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User-Driven: A Product Innovation Design Method for a Digital Twin Combined with Flow Function Analysis

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Abstract: Since the lack of a specific design method, guidance and user participation in the product innovation design of digital twins, a product innovation design process of a user requirement-driven digital twin combined with flow function analysis is proposed based on the constructed innovation design model of the PPE-PVE-VVE-VPE digital twin. First, to obtain the orientation of the product innovation design, the user requirement knowledge graph is generated on the basis of product functional decomposition to intuitively express the mapping relationship between user requirements and product functional components. Then, composition analysis of the prototype physical entity (PPE) is conducted in the physical domain; flow function analysis identifies the prototype virtual entity (PVE) defects in the virtual domain; the vision virtual entity (VVE) is solved via flow evolution path as well as evaluated and selected from the users' perspective to display simulation and rehearsal analysis. Finally, the vision physical entity (VPE) is constructed through the interaction and mapping of the VVE in the physical world, and users are involved in the operation of the VPE. The feasibility and effectiveness of the proposed method are verified by rede-signing a no-tillage maize seeding monomer.

Keywords: user-driven; digital twin; flow function analysis; innovation design; no-tillage maize seeding monomer

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1. Introduction

The successful design and development of a product consists of the determination of the product to be designed and the design method [1]. The former part is to acquire user requirements and how to present them when designing the product and the latter one is to know how to use the relevant techniques and methods in engineering design theory to design the product.

When product improvement and innovation are carried out, the users' requirement should be analyzed first to convert the acquired user requirement into design tasks or to identify the problems that exist in the product. Continuous innovation design is the process of the product functions continuously meeting the functional requirements of the users [2]. With the thriving science and technology and evolving product design methods, the competition for functional and service innovations is getting more intense among products, and user satisfaction has become the main focus of the competition among enterprises [3]. However, the traditional requirement analysis method is limited by problems such as difficulty in collecting user requirements and a long response period. User participation is primarily confined to the determination stage of the design task [4]. This leads to insufficient guidance of user requirements for product innovation and design, and failure to form a real-time participation and guidance mechanism for user requirements in the product design process. Hence, the requirements are prone to disconnect with functional solutions.

Digital twin is a key enabling technology in the era of intelligent manufacturing. A digital twin creates virtual models of products in virtual space by digitizing physical products, realizes the interaction between physical and virtual products with the help of data transmission technology, and achieves innovation design in the process of physical and virtual interaction iteration. The application of digital twin technology has many advantages, it allows better handling of user data and also enables accurate simulation, analysis, and monitoring of the target product. Therefore, designers can more accurately tap into design problems and specific design subtasks, and the technology has improved product intelligence and design quality. With its excellence in accuracy, efficiency, and visualization, the digital twin has been widely used in all stages of the engineering design cycle [5,6], which greatly shortens the design cycle and reduces development costs. However, the innovative design of the products based on DT at this stage can be regarded as a black box model that lacks specific method support and path guidance. As a conceptual design method that combines static analysis and dynamic description, flow function analysis provides a fine-grained analysis of the function realization process of technical systems from material flow, energy flow, and signal flow, and the guidance for improved design of products by identifying functional defects [7,8]. The integration of flow function analysis and digital twin can contribute to the analysis and solution of problems with the product conceptual design when the digital twin is applied.

Flourishing science and technology have sped up product upgrading. Dynamic market changes require a shorter time for product development and an accurate understanding of product innovation direction [9]. In the context of intelligent manufacturing, there are more advanced and convenient methods to obtain product-oriented user requirements [10]. Driven and guided by user requirements, this paper takes it as the starting and ending point of innovation design and makes users participate in several stages of the product innovation design process. That is to say, users as data resources are supposed to provide direction for the design process, users as co-designers are supposed to participate in the evaluation and screening stage of product design requirements in the virtual world, and users as subjects are supposed to assist in the physical world testing of the new product requirements. As the basis of the design methods, digital twin technology and product flow function analysis are used to study the user-driven product innovation design process and methods, and the innovative design of the no-tillage maize planter seeding monomer is verified by example.

The following sections of this paper are arranged as follows:

Section 2 introduces the relevant theoretical basis. Section 3 constructs a product-oriented user requirement knowledge graph to provide directions for product innovation design. Section 4 describes the process of product innovation design based on digital twins and integrates the flow function analysis method to achieve the solution, construction, and transformation of vision products. In Section 5, the method proposed above is verified by project examples. Section 6 highlights the conclusions and the future work of this study.

2. Related Research Foundation

2.1. Requirement-Driven Product Innovation Design

Requirements may be described as the attributes, conditions, or capabilities that a technical system or component must satisfy or possess to meet standards, specifications, or other formal documents [11]. User requirements refer to the requirements of general product quality put forward by users to meet their requirements, which are expressed as the improvement of product functions or performances. User requirements are also the driving force and starting point for enterprises to improve their products [4]. As the essence of product innovation design, user requirements are mapped into functional expectations for products by mining requirement information to clarify design tasks. Research on user requirements can improve user satisfaction with products and enhance enterprise competitiveness.

Understanding and implementing user requirements has always been recognized as an important factor in the process of product design and development. In traditional product design, the processes of proposing user requirements and solving technology are so complicated and lengthy that those requirements are often directly ignored, hence the technology-driven innovation mode is formed. However, the completed design results may not coincide with the user requirements. Along with the increasing competition for products, scholars and companies have begun to focus on product design issues from the perspective of user requirements. In the early studies, user requirements were only limited to the acquisition of design tasks or design constraints, and various models were proposed to classify, transform, and quantitatively describe the requirements. For example, the Kano model is a classic method, which enables designers to qualitatively find the breakthrough point of product design by sorting user requirements [12], and the fuzzy Kano model which describes user requirements quantitatively [13,14]. The QFD (Quality Function Deployment) model identifies the voice of the customer, and converts the user requirements into the function and performance parameters in the product design process by designers [15], which derives the fuzzy QFD model that transforms the user's uncertain information in the design into intuitive mathematical functions, and assists the designer in making decisions on the product design scheme [16]. The AHP (Analytical Hierarchy Process) identifies design objectives by quantifying requirements and ranking them at the stage of conceptual design [17], and later scholars have combined the advantages of several theories to better guide design [18]. As the competition is getting increasingly intense among products, companies and designers are inviting users to collaborate on design in a virtual immersive manner [19]. In the post-information era, the expression and acquisition of user requirements are more convenient, and the research of user requirements in product design should be transferred to the processing analysis and visual representation of requirements texts [20]. At present, there are two main ways to excavate the texts of user requirements: one is to identify requirements features by processing a large number of text data based on the above available methods [21], and the other is to build training sets based on artificial intelligence algorithm [22,23].

In the existing product design process, user requirements are only reflected in the design requirements and constraints at the front end, but not incorporated in the later design process and production trial, which may limit the real purpose of product innovation and design. At the same time, the acquisition and expression of user requirements should not only be isolated textual information in the traditional form, but also connect the product with the requirements for a visual description. As a means of data processing and analysis as well as visual representation, a knowledge graph can visually express the relationship between user requirements and products in a graphical way [24]. It can reflect the core requirements of users at product level and realize the design for the public and the whole process of requirements design.

2.2. Digital Twin and Product Design

2.2.1. Application of Digital Twin in Product Design

The product design process can be divided into stages, including problem analysis, conceptual design, technical design, and detailed design. The problem analysis stage is supposed to define the object to be designed and to determine various constraints, standards, and available resources. The goal of the conceptual design stage is to determine the functional working principle of the system, draft the functional structure, and select the functional carrier to figure out feasible schemes according to the user requirements. The technical design is aimed to complete the overall structure design of the product and the detailed design stage is to complete all drawings for production and technical documents [25].

Digital Twin (DT) as a new design tool is currently widely used in product design and improvement. Tao et al. proposed an iterative design model of big data products based on DT, and the fusion of physical and virtual data was the core of that model [26]. From the point of view of the design task, Bai et al. took into account the user factors and realized the scenario model construction of the physical and virtual domains of DT [27]. Li et al. analyzed the connotation of integrated development of complex product designing and manufacturing, which were based on DT, and then proposed a framework of complex product ring design [28]. Based on the proposed framework, key enabling technologies were explored from requirement analysis to conceptual design. According to the characteristics of intelligent products, Zhou et al. extended the modeling method of the functional model in TRIZ based on DT and constructed the functional models of physical entities, virtual entities, and interaction modules [29]. Tan et al. introduced DT technology into the improvement innovation of bag-type dust collectors and used the data-driven innovation design modeling of it to obtain a conceptual scheme for user requirements [30]. Hibernia et al. proposed the concept of using digital product avatars to represent product life-cycle information for design improvement [31]. Liu et al. proposed a DT process model framework based on process knowledge and evolutionary geometric features to solve the problem of over-idealized solid models and process parameters in product processing [32]. Huang et al. elucidated to the mechanism of product manufacturing based on DT, constructed a DT model including a virtual space, physical system, and actual manufacturing environment, and thus verified the applicability of the model in a conveyor system [33]. Wu et al. combined the TRIZ functional modeling method with the five-dimensional DT framework and proposed a modeling method for intelligent product service systems based on DT, and improved the concept of intelligent product service systems [34]. Damjanovic-Behrendt et al. investigated the design method of an open-source DT demonstrator applied to the field of intelligent manufacturing and verified the feasibility of an open-source DT modeling technology construction with a micro-service system [35]. Lim et al. built a DT-based system for product family reconfiguration and optimization that uses context awareness to enhance efficiency [36]. Dong et al. discussed a product redesign approach around product functional analysis and DT [37].

DT can also help to enhance the virtualization of conceptual schemes in the design process. Ma et al. proposed a framework for DT with enhanced human–computer interaction in the product life-cycle, which can observe the interaction between designers and products during the conceptual design phase [38]. Illmer et al. developed a method that allowed users to ignore the detailed structure of products and directly generated virtual processing technology by utilizing relevant resources in the conceptual design stage [39].

2.2.2. Process Model of Digital Twin Innovation Design

DT is based on the physical world and goes beyond it to build digital product entities in the virtual world. The DT model is a digital externalized representation of the real physical world or system that can be used to understand, predict, optimize and control the real world or system, and the construction of a DT model is an important prerequisite for realizing the technology application. Studying the construction of DT models can facilitate the promotion and application of DT technology.

Since the concept of DT was proposed, many scholars have researched DT models from different perspectives. Grieves defined a three-dimensional DT model, including the virtual model, the physical model, and the data interaction between the physical model and the virtual model [40]. Based on the characteristics of data interaction, Schroeder proposed a three-dimensional model composed of a physical device twin module, twin data module, and user information interaction module [41]. A generic model of the real entity model–view–view model was put forward by Tavares [42]. With the application of virtual information as the core, Zheng constructed a DT model including a physical full-factor perception module, information processing module, and virtual full-parameter module [43]. By emphasizing the prediction and decision-making roles of the virtual module, a four-dimensional DT structure model was proposed by Borangiu [44], including data acquisition and transmission module, virtual module, prediction module, and decision-making module. Tao put forward the composition of DT workshop, and on this basis proposed a five-dimensional structure of DT, including the physical entity part, the virtual entity part, the twin data part, the interactive connection part, and the service function part [45].

All of the above-mentioned DT models include physical entities and virtual digital twins and discuss the application process of digital twins around the physical layer and the digital virtual layer. However, few scholars have explored the physical entities and twins in-depth, hence have failed to elaborate on the process of how physical entities and virtual entities derive new products when applying DT technology to product design.

2.3. Flow Function Analysis

2.3.1. Application of Flow Function Analysis in Product Design

Flow refers to the movement of material, energy, and signal in the technical system and environment. The product functions can be realized based on the orderly movement of matter flow, energy flow, and signal flow, and the input and output of flow between components and operations. Additionally, the fine-grained analysis of the product function realization process from the three dimensions of material flow, energy flow, and signal flow can guide the product innovation design process more effectively.

Flow function analysis, as a dynamic product function analysis method, has strong potential for application in product improvement and innovation. Pahl and Beitz proposed a function analysis model based on the conversions of material, energy, and signal flow [25]. Isermann et al. proposed an energy flow and signal flow model for modern mechanical systems and divided the control system by levels [46]. Hu et al. used flow names and flow attribute descriptions to characterize the mapping relationships between functional inputs and outputs and constructed a functional representation model for the conceptual design scheme of multidisciplinary signal conversion [47]. Sun et al. took the material flow, energy flow, and signal flow as the research objects, and analyzed the bottleneck and over-conversion of flow in the technical system, which provided new ideas to solve the problem [48]. Jiang et al. explored the evolution mechanism of DT workshops from the perspective of the interrelationship of signal flow, material flow, and energy flow [49]. Kang et al. constructed the input flow, output flow, and functional similarity matrix through product function model analysis and function similarity quantification, and proposed a matrix-based solution method for a multifunctional product conceptual scheme [50]. Zhang et al. used function-based modeling to describe the meta-function and input–output flows, used the bonding diagram to describe the dynamic behavioral attributes of input–output flows, established the functional carrier model based on the parts-couplings, and generated the design solution through functional decomposition and carrier mapping [51]. Liu et al. explored the generation process of harmful functions from the perspective of flow, established a function–effect–state model to analyze the evolution process of flow, and introduced the concept of a threshold value to quantitatively analyze the harmful functions [52]. For complex mechanical and electronic products, Zhang et al. proposed a solution method of defective flow identification and flow evolution law based on resource analysis and root cause analysis [53,54], and researched the construction method of defective flow network for complex products [55]. Based on the temporal and dynamic nature of the three-dimensional flows, Fu et al. proposed a modeling method that separately elaborates the material flow function, energy flow function, and signal flow function, redefined the defective flow and proposed a targeted flow evolution law to solve the problem [56].

2.3.2. Basic Definition of Flow

The realization of product function is the variation of flow between product components [45] that is reflected as the variability of input and output flows in the process of function realization. The flow in project design can be divided into three categories: material flow, energy flow, and signal flow. Material flow is the process of change in the form, location, or inclusive mixture of two or more substances. The material flow is often used as the processing object or working object in the product, which enables users and designers to visualize the change of materials. Energy flow refers to the process of energy transfer and transformation required for the product to complete its function and is the driver of material movement changes and signal conversion transmission. Signal flow is expressed as the form of interaction between material flow and energy flow in the technical system. The signal flow in the product is mainly used for control, and the goal of signal flow is to collect material, energy, and environmental information in the product, and to process and regulate the material and energy flow.

The variability of three-dimensional flows (material, energy, and signal flows) is reflected in the difference between the number of flow outputs and inputs and the change in flow properties. The change of flow properties includes the change of flow types such as material size, signal flow type, and the change of flow state properties such as position and force. The former cannot be described quantitatively, while the latter has a continuous definition domain that can be described quantitatively. The material flow and energy flow in the product have the nature of conservation and can be described quantitatively. Since the signal flow is not conserved, it cannot be described quantitatively directly, but can indirectly achieve the quantitative representation of the signal flow.

2.3.3. Characterization of Flow Function

Flow is characterized by flowability, transitivity, and convertibility in the process of realizing function among product components. To study the function of a product, it is necessary to start from the product components which realize the function, elaborate on the representation of a single component in the process of function realization, integrate the flow function of a single component along the transfer path, which can quantitatively indicate the process of flow in realizing the function of the overall product, and provide a theoretical basis for discovering and defining defective flow. The flow passes through the components to transform and achieve specific functions, as shown in Equation (1).

$$F = \left\{ \left(\bigcup_{i=1}^{3} W_i \right), \left(\bigcup_{j=1}^{n} V_j \right), C \right\} \quad (1)$$

In the formula: F is the function achieved by the flow during the movement of a component.

W_i is the combination of input and output flow pairs in a component, including at most three-dimensional flows: signal flow, material flow, and energy flow.

V_j for changes in the flow properties in the component, such as the conversion of mechanical energy into wind energy in the energy flow.

C for components required for functional implementation.

For example, $F_{\text{Rotation}} = \left\{ \left(W_{\text{Energy Flow}} \right), \left(V_{\text{Electricity}} \to V_{\text{Mechanical Energy}} \right), C_{\text{Motor}} \right\}$, F_{Rotation} is the rotation function implemented by the component, $W_{\text{Energy Flow}}$ is the pair of input and output energy flows, $\left(V_{\text{Electricity}} \to V_{\text{Mechanical Energy}} \right)$ is the change in the type attribute of the flow, and C_{Motor} means that the component required to implement the function is a motor.

In the reference [56], the author has classified the three-dimensional flow of products (material flow, energy flow, and signal flow) into six types according to the activity state, namely, returned flow, clogged flow, insufficient flow, ideal flow, redundant flow, and harmful flow (see Figure 1).

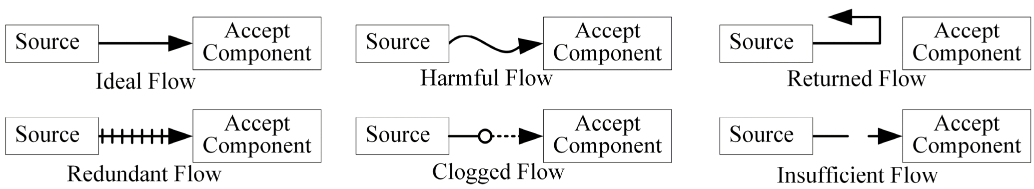


Figure 1. Classification of flow in products.

Returned flow: a flow that reverses from the output end to the input end during transmission and is affected by itself or the external environment.

Clogged flow: a flow that is not smooth and cannot realize normal function due to flow obstruction. When the flow is completely blocked, it is a special form of clogged flow. Stagnant flow refers to a flow that is temporarily or permanently at a standstill.

Insufficient flow: a flow with a flow flux below the allowable value of the flow channel, in which the system function is not fully realized.

Ideal flow: a flow with optimal flow flux for smooth operation.

Redundant flow: an excessive flow that is beyond the allowable value of the flow channel.

Harmful flow: a flow that brings out harmful effects.

The flow functions are classified for the different actions. 'Source' characterizes the ability of the technical system to provide input flows. 'Storage' describes the ability of the system to accumulate and store flows in the sequence of events. 'Operation' refers to the ability of the system to balance input and output flows and accomplish the goal. 'Transmission' refers to the ability of the system to transfer flows from the previous functional unit to the next. 'Sink' indicates the ability of the technical system to receive flows. In addition, signal flow also has two functions, 'Measurement' is the ability of the system to convert physical measurements into information, and 'controlling' is the ability of the system to convert information into physical results. The specific classifications and symbols are shown in Figure 2.

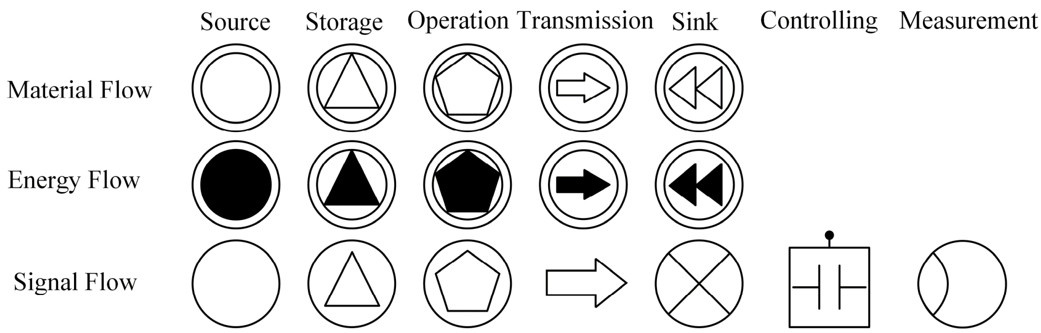


Figure 2. Classifications and symbols of flow function.

2.4. Proposed Method

Compared with Function Analysis System Technique (FAST), the flow function analysis method can reflect the dynamic and temporal nature of the function realization process. At the same time, the environmental factors of the product can be analyzed in the form of energy flow or signal flow. In comparison with traditional simulation modeling analysis theory, the DT theory has characteristics of dynamic evolution of a physical model and twin model. The twin model is not only the twin of the product but also the twin of the operating environment. DT and flow analysis, as two design tools, dynamically analyze the functional situation of the product from the perspective of the physical presence and virtual information quantity. Both analysis processes are centered on physical presence, which is modulated by information virtual quantity. The two theories show strong practicality and creativity in the innovative design of mechanical products, providing new theoretical support for designers. The innovative design solutions based on DT technology originate from and transcend the physical domain, but there is no other theoretical support in its application, and the solution process of function carriers lacks specific implementation methods. The fusion of flow function analysis methods in the process of DT-driven product innovation design can solve the problem of poor relevance and guidance in solving conceptual solutions in DT product design.

Therefore, this paper takes user requirements as the driving force to establish user requirements knowledge graph, which aims to visually express and identify defective functional components. By using the capability of iterative evolution and interaction between the physical domain and the virtual domain of DT, the data are obtained from the physical domain, and the flow function model is constructed in the virtual domain, as well as the innovation scheme is solved based on the flow evolution path. The selection of the optimal scheme is carried out from the perspective of users, and the VVE is constructed accordingly.

After the verification of simulation and rehearsal, the VVE is mapped to the physical world to construct the VPE. Users as subjects assist in the operation of the VPE under the real constraints of the physical world. The design process constructed in this manuscript makes the mapping from user requirements to product functions more accurate and forms the real-time participation and guidance of user requirements in the product design process. The research can effectively solve the problem of a lack of specific method support and path guidance in digital twin product design, and improve the quality and efficiency of innovative design. The research framework is shown in Figure 3.

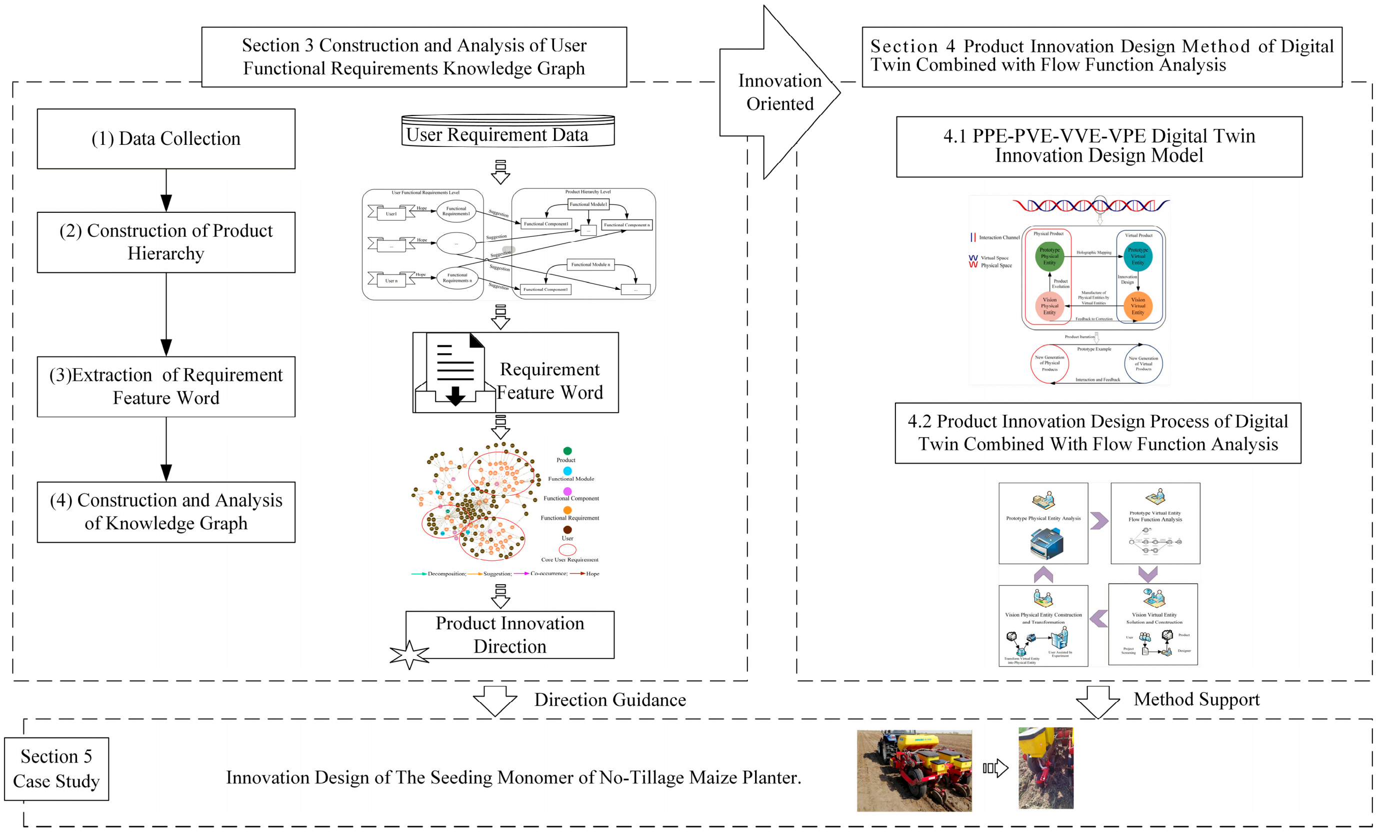


Figure 3. Frame of the manuscript.

3. Construction and Analysis of User Functional Requirements Knowledge Graph

A knowledge graph is a new graphical language that describes knowledge resources and their carriers by visual means and can be used for data mining, analyzing, and graphical constructing [57].

User functional requirements (hereafter the same as user requirements) are the requirements and desires of users to achieve the functions of the product. The purpose of this section is to use the capability of data visualization of a knowledge graph to express relevance, establish the connection between product functions and user requirements, and determine the direction of product innovation from the view of the majority of users, which has practical significance for guiding product design. The process of constructing the user requirements knowledge graph is shown in Figure 4, and the specific steps are as follows.

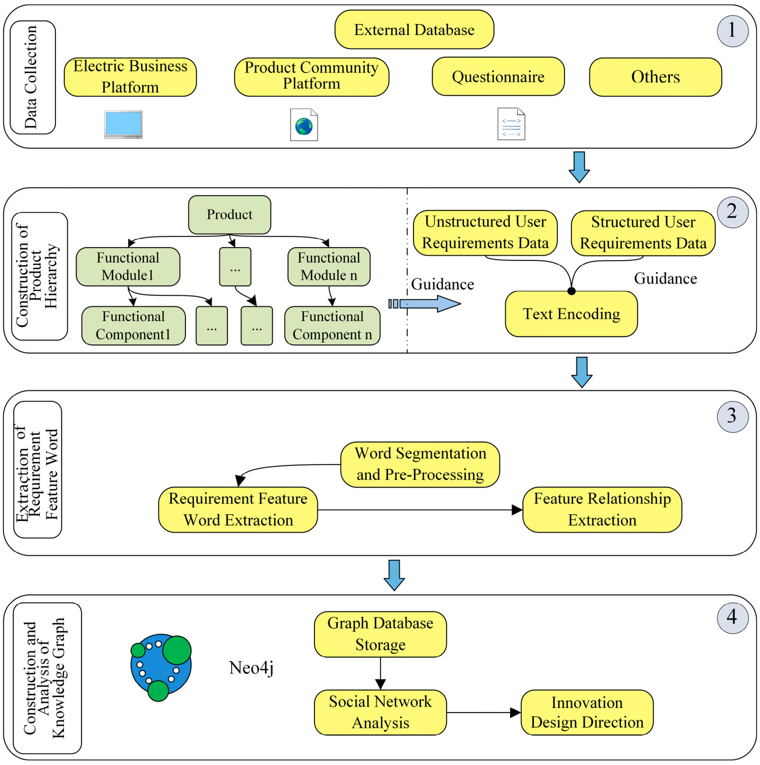


Figure 4. The process of constructing a user requirements knowledge graph.

(1) Data Acquisition

The sales volume leads to different percentages of structured data and unstructured data in user requirements. Structured data is easier to analyze and the corresponding technology is mature enough. For products with large sales volumes, such as floor sweepers and electric vehicles, crawler technology is mainly used to collect semi-structured and unstructured user functional requirements text data from e-commerce platforms and product communities. User feedback survey methods such as telephone interviews and questionnaires are used to assist in obtaining structured data. For products with small sales volume, such as CNC machine tools and shield machines, researchers mainly use telephone interviews, questionnaires and other user feedback surveys to acquire structured text data, and use crawler technology to assist in acquiring semi-structured and unstructured user functional requirements data in the product sales platform.

(2) Construction of Product Hierarchy

The purpose of constructing the product hierarchy is to classify the user functional requirements text data hierarchically. The construction of the product hierarchy is divided into three types: manual construction, semi-automatic construction, and automatic construction [58]. The construction process of the product hierarchy should indicate the functional structure relationship between product-functional and module-functional components. Since the study of the conceptual hierarchy of products is mostly conducted from the perspective of functional decomposition, the manual construction method is mainly used. Based on the reverse fishbone, the product function is decomposed to build a product hierarchy level.

Decomposition of products into functional modules, as shown in Equation (2) [36].

$$P = \bigcup_{i=1}^{n} M_i, i = 1, 2, 3 \ldots n \quad (2)$$

where P is the target product, M_i is the i functional module of the target product, and $M_i = \{C_{i_1}, C_{i_2}, \ldots, C_{i_{mi}}\}$. Thus, the above equation can be expressed from the functional components [36]:

$$P = \bigcup_{i=1}^{n} \bigcup_{j=1}^{n} C_{im_j} \tag{3}$$

where C_{im_j} is the j functional component of the i functional module of the product, $i,\ j = 1, 2, \ldots, n,\ m_j = 1, 2, \ldots, m$.

Since users' functional requirements for the product only stay on the surface of the popular functions, and few of the requests are related to the functional components of the product, the user requirements text processing can realize the classification of user requirements by the functional component level of the product (see Figure 5). At the same time, the processing of user requirements text can also modify the constructed product hierarchy.

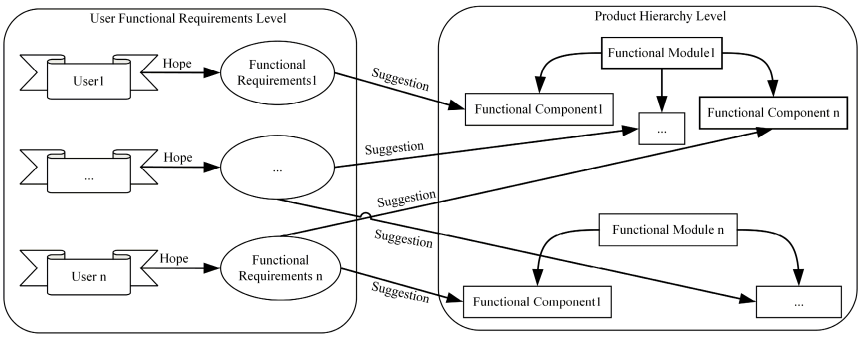


Figure 5. Mapping relationship between user requirements and functional components.

(3) Extraction of Requirement Feature Words

Requirement feature words are the characteristic words of users to express the content of requirements. The selection of feature words should contain the terms of the product domain to which they belong and the words or phrases that can summarize the user requirements. As a kind of entity, there are three types of feature word extraction: traditional entity extraction, machine learning-based entity extraction, and neural network-based entity extraction [59]. The extraction of feature words from documents requires two processes: one is word separation and text pre-processing, the other is feature word extraction. A dictionary of requirements is required to be constructed before word separation to improve the accuracy of word separation.

The relationship extraction of feature words is a key step to link scattered knowledge units into a network. Relationship extraction is to obtain some semantic relationship or class of relationship between entities through documents or semantics [60]. The relationship extraction includes two modes, namely, extraction of a relationship itself as well as extractions of an entity and relationship at the same time. The former can be further divided into template-based relationship extraction, machine learning-based relationship extraction, and deep learning-based relationship extraction [61]. The pattern matching-based relationship extraction method requires domain experts to develop extraction rules and match the rules with data to complete extraction.

(4) Construction and Analysis of Knowledge Graph

(A) Construction of Knowledge Graph

Knowledge graphs are constructed in two ways: bottom-up and top-down [62]. The bottom-up approach is a data-driven approach, which is applicable to open domain knowledge graphs. The top-down construction is mostly applied to industry-specific vertical domains, and can meet the requirements of professionalism, complex and changeable business requirements, and high-quality data. The top-down construction of the knowledge graph is used for known products.

The user requirements knowledge graph defined in this paper consists of five nodes: user, requirement, functional component, functional module, and product. Corresponding relationships need to be established among each node. The relationship between feature words of functional requirements is co-occurrence. The product is decomposed into each functional module, and the functional module is decomposed into functional components. The functional requirements suggest that the functional components have what the user wants. According to the relationship between the nodes, the model of a user requirement knowledge graph can be constructed, as shown in Figure 6.

(B) Knowledge Graph Analysis Based on Social Network

A social network is composed of network nodes (social actors) and edges (relationships), which investigates on the network structural relationships and their properties [63]. The knowledge graph is also a complex network model consisting of nodes and edges (relations), and the centrality of the knowledge graph network can be clarified by using the social network analysis method. By analyzing the betweenness centrality of the knowledge graph, the claims of most users to product functional components indicate that the node may be defective. Since there are unintuitive and inaccurate descriptions of the users' requirements for the product, the construction of a user requirements knowledge graph can only provide directions for finding product functional defects and functional improvements.

Through the crawler technology, some user reviews of Xiaomi electric toothbrushes (T300 type) on the JD e-commerce platform were obtained. The knowledge graph is constructed in the way described in this section in Figure 7. Through the analysis of the betweenness centrality of the knowledge graph, the users focused on the functional components of the toothbrush head, motor, and battery of the toothbrush, indicating that the direction of product innovation should be around the above components.

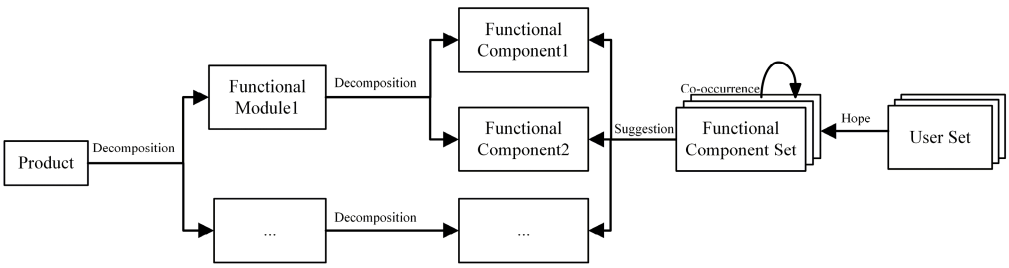


Figure 6. Knowledge graph model of user functional requirements.

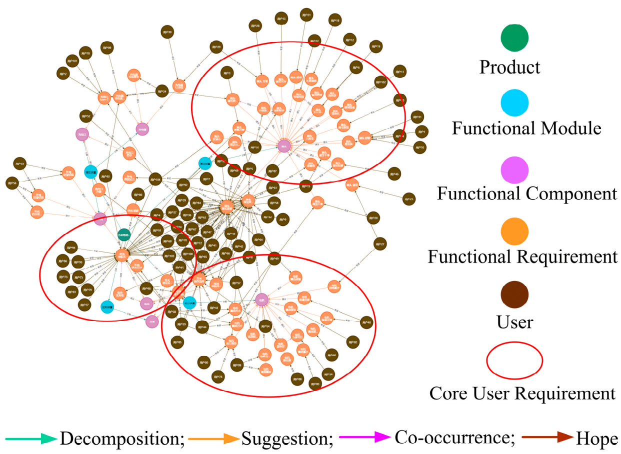


Figure 7. Example of knowledge graph analysis of user requirements.

4. Product Innovation Design Method of Digital Twin Combined with Flow Function Analysis

4.1. PPE-PVE-VVE-VPE Digital Twin Innovation Design Model

In the usage scenarios of DT, the DT model is the ontology, the physical entity is the reference object or experimental object, and the data is the information reflected by the reference object or generated around the reference object in the process. The rehearsal and simulation are ways to explore the improvement or optimization of the physical entity based on the model. According to existing research, this paper carries out product an innovation design process based on the DT theory. PPE-PVE-VVE-VPE digital twin innovation design model is shown in Figure 8. Innovation design incorporating DT is an ongoing and iterative process that can be described as a continuous iteration of interactions between physical and virtual entities. The innovative evolution of the product is realized through a tortuous spiral process of multiple interactive iterations in the product life cycle. The innovation design process expands the description of the physical and virtual entities to clarify the details of the single innovation process. The model of a physical entity can be topologized as a prototype physical entity (PPE) that exists in nature and a vision physical entity (VPE) that people want [64]. In a similar way to the physical entity, the virtual entity is expanded into a prototype virtual entity (PVE) with an equivalent mapping to the prototype physical entity (PPE), and a vision virtual entity (VVE) with an equivalent mapping to the vision physical entity (VPE). In the subsequent sections, the proposed DT innovation design process is used as the basic framework for detailed theoretical description and application.

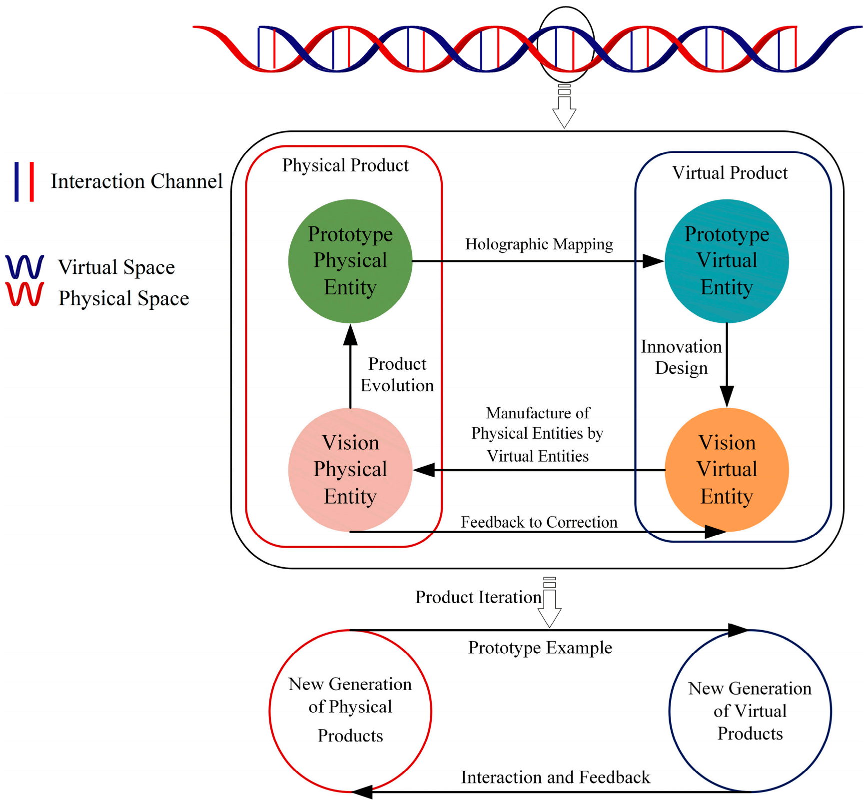


Figure 8. PPE-PVE-VVE-VPE Digital Twin Innovation Design Model.

The PPE-PVE-VVE-VPE digital twin innovation design model is divided into four stages.

(1) Clarify the composition of the PPE by using the physical product as the prototype physical entity.

(2) Make a holographic projection of physical entities into virtual space to construct PVE and analyze the defects of the PVE products in virtual space.
(3) Based on the defect analysis of the PVE, solve the innovation scheme and construct the VVE which should be simulated and rehearsed in virtual space.
(4) Based on the interaction between virtual and reality, replicate the VVE to the physical space to construct the VPE, which moves under the constraints of the real environment of the physical world. The VPE that meets the actual operating conditions of the physical world is transformed into a new PPE, and those that do not meet the requirements are returned to the VVE to re-conduct function solving as well as the simulation and rehearsal.

4.2. Product Innovation Design Process of Digital Twin Combined with Flow Function Analysis

Specifically, operable method support and path guidance are required in the DT innovation design model proposed in Figure 8. Based on this model, this section proposes the product innovation design process with a combination of DT and flow function analysis, as shown in Figure 9, including PPE analysis, functional analysis of PVE flow, VVE solution and construction, VPE construction and transformation.

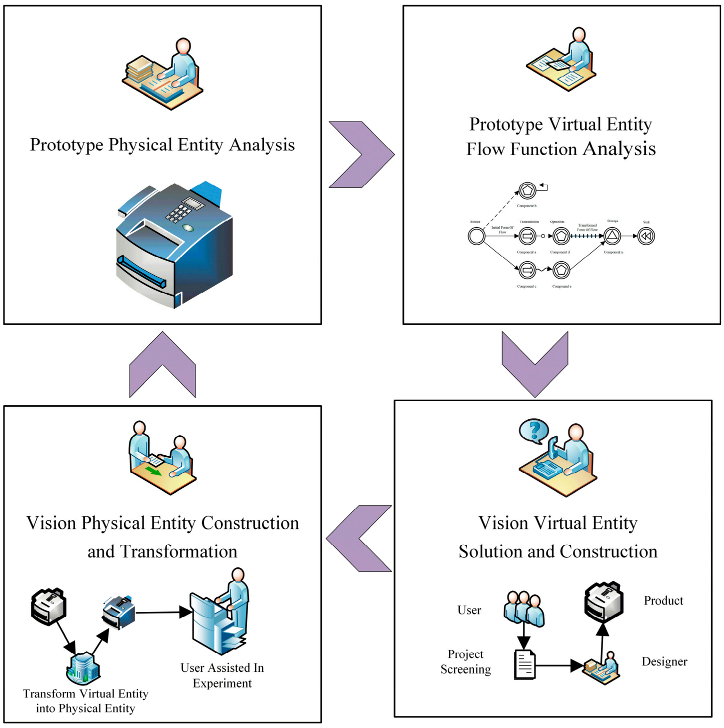


Figure 9. Innovation design process of digital twin combined with flow function analysis.

(1) PPE (Prototype Physical Entity) Analysis
PPE is the basis for improvement and innovation. Through the PPE analysis, functional components (real physical structure), super-system components, properties of material flow, energy flow as well as signal flow, and functional behaviors are clarified.
(2) PVE (Prototype Virtual Entity) Flow Function Analysis
PVE is the re-establishment of all production factors of PPE in virtual space by using sensors or other data acquisition methods, which includes functional components, super-system components, three-dimensional flows and their functional behaviors.
PVE is a holographic mapping of the PPE. The flow function analysis of PVE is based on the analysis of the products in the physical domain. In the virtual domain of DT, the flow paths and transformation forms of material flow, energy flow, and signal flow are analyzed, and the flow channels, accumulation and consumption of the flows

are identified, which provide guidelines for product improvement and innovation. However, different from the function model of physical products, it should be adjusted on the basis of the entity model in the physical domain. For the virtual flows, the PVE function symbols are shown in Figure 10.

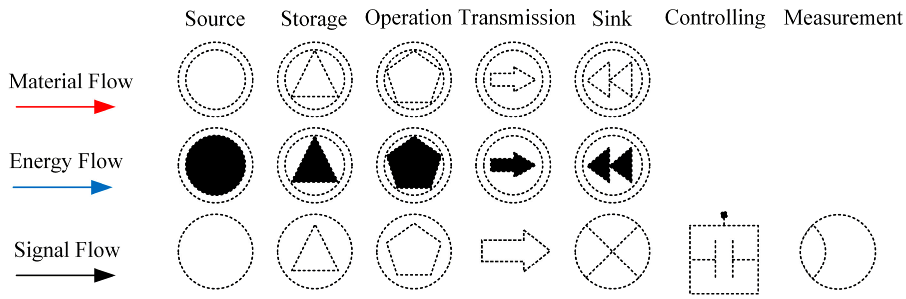


Figure 10. PVE function symbols and classifications.

When analyzing the flow function of PVE, the components that users focused on (i.e., the innovation direction fits) should be the core analysis point. The steps are as follows.

(a) Respectively, find system components, super-system components, and system functional objects through which material, energy, and signal flow in a product pass.
(b) Identify the flow functions and categories realized by the material flow, energy flow, and signal flow among each component, and clarify the initial form and transformation form of the flows.
(c) Analyze the flow direction and transmission path of product material, energy, and signal flow based on a time sequence.
(d) Use a graphical representation to demonstrate flow function relationships and flow paths, and create a flow function model diagram.
(e) Identify defective flows in the flow function model.

The function model of signal flow in the DT space is built as an example, as shown in Figure 11.

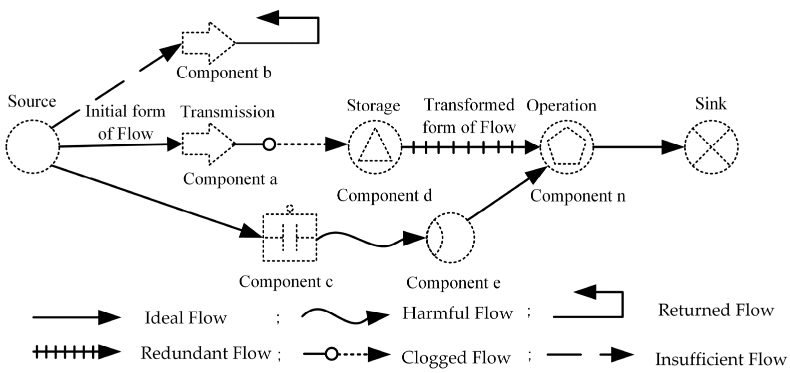


Figure 11. Signal flow function model in virtual domain.

The flow function model takes "source" as the starting point and "sink" as the ending point. The component title is marked directly below the component flow function. The functions of material flow, energy flow, and signal flow between each component are connected by returning, clogging, insufficient, ideal, redundant, and harmful flow segments with flow transformation patterns marked on the segments. The function model of the signal flow is constructed according to the generation of signal flow, the flow path between components, and the time sequence of disappearance.

(3) VVE (Vision Virtual Entity) Solution and Construction

(I) Getting VVE Based on Flow Evolution Paths

The key aspect of product innovation design is to solve the function and obtain a new functional principal solution or functional realization scheme [65]. The flow function analysis method analyzes the flow transfer path and transformation of material flow, energy flow and signal flow in the product, screens the spatial and temporal distribution of the three-dimensional flows and the accumulation and consumption of each link, performs defective flow improvements based on the flow evolution paths, thus solves and constructs VVE through the improvement of defective flows and the evolution of the ideal flow.

According to the defects and evolutionary directions of different flows, nine flow evolution paths have been proposed in the literature [56] (see Appendix A) in order to provide effective guidance on enhancing the beneficial flow, eliminating the harmful flow, and achieving innovative product design. Matching relationship between flow evolution paths and defective flows is shown in Table 1.

Conceptual design focuses on being user-oriented and generating new design solutions based on product improvement directions. Designers propose several conceptual solutions based on the flow evolution paths to correct and improve the defective flows in virtual space. The extensibility and virtualization of the DT space allow the visualization of the conceptual solutions in front of the designers, forming VVE.

(II) Evaluation of Conceptual Solutions

The user's perspective is used to filter out solutions that better fit their requirements to construct the VVE, which enhances the user's participation in the product innovation design process. Meanwhile, whether the new design satisfies the user's requirements is indirectly verified. The fuzzy comprehensive evaluation method quantitatively evaluates the satisfaction degree of upgraded product function and the matching degree of requirement by setting evaluation factors from the perspective of the user. It should be pointed out that the rationality of the selected evaluation factors is a direct contributor to the selection results. The selection of evaluation factors should be in line with the direction of product improvement and user requirements. To achieve this, the design experts should bring their advantages of rich experience and extensive knowledge in this field into full play, and reason with the evaluation factors based on the available product design standards or experience [66]. The evaluation factor set is supposed to be selected based on whether it is irreplaceable, practical, scientifically rational, integral, and all-rounded.

The steps of a fuzzy comprehensive evaluation for user-oriented functional dimensions are as follows.

Step 1. Identify the comment set A.

$$A = (a_1, a_2, \ldots, a_m) = (Good,\ Slightly\ Good,\ Medium,\ Bad,\ Very\ Bad)$$

Step 2. Determine the set of evaluation factors T.

$$T = (t_1, t_2, \ldots, t_n) = (Convenient\ operation,\ Reasonable\ function,\ Efficiency\ of\ completion,\ \text{Stable operation} \ldots)$$

Step 3. Determine the set of weight vectors W.

$$W = (w_1, w_2, \ldots, w_n)$$

where $0 < w_i < 1$, and $\sum_{i=1}^{n} w_i = 1$, w_i denote the weight coefficients under the i evaluation index.

Step 4. Determine the affiliation and single-factor evaluation matrix. The evaluation of a single indicator t_i yields a single-factor evaluation matrix.

$$R_i = (r_{i1}, r_{i2}, \ldots, r_{im})$$

Step 5. Calculate the comprehensive evaluation matrix B.

$$B = W \times R = (b_1, b_2, \ldots, b_m)$$

where $b_j = \sum_{i=1}^{n} w_i r_{ij}$ $(j = 1, 2, \ldots, m)$

(III) VVE Simulation and Rehearsal
VVE is derived and detached from PVE. The main purpose of the construction of VVE is to visually express the shape parameters, assembly relations and actual operation. Through 3D modeling and rendering software (such as NX-electromechanical conceptual design module, Unity 3D, Catia, AMESim, 3DMax, Blender, Maya, etc.) combined with system simulation software (such as MATLAB, ANSYS, ABAQUS, ADAMS, EDEM, Visual Studio development platform, etc.), the rehearsal and verification of VVE are realized.

Table 1. Matching relationship between flow evolution paths and defective flows.

Classification of Flow	Characteristics of Flow	Flow Evolution Path
Returned flow	The output end flows back to the input end during transmission	FE3 change flow properties, FE9 parasitic flow
Clogged flow	The effect of flow obstruction, the flow is not smooth and cannot achieve normal function	FE2 introduces new channels, FE3 changes flow properties, FE4 improves flow channels
Insufficient flow	The flow flux is less than the allowable value of the flow channel, and the system function is not fully realized	FE3 change flow properties, FE7 reduce flow conversion, FE9 parasitic flow
Ideal flow	Optimal flow flux for smooth operation	FE5 recycling flow, FE6 cut-off flow, FE8 cut-off flow channel
Redundant flow	The flow flux is larger than the allowable value of the flow channel, and the excess flow cannot pass through	FE2 introduces new channels, FE4 improves flow paths
Harmful flow	Harmful effects on other flows or flow channels	FE1 introduces new flows, FE3 changes flow properties, FE6 cut-off flow

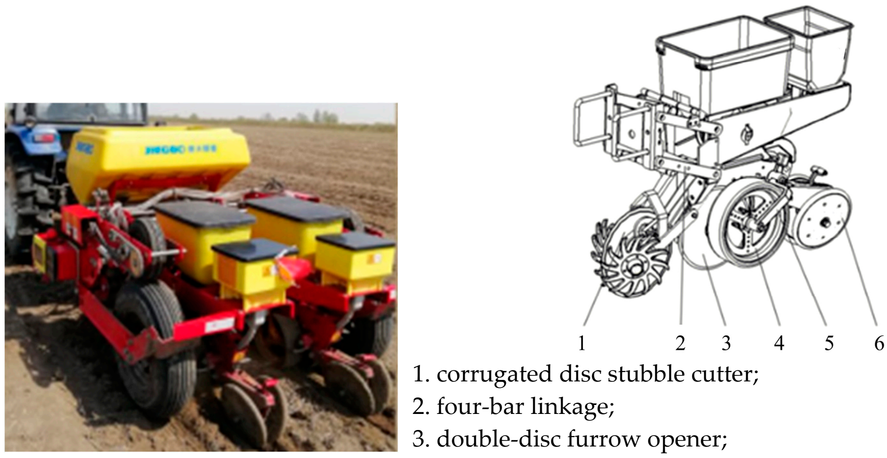
(4) VPE (Vision Physical Entity) Construction and Transformation
According to the interactive mapping of the VVE and VPE, the virtual to physical transformation is realized through workshop manufacturing activities; thus, realize the construction of the VPE. In the transformation process of the VPE, users, as experiencers, truly participate in and judge the VPE that moves under the constraints of the real environment of the physical world. Those physical entities that satisfy the following two points can be transformed into the new prototype. The first is in line with the actual operating constraints of the physical world, and the second is in line with the actual usage requirements of users. The physical entity part that does not meet any of the two points should return to the previous step for redesigning.

5. Case Study

A no-tillage maize planter is a key tool for conservation tillage, and its seeding monomer as a core component can complete stubble breaking, furrowing, seeding, soil-covering all at one time. However, due to the adhesion of soil-touching parts during the process of sowing, some problems occur that affect the quality of the seeding operation, such as operation failure, seeds bouncing and poor soil cover. In this section, the process model of product innovation design of DT combined with the flow function analysis is applied to guide the innovation design of the seeding monomer of the no-tillage maize planter.

5.1. Composition and Working Principle of Seeding Monomer

This paper takes the seeding monomer of 2BMQ type no-tillage maize planter produced by Heilongjiang Harbin Dewo Science and Technology Development Co., Ltd. (Harbin, Heilongjiang, China) as the prototype, whose structure is shown in Figure 12. It is mainly composed of corrugated disc stubble cutter, four-bar linkage, double disc furrow opener, depth-limiting wheel, support arm, soil-covering wheel, etc.



1. corrugated disc stubble cutter;
2. four-bar linkage;
3. double-disc furrow opener;
4. depth-limiting wheel;
5. support arm;
6. soil-covering wheel.

(**a**) (**b**)

Figure 12. Schematic diagram of the seeding monomer of no-tillage maize planter. (**a**) Schematic diagram of the no-tillage maize planter; (**b**) Schematic diagram of the seeding monomer.

The seeding monomer of the no-tillage maize planter is hooked up to the whole machine frame and is towed by the tractor to work [14]. During the sowing operation, the corrugated disc stubble cutter cuts into the soil, and cuts the stubble and straw on the sowing path to complete the organizing of the seedbed. Then, the double-disc furrow opener cuts the soil along the seeding path to form a seeding ditch, and the seed-metering device sends maize seeds to the bottom of the seeding ditch to complete the sowing operation. The soil-covering wheel arranged in a V-shape squeezes the soil on both sides of the seeding path into the seeding ditch. The soil-covering wheel rolls and compacts the covering soil to complete the operation.

5.2. Construction and Analysis of User Requirements Knowledge Graph

(1) Data Acquisition

Although the sales volume of the selected product is low, and the usage time and user range are relatively fixed, no relevant suggestions can be found in the comments and suggestions section of its official website (https://www.nongjitong.com/company/dewo/feedback.html accessed on 1 April 2022). Through cooperation with enterprises, this paper collects data from 15 April 2022 to 31 May 2022, by means of interviews and questionnaires from users. A total of 80 data provided by users are collected (71 data are filtered for the description of product functional requirements). The interview and questionnaire data collection card is shown in Appendix B.

The user requirements are processed with the content of user suggestions for the product in the data collection card as the main content and the components suggested by users for improvement as the auxiliary content. The purpose of data processing is to clarify the mapping relationship between the functional requirements of user concerns and the functional components of the product.

(2) Construction of Product Hierarchy
Functional decomposition of the seeding monomer is carried out according to Equation (2), and the functional hierarchy of the product is constructed, as shown in Equation (4).

$$P = \sum_{i=1}^{5} M_i = \left\{ \begin{array}{c} Seedbed\ Collating\ Module,\ Depth - Limiting\ Furrowing\ Module, \\ Transmitting\ Module,\ Seeding\ Module,\ Soil - Covering\ Module \end{array} \right\} \quad (4)$$

where $P = Seeding\ Monomer$, $M_1 = \{Weeding\ Wheel, Corrugated\ Disc\}$,
$M_2 = \{Profiling\ Depth - Limiting\ Wheel,\ Double - Discfurrow\ Opener\}$,
$M_3 = \{Racks, Sprockets\}$,
$M_4 = \left\{ \begin{array}{c} Seed\ Box,\ \text{Seed} - Fertilizer\ Box,\ Seed - Metering\ Device, \\ Seed\ Tube,\ Seed - Fertilizer\ Tube,\ Seed - Metering\ Device\ Alarm \end{array} \right\}$,
$M_5 = \{Soil - Covering\ Wheel\}$.
The conceptual hierarchy of the product is decomposed according to the above functions, as shown in Figure 13.

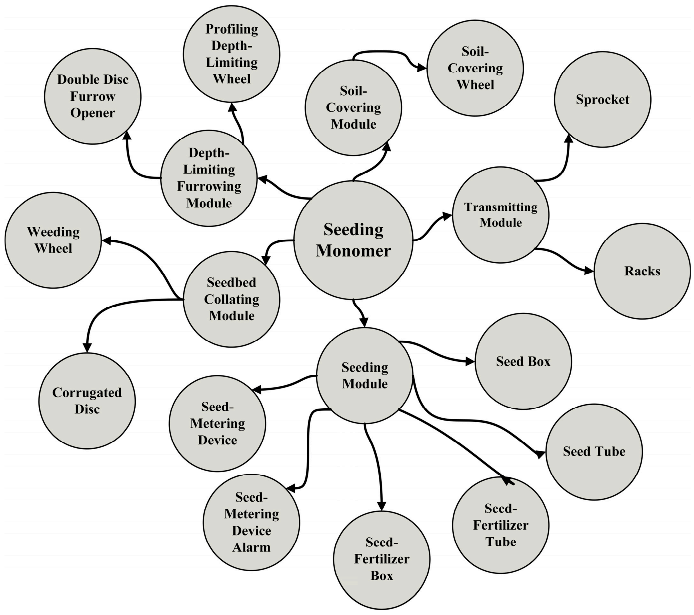


Figure 13. Product hierarchy of seeding monomer.

(3) Requirement Feature Words
Since the audience range of the product is relatively fixed, and the construction of terms used in the seeding monomer has not formed a norm, the construction process of the dictionary of requirement feature words is constructed jointly by designers and sales personnel. Due to the small number of requirement texts, this paper adopts artificial word separation to analyze the texts. Only some requirement feature words are provided in Appendix C for demonstration.
The text analysis and processing of user requirements performed in the stage of constructing the product concept system have already clarified the functional hierarchy of the technical system and the product keywords, and the extraction of feature relationships can be realized by directly calculating the co-occurrence of the feature words during the relationship extraction. The relationship of feature words is shown in Appendix D.

(4) Construction and Analysis of User Requirements Knowledge Graph
By bulk importing the above data in Neo4j software, the user requirements knowledge graph is established (see Figure 14). The betweenness centrality based on social

network analysis identifies the functional components of the product that may have functional defects as well as the direction of functional improvement from the perspective of the users as a whole. Through the betweenness centrality analysis, it is concluded that the main focus should be on the improvement and innovation design of components such as the corrugated disc, the profiling depth-limiting wheel, soil-covering wheel.

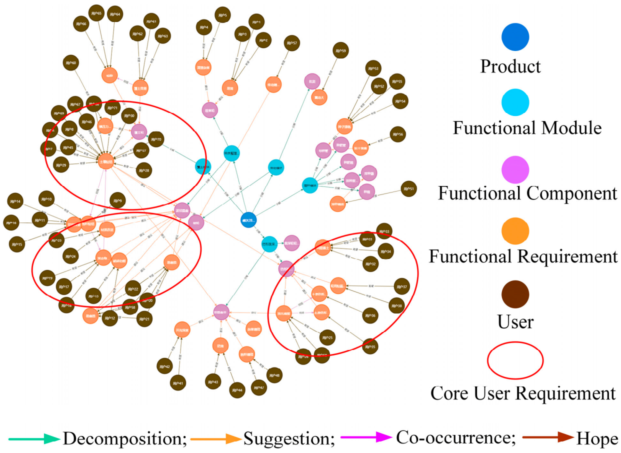


Figure 14. User requirements knowledge graph of seeding monomer.

5.3. Innovation Design of Digital Twin Combined with Flow Function Analysis

(1) PPE Analysis

The PPE of seeding monomer of the no-tillage maize planter consists of the physical mechanical structure, the flows, and the functions achieved.

The material flow is maize seed, seed fertilizer, soil, and straw residues. The sowing of seeds is achieved through changes to all four. The energy flow is the mechanical energy transferred through the racks since the machine is hooked up to the tractor to work. Additionally, the signal flow is the manifestation of the above material and energy flows.

Super-system component: soil

Object: maize seed, fertilizer, soil, straw residues

Functional components of product: racks, weeding wheel, corrugated disc, profiling depth-limiting wheel, double-disc furrow opener, depth-limiting wheel scraper, seed box, fertilizer box, sprockets, seed-metering device, seed tube, fertilizer tube, seed-metering alarm, soil-covering wheel.

(2) PVE Flow Function Model Construction and Analysis

PVE is a digital mapping implemented by PPE in virtual space using holographic mapping technology. The mapping process includes functional components, super-system components, three-dimensional flows and its functional behavior of seeding monomer.

From the knowledge graph, it can be seen that users mainly focus on the functional improvement and innovation design of components such as corrugated discs, profiling depth-limiting wheels and soil-covering wheels, so the above components should be the main focus in flow function analysis.

The seeding monomer works by mixing soil, seed-fertilizer and seeds, and the list of material flow functions is shown in Appendix E.

The no-tillage seeding monomer is hooked up to the tractor in the form of traction, and the power is transferred directly to the other devices through the racks. The energy flow function is listed in Appendix F.

The no-tillage seeding monomer is a kind of machinery with low automation, and the sensors of the no-tillage seeding monomer are only used to supervise whether the seeding monomer is working properly. The no-tillage seeding monomer usually adopts the form of manual pre-intervention to adjust the seeding monomer to the required working form, etc. This paper focuses on the overall process of the sowing function realization of seeding monomer, so the number of seeds metering during the sowing process is taken as the signal flow, and the list of signal flow functions is shown in Appendix G

The three-dimensional flows function models are constructed separately according to the above table, as shown in Figure 15.

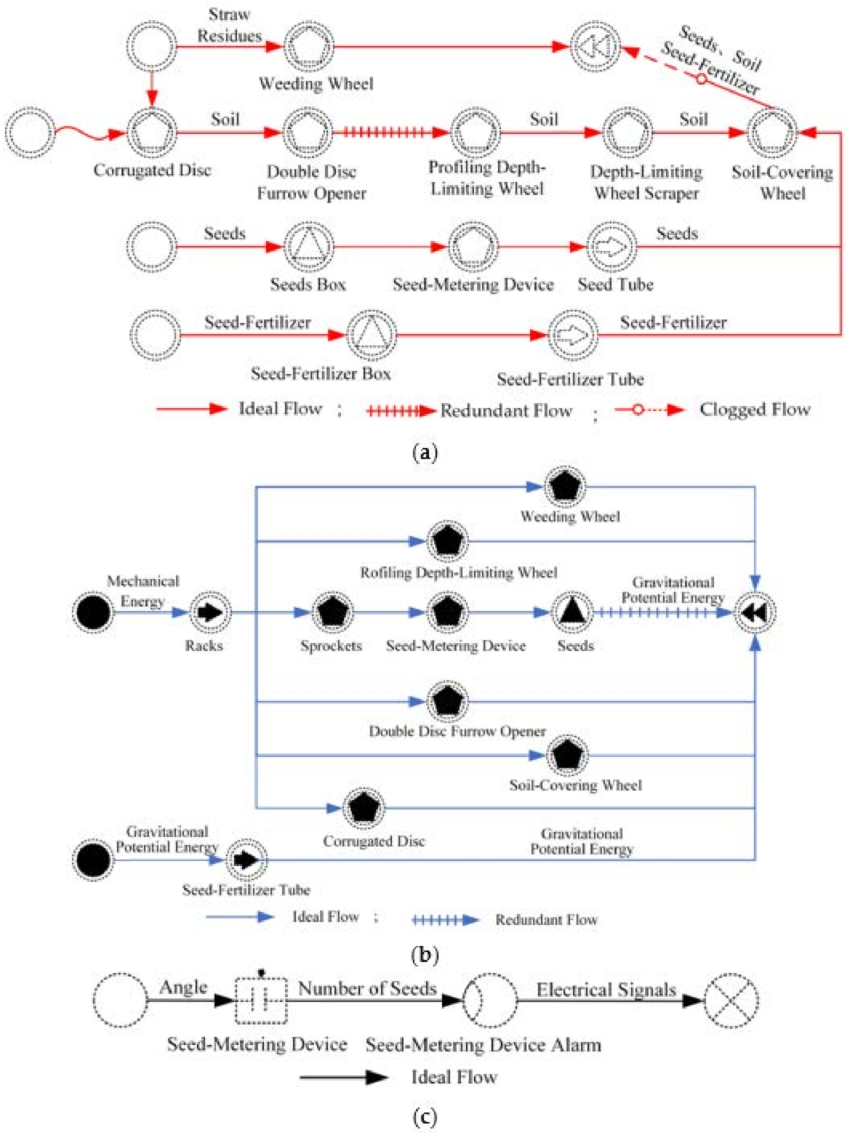


Figure 15. The flow function model of no-tillage seeding monomer. (**a**) Material flow function model; (**b**) Energy flow function model; (**c**) Signal flow function model.

(3) VVE Construction and DT Simulation

(I) VVE Solution

Based on the flow function model, four defective flows are identified, as shown in Figure 16.

For the redundancy of straw residues or soil to the corrugated disc in Figure 16a, conceptual solution 1 is proposed by applying FE2 to add soil-scraping devices for cleaning soil on both sides of the corrugated disc; conceptual solution 2 is proposed by applying FE3 to change the wave structure of the corrugated disc.

For the redundancy of soil inside the profiling depth-limiting wheel in Figure 16b, FE2 is applied to propose conceptual solution 3 to increase the scraping mechanism inside the profiling depth-limiting wheel. FE3 is applied to propose conceptual solution 4 to adjust the position of the double-disc furrow opener and profiling depth-limiting wheel so that the profiling depth-limiting wheel fits on the double-disc furrow opener. FE3 is applied to propose conceptual solution 5 to increase the waist-shaped hole dredge area of the profiling depth-limiting wheel.

For the redundancy of the seeds energy in the process of falling on the soil in Figure 16c, FE2 is applied to propose a conceptual solution 6 to add a seed-pressing wheel behind the seed tube.

For the problem of insufficient soil coverage in the soil-covering wheel in Figure 16d, FE7 is applied to propose conceptual solution 7, where a scraper is installed around the soil-covering wheel and soil-separation point.

The above conceptual schemes are visualized by SolidWorks 3D modeling software in virtual space. Additionally, since conceptual scheme 3 does not produce substantial structural changes, it is not visually modeled here, as shown in Figure 17.

(II) Evaluation of Conceptual Solutions According to the above conceptual solutions, the possible permutations and combinations are constructed, as shown in Equation (5).

$$\text{VVE Set} = \{(1,3,6,7),(1,4,6,7),(1,5,6,7),(2,3,6,7),(2,4,6,7),(1,2,5,6,7)\} \quad (5)$$

This manuscript randomly surveyed 10 user samples.

Step 1. Determine the comment set A.

$$A = (a_1, a_2, a_3, a_4, a_5) = (Good,\ Slightly\ good,\ Medium,\ Bad,\ Very\ bad)$$

Step 2. An evaluation set is established and scored from the user's perspective to sift through the virtual entity sets of the above requirements. The innovative design of the seeding unit is intended to improve the problems of the product, such as work failure by the sticky wet soil, seeds bouncing, seeds drying, which is also a direction that users are concerned about. Therefore, the quality of seeding, durability of structure, and stability of operation are selected as evaluation factors to establish an evaluation factor set.

$$T = (t_1, t_2, t_3) = (Quality\ of\ seeding,\ Durability\ of\ structure,\ Stability\ of\ operation)$$

Step 3. Determine the set of weight vectors for the set of evaluation factors W.

$$W = (w_1, w_2, w_3) = (0.4, 0.3, 0.3)$$

where $0 < w_i < 1$, and $\sum_{i=1}^{n} w_i = 1$, w_i denote the weight coefficients of the i evaluation factors.

Step 4. Determine the evaluation matrix. The evaluation of a single factor t_i yields a single factor evaluation matrix $R_i = (r_{i1}, r_{i2}, \ldots, r_{im})$.

$$R_1 = \begin{bmatrix} 0.2 & 0.2 & 0.3 & 0.3 & 0 \\ 0.1 & 0.2 & 0.3 & 0.2 & 0.2 \\ 0 & 0 & 0.1 & 0.5 & 0.4 \end{bmatrix}, R_2 = \begin{bmatrix} 0.2 & 0.2 & 0.2 & 0.2 & 0.2 \\ 0.1 & 0.2 & 0.3 & 0.2 & 0.2 \\ 0 & 0.2 & 0.2 & 0.3 & 0.3 \end{bmatrix},$$
$$R_3 = \begin{bmatrix} 0.1 & 0 & 0.3 & 0.4 & 0.2 \\ 0.1 & 0.2 & 0.3 & 0.4 & 0 \\ 0.2 & 0 & 0.2 & 0.2 & 0.4 \end{bmatrix}, R_4 = \begin{bmatrix} 0.1 & 0 & 0.4 & 0.1 & 0.4 \\ 0.2 & 0.2 & 0 & 0.4 & 0.2 \\ 0.1 & 0.1 & 0.3 & 0.2 & 0.3 \end{bmatrix},$$
$$R_5 = \begin{bmatrix} 0.1 & 0.1 & 0.2 & 0.3 & 0.3 \\ 0.1 & 0.2 & 0 & 0.4 & 0.3 \\ 0 & 0.1 & 0.3 & 0.3 & 0.3 \end{bmatrix}, R_6 = \begin{bmatrix} 0.4 & 0.2 & 0.3 & 0.1 & 0 \\ 0.3 & 0.3 & 0.3 & 0.1 & 0 \\ 0.4 & 0.5 & 0.1 & 0 & 0 \end{bmatrix}$$

Step 5. Calculate the comprehensive evaluation matrix B.

where $b_j = \sum_{i=1}^{n} w_i r_{ij}$ $(j = 1, 2, \ldots, m)$.

Inputting into the above equations comes to the following conclusion:

$$B_1 = [0.11, 0.14, 0.24, 0.33, 0.18],\ B_2 = [0.11, 0.2, 0.23, 0.23, 0.23],$$
$$B_3 = [0.13, 0.06, 0.27, 0.34, 0.2],\ B_4 = [0.13, 0.09, 0.25, 0.22, 0.31],$$
$$B_5 = [0.07, 0.13, 0.17, 0.33, 0.3],\ B_6 = [0.37, 0.32, 0.24, 0.07, 0]$$

The evaluation matrix directly shows that VVE 6 (i.e., the combination of options 2, 5, 6, and 7) in the vision entity set is more popular among the surveyed users. Compared with the prototype physical product, the shape parameters of the corrugated disc are changed in the seedbed-collating module of VVE 6 (peak height 9 mm, width 27 mm, and the angle between the corrugated peak surface and the horizontal plane is 34°), and the corrugated disc scraping mechanism is added. In addition, the dredge area of the waist hole of the depth-limiting wheel is increased, the seed-pressing wheel is added to the rear end of the seed tube, and scrapers are added around the soil-covering wheel.

(III) VVE Simulation and Rehearsal

The vision virtual seeding monomer is constructed in the virtual space for simulation and rehearsal. The service environment of the seeding monomer is sticky wet no-tillage black soil. Based on the collected soil data and the improved seeding monomer scheme, the modeling and rendering of VVE is realized in Cinema 4D (see Figure 18).

The simulation and rehearsal of the VVE in the virtual environment are mainly reflected in the adaptation of the structure of the improved part to the parameters of the working environment. The discrete element method enables discrete element modeling of the sticky wet soil environment, seeds, etc., and achieves simulation verification combined with the seeding monomer. Based on the discrete element method, this paper carries out functional simulation of the vision virtual seeding monomer, focusing on the anti-sticky performance of the seeding monomer and the bouncing situation during seed sowing. At the same time, the innovative corrugated discs need to be verified for their crushing effect on sticky wet soil and straw residues. According to the above analysis, this part of the simulation is divided into two parts by combining the actual working principles of the seeding monomer.

In the first part, based on EDEM and combined with the actual sowing environment and requirements, relevant parameters are set to realize the simulation of the anti-sticky performance of seeding monomer under the condition of sticky wet soil and the bouncing situation of the seeds during sowing, as shown in Figure 19. In this part, two types of particles, soil (see Figure 19a) and maize seed (see Figure 19b) are constructed. Since soil particles are small in the real world, to simplify the difficulty of simulation and rehearsal in the virtual space, a 5 mm sphere particle with a density of 2100 kg/m^3, Poisson's ratio of 0.41 and a shear modulus of 1.24×10^6 Pa is chosen as an approximate substitute. Similarly, maize seed particles are approximately constructed with three-sphere filling accuracy, with a density of 1200 kg/m^3, Poisson's ratio of 0.4, and a shear modulus of 1.3×10^8 Pa. Additionally, the equipment-related parameters are all derived from the real seeding monomers in the physical world.

The parameter results of the DT model for the improved seeding monomer in virtual space are shown in Figure 19c. The establishment processes of the DT simulation model are as follows. The maize seeds are generated by the particle factory set in the seed box and fall into the soil through the seed tube of the seed-metering device. The soil particles are generated by the particle factory and stacked to realize the construction of the soil particle bed, which is the functional object of the seeding monomer to realize the sowing function. The same motion constraints as in the physical environment are imposed on the seeding monomer, which is expected to be represented as a real mapping of physical entities in virtual space. The operation process of the digital twin of the seeding monomer in virtual space is shown in Figure 19d.

Figure 20 is the working state diagram of the seeding monomer DT in virtual space after the improvement of simulation and rehearsal, where the overall constraints of the seeding monomer DT is consistent with those in the real world [67] and the forward speed is 8 km/h. The working condition of each improved device in the virtual sticky wet soil environment can be clearly seen from Figure 20.

In Figure 19, the soil adhesion on the surface of the corrugated disc is lighter after the corrugated shape structure is improved (see Figure 20a), and the clay stuck on the improved corrugated disc can be removed by the additional scraping device. The soil stuck on the inner side of the depth-limiting wheel is lighter after the waist hole form of the depth-limiting wheel is improved (see Figure 20b), and the stuck soil is scraped off when passing through the additional scraping device on the inner side of the depth-limiting wheel. After the seeds are discharged from the seed-metering device, they free fall into the soil through the seed tube, and some of the seeds are pressed into the soil through the additional seed-pressing wheel (see Figure 20c). When the soil-covering wheel is covering the soil, the bonded soil falls back to the ground through the scrapers set around the wheel (see Figure 20d).

In the second part, based on EDEM, related parameters of discrete elements are set in combination with no-tillage seeding environment and requirements to realize the crushing simulation of soil and straw residues by corrugated discs of seeding monomer, as shown in Figure 21. The parameters of the soil particle bed are set in the first part, and hardened soil is quickly replaced by small soil particles and the bond key between particles is established to realize the simulation (see Figure 21a). Straw residues are filled with pre-constructed straw residue particles and the bond key between particles is established to realize the simulation (see Figure 21b). Therefore, a total of three types of ordinary soil particles, hardened soil particles, and straw residue particles need to be constructed in this part. The density of small soil particles is 2100 kg/m^3, Poisson's ratio is 0.41, and shear modulus is 1.24×10^6 Pa. The density of straw residue particles is 110 kg/m^3, Poisson's ratio is 0.33, and shear modulus is 6.3×10^6 Pa. The equipment-related parameters are all derived from the real seeding monomers in the physical world. The parameter results of the DT model for the seedbed-collating module in virtual space are shown in Figure 21c. The establishment processes of the DT simulation model are as follows. After the construction of the soil particle bed, straw residues and hardened soil is realized by using the particle factory, constraints are added with reference to the motion process of this functional module in the physical world. The operation process of the DT in the virtual space is shown in Figure 21d.

Figure 22 shows the working state of the improved corrugated disc after simulation and rehearsal, the overall structure of the seeding monomer in the simulation process is consistent with that in the real world, and the forward speed is 8 km/h. It can be seen from Figure 22 that the improved corrugated disc still has a good crushing effect on the soil and straw, and the change of the corrugated shape does not affect the crushing function of the mechanism.

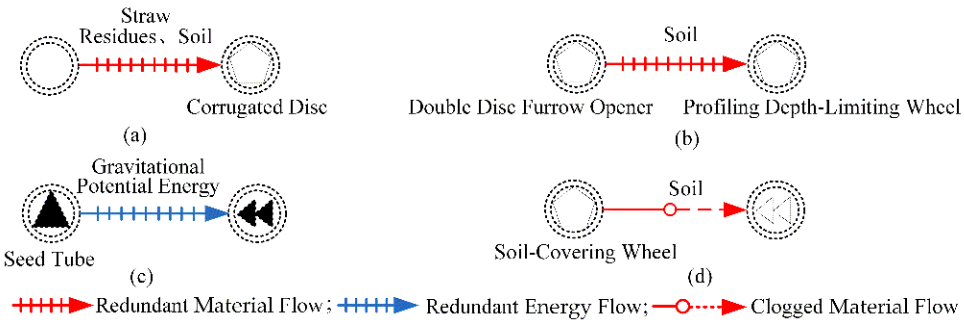


Figure 16. Simulation results of anti-sticky performance of seeding monomer digital twins. (**a**) Soil adhesion situation on corrugated disc; (**b**) Soil adhesion situation on profiling depth−limiting device; (**c**) Pressing situation on seed−pressing wheels; (**d**) Soil adhesion situation on soil−covering wheel.

Figure 17. Crushing results of corrugated disc DT.

Figure 18. Model diagram of defective flows. (**a**) Defective material flow model of corrugated disc; (**b**) Defective material flow model of profiling depth−limiting wheel; (**c**) Defective energy flow model of seed tude. (**d**) Defective material flow model of soil−covering wheel.

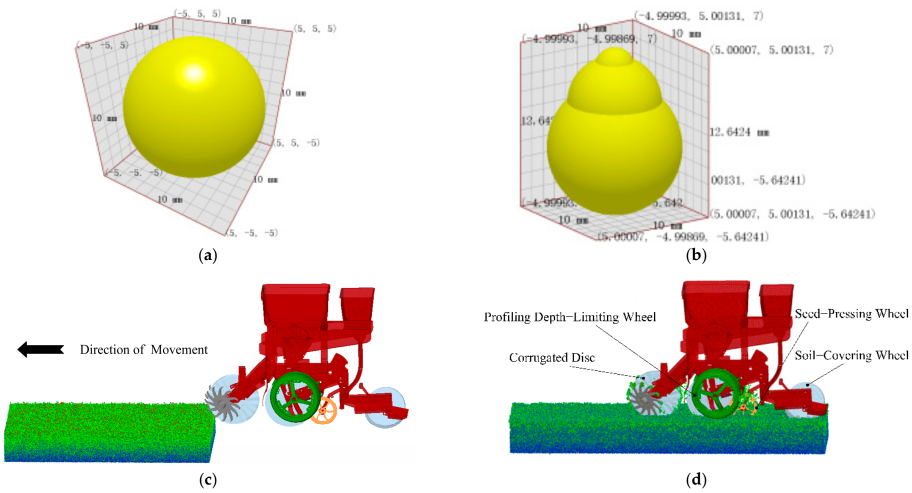


Figure 19. Schematic diagram of the conceptual scheme.

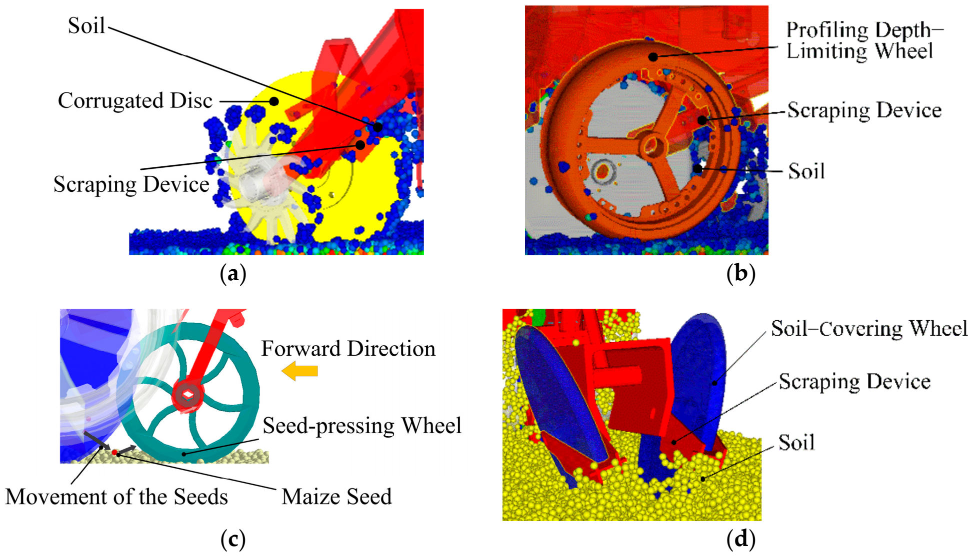


Figure 20. Rendering of vision virtual seeding monomer in virtual space.

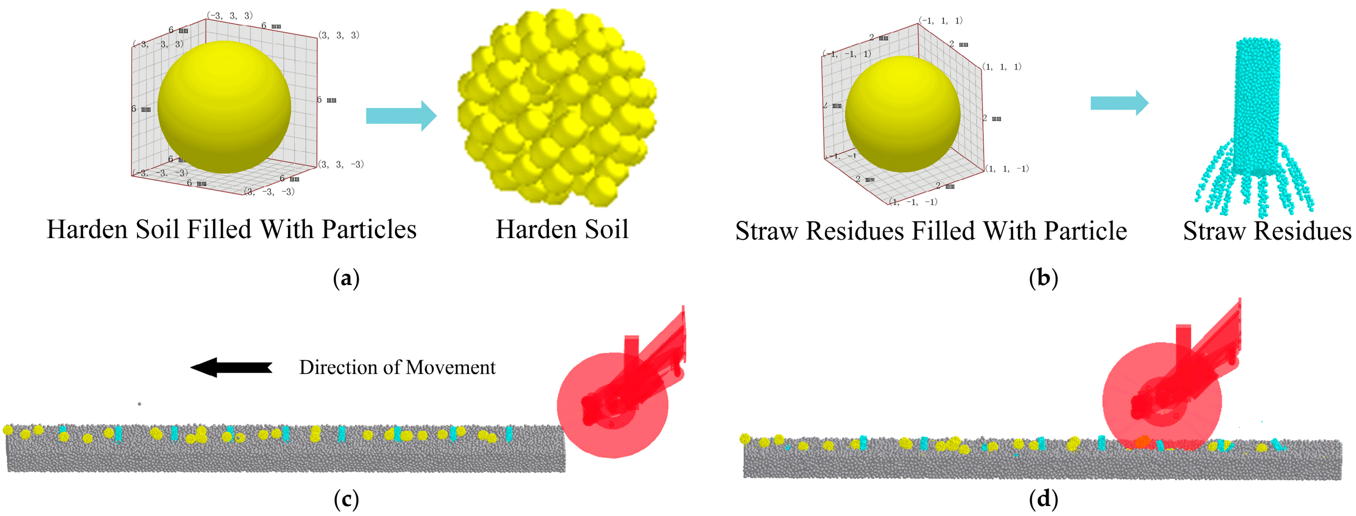


Figure 21. Simulation diagram of anti−sticky performance of seeding monomer digital twin. (**a**) Soil particle setting; (**b**) Maize particle setting; (**c**) Particle generation and equipment motion constraints added; (**d**) Simulation is running.

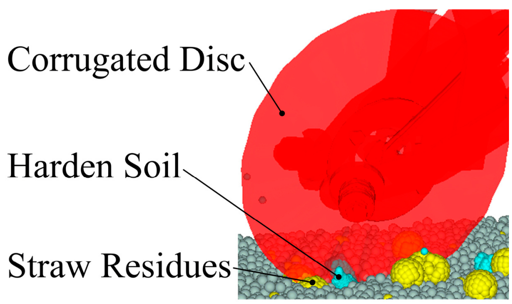


Figure 22. Schematic diagram of DT crushing simulation of corrugated disc. (**a**) Harden soil construction; (**b**) Straw residues construction; (**c**) Particle−bed construction and motion constraint added; (**d**) Running process of simulation.

(4) VPE Construction and Transformation The VVE determined after the evaluation is mapped and transformed to VPE, including detailed design, process design, parts

processing, product assembly, production debugging, etc. The redesigned VPE of the seeding unit is shown in Figure 23.

Figure 23. Transformation of VVE.

(5) Field Experiment Verification
Users test the vision physical seeding monomer on an experimental field in Harbin Pingfang District in June 2022. The field test shows that: compared with the original model, the amount of residual clay in the seedbed-collating device, depth-limiting device and soil-covering device decrease by 57.5%, 10% and 26.2%, respectively, and the number of seeds bouncing decreases by 65%.
Compared with the prototype seeding monomer, the designed no-tillage seeding monomer achieves functional optimization with minimum cost and solves the problems of the no-tillage seeding monomer such as work failure caused by sticky soil of the corrugated disc and profiling depth-limiting wheel, seed bouncing in the process of seed-tube sowing, and seed drying caused by soil adhesion during soil-covering wheel operating. After virtual simulation and actual sowing verification in the physical world, the VPE meets the agronomic requirements, and the innovatively designed no-tillage sowing monomer is transformed into a new type.

6. Conclusions and Prospect

This study integrates technical means and design methods such as knowledge mapping, digital twin, and flow function analysis, to propose a product innovation design method, which combined user requirement-driven digital twin with flow function analysis. The feasibility of the proposed method is verified by applying it to the improved anti-sticking design of the no-tillage maize seeding monomer.

The main contributions of the current research can be concluded as follows.

(1) To begin with, the products are finely decomposed according to the functional structure. The knowledge graph of user requirements is subsequently constructed based on mapping the relationship between user requirements and product functional components. Moreover, the social network analysis of the knowledge graph is carried out to obtain the direction of the product innovation design. Through the real-time participation and guidance of user requirements in the product design process, the alignment between product development solutions and user functional requirements is improved.

(2) In addition, the PPE-PVE-VVE-VPE digital twin innovation design model is constructed. Additionally, interactive iteration between the physical entity and the virtual entity is demonstrated as a specific process. The process enhances the applicability of the digital twin in product design.
(3) This paper proposes a product innovation design process based on a user requirements knowledge graph, combining the advantages of virtual-real synthesis of digital twin as well as the dynamic and temporal properties of flow function analysis. Effectively, the process solves the problems of lack of specific methods and path guidance in digital twin product design, and the problem of low user participation. At the same time, it provides new ideas and methods for product innovation design.

Although the proposed method has many advantages and also realizes the innovative design of a seeding monomer, there are still several limitations. (1) The proposed method guides the process of digital twin product design from the user's perspective by screening conceptual solutions and simulating the screening results. However, the proposed method does not provide a formal representation of the user's requirements. It meant the results of product design cannot establish a stable mapping relationship with the requirements and cannot ensure that each requirement is verified. Such results may increase the time cycle and cost of product iteration design [11]. (2) In the proposed method, there is a limitation to simulation verification after the user selects the conceptual solution, so the simulation result may be reasonable but not optimal. (3) Based on the virtual–real interaction characteristic, the innovation design model of digital twin illustrates the specific process, but the application of this model is inseparable from the previous generation of products.

The limitations mentioned above indicate the possible future research direction. In the future, we will focus on the following three research aspects: (1) Achievement formal representation of requirements. User requirements and product function structures are supposed to be mapped to automatically realize the user satisfaction verification of products. (2) Integration of other conceptual screening methods to improve the merit of screening methods. (3) Optimization of the digital twin innovation design model to achieve the descriptions of the original innovation design of products.

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Appendix A. Flow Evolution Path

Flow Evolution Path
FE1 introduces new flows. To introduce material flow/energy flow/signal flow into the system or super-system
FE2 introduces new channels. To transfer the flow within the system to the supersystem, or to reallocate the flow path through the bypass channel within the system.
FE3 changes flow properties. To change the potential, resistance, and other attributes of the flow to improve the liquidity.
FE4 improves flow channels. To enhance the properties of flow channel or to clear problem regions to enhance liquidity.
FE5 recycling flow. To utilize recyclable materials, energy, information, and other resources.
FE6 recycling flow. To cut unnecessary defect flow or harmful flow.
FE7 reduces flow conversion. To remove intermediate links and reduce the number of flow conversions and transmission levels.
FE8 cut-off flow channel. To cut damaged and unnecessary flow channels
FE9 parasitic flow. To attach one flow to another for synergy.

Appendix B. Interview and Questionnaire Data Collection Cards

Product technical parameters	Transmission form: rack using hook-up traction, seed-metering device using chain drive Seed-metering device form: finger-clip type Weeding form: bilateral involute gear type Loose soil stubble form: corrugated disc Sowing and furrowing form: double disc Profiling form: double side widened rubber wheel Soil-covering form: V-shaped opposed rubber wheel Functions of alarm: alarm when missing sowing, and count grain numbers Sowing depth (mm): 10–75 Adjustment range of plant spacing (mm): 70–410		
Users are asked to answer the following questions based on real-life situations you have encountered during the operation of the seeding monomer.			
Username	Gender	Interview time	Duration of user operation
Contact number		Product number	
			Very satisfied → Very dissatisfied
Degree of user satisfaction with the whole machine during the realization of the seeding monomer function			5 □ 4 □ 3 □ 2 □ 1 □
Degree of user satisfaction with the components during the realization of the seeding monomer function			5 □ 4 □ 3 □ 2 □ 1 □
Year of product purchase			
Place of product use			
Working environment of the product			
Suggestions for the product			
Recommended components for improvement			
Advantages/Disadvantages of our products compared with similar products			

Appendix C. List of Feature Words

Products	Function Modules	Functional Components	Display of Feature Word
seeding monomer	profiling depth-limiting module	profiling depth-limiting wheel	pre-adjustment, soil adhesion, gap plugging, soil ridge profiling form, soil ridge profiling height, sticky soil around the wheel
		Double-disc furrow opener	furrowing depth, anti-blocking, soil adhesion, straw winding, weed winding, pre-regulation
		depth-limiting wheel scraper	clay removal, wheel scraping
	seedbed collating module	weeding wheel	easy to block, weeds cleanup
		corrugated discs	soil adhesion, straw adhesion, crushing function, stubble cutting effect, mixture adhesion, easy to wear, material improvement
	seeding module	seed-metering device	seeding accuracy
		seed tube	seed bouncing, clay clogging
	transmitting module	sprockets	transmission accuracy, easy to wear
		racks	high vibration
	soil-covering module	soil-covering wheel	soil-covering effect, seeds drying

Appendix D. Result Table of Co-Occurrence Relationship of Feature Words

Products	Function Modules	Functional Components	Feature Word Pairs
seeding monomer	profiling depth-limiting module	profiling depth-limiting wheel	pre-adjustment–soil ridge profiling form pre-adjustment–soil ridge profiling height
		Double-disc furrow opener	pre-adjustment–furrowing depth
	soil-covering module	soil-covering wheel	soil-covering effect–seeds drying
	seedbed collating module	corrugated discs	soil–straw–mixture adhesion

Appendix E. List of Material Flow Function of No-Tillage Seeding Monomer

System/Super-System Components	Initial Form of Flow	Function of Flow	Transformed Form of Flow	Category of Flow
Weeding wheel	Straw residues	Operation	-	Ideal
Corrugated discs	Straw residues, Soil	Operation	-	Harmful
Double-disc furrow opener	Soil	Operation	-	Ideal
Profiling depth-limiting wheel	Soil	Operation	-	Redundant
Depth-limiting wheel scraper	Adhesive soil	Operation	-	Ideal
Seed box	Seeds	Storage	-	Ideal
Seed-fertilizer box	Seed-fertilizer	Storage	-	Ideal
Seed-metering device	Seeds	Operation	-	Ideal
Seed tube	Seeds	Transmission	Seeds	Ideal
Seed-fertilizer management	Seed-fertilizer	Transmission	Fertilizer	Ideal
Soil-covering wheel	Seeds, Seed-fertilizer, Soil	Operation	Seed, Seed-fertilizer, Soil mixture	Clogged

Appendix F. List of Energy Flow Functions of No-Tillage Seeding Monomer

System/Super-System Components	Initial Form of Flow	Function of Flow	Transformation Form of Flow	Category of Flow
Racks	Mechanical energy	Transmission	-	Ideal
Weeding wheel	Mechanical energy	Operation	-	Ideal
Corrugated discs	Mechanical energy	Operation	-	Ideal
Double-disc furrow opener	Mechanical energy	Operation	-	Ideal
Profiling depth-limiting wheel	Mechanical energy	Operation	-	Ideal
Sprockets	Mechanical energy	Transmission	-	Ideal
Seeding monomer	Mechanical energy	Operation	-	Ideal
Seeds, Seed-fertilizer	Mechanical energy	Storage	Gravitational potential energy	Ideal
Soil-covering wheel	Mechanical energy	Operation	-	Ideal

Appendix G. List of Signal Flow Functions of No-Tillage Seeding Monomer

System/Super-System Components	Initial Form of Flow	Function of Flow	Transformation Form of Flow	Category of Flow
Seed-metering device	Angle	Controlling	Number of seeds	Ideal
Seed-metering device alarm	Number of seeds	Measurement	Electrical signals	Ideal

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