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Optimization and Practical Exploration of the Product Design Process in the Background of Digital Empowerment

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Abstract: Against the backdrop of the digital economy, technologies such as big data, generative artificial intelligence, and digital twins are deeply involved in the whole chain of product research and development, promoting the transformation of traditional product design from experience-driven to data-driven. Aiming at the problems existing in traditional processes, including subjectivity in demand research, fragmented links with long iteration cycles, high costs of physical prototypes, and lagging user feedback, this paper adopts a combined method of literature analysis and case study. It sorts out the existing pain points of traditional processes, analyzes the empowerment logic of digital technologies in each design link, and constructs a full-process framework for digitally-transformed product design. Optimization paths are proposed from five dimensions: demand mining, concept generation, simulation verification, collaborative iteration, and implementation transformation, and implementation strategies are summarized and combined with industrial practices. The study shows that digital empowerment can effectively shorten R&D cycles, reduce trial-and-error costs and improve the market adaptability of products. Nevertheless, data governance, human-machine collaboration mechanisms and talent team building should be simultaneously improved to fully release the efficiency of digital design.

Keywords: Digital empowerment; Product design; Process optimization; Human-machine collaboration; Digital twin

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1. Introduction

The digital transformation of the manufacturing industry has become a key starting point for the high-quality development of the real economy. As the source link of product R&D, product design directly determines product functions, user experience, production costs and market competitiveness. Traditional product design follows the linear process of “market research — conceptual conception — drawing drafting — physical prototyping — test modification — finalization and mass production”. It relies heavily on designers’ personal

experience, and serious information barriers exist among various departments. Demand analysis mostly adopts traditional methods such as questionnaires and offline interviews, where users' real demands are easily filtered out. Scheme verification mainly depends on physical prototypes. Repeated prototyping and modification will extend R&D cycles, increase development costs and weaken market response speed.

With the continuous iteration of tools including generative artificial intelligence, big data analysis, digital twins and cloud-based collaborative simulation, digital technologies break the linear constraints of traditional design processes and open up data flows among user demands, creative design, simulation testing and manufacturing, forming closed-loop iteration for design links. More and more enterprises introduce digital tools into product development so as to shorten R&D cycles and improve scheme innovation as well as market adaptability. However, the digital transformation of some enterprises merely stays at the stage of replacing manual drawing with digital drawing software. The reconstruction of the full-process system has not been completed, the value of data has not been fully tapped, and imperfect human-machine collaboration mechanisms hinder the performance of digital design. Accordingly, exploring improvement approaches for product design processes under digital empowerment and summarizing practical problems and countermeasures are of vital significance for promoting the high-quality development of the manufacturing industry.

2. Practical pain points of traditional product design processes

Traditional product design proceeds in a linear sequence. Departments of design, marketing, technology and production operate independently, which exposes numerous shortcomings amid rapidly-changing consumer demands.

2.1. Strong subjectivity in demand mining and insufficient accuracy of demand transformation

In the traditional mode, market research mainly relies on offline questionnaires, interviews and manual analysis of competing products with limited sample sizes. Designers interpret market information based on personal experience, which is prone to subjective prediction bias and fails to capture users' fragmented and implicit real demands. Lan Yuqi et al. hold that user experience research under artificial intelligence has shifted from small-sample surveys to big-data-supported full-coverage analysis [1]. It is common for design schemes to be divorced from market demands under the traditional mode, and user satisfaction often fails to meet expectations after products are launched. Demand information tends to decay in cross-department transmission, and end-user demands from the marketing department cannot be fully delivered to design teams.

2.2. Fragmented process links and low iteration efficiency

The traditional design process advances unidirectionally. Structural design is carried out after conceptual design, and performance tests are conducted after physical prototypes are completed. When defects are detected in tests, early design drawings need to be revised retroactively, resulting in substantial rework and time consumption. Information is not shared among design, technology and manufacturing departments. Production process constraints are rarely considered in the design phase. Some creative schemes face great

difficulties in technological realization, and feasibility defects are only discovered in the production phase, leading to severe waste of design resources.

2.3. High costs of physical prototype testing and delayed risk exposure

Performance verification is highly dependent on physical prototypes whose fabrication consumes materials and working hours. Iterations of multiple versions bring high costs. Test conditions for safety performance and extreme working conditions of some products are limited. Many potential defects are only exposed in mass production and application. Delayed risk exposure will bring higher modification costs and damage to brand reputation.

2.4. Low user participation and absence of closed-loop feedback

In the traditional mode, users are mostly involved only in preliminary research and post-launch evaluation. They rarely participate in design and testing phases without real-time feedback channels. User opinions are collected only after product finalization, which can hardly guide the optimization of early-stage product design and impedes continuous product iteration and upgrading.

3. Internal logic of product design process empowered by digital technologies

Digital empowerment is not simply replacing hand-drawn drawings with software. Instead, it reconstructs the full process of demand, creation, verification, collaboration and implementation relying on big data, generative AI, digital twins and cloud-based collaborative simulation technologies. It promotes the transformation of product design from experience-driven to data-driven mode and upgrades linear processes into closed-loop iterative processes, realizing both efficiency improvement and design-mode reform [2].

Big data mines fragmented user information from e-commerce platforms, social media and product operation records to output quantitative design indicators and reduce bias in demand interpretation. Algorithms can convert customers' vague demands into concrete design parameters [3]. Generative AI expands creative schemes and realizes human-machine collaborative creation, allowing designers to focus on scheme evaluation and selection. Digital twins and virtual simulation build digital prototypes for multi-dimensional simulation tests to identify design risks in advance and reduce the number of physical prototypes. Cloud-based collaboration breaks information barriers to realize multi-agent online cooperation, and design data can be directly delivered to production links. User-end operational data flows back to design links to form a complete iterative closed-loop. Data elements connect all business nodes to balance innovation efficiency, scheme feasibility and market adaptability.

4. Optimization paths for product design processes under digital empowerment

Digital technologies transform traditional unidirectional design processes into closed loops: data-driven demand mining — human-machine collaborative concept generation — multi-dimensional virtual simulation verification — cross-role cloud-based collaborative iteration — data-connected implementation and transformation — feedback-driven continuous optimization.

4.1. Optimization of demand mining link driven by data

Demand analysis serves as the starting point of product design. The core of digital transformation is to

expand data sources and convert vague demands into vectorized parameters. On one hand, multi-source data are integrated, including online user comments, consumption behavior data, public parameters of competing products, historical product operation-maintenance data, as well as traditional user interviews and questionnaires to enrich demand samples. Natural language processing is adopted to parse text data, extract users' frequent pain points, aesthetic preferences and functional requirements, and eliminate invalid noise data. On the other hand, a demand analysis model is established to convert users' vague perceptions into executable design parameters. For instance, users' requirement for "comfortable grip feeling" can be transformed into quantitative indicators such as dimension, surface radius, and weight. Standardized demand lists are shared with design and technical teams to reduce deviations in cross-department information transmission.

4.2. Optimization of concept scheme generation link with human-machine collaboration

In the conceptual design phase, the traditional designer-led brainstorming is transformed into a human-machine collaboration mode where AI assists divergent creation and designers make convergent decisions. Wu Jing et al. constructed an AIGC-aided product design framework based on prompt optimization, which improves design quality through collaborative cycles of demand analysis, concept generation and scheme evaluation [4]. After designers input product positioning, constraints, and quantitative demand parameters, generative artificial intelligence tools can rapidly generate multiple modeling sketches, color schemes, and structural concepts to expand creative scope and break traditional thinking sets. Nevertheless, AI-generated schemes contain logical loopholes and impractical technological problems and cannot be directly adopted as final versions. They need to be screened, revised and re-created according to industrial experience, technological levels and cost budgets. Total reliance on AI outputs should be avoided. Besides, a scheme library should be built to store previous successful schemes and corresponding constraints for reference in new projects so as to achieve better outcomes.

4.3. Scheme verification optimization based on digital twins and simulation technologies

The traditional verification mode relying on physical prototypes is transformed into a mode dominated by virtual simulation supplemented by physical prototypes. Three-dimensional digital models are applied to build digital-twin virtual prototypes for multi-dimensional simulation tests: mechanical simulation for structural-strength inspection, fluid simulation for product operation under different working conditions, ergonomic simulation for comfort verification, and process simulation for predicting processing and assembly feasibility. Multi-parameter comparative tests are completed in virtual environments to select optimal parameter combinations. A small number of physical prototypes are produced for physical verification after virtual-simulation iterations. Most design defects are eliminated in virtual phases, greatly reducing prototype quantity and test duration. Complete reports are output after simulation, with risk points and optimization directions supporting subsequent revisions.

4.4. Cross-department iteration optimization on cloud-based collaborative platforms

Cloud-based collaborative design platforms are established to open up data channels for design, marketing, technology and supply-chain teams and replace traditional file-transfer-based cooperation. All three-dimensional models, demand documents and simulation reports are stored on cloud platforms with corresponding access permissions for each role. Process engineers can directly view design models to judge

processing difficulties in advance. Supply-chain staff can synchronously check material-supply feasibility and put forward revision suggestions in early design phases, preventing unfeasible schemes discovered only after design completion. Opinions from all parties are marked on corresponding model nodes. Revised versions are automatically saved with traceable versions to reduce communication errors. Cross-domain collaboration effectively avoids the trap of "aesthetically appealing but unmanufacturable" designs and balances innovation and implementability.

4.5. Realizing transformation from design to production through data connection

After product design finalization, digital three-dimensional models, parameter lists and bill of materials are directly output to downstream manufacturing systems to realize lossless transmission of design data. Manual secondary entry of drawings is not required, thus reducing man-made transcription errors. According to Zhang Chao et al.'s research on digital manufacturing of household wood products, the connection between design data and manufacturing systems can significantly improve production efficiency and processing accuracy [5]. Design data are connected with 3D printing and numerical-control processing equipment to realize rapid small-batch trial production and accelerate transformation from digital models to physical products. After products are launched into the market, operational data and user feedback are collected, cleaned and analyzed, then fed back to design modules to identify defects in practical application, which provides basis for iterative optimization of next-generation products and realizes continuous optimization throughout the whole product life cycle.

5. Practical case analysis of digitally-enabled product design processes

A domestic household-appliance enterprise has built a complete digital product-development system and systematically reformed its original design processes. In the demand phase, multi-source data including e-commerce comments, after-sales feedback and offline surveys are integrated. Text-analysis technology is adopted to analyze users' major demands for household appliances in terms of appearance, noise-reduction performance and operation experience, forming a demand list containing 23 quantitative indicators.

In the conceptual phase, designers adopt generative-AI tools to produce multiple appearance schemes. Three schemes are selected for verification from the perspectives of modeling language, brand recognition and technological feasibility. Digital-twin prototypes are built to carry out noise simulation, structural-strength simulation and human-computer operation simulation, with multi-round parameter debugging in virtual environments. Compared with the pre-transformation period, the quantity of physical prototypes is reduced by approximately 60 %, and the R&D cycle is shortened by about one-third.

With cloud-based collaborative platforms, technical and supply-chain personnel participate in early design phases to solve numerous problems. After product launch, continuous user-usage data provide references for subsequent version updates. The enterprise's practice proves that digital transformation is not merely the upgrading of software tools but the reconstruction of process systems. However, practical problems still exist: some designers rely excessively on AI-generated schemes with weakened original thinking; inconsistent data standards among business systems block data flow; some designers lack in-depth understanding of digital-simulation tools, which undermines process efficiency.

6. Dilemmas and countermeasures for implementing digitally-enabled product design processes

6.1. Existing dilemmas in digital-process implementation

First, imperfect data-governance systems. Multi-source data adopt inconsistent standards and formats among different business systems with uneven data quality. Invalid or noisy data interfere with demand judgment. Some enterprises lack data-security management systems, bringing leakage risks for product-design models and core parameters. Second, unbalanced human-machine collaboration. Some enterprises over-emphasize AI and directly take AI outputs as final schemes, ignoring designers' value judgment, aesthetic perception and process experience. By contrast, some designers stick to traditional working habits and reject digital tools, making digital transformation a mere formality. Third, insufficient compound-talent supply. Digitally-enabled product design calls for designers with both professional product knowledge and digital capabilities such as simulation and data analysis. Most existing designers excel in creative modeling yet are weak in data analysis and simulation evaluation. Fourth, mismatched organizational mechanisms. Some enterprises still adopt traditional function-segmented organizational structures. Departments of marketing, design and technology operate in isolation without complementary evaluation systems.

6.2. Optimized implementation countermeasures

First, improve data governance and security guarantees. Unify data standards throughout design chains and establish data cleaning and verification mechanisms to guarantee input-data quality. Divide data access permissions, encrypt core design models and technical parameters, and build traceable data-access logs to prevent intellectual-property leakage. Second, clarify human-machine collaboration positioning and stick to designers' dominant role. Adhere to the principle of "AI for assistance and humans for decision-making". Generative-AI and simulation tools are used for creative divergence and computational deduction, while aesthetic judgment, value selection and scheme decision-making are undertaken by designers to exert human innovative thinking and comprehensive evaluation and avoid homogenization defects of AI schemes. Third, strengthen compound-talent team building. Provide training on simulation tools and data-analysis skills for existing designers, recruit compound talents with multidisciplinary knowledge of design, digital technology and manufacturing processes, and build cross-post cooperation teams to facilitate information sharing. Fourth, promote supporting reforms of organizations and systems. Break departmental barriers and set up cross-department product-development project teams. Take process feasibility and market adaptability into design assessment indexes, enabling technical and supply-chain personnel to participate in early-stage design and realize matching between digital processes and organizational systems.

7. Conclusion

Digital waves bring profound changes to product-design modes. Digital empowerment is not a simple upgrade of tools but the systematic reconstruction of full processes covering demand mining, conceptual creation, simulation verification and collaborative development. This study constructs a data-driven closed-loop product-design process model, puts forward five optimization paths on the basis of enriching digital-design theories and provides reference cases for manufacturing enterprises. Digitally-driven closed-loop product-development routes are fundamentally different from previous experience-guided unidirectional processes and physical-test-oriented modes. Virtual verification of design schemes can

accelerate new-product launch, reduce R&D risks and enhance product market share. To achieve these goals, enterprises should not only optimize processes, but also pay attention to hardware-software construction, data sorting and talent allocation, and adhere to designers' dominant position in innovation. In the future, integrating technologies, creativity and markets through whole-life-cycle data flow will remain a key research topic for the industry.

Disclosure statement

The author declares no conflict of interest.

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