarchical structural parameters). (**c**) External drive programming (e.g., adjustment of structural parameters by shape memory, magnetic control, thermal stimulation, and thus control the mechanical properties of the material from one state to another state).

- **Step 16.2: Exogenous factors programming method (external driving force programming).** As shown in Figure 13: External factor programming refers to programming and regulating the mechanical properties of metamaterials based on geometric or structural design combined with external force stimulation programming. External force stimulation is usually achieved by using smart materials as substrate materials. This material can undergo morphological changes when stimulated by external factors such as light, temperature, and moisture. This programmable method can also be referred to as 4D programming [169]. Among them, thermally driven programming based on thermal stimulus-responsive materials is the main method. Secondly, magnetic drives and pneumatic drives can also realize this programmable strategy. It is worth noting that, unlike geometric or structural programming (after the metamaterial is manufactured according to the programming method, the mechanical properties cannot be changed in real-time, that is, pre-programmed), exogenous programming can control the mechanical properties in real time after manufacturing. Thermally driven programming refers to base on the stimulation of materials by temperature, and combined with geometric or structural design, the mechanical behavior of metamaterials can be controlled and switched between multiple different states in real-time. For example, Yang et al. proposed a metamaterial constructed by shape memory alloy (SMA) hinge and ring origami unit cells [218]. The SMA "γ" -shaped hinge can change the deformation angle ($\theta_1, \theta_2, \theta_3, \theta_4$) of the unit cell in the range of $1^\circ \langle\theta\rangle 180^\circ$ under the state of thermal stimulation, and different θ angle combinations have different unit cells Deformation state (mainly inward or outward deformation, which can be represented by "0" and "1" respectively) [218]. The unit cells with "0", "1" states are programmed and arranged (such as 111, 110, 100, or 000) to form a metamaterial, which is heated under a controlled heating time (such as 0s, 30s, 60s, 90, 120 s) It can realize complex programming deformation along the X, Y, and Z directions respectively (such as 100-000-100-000 programming configuration) [218]. Magnetically driven programming means that by using magnetic materials as substrate materials or doping them into substrate materials, metamaterials can be controlled by an external magnetic field to produce geometric or structural changes, thereby controlling their mechanical properties. For example, Haghpanah et al. proposed an electromagnetic switching unit cell obtained by embedding an electromagnetic switch into a two-dimensional orthotropic lattice (with two deformation states of activation or deactivation under electromagnetic control) [219]. The unit cells are programmed and arranged (0, 1 programming), and in the two modes of electromagnetic activation or deactivation, real-time active control of Poisson's ratio $v_{xy}\left(d\varepsilon_x/d\varepsilon_y\right)$ between 0.15–1 can be realized [219]. Pneumatic actuation programming refers to the complex programming control of metamaterial deformation through pneumatics. For example, Mark et al. proposed an Auxetic unit cell controlled pneumatically [220]. Under inflation or deflation control, it can display transverse shrinkage deformation characteristics under the influence of Poisson's ratio $v = -\varepsilon_x/\varepsilon_z$ [220]. Then, the auxetic unit cells and the normal unit cells are programmed and configured in the pneumatic bellows, and under the alternate control of the pneumatic drive, the constructed metamaterial can realize controlled crawling motion [220]. In addition, in addition to the above-mentioned main methods, there are other ways of exogenous programming strategies, such as actuator programming [221], electric field-driven programming [222], and hydraulic-driven programming [203,223].
- **Step 17–18: Check.** Same as steps 4–5, this step is the designer's subjective and empirical inspection. At the same time, according to nonlinear design thinking, it is also possible to return to any step that has been performed.

Section 4. The mechanical properties test of programmable mechanical metamaterials

This part is divided into five steps (Figure 9):

- **Steps 19–22: Analysis of mechanical properties of programmable mechanical metamaterials.** The steps and methods of testing the mechanical properties of metamaterials are the same as steps 7–10. See steps 7–10.
- **Step 23.1: Determine the mechanical properties of the programmable mechanical metamaterial.** As shown in Figure 9 and Tables 5 and 6, metamaterials can be programmed to produce numerous programmable mechanical properties. These mechanical properties can meet the demands of different subsequent design applications, and they can also stimulate or inspire innovation in design applications.
- **Step 23.2: Determine the construction method and thinking of programmable mechanical metamaterials.** In addition to metamaterials with programmable mechanical properties that can be used for subsequent design applications and innovations, programmable construction methods and thinking can also be used for design applications and innovations. Only materials with extraordinary mechanical properties can be called metamaterials. Therefore, when the researched material does not have extraordinary mechanical properties but has typical programmable properties, its programming control thinking and methods around materials can also be used for design innovation and design application research and development.

Table 5. Examples of programmable mechanical properties based on geometry or structure.

Geometry or Structure Types	The Examples of Programmable/Tunable Properties
Origami Geometric parametric programming	Stiffness [214,223], Poisson's ratio [224], Deformation [225], Multistability [226], Compressive modulus [191]
Krigami Geometric parametric programming	Deformation [168], Stiffness [227], Stress–strain curve [228], Hyperelasticity [229]
Lattice Geometric parametric programming	Poisson's ratio [230], Deformation [231], Stiffness [207], Energy absorption [232]
Other Geometric parametric programming	Poisson's ratio [193], Deformation [211]
Geometric hierarchical structure programming	Poisson's ratio [233], Deformation [203], Stiffness [234], Energy absorption [235]
Substrate materials hierarchical programming	Coefficient of thermal expansion [236], Poisson's ratio [209], Deformation [237]

Table 6. Examples of programmable mechanical properties based on external driving forces.

Type of External Drive	Programmable/Tunable Properties
Thermal stimulation drive programming	Poisson's ratio [238], Deformation [218], Stiffness [239]
Magnetic drive programming	Poisson's ratio [240], Stiffness [192], Multi-stability [192], Deformation [241]
Pneumatic drive programming	Deformation [242], Stiffness [243]
Actuator drive programming	Hydrophobicity [221]
Electric field drive programming	Young's modulus [222]
Hydration drive programming	Stress–strain [223], Deformation [223], Stiffness [203]

- **Step 24–25: Check.** According to the test and analysis results of steps 19–20, the designer needs to objectively check whether the work at this stage is optimal or meets the design application demands. If yes, then continue. If not, return to check. At the same time, according to non-linear design thinking, it is also possible to return to any step that has been performed.

Section 5. Design application innovation based on programmable mechanical metamaterials.

This part is divided into seven steps (Figure 9):

- **Steps 26–27: Demands research and definition.** Empathy and insight are fundamental approaches to demands for research and definition. Under their guidance, the methods for realizing demands collection and definition are shown in Figure 14. In addition, the status of demands in the entire design method process model needs to be emphasized again: First, under the guidance of the design non-linear thinking, demands can be the first step in the overall design method process model. Starting from the definition of the demands, unit cells and programmable mechanical metamaterials are designed based on the demands, and the design applications are generated to meet the demands. Secondly, according to the thinking of driving design innovation with material innovation, the demand can also be placed later. After constructing the programmable mechanical metamaterials, the designer matches the demands to the programmable mechanical properties and thus conducts the design innovation research.

Figure 14. Examples of methods for demands research and definition.

- **Step 28: Ideate.** Based on the collection and definition of demands, designers need to propose solutions to solve problems or meet demands. This process is called the creative process. There are many ways to realize ideas. However, no matter what the method is, one key point is the most important: collect or design as many solutions as possible. Only with a large number of solutions can designers better select the optimal solution to solve or meet the needs of users. As shown in Figure 15, this study lists some of the most important creative strategies and methods at present.

- **Step 29: prototype.** After the ideas have been generated, some of the better-evaluated creative solutions need to be selected for prototyping. Design prototyping refers to the production of low-cost, scaled-down products or solutions to test the feasibility of design ideas and reveal possible design problems. At the same time, prototyping can also test the practicability of the design plan from conception and paper to actual production. These issues will be further addressed in prototype iterations. As shown in Figure 16, prototyping is basically divided into two schemes.

Figure 15. Examples of ideate methods.

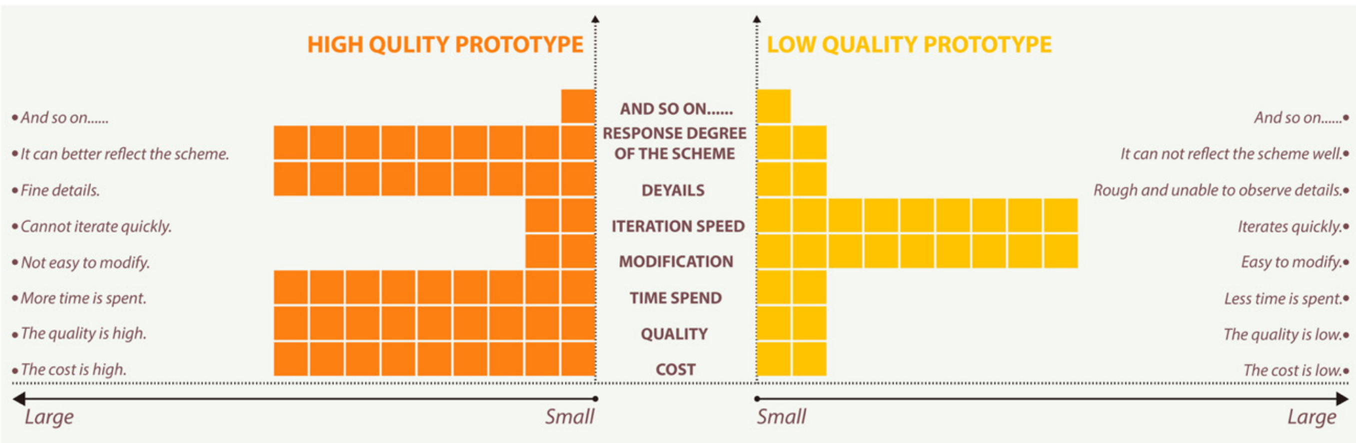

Figure 16. Examples of classification and characteristics of prototypes.

- **Steps 30–31:** Test and feedback. After the prototype scheme is determined, the designer needs to conduct further testing and feedback. First, the designer checks by himself to determine the problems. Secondly, by inviting users to provide comments based on their actual experience. The designer returns to the previous process to check the problem and redesign according to the modification opinion. At the same time, as shown in Figure 9, under the guidance of the core concept of non-linear design thinking and on-demand programming for design application innovation, modifications are not limited to the Design Application Innovation section. Modification comments can return to any step in steps 1–29. This reflects the purpose of the method process model with user demands as the core.

- **Step 32: Design innovation.** This design method process model does not aim at a specific design application, but rather at satisfying the needs of the user and solving problems in a demand-driven manner. In addition, according to the thinking logic that material innovation drives design innovation, the direction of the design application is not determined at the beginning of the process but is inspired and determined based on the results of material innovation. Therefore, as shown in Figure 9, based on these two logics, the design scheme cannot determine the specific design application direction at the beginning but determines the direction along with the advancement of the design process model or at the end of the design process model.

4.3. Case Verification

4.3.1. Taking Energy-Saving Building Skin Design as an Example to Demonstrate the Rationality of IDTPMM Process Model

Tang et al. proposed a programmable kiri-kirigami metamaterial and explored the design of energy-saving building skin based on this metamaterial. Details can be found in reference [168]. First, inspired by the kirigami structure, Tang et al. designed a "Louvres" Kirigami unit cell, which can achieve locally tilted clockwise or counterclockwise through the programming control of its notches [168]. As the unit cells can be programmed to realize different deformation states, hence, by tessellation of the unit cells, the scheme can programmatically realize different patterns [168]. Second, by covering the notches with heat-shrinkable tape (polyolefin tape), the programmable tilt direction of this metamaterial can be remotely controlled by temperature [168]. Third, based on building energy-saving requirements, the metamaterial is applied to building skin design. Stimulated by the light temperature, this design scheme can adjust the illuminance and temperature of sunlight entering the room through the deformation of the skin (enough light means high temperature) [168]. According to the actual test of Tang et al.: using this design scheme, indoor energy consumption can save 26% of lighting power and 47.4% of air conditioning power [168].

As shown in Figure 17, Tang et al. propose a design thinking that is based on programmable kiri-kirigami metamaterials (constructed by a combination of endogenous and exogenous programming methods) to achieve energy-efficient building design. This thinking reflects, to a high degree, all the elements of the IDTPMM process model. Furthermore, the thinking takes the demand for energy-efficient buildings as the preferred factor, which reflects the non-linear feature of the IDTPMM process model (as shown by the "on-demand programming control logic line" in Figure 17). In this thinking, designers can modify relevant metamaterial construction elements (such as primitive design, programming construction, and realization of metamaterials) according to the needs of energy-saving buildings at any time. At the same time, this thinking advocate direct programming control of metamaterials to produce design results, which eliminates many intermediate steps and elements (such as relying on other machines or electronic devices) and greatly increases the efficiency of solving problems and meeting needs. Furthermore, in contrast to traditional design thinking (e.g., the development of low-energy lighting and heating), this thinking directly relies on materials research to achieve a more sustainable and environmentally friendly solution, which is in line with the people's expectation of energy efficiency development in buildings. Based on this design thinking, this study concludes that the IDTPMM process model is reasonable and valuable.

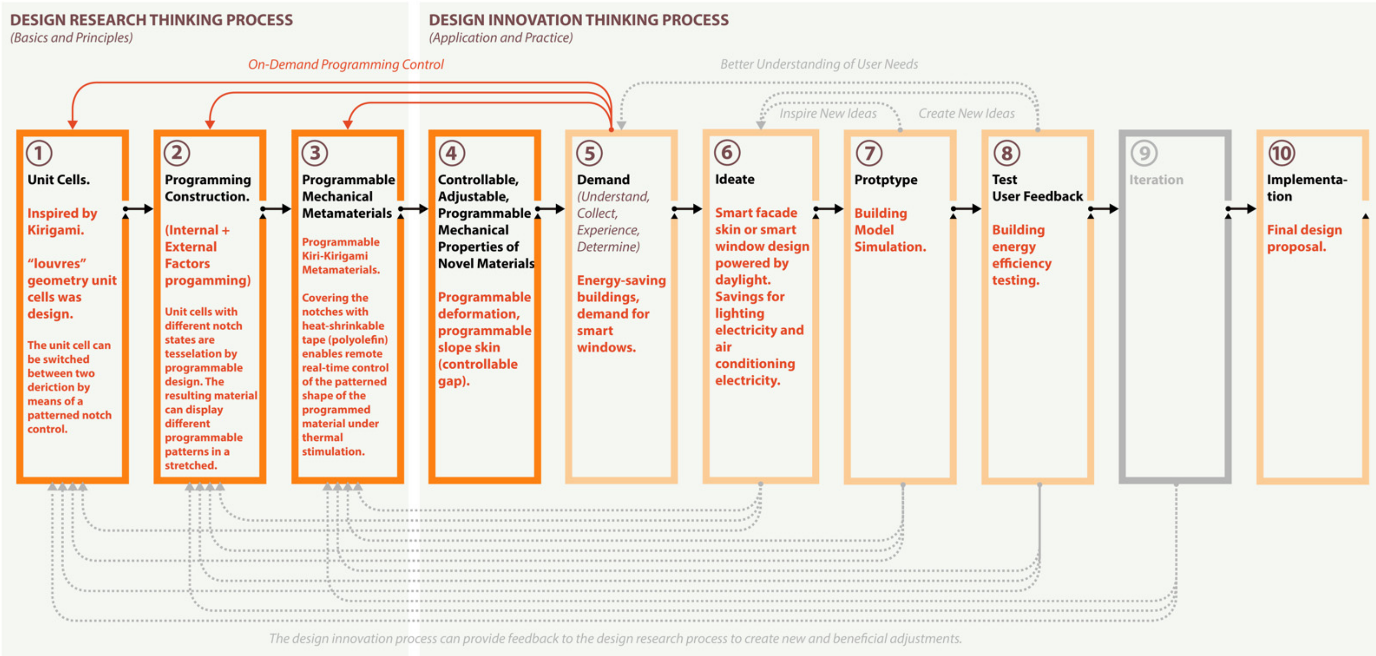

Figure 17. Combined with the IDTPMM process model, this study analyzes and sorts out the design thinking process of Tang et al.'s energy-saving building skin design scheme.

4.3.2. Taking Responsive Architectural Design as an Example to Demonstrate the Rationality of IDMPMM Process Model

Holstov et al. proposed a material preprogramming method and explored responsive architectural design based on this method [244]. First, inspired by the responsive behavior of plants, Holstov et al. designed a unit cell consisting of hierarchical composite materials (active and passive layers) and structural design (Figure 18a) [244]. Stimulated by humidity, this unit cell will responsively generate deform (Figure 18b) [244]. Second, by tessellation of the unit cells, a hygromorphic composite material can be obtained (Figure 18c), which can be controlled by different pre-programmed schemes to produce rich morphological change responses (Figure 18d) [244]. Moreover, according to prototype testing (Figure 18e), the material has longer durability. Finally, according to the design demands of responsive buildings, Holstov et al. gave a design scheme around modular outdoor seating (Figure 18f) and an indoor adaptive system (Figure 18g). Meanwhile, other climate-responsive building design options also be discussed (Figure 18h) [244].

As shown in Figure 19, Holstov et al. proposed a design method process that uses material external factors programming design logic to realize architectural design schemes. While it does not use the concept of metamaterials, it uses preprogrammed construction logic. This design method process is fully consistent with the IDMPMM process model. Moreover, the method process flexibly uses the steps in the IDMPMM process model. The method process based on material programming innovation achieves that architectural design can become more intelligent only by relying on material or material innovation, without relying on "traditional electronic or mechanical equipment". Based on the method process (Figure 19), this study believes that the IDMPMM process model is reasonable and effective.

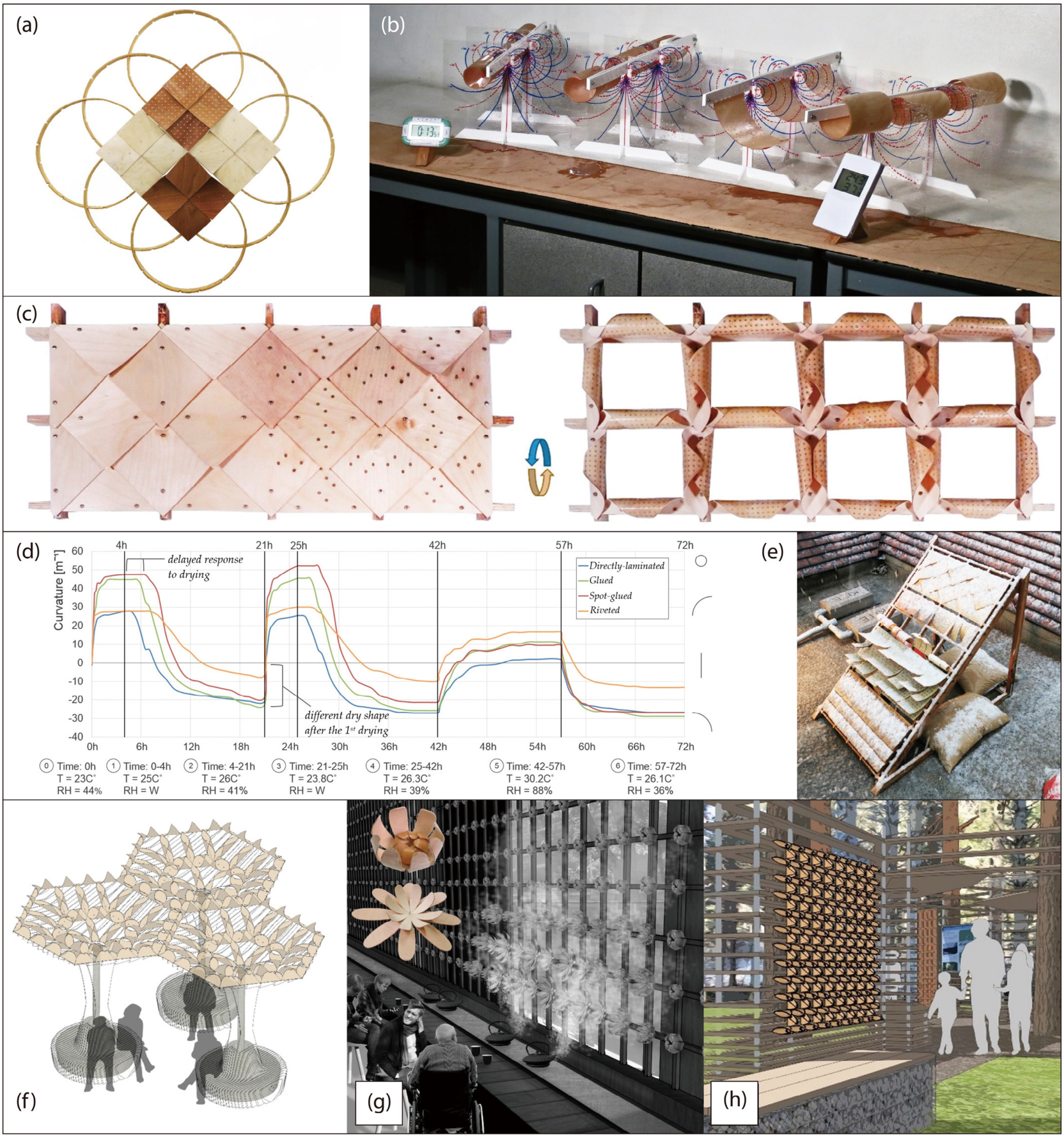

Figure 18. Programmable materials and responsive architectural design proposed by Holstov et al. [244]. (**a**) Material unit cells composed of different substrate materials. (**b**) Testing of the programmable behavior of material unit cells. (**c**) Example of deformation behavior of hygromorphic composite material. (**d**) Deformation response of hygromorphic composite material with different preprogrammed states. (**e**) Durability testing. (**f**) Modular outdoor seating design. (**g**) Indoor Adaptive System Design. (**h**) Other climate-responsive building design options.

Figure 19. Combined with the IDMPMM process model, this research analyzes and sorts out the design method process of the responsive building skin design scheme (the colored part is the main part, and the gray part is the unvolved steps).

5. Discussion

The IDTPMM and IDMPMM process models have been established against traditional design thinking and method and using interdisciplinary research tools. As shown in Figures 7 and 20, this research compares it with the design thinking and method based on programmable materials, and the traditional design thinking and method. The advantages of this study can be summarized as follows: First, research based on novel programmable mechanical metamaterials can enable design research to achieve design innovation based on the driving of material innovation. This can greatly expand the research field of design research and enhance the ability of design innovation. Second, the on-demand programming control characteristics of IDTPMM and IDMPMM process models can achieve that design research change from passive use of existing material mechanical properties to active programming control of material mechanical properties on demand. This greatly enhances the controllability and programmability of material substances in design research. At the same time, this also greatly enhances the ability of design research to control the design carrier. Third, the nonlinear characteristics of IDTPMM and IDMPMM process models can well integrate human demands into all elements of the design process. This can fully reflect the core design principles of on-demand design and human-centered design. Fourth, IDTPMM and IDMPMM process models have well clarified the relationship between design thinking and design methods. It determines the basic model of the relationship between the two: design thinking guides design methods, design thinking is realized by design methods, and different design method processes can connect design thinking in a series manner and explain the connotation of design thinking in detail. Fifth, the IDTPMM and IDMPMM process models cover both basic research and applied research, with typical interdisciplinary features. Compared with traditional design, which only focuses on the characteristics of applied research, this mode makes design research begin to develop in the direction of both scientific and practical characteristics. At the same time, based on basic research, design applied research will become more solid and reliable. Sixth, the IDTPMM and IDMPMM process models blur professional limitations and boundaries within the design field. Compared with traditional design research, this kind of solution does not determine the direction, field, or profession of the design research (such as architectural design direction or industrial design direction) at the beginning of design activities. Instead, after determining means that can solve a problem or meet a need based on basic research, depending on the type of solution, a design field or specialty will be identified at the end stage of the design activities. This enables design research to become freer and can get rid of the restrictions of the previous design internal professional division when solving the problem and satisfying the demands. At the same time, it is also of great significance for the innovation of design science research systems.

However, there are still some problems with IDTPMM and IDMPMM process models. First, due to limited space, this study did not provide a detailed and comprehensive description of all the elements involved in the IDTPMM and IDMPMM process models, but only a systematic overview. This may cause difficulties for specific use by designers or engineers. With the deepening of research in the later stage, more detailed details and data need to be added to the IDTPMM and IDMPMM process models. In the future, this research will also conduct more detailed research and presentation on different design method process branches. Second, in the field of design science, there are few such interdisciplinary design thinking and methods. At the same time, due to its excessive novelty, there are few reference standards and theories. So, its legitimacy is still somewhat questionable, and there may be some errors. This requires long-term in-depth discussion and revision in the future. Third, it currently lacks detailed and rich demonstrations of design practices. Therefore, it needs further practical demonstration to become more perfect.

TYPE.	(a) INTERDISCIPLINARY DESIGN THINKING AND METHODS BASED ON PROGRAMMABLE MECHANICAL METAMATERIALS	(b) DESIGN THINKING AND METHODS BASED ON PROGRAMMABLE MATERIALS	(c) TRADITIONAL DESIGN THINKING AND METHODS USING TRADITIONAL MATERIALS
NOVELTY OF THE DESIGN CARRIER	**HIGH** *(mechanical metamaterials are the latest frontier research direction)*	**UPPER-MIDDLE** *(programmable materials is a relatively new category of research direction)*	**LOW** *(research using traditional materials, no novelty)*
DEGREE OF TECHNOLOGICAL ADVANCEMENT	**HIGH**	**UPPER-MIDDLE**	**LOW**
DIVERSITY OF DESIGN THINKING AND METHODS	**RICH** *(encompassing multidisciplinary knowledge, thinking and methods)*	**UPPER-MIDDLE** *(encompassing multidisciplinary knowledge, thinking and methods)*	**SINGLE** *(covers design knowledge and methods only)*
CREATIVITY IN DESIGN THINKING AND METHODS	**STRONG**	**UPPER-MIDDLE**	**MEDIUM**
SCOPE OF THE DESIGN STUDY	**BROAD** *(involving multidisciplinary knowledge such as materials science)*	**UPPER-MIDDLE** *(involving multidisciplinary knowledge such as materials science)*	**NARROW** *(single subject knowledge)*
INTELLIGENCE DEGREE	**STRONG** *(the latest representation of material intelligence)*	**UPPER-MIDDLE** *(a relatively novel representative of material intelligence)*	**POOR** *(no intelligence)*
SCIENTIFIC AND FEASIBLE	**STRONG** *(using multiple interdisciplinary experimental and analytical methods)*	**UPPER-MIDDLE** *(using multiple interdisciplinary experimental and analytical methods)*	**POOR** *(using traditional design analysis methods, excessively relying on human subjective initiative)*
RIGIDITY AND COMPLEXITY	**STRONG**	**UPPER-MIDDLE**	**LOW**
COORDINATION AND COOPERATION BETWEEN THINKING AND METHODS	**STRONG**	**UPPER-MIDDLE**	**UPPER-MIDDLE**
TIMELINESS OF THINKING AND METHOD PROCESS	**HIGH** *(adjustable on demand at any time)*	**UPPER-MIDDLE** *(Can be adjusted as needed)*	**LOW**
SATISFACTION OF USER NEEDS	**HIGH**	**UPPER-MIDDLE**	**UPPER-MIDDLE**
DESIGN EFFICIENCY	**HIGH** *(direct material-based design innovation, eliminating many intermediate steps)*	**UPPER-MIDDLE** *(direct material-based design innovation, eliminating many intermediate steps)*	**GENERAL** *(there are many other intermediate steps besides materials)*
COMMERCIAL VALUE OF DESIGN RESULTS	**HIGH**	**UPPER-MIDDLE**	**UPPER-MIDDLE**
MATERIAL CONSTRAINTS ON DESIGN OPTIONS	**SMALL**	**SMALL**	**LARGE**
AESTHETIC VALUE OF DESIGN RESULTS	**HIGH** *(coexistence of scientific beauty and artistic beauty)*	**HIGH** *(coexistence of scientific beauty and artistic beauty)*	**UPPER-MIDDLE** *(artistic beauty)*
DESIGN INNOVATION LOGIC	**Driving Design Innovation Based on Material Innovation**	**Driving Design Innovation Based on Material Innovation**	**Design innovation has nothing to do with materials**
MATERIAL CONTROLLABILITY	**Active control of materials on demand**	**Active control of materials on demand**	**Passive use of existing materials**
DESIGN APPLICATION DIRECTION	**Determine the final design application direction based on requirements**	**Determine the final design application direction based on requirements**	**Subjectively determine the direction of design application and conduct design research**

Figure 20. A comparative analysis of the typical characteristics of the three types of design thinking and methods. (**a**) Characteristics of interdisciplinary design thinking and methods based on programmable mechanical metamaterials; (**b**) characteristics of design thinking and methods based on programmable materials [26,29–43,45–47,56,57]; (**c**) Characteristics of traditional design thinking and methods using traditional materials [10–16,245].

6. Conclusions

The development of thinking and methods is of great importance to design research, and it is the heart of the design science endeavor. At the same time, with the interdisciplinary trend and background, compared with other fields, single-design research has become weaker and weaker. If no action is taken to enrich the content of design thinking and method research and design interdisciplinary research to improve the theoretical and scientific nature of design research, design risks being replaced and outdated due to lack of influence. At the same time, programmable mechanical metamaterials are a new class of materials with extraordinary programmable, controllable, and tunable mechanical properties, which are at the forefront of scientific and engineering innovation. Therefore, in the face of this background and situation, this study introduces this emerging research direction into design research. Based on theoretical research and using interdisciplinary research methods (grafting methods), a set of results of interdisciplinary design thinking and methods was tentatively produced. The results are expressed in the form of the IDTPMM and IDMPMM process models, respectively. Then, this research selected two architectural design cases to discuss their rationality. IDTPMM and IDMPMM process models take programming on demand as the core element and material innovation drives design innovation as the innovation element. They have typical interdisciplinary and innovative characteristics and are of great significance for promoting the scientific and intelligent development of design research with materials as the main content. Under their guidance, a new field of interdisciplinary design research—interdisciplinary design research based on programmable mechanical metamaterials will flourish. Based on this, designers will design more novel and innovative designs and applications to meet people's needs and improve people's material living standards. Although the results of this research are presented in the absence of a large number of design practices, their great value can already be seen in the existing few practices. At this stage, the results of this study may be tentative. However, the IDTPMM and IDMPMM process models will definitely flourish in the future. Interdisciplinary design thinking and methods will surely become the main method leading design research in the future. It is believed that with the continuous development of science and technology in the future, interdisciplinary design research based on programmable mechanical metamaterials will definitely produce new breakthroughs and achievements. This will not only completely change the existing design thinking and methods but also subvert all contents of design scientific research.

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