

REVIEW

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Design Theory and Method of Complex Products: A Review

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Abstract

Design is a high-level and complex thinking activity of human beings, using existing knowledge and technology to solve problems and create new things. With the rise and development of intelligent manufacturing, design has increasingly reflected its importance in the product life cycle. Firstly, the concept and connotation of complex product design is expounded systematically, and the different types of design are discussed. The four schools of design theory are introduced, including universal design, axiomatic design, TRIZ and general design. Then the research status of complex product design is analyzed, such as innovative design, digital design, modular design, reliability optimization design, etc. Finally, three key scientific issues worthy of research in the future are indicated, and five research trends of “newer, better, smarter, faster, and greener” are summarized, aiming to provide references for the equipment design and manufacturing industry.

Keywords: Product design, Design theory and method, Innovative design, Digital design

1 Introduction

Design is the starting point for all human activities with purpose, as well as the forerunner and preparation of all creative practices. Mankind reforms the world through labor, creating material and spiritual wealth, while the most basic and primary creative activity is creation. Design is a creative thinking activity that pre-plans the creation activities, as well as the process of planning and envisioning the activities expressed through specific carriers. Complex product design refers to conception, modeling, analysis, and optimization on the working principle, configuration and modeling of the product, transmission mode of force and energy, movement mode, control method, material and geometry of the component, service condition, performance reliability, recyclability, etc., and transforming them into a concrete blueprint as a manufacturing process.

At present, there is no uniform definition of design in the scientific academia. Beitz et al. [1] believes that

design is to make ideas come true, which tries to meet the requirements in the best possible way. Professor Victor Papanek from the United States [2] argues that design is a conscious, intuitive effort to build meaningful order. Youbo Xie [3], an academician of the Chinese Academy of Engineering believes that design is essentially a process of flow, integration, competition and evolution of knowledge. He pointed out four basic laws of design science: the law of design based on existing knowledge, the law of incompleteness of design knowledge, the law of design focus on new knowledge acquisition, and the law of competitive of design knowledge.

As the most important part of the product life cycle, product design plays an extremely important role, determining the functional quality of the product as well as the value of manufacturing and service. The key factors affecting product competitiveness, such as product structure, performance, cost, maintainability, human-machine environment and style, are closely related to the design. The gap in product quality is first of all the gap in quality of product design. About 50% of product quality accidents are caused by poor design, and the product design cycle accounts for 47% to 53% of the production cycle

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[4]. In the product life cycle, the design phase determines 70% of the cost of the entire product development, while the manufacturing phase and subsequent related phases only determine about 30% of the total cost [5].

The competition in modern manufacturing industry is often the competition of product design. The innovation ability of product design has become the core for manufacturing enterprises to maintain competitiveness. Therefore, research on modern design theory, method and practice is of great significance for improving the core competitiveness of manufacturing enterprises.

2 Types of Design

In the manufacturing field, product design can be divided into different types according to different classification standard. For example, according to the design process, product design can be divided into creative design, conceptual design, principle design, overall design, whole machine design, top-level design, system design, scheme design, detailed design, stereotype design, technical design, calibration and inspection design, test and maintenance design, etc.

According to the content of the design, product design can be divided into requirement design, functional design, performance design, quality design, structural design, layout design, mechanism design, physical design, forming design, assembly design, precision design, ergonomics design, industrial design and other types.

According to the design tools used, the product design can be divided into computer-aided design, simulation design, experimental design, human-computer interaction design and so on.

According to the innovation intensity of product design, design can be divided into the following five types:

- Original design: Based on breakthroughs in scientific principles and engineering technology, the original innovative design of products is conceptually realized. For example, the steam engine in 1712, the internal combustion engine in 1876, the car in 1886, and the aircraft in 1903, all of which were not born without the original design.
- Promotive design: Based on the existing design, the principle, function and performance of the product are achieved through breakthrough improvement, with effects of a new generation. For example, from landline telephone to mobile phone to smart phone, from machine tool to CNC machine tool to smart machine tool, from networking to the World Wide Web to the Internet of Things.
- Improved design: Changes and additions to existing designs are made under the same basic principle. For

example, in electric lamps, tungsten filaments are used instead of carbon filaments, and argon is used instead of vacuum. High-pressure steam engines, steam turbines, and multi-cylinder steam engines are all improvements to the design of steam engine.

- Integrated design: The complementary integration of various design elements makes the qualitative change of product function. For example, the iPhone uses a large-size touch screen, retina screen, face recognition, distance sensing, gyroscope, GPS and other multi-sensors to work together, which forms unique innovation and competitive advantage.
- Reference design: Through the analysis and reference of the principle of various phenomena, a product with similar structure and function is derived. For example, by drawing on the shape characteristics of the barchan dunes, a barchan-dune vortex flame stabilizer is designed [6].

3 Four Schools of Product Design Theory and Method

With the continuous development of productivity, science and technology, the design process has gone through the intuitive design phase, the empirical design phase, the semi-theoretical and semi-experience phase, and is now in the modern design phase [7]. In this long process of development, design and design science are constantly developing in depth and breadth, whose theories and methods are constantly updated. Four typical schools of design theory and method are universal design, axiomatic design, TRIZ and general design.

(1) Universal Design

German scholars Pahl and Beitz [8] proposed a fairly representative, authoritative and systematic product design methodology in the 1970s. They summarized the experience of the excellent design process and developed the general design based on the system theory, which is known as the universal design methodology. The theory establishes work plans for the designer at each design stage, which include strategies, rules, and principles, so as to form a complete design process model. Emerging from slightly earlier barrier-free concepts and broader accessibility movement, universal design now seeks to blend aesthetics into these core considerations, which begins to be applied to the design of technology, human-computer interaction, instruction, services, and other products and environments [9–11].

(2) Axiomatic Design (AD)

Suh et al. from MIT [12] have systematically studied design theory since 1990 and proposed the axiomatic design. Two basic axioms are proposed in AD: one is the independence axiom involving the relationship between function and design parameters, that is, all functions are implemented independently of each other, so the design parameters only affect its subsidiary functions. The other is the information axiom, which is mainly aimed at reducing the information content of design results and minimizing the design complexity. In AD, design problems are modeled as mappings between demand domain, functional domain, structural domain, and process domain, and many engineering design issues are based on this model. The extended method is now mainly used for the reliability design of complex systems, covering the whole product lifecycle including early factors that affect the entire cycle such as development testing, input constraints and system components [13, 14].

(3) TRIZ Theory

The TRIZ method proposed by Altschuller from the former Soviet Union [15] is based on the statistical analysis of the development and treatment principles of 2.5 million high-level invention patents, which establishes a comprehensive theoretical system consisting of a series of methods and algorithms supporting the innovative design process, including technical system evolution rules, trait-field analysis, inventive problem solving methods, typical techniques for system opposition, and an application knowledge-base of physics, chemistry, and geometry. As a practical methodology for generating innovative solutions for problem solving, TRIZ tends to be integrated with Quality Function Deployment (QFD), forming a strong support tool from product definition, concept design to detailed design [16–18].

(4) General Design Theory (GDT)

Yoshikawa and Tomiyama, researchers at University of Tokyo, Japan, proposed GDT through research on cognitive problems in design activities, and considered that design is essentially a process of decomposition, mapping, and synthesis [19]. GDT introduces a metamodel to represent this gradual process, which uses a limited set of attributes to describe the state of the design object at a particular stage of the design process, the constituent entities of the design object, and the relationship between the entities and their dependencies.

The refinement process of the design is realized by the mapping mechanism between the metamodels. In the recent years, with the model of coupled design process, which is the improvement of GDT, the complex changes and realistic design processes on the category of sets and topological spaces can be elucidated more clearly [20, 21].

The application of system science concepts and methods has rapidly driven and influenced the study of design theories and methods, which shifted the design from an art category to a scientific category. Design theory and method, as a scientific approach to achieve design goals, have become an important pillar of design culture.

4 Key Technologies for Complex Product Design

4.1 Innovative Design Based on Big Data and Knowledge Engineering

The focus of product design has shifted from traditional experience-based design to innovation design based on big data and knowledge engineering. Through the combination of new theories, new technologies and new ideas, the innovation design concept of product design requires a large amount of design knowledge, design principles and design methods. Design knowledge resources has become the most important intelligence and asset for enterprise innovation. The acquisition, processing, discovery and evolution of design knowledge using design big data, assisting and promoting the creative ideas of designers, is the key to realize innovative design.

Based on big data for innovative design, aiming at the characteristics of large capacity, high generation rate, and heterogeneous data types, the state changes of products during use and maintenance were analyzed, and the nature, law and internal relationship of problems was discovered. Through the integration of data and knowledge in each stage, a feedback mechanism is formed to guide the innovative design in demand analysis, functional analysis, structural analysis, etc. [22]. Rahman et al. [23] studied the designer's continuous decision behavior based on fine-grained design action data and unsupervised clustering method, and developed a design thinking research platform driven by big data, with the help of which he studied the designer's design behavior to realize innovative design. Ghosh et al. [24] proposed a framework for acquiring user-product interaction data using embedded sensors. By integrating and analyzing interactive data, user data was mapped to the design space to assist designers in innovative design. Based on the data mining method, combined with the actual working condition data and cluster analysis, the multi-objective genetic algorithm was proposed by Kan et al. [25] to solve the multi-objective analysis problem and guide the product innovative design. Aiming at the inheritance and

innovation of product design, Zhang et al. [26] proposed a hierarchical function solution framework of mixed mapping, which included four design fields: function, working principle, behavior and structure. The relationship is shown in Figure 1. The framework combines the creative thinking of the designer with the reasoning and calculation ability of the computer to effectively promote the creative innovation of products.

Innovative design based on knowledge engineering, through the effective packaging, management, reuse and sharing of design knowledge, experience and rules of various disciplines at various stages of the product, guides the entire design process, and accelerates the process of product design, which facilitates the accumulation of enterprise knowledge, and improves the efficiency and innovation of design content at all stages of product design. Based on the knowledge framework, by reusing and synthesizing the original understandings in various disciplines, Chen et al. [27] established a corresponding knowledge base and developed a prototype system for the multidisciplinary intelligent creative concept design platform to assist designers in innovative design of multidisciplinary systems. Huang et al. [28] established an internal design knowledge base model integrating semantic search framework, and established a semantic-based internal knowledge search mechanism to support the accumulation and reuse of experience in product design, which improved product design efficiency, and promoted product innovation. Wu et al. [29] proposed a method that combines causal maps and qualitative analysis to integrate design knowledge in the form of causality through system modeling, thereby reducing the dimension of multidisciplinary design problems and improving product design effectiveness. Luo et al. [30] built a design knowledge network based on 5 million known patent records, and integrated knowledge mining and

knowledge learning into a data-driven visual design system to provide tool support for designers to determine innovative design directions in technical space.

Therefore, by data mining, processing, integration and management of big data in design, building knowledge maps and knowledge networks, promoting association and migration of innovation design knowledge, can effectively assist designers to carry out creative innovation, stimulate original ideas and achieve product innovative design.

4.2 Digital Design Based on Digital Prototype and Digital Twin

Digital design is the integration of digital technology and design technology. It utilizes digital design resources and design knowledge to realize the digital definition of products from demand analysis, functional design, detailed structural design to assembly design, providing a fully digital basis for product processing, manufacturing, service and maintenance. Digital technology has brought about a change from “traditional experience-based design patterns” to “scientific design patterns based on modeling and simulation” for product design. The United States listed design tools based on modeling and simulation as one of the four key capabilities of priority development in the US Defense Manufacturing Program in 2010 and later [31].

Digital prototype technology is a typical means of digital design. Based on CAx/DFx, virtual reality, simulation technology and computer graphics, the discrete product design development and analysis process are integrated to replace or simplify the physical prototype. Therefore, design optimization, performance test, manufacturing simulation, and service simulation can be carried out visually by the virtual digital prototype for product

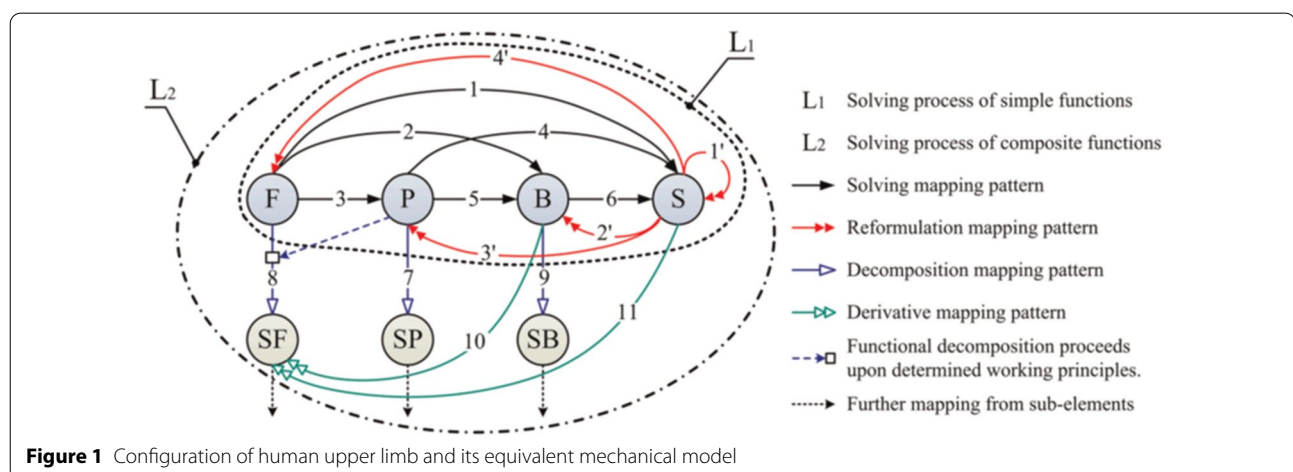


Figure 1 Configuration of human upper limb and its equivalent mechanical model

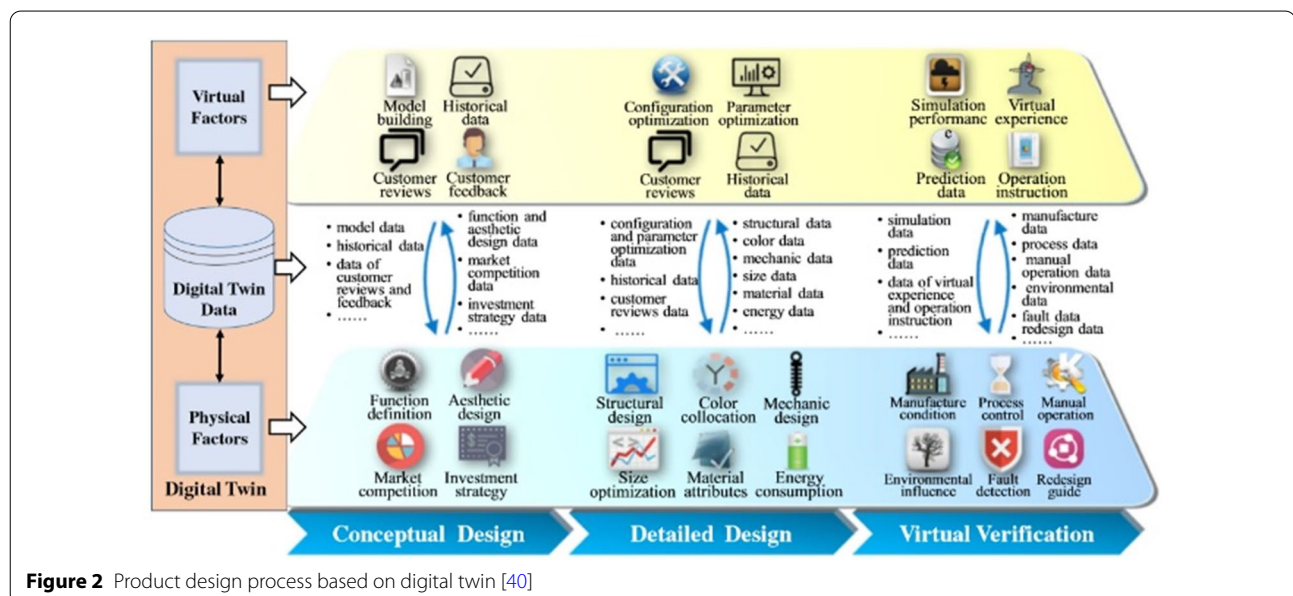
designers, manufacturers, and users in the early stages of product development.

The main directions of digital prototype design include interactive design of product modeling, visualization analysis of physical field, virtual assembly and maintenance, and simulation optimization of service process. Turkkan et al. [32] proposed a multi-segment energy minimization framework integrating linear elastic theory, which realized the static analysis of the dynamic prototype of the flexible machine, reducing the modeling complexity of the digital prototype and improving the efficiency of calculation. Arastehfar et al. [33] built a digital prototype based on high precision and flexibility standards, and improved the effectiveness of user evaluation of physical characteristics of products by determining the best digital prototype-user interaction, promoting the design communication at the stage of digital prototype modeling and simulation. Song et al. [34] developed a product-user interaction system based on virtual reality and digital prototype, which allowed designers to improve their products by recording user's virtual interactions and product evaluation feedback. Robinson et al. [35] established the relationship between the characteristic parameters of the digital prototype model and the attribute parameters in the stage of product manufacturing, and simplified the definition of the digital prototype parameters related to the decision of the manufacturing stage, effectively avoiding the problem of disconnection of parameters between the stage of product design and manufacturing, and improving the efficiency of product design. Ai et al. [36] proposed a rapid prototype design method based on the integration of multidisciplinary

collaborative configuration and performance simulation. In the presented method, product scheme was generated rapidly by configuration reasoning based on product family model integrated multi-domain knowledge, and the product performance prediction was achieved by digital prototype simulation of multi-domain model.

In recent years, researchers have developed digital twin technology by integrating digital prototyping and augmented reality technology. It was first proposed by Professor Grieves of the University of Michigan in the product lifecycle management course in 2003 and was defined in subsequent articles as a digital system that includes physical products, virtual products, and connections between them [37]. Digital twin is a kind of technical means that makes full use of data of physical models, sensor updates, running history, etc., integrates multiple physical attributes, and realizes real-time synchronization and accurate mapping of real equipment states in virtual space, making digital prototype synchronized and evolved along with real products throughout the life cycle, so as to reflect the full life cycle of physical equipment [38].

Product design based on digital twin emphasizes life cycle virtual-real fusion and virtual simulation model building with ultra-high realism, using real data driven and performance prediction to achieve improvement in design quality and efficiency. Söderberg [39] proposed a digital twin concept based on geometric assurance, including FEA (finite element analysis) functionality, Monte Carlo simulation, etc., to develop robust products and to distribute tolerances in the production phase, and to improve efficiency of digital design in an all-round



way. Tao et al. [40] proposed a new method of product design based on digital twin, and studied the product design framework based on digital twin. As shown in Figure 2, the complex products were simulated by integrating multi-physics, multi-scale and multi-probability, which achieved high quality and efficient product design. Liu et al. [41] proposed a method for product quality evaluation based on digital twin, constructed a digital twin evaluation model for processing, achieved real-time mapping between process acquisition data and product design data, so as to simulate and evaluate machining processes and parameters. Schleich et al. [42] proposed a comprehensive reference model based on the concept of skin model, which ensured the adaptability of digital twin in the stage of product design and manufacturing, and also the consistency of physical properties of products, improving the operability of product design and ensuring efficiency and quality of product design.

Based on the existing research on product design process and framework on digital twin, the coordination between existing real equipment and digital mirroring in design, and the iterative collaborative optimization mechanism of virtual-real symbiosis, can be used in the design of next generation products by the virtual-real interaction feedback, data fusion analysis, decision iterative optimization and other means, to realize the product redesign based on digital twin, which shortens the cycle of complex product design and improves the design precision and quality.

4.3 Customized and Modular Design

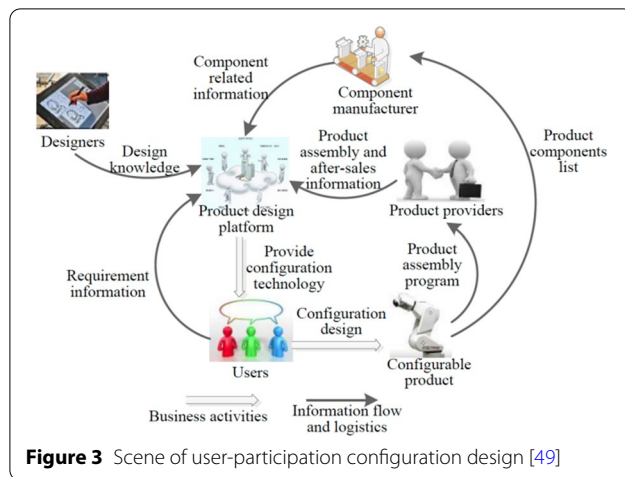
Product design is gradually turning to customer-centric. Customization can be understood as a producer's dedication to meet customer needs on an individual basis. In the process of product customization, in order to speed up the customization process and reduce costs, the modular design of the product came into being. Through the combined configuration of modules, it is the key to improve the product market competitiveness by responding quickly to the individual and diverse needs of customers and satisfying the customization needs of customers.

Customer demand analysis is the premise and guidance for customized design. Through customer segmentation and cluster analysis, customer preference calculation and market demand mining are carried out to achieve precise and personalized customized design. Wang et al. [43] trained two classifiers based on BLSTM and CRF through deep learning method, established a mapping between customer requirements and product design parameters, which realized automatic identification matching between customer demand and design parameters. Murat et al. [44] proposed a value-driven design method

for complex engineering system design problems in the aerospace industry. The concept design analysis method was used to map the captured customer requirements to engineering features, and a measurement model for design evaluation, sensitivity analysis, and engineering design optimization was established. Guo et al. [45] proposed an implicit customer demand processing method based on cloud service platform. User demand data was collected through metaphor extraction technology, then product design attribute was clustered and mapped, and finally product design process was guided through visualization technology.

The modular design of complex product is an important means of rapid customization. Specifically, the modular design divides and designs a series of common functional modules based on the market prediction and functional analysis of the products, analyzing different functions or product structures with different performances and different specifications, and finally composing different variants of products through the selection and combination of modules based on customer demand. AlGeddawy et al. [46] designed an automatic generation method of product hierarchy based on hierarchical clustering to solve the problem of hierarchical feature acquisition of complex product structure, and determined the optimal level of granularity and number of modules. Li et al. [47] solved the design structure matrix (DSM) which represents the hierarchical relationship of product components by assembly information extraction algorithm. Based on this, the hierarchical clustering algorithm was used to cluster the component DSM, and the module division of complex system was realized. Xu et al. [48] proposed a modular design method for complex process equipment. Through the analytic hierarchy process, the relationship matrix between components and the influence weight of module driving force on components was calculated. Then the cluster genetic algorithm was used to optimize the module, making the stability of the internal components of the module maximized and achieving a robust modular design.

The rapid configuration design of complex product is similar to the modular design, but it is mainly based on the functional structural unit, and studies the packaging methods such as configuration variables, configuration rules, customer requirements conversion, version management, etc., obtaining different product customization parametric models through the connection relationship between functional structural units. Jing et al. [49] studied specific implementation method of user-participation configuration design, including analyzing participation process and building user-participation configuration design scene, as shown in Figure 3, so as to realize product customized design better. Zheng et al. [50] proposed



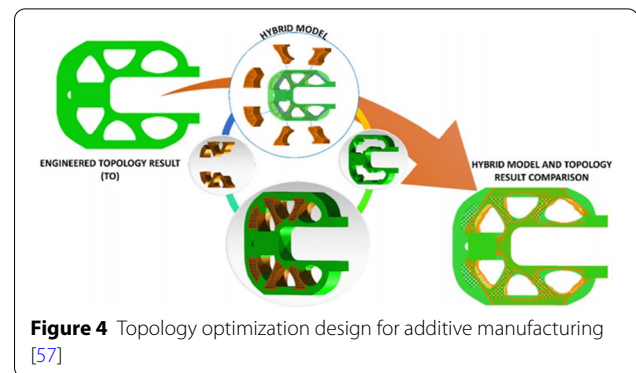
a structural design method for mechatronic systems. By configuring interface compatibility rule of the design method and elimination algorithm, the number of alternative configurations for the optimal design solutions is significantly reduced. Wei et al. [51] proposed a multi-objective configuration optimization method based on fuzzy selection mechanism. The design configuration of the product was optimized based on the improved non-preferred sorting genetic algorithm, and the Pareto optimal solution to the product configuration problem was obtained.

Through customized and modular design methods, the designed products can meet the individual needs of customers. However, at present they are mainly used in complex products and equipment, instead of in common product design. As customers' individual needs become more and more different, the demand for customization will become higher and higher.

4.4 Product Design for Additive Manufacturing

Additive manufacturing is different from the traditional processing mode for cutting and assembling of raw material, and it is a manufacturing method that is “bottom-up” through material accumulation. From the development of equal material manufacturing and subtractive manufacturing to additive manufacturing, the transformation from “design for manufacturing” to “manufacturing for design” has brought about a new way of product design [52]. Through the adaptive slicing planning design and topology optimization design for additive manufacturing, the accuracy and quality of additive manufacturing are effectively improved.

The adaptive slicing planning design for additive manufacturing is mainly to multidimensionally characterize the morphological features of the internal and external surfaces of the manifold mesh model,



achieving high-precision slicing planning of geometric mesh models with variable internal and external surface morphology. Yadroitsev et al. [53] proposed an additive manufacturing slicing algorithm that analyzes the necessary SLM (selective laser melting) parameters that affect the trajectory, layer and final product quality of each level. Ahsan et al. [54] quantified the combined effects of additive manufacturing construction direction and tool path direction on part and process attributes by analyzing the generated geometry, ensuring manufacturability and minimize fabrication complexity in additive manufacturing processes. Siraskar et al. [55] used a modified boundary octree data structure algorithm to convert the object 3D engraving file into an octree data structure, and realized the adaptive slicing design of the part according to the geometry, manufacturing parameters and tolerances. The number of layers was reduced, while the manufacturing quality of the parts can be ensured. Tian et al. [56] proposed a novel design and fabrication method of porous metal-bonded grinding wheel based on triply periodic minimal surfaces and additive manufacturing. With control equation, porous metal-bonded grinding wheel with well-formed pores and firmly-embedded abrasives can be realized.

The topology optimization design for additive manufacturing is to combine the additive manufacturing design criteria and the topology optimization method to study the design method of design and manufacturing integration under the constraint of additive manufacturing process. Additive manufacturing enables the production of sufficient complex geometries, making it possible to manufacture the best design result for topology optimization theory. Primo et al. [57] studied the topology optimization of C-Clip geometry for additive manufacturing, where structural optimization has been applied using an innovative approach based on the lattice structure design. The results of topology optimization are shown in Figure 4. Mirzendehtdel et al. [58]

introduced the concept of “support structure topology sensitivity”, which combines performance sensitivity to achieve maximum performance of topology optimization framework under structural constraints. Haertel et al. [59] studied the application of density-based topology optimization in heat exchanger additive manufacturing, and maximized the conductivity of the heat exchanger over a given pressure drop and air side temperature range by establishing an internal flow topology optimization model of steady state, thermal state and fluid dynamic coupling. Zegard et al. [60] proposed an infrastructure topology optimization method for additive manufacturing. For the specific case of topology optimization of 3D density, a program for result checking and generation of additive manufacturing output was developed.

As a new manufacturing process, additive manufacturing has attracted the attention of various industries. It is not limited by complex shapes and can be manufactured with multiple material. However, compared with the traditional cutting process, the additive manufacturing parts have lower dimensional accuracy, poorer surface precision and step effect. Therefore, the precision quantitative design for additive manufacturing is also one of the research hotspots in the future.

4.5 Product Design for Green Manufacturing and Remanufacturing

Environmental protection has received more and more attention from all over the world. As a major energy consumer, the equipment manufacturing industry is also aware of the importance of green production. Design technology for green manufacturing and remanufacturing emphasizes the harmonious coexistence between human and nature, the efficient recycling of resources, and the principle of “reduce, reuse and resources”, with low consumption, low emission, and high efficiency as the basic characteristics.

Product low-energy design for energy-saving is the core of design technology for green manufacturing. Through the establishment of the energy flow analysis and energy coupling model of the product life cycle, the energy consumption in product manufacturing and product service are analyzed and monitored, and the low-energy design of complex product is realized with the goal of low energy consumption and good service performance. Yang et al. [61] established an energy model including mechanical power and thermal efficiency by studying the trot motion of the quadruped robot, and designed a foot trajectory based on Fourier series to reduce joint energy consumption. To cut energy consumption prediction due to the machining features causing tool wear and expensive data labelling, Lu et al. [62] builds a prediction model and

emphasises training with limited experimental data by proposing an ensemble transfer learning approach. Seow et al. [63] designed and developed an energy consumption simulation system for complex product manufacturing process, as shown in Figure 5, which can support the input and output modeling of energy consumption in the complex product manufacturing process to find the source of energy consumption.

Vibration and noise exist inevitably in service of complex product. Useless vibration will cause waste of energy and noise will cause harm to the operator's body. Therefore, the product design for vibration and noise reduction oriented to environmental protection is also an important research content of design technology oriented to green manufacturing. By establishing the dynamic characteristics analysis of the product structure and accurate prediction model, vibration and noise reduction design of the complex product structure is realized with the aim of good anti-vibration performance, low noise and strong anti-interference ability in the service process. Guo et al. [64] applied nonlinear energy absorption to the rotor system, and proposed the suppression mechanism of the passive target energy transfer on the rotational amplitude of the rotor system at critical speed, reducing the resonance amplitude of rotor system without prior knowledge of imbalance values. Jung et al. [65] studied the vibration and noise reduction design for electromagnetic exciting forces, and response surface methodology was applied to realize the noise reduction design of the engine by selecting key design variables to optimize the rotor shape. Zoghaib et al. [66] designed a constrained elastomer for industrial noise reduction using the vibroacoustic study, which can be easily trimmed and bonded to the vibrating structure to reduce radiated noise. Zhang et al. [67] designed a free layer viscoelastic damping material structure to suppress the main discrete frequency noise of the axial piston pump, which significantly reduced the noise and vibration of the axial piston pump from experiment data.

After the product reaches its end of life, it needs to consider the recycling of its parts to reduce the waste of resources. Therefore, it is necessary to study the detachable design of the product structure for remanufacturing. Through the product structure design method for non-destructive disassembly, the quantitative evaluation method of product disassembly damage, and the product disassembly sequence planning method, the efficient non-destructive disassembly and classification recycling planning design of complex product are realized. Yang et al. [68] optimized the disassembly line balance model by using the multi-target disassembly line balance fruit fly optimization algorithm for the low carbon disassembly sequence design of the abandoned

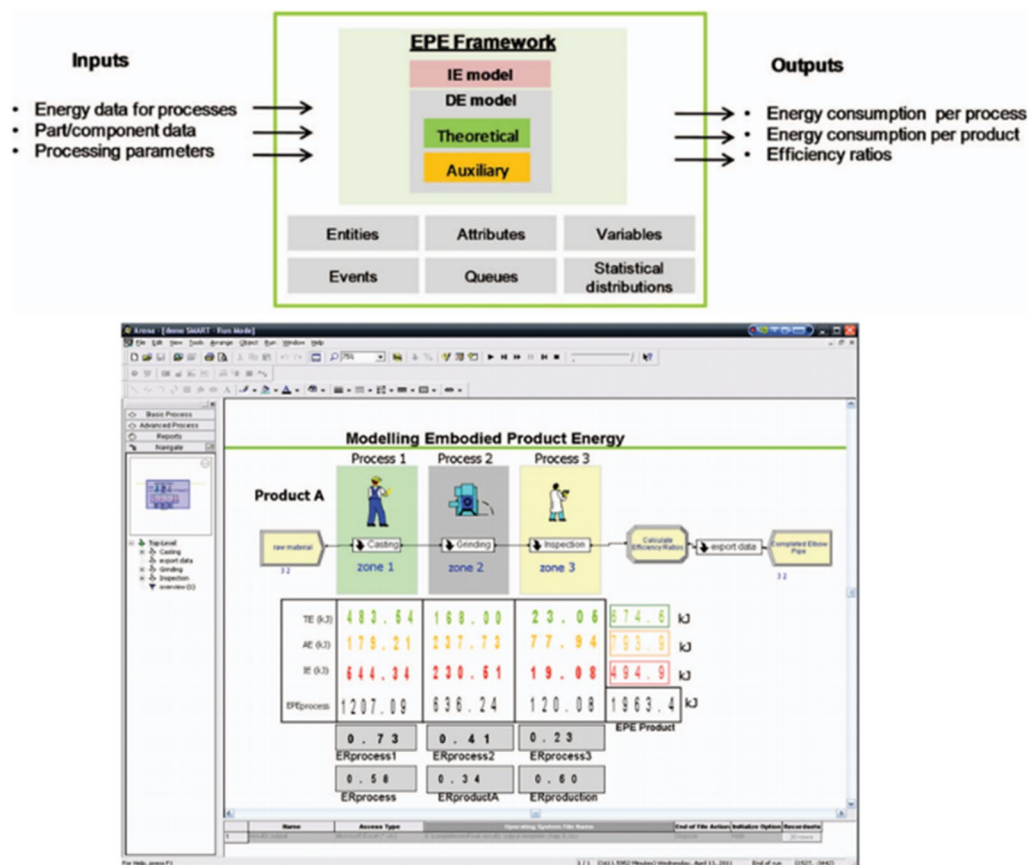


Figure 5 Energy consumption simulation model and system in manufacturing process [63]

mechanical device, and determined the device structure model of the optimal disassembly sequence by fuzzy analytic hierarchy process. Cheng et al. [69] proposed a heavy-duty machine tool module division method for green remanufacturing. The modular clustering algorithm based on atomic theory was employed, which was associated with the correlation and similarity between the design parameters in the structure domain and the remanufacturing domain, for the ideal modules of heavy-duty machine tools to be discovered. For the purpose of accurately extracting “Design for Remanufacturing” targets and shortening design cycle, Ke et al. [70] proposed an intelligent design for remanufacturing method based on vector space model and case-based reasoning, which can accurately generate design scheme to satisfy the customer demands. Umeda et al. [71] proposed a computer-aided design method for semi-destructive disassembly with split lines. The split line is a shape feature of a product that enables to destruct the product into required shape, thereby improving the utilization of waste. Based on the established stochastic disassembly network graph,

combined with different disassembly decision-making criterion, Tian et al. [72] developed stochastic models for disassembly time analysis to predict the product disassembly cost more accurately.

In addition, it is also of great significance to research on the optimization of the size and shape of the product structure for light weighting. Gan et al. [73] proposed an effective and efficient method for topology optimization with a time-variant reliability constraint. By using the PHI2 method and an improved response surface method to estimate the time-variant reliability level and satisfy the reliability constraint, the efficiency of the optimization calculation has been improved. Through the product structure size, shape and topology integrated design for material saving, the weight of the product can be reduced while its performance will be increased.

4.6 Reliability-based Design Optimization Technology

Product quality is not only manufactured, but also determined by design. Reliability-based design optimization technology (RBDO), focusing on quality and

reliability information of design process, assisting designers to develop reasonable product design and optimization solutions against factors affecting product reliability and quality, ensuring comprehensive product quality, is of great significance to enhance the core competitiveness of equipment manufacturing industry.

RBDO has been well developed to obtain reliable and cost-effective designs of many complex engineering problems under various uncertainties. One of the applications is RBDO of fatigue-sensitive structures for which engineers would like to evaluate an accurate fatigue lifespan. By applying RBDO to the fatigue-sensitive structures, their design could then be fine-tuned to reduce needless costs while satisfying the target reliability of fatigue performance. A cost-effective design of complex product reduces the initial investment, while a fatigue-reliable design saves maintenance cost in the lifespan. Hence, RBDO can achieve both the reduction of initial investment and maintenance cost.

RBDO is an optimization method based on reliability analysis. In each design iteration, RBDO requires reliability analysis of performance measures. Reliability analysis methods can be classified into two groups: (1) sensitivity-based methods and (2) sampling-based methods. The representative sensitivity-based methods include the first-order reliability method [74–77], the second-order reliability method [78–80], and the dimension reduction method [81–83]. The first-order reliability method and second-order reliability method approximate a performance measure at the most probable point using first- and second-order Taylor series expansion, respectively, and the dimension reduction method approximates a multi-dimensional performance function with a sum of lower-dimensional functions to calculate the probability of failure. In order to find the most probable point, the sensitivity (gradient) of performance function needs to be calculated. However, for many complex engineering applications, e.g., fatigue of wind turbine blades [84], accurate sensitivities of performance functions are not available. Therefore, in such applications, the sensitivity-based methods, which require the sensitivities of performance functions to find the most probable point, cannot be directly used. On the other hand, the sampling-based methods do not require the sensitivity of performance function to calculate the probability of failure. Instead, the sampling-based methods directly calculate the probability of failure using Monte Carlo simulation. However, the sampling-based methods could be computationally inefficient because the simulation may require thousands of analyses of a performance function.

According to the reliability analysis methods, RBDO can be performed using sensitivity-based reliability analysis and sampling-based reliability analysis. Common sensitivity-based RBDO methods incorporate

probabilistic constraints that can be evaluated using (1) the reliability index approach and (2) the performance measure approach. The most probable point in the reliability index approach represents the probability of failure at the current design, while the most probable point in the performance measure approach represents the target probability of failure [67]. Both sensitivity-based RBDO methods require the design sensitivity of a probabilistic constraint at the most probable point. The design sensitivities of probabilistic constraints require the sensitivity of the corresponding performance functions. Thus, the disadvantage of sensitivity-based reliability analysis methods, i.e., requiring sensitivity of performance function, still exists in the sensitivity-based RBDO methods. In order to handle complicated engineering problems, e.g., fatigue reliability of composite wind turbine blades [85], sampling-based RBDO methods are more appropriate because they do not require sensitivity of performance measure. Moreover, the design sensitivity of probabilistic constraints has been developed for sampling-based RBDO without requiring sensitivity of performance measure [86]. Due to the expense of Monte Carlo Simulation, which is used to estimate the probability of failure in sampling-based RBDO, surrogate models are often used to reduce computational cost. A challenge when using sampling-based RBDO is developing an accurate surrogate model to replace complicated, nonlinear, and implicit performance function. Peng et al. [87–90] proposed a nonparametric uncertainty representation method of design variables with different insufficient data, and the Gaussian interpolation model for sparse sampling points and/or sparse sampling intervals was constructed through maximizing the logarithmic likelihood estimation function of insufficient data.

Recently, solving time-dependent reliability problems attracts a significant attention from a wide range of engineering scope. The majority of the RBDO approaches addressing these challenging problems first converts the time-dependent reliability problems to time-invariant reliability problems, then uses traditional RBDO methods to calculate the reliability and the sensitivity for targeting the RBDO optimum. Among existing solutions to the time-dependent reliability problems, the most dominating one is the outcrossing rate method, in which the outcrossing rates of performance functions at arbitrary moment are calculated first and then transformed to reliability with the assumption of Poisson process, Markov process or their improved models. For example, Jiang et al. [91, 92] successfully developed a method to transform the evaluation of the time-dependent system outcrossing rates into the calculation of a time-invariant system reliability. Wang et al. [93] proposed a new non-probabilistic time-dependent RBDO method under the mixture of time-invariant and time-variant uncertainties.

By defining an equivalent most probable point, Fang et al. [94] transformed the original time-variant RBDO problem to an equivalent time-invariant RBDO problem formulated by performance measure approach. To handle the temporal uncertainty, Li et al. [95] presented a sequential Kriging modeling approach for time-variant reliability-based design optimization involving stochastic processes. However, it is difficult to use the aforementioned approaches to handle complex RBDO problems which involve both spatial- and temporal-varied random field and/or random process, e.g., RBDO of wind turbine blades considering fatigue due to rain erosion [96].

In a summary, future RBDO research would incorporate advanced methodologies to address spatiotemporal variant, multivariable correlated, multi-field coupled, and multidisciplinary intersected complex problems.

5 Key Scientific Issues Worth Studying in the Future

The development of science brings about the integration of technology. The intersection of natural sciences and social sciences, and the emergence of marginal disciplines such as cybernetics, systems theory, and information theory provide new theoretical support for modern design, while the development of computer technology, network technology, and artificial intelligence technology provides new design media and tools for modern design. In this paper, three key scientific issues worthy of research in the future are summarized, aiming to provide research ideas for the industry of equipment design and manufacturing.

(1) Initial Concept Formation, Deduction and Evolution in Product Forward Design

Forward design aims to meet the needs of the market and users for various aspects of the product, through concept formation, functional design, whole machine design, layout design, structural design, precision design, performance design and process design, to realize the whole process of top-down design, from abstract to concrete, and from fuzzy to certain. In the early stages of concept design for complex product, the knowledge is extremely barren and highly abstract, which results in the initial design concept formed by the jump non-continuous intuition easy to prematurely converge, difficult to uniformly characterize, and figuratively evolve. Therefore, it is necessary to research on the forward divergence and continuous reasoning of the intuitive inspiration concept, the mixed representation and equivalent mapping of descriptive semantics and graphical symbols in the initial design concept, the extraction of implicit rules and

high-dimensional features of customer demand preferences, etc.

(2) Implicit Design Knowledge Acquisition in Intelligent Design with Big Data

Intelligent design combines intelligent technology and design technology, simulating human thinking activities by computers, so that computers can undertake various complex engineering tasks much better in the design process, becoming an important auxiliary tool for designers. From the perspective of product design and manufacturing, it is a major difficulty to perceive, acquire, process and service in a tolerable time, and intelligently acquire a variety of potentially valuable design bases and rules that are embedded in the product design. The points worth studying in the future include the implicit design knowledge discovery and multidisciplinary design knowledge correlation based on deep learning, big data mining of product design knowledge, matching rule acquisition of product design parameters, design constraints and design knowledge, correlation model construction of product design parameters, generation of multidisciplinary design knowledge network, etc.

(3) Trans-scale Material-configuration-functional Coupling Modeling in 4D Printing Design

The material-structure integrated technology has changed the structural design from “single scale, single material, single function and single physical field” to “multi-scale, multi-material, multi-functional composite and multi-physical field coupling”. 4D printing is one of the emerging frontier technologies in the field of equipment manufacturing in recent years, which uses intelligent material to obtain self-deformable and self-assembled objects by additive manufacturing. The temporal variation of the product shape structure and the hard control of the geometric topology deformation make the product design for 4D printing more challenging than 3D printing. So, it is necessary to study the scale effect of material and structure, and to construct a material-configuration-functional coupling model under multi-dimensional and multi-physical field. The researches on 4D printing deformation sequence planning and expandable design technology, variable performance-oriented deformation object design and optimization technology, and variable function-oriented deformable metamaterial structure design technology for 4D printing are also indispensable for 4D printing design of variable shape, variable performance and variable function.

6 Research Trends of Complex Product Design Theory and Method

At present, design and manufacturing of complex product and equipment still face a series of new challenges and scientific difficulties, including the forward whole process of design and manufacturing, the integration of structural, material and function, the extreme of service environment and working conditions, rapid agility of market response, high quality of equipment quality and accuracy, autonomy of operation, decision and control, greening of equipment manufacturing and service. These new challenges place higher demands on product design. Driven by the independent development of modern equipment and the theoretical innovation of product design, the research hotspot of complex product design in recent years has focused on the five trends of “newer, better, smarter, faster and greener”.

- Newer. It is embodied in the theoretical innovation design, conceptual design and forward design, and also reflects the integrated design of new function, new mechanism, new structure, new process and new material.
- Better. Design for quality and lean design of complex product can improve product design quality for the whole life cycle, with more stable structures, more powerful functions, better performance and more reliable quality.
- Smarter. Frontier information technologies such as big data and artificial intelligence are applied to the design process of complex product, which assists designers to realize the organization and push of design knowledge, to achieve intelligent design with user-friendly interaction.
- Faster. Cloud computing based distributed networked collaborative design is proposed to quickly respond to customers’ personalized and diversified product requirements, rapidly produce customized products that meet customer needs, and shorten product design and manufacturing cycle.
- Greener. Aiming at harmlessness, reduction, reuse and re-resource, it strives to alleviate and reconcile the increasing intensified conflicts between ecosystem and manufacturing system at the system level, and realizes harmonious sustainable green development of human, machine and environment.

Four authoritative international journals in the field of product design have been statistically analyzed in this paper, including *International Journal of Mechanical Sciences* (Impact Factor: 6.772, Q1), *Computer-Aided Design* (Impact Factor: 3.652, Q1), *Mechanism and Machine Theory* (Impact Factor: 4.930, Q1), and *Journal of Mechanical*

Design (Impact Factor: 3.441, Q2), respectively adding up the number of papers from 2011 to 2021 on the five themes of “newer, better, smarter, faster and greener”. (Note that Impact Factor information comes from Clarivate’s 2021JCR released on June 28, 2022.) As can be seen from Figure 6, the number and trend of papers published in the four journals under the five themes have roughly the same pattern. In recent years, researchers have accelerated their exploration of new material, new method and new process, and the research heat on “newer” has also shown an increasing trend year by year. Design quality and design efficiency have always been the focus of designers. Aiming at improving product performance and accelerating the design process, researches on “better” and “faster” have maintained a high and stable heat in the past decade. Due to the rapid development of information science, “smarter” related research has been popular during this decade, and it can be foreseen that the new generation of artificial intelligence will continue bringing a major development to the intelligent design. Compared with other themes, the research on “greener” has a relatively lower research heat. With the awareness of green energy conservation and environmental protection, researches on design for green manufacturing, remanufacturing and lightweight manufacturing may accelerate.

7 Conclusions

- (1) Design is the foundation of manufacturing, and there will be no advanced manufacturing without advanced design. Under the current trend of digitalization, informatization and intelligence of product manufacturing, the strong integration of different disciplines has brought great challenges and opportunities to product design.
- (2) The concept and connotation of design have been expounded systematically in this paper, and the different types of design are analyzed. The four schools of design theory such as universal design, axiomatic design, TRIZ and general design have been discussed. The research status of key technologies for complex product design such as innovative design, digital design, modular design and reliability optimization design have been reviewed.
- (3) Three key scientific issues worthy of research are discussed, including initial concept formation, deduction and evolution in product forward design, implicit design knowledge acquisition in intelligent design with big data, and trans-scale material-configuration-functional coupling modeling in 4D printing design. Five research trends of “newer, better, smarter, faster and greener” are summarized, providing research ideas for the equipment design and manufacturing industry.

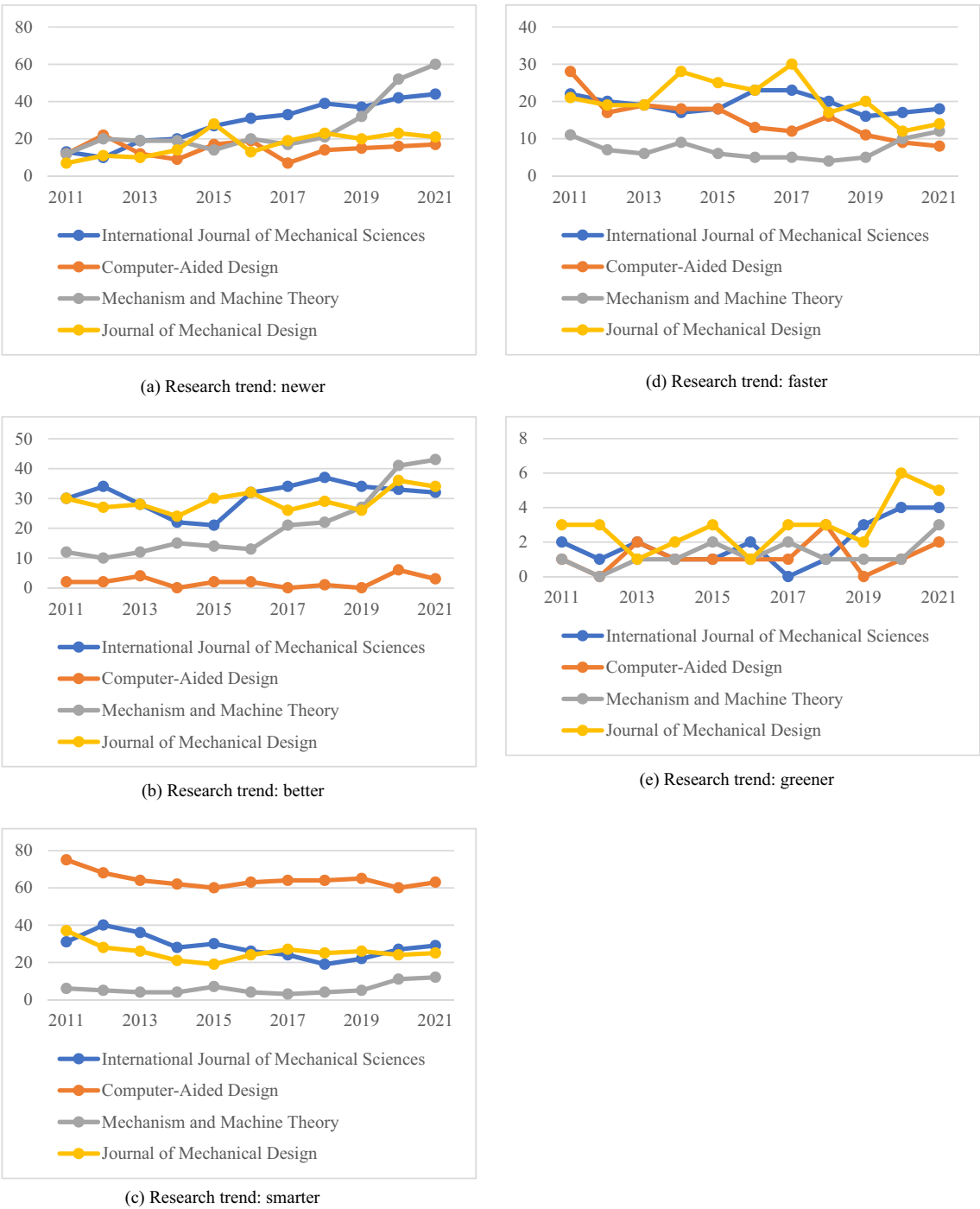


Figure 6 Statistical analysis of papers in authoritative international journals in the field of design

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Author contributions

CQ wrote the manuscript; JT was in charge of the whole paper; ZL designed the structure of the paper; HM collected data; WH improved the manuscript. All authors read and approved the final manuscript.

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