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Representation and Storage of Design Knowledge by Integrating CAD Annotation and Conceptual Design Method

Dongfei Xu [1], Guanghui Wang [1], Chen Cai [1] and Cuiqiang Yan [1]

[1] College of Engineering, China Agricultural University, Beijing 100083, China

Corresponding author: Guanghui Wang, 97554@cau.edu.cn

Abstract. Conceptual design is a knowledge-intensive process, and the reuse of design knowledge is a key focus for modern manufacturing enterprises. Computer-aided design (CAD) is the ultimate recording tool in the conceptual design process, but it lacks knowledge transmission in the early design process. To address it, an intelligent design knowledge representation and storage method based on conceptual design methods and CAD annotations is proposed. Specifically, an improved axiomatic design (AD) theory applied to the conceptual design process is proposed, adding design knowledge domains to the customer, functional, and physical domains. By integrating requirement analysis, improving axiomatic design (AD) and function analysis, a conceptual design pattern for new products is established to obtain the mapping relationship between design knowledge and design scheme structure, which is regarded as a design knowledge representation process. The conceptual design scheme can then be presented in CAD software, and the design knowledge from the conceptual design process is annotated into its 3D model. The advantage of this method is that it can effectively combine design knowledge with design solutions, expressing design knowledge in a more intuitive and storable form, which is conducive to knowledge reuse. Moreover, this study develops a Model Knowledge Base (MKB) using Visual Studio, MySQL, and MongoDB to identify and store components and corresponding annotations intelligently. Through it, design knowledge is migrated and stored. Finally, the practicality of the proposed method has been verified through a case study of a conceptual design of a soil collection device.

Keywords: Improving axiomatic design (AD), CAD annotation, Conceptual design, Model Knowledge Base (MKB)
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1 INTRODUCTION

The manufacturing industry is facing increasing competition. Improving its product development process is critical to bringing new, high-quality products to market quickly and cost-effectively. Many vital decisions that affect the product to be manufactured and marketed are made during the conceptual design phase of the engineering process, so any improvements made during this phase have a significant positive impact [1]. Conceptual design is when designers, according to customer needs, determine the appropriate physical structure and components of the product to meet its functional requirements by exploring various ideas and decisions [2-4]. Product conceptual design is the process of generating design knowledge. Modern manufacturing companies tend to utilize collaborative design and model reuse to improve product quality and reduce cost and product design time [5-6]. Most product designs combine elements of other product designs accumulated in the enterprise design knowledge system, and the creation of new products can increase collective design knowledge [7-8].

The concept generation is limited by the designer's experience and previous design knowledge [9-10]. Nevertheless, other than the corresponding design authors, it is difficult for other designers to understand or reuse their design decision path in the subsequent period [11]. As a result, many companies develop internal design guidelines that integrate knowledge of the product development process. In this case, they are not only CAD-oriented but also design process-oriented. Design guidelines focus on the entire design process, providing effective transitions of information and knowledge between design phases [12].

CAD models are centered around the geometric and topological descriptions of products, and occupy an important position as the recording method for product conceptual design schemes [13]. Traditional computer-aided design often focuses more on the geometric information of physical products at the detailed design stage. It ignores the nongeometric information (such as specifications, required functions, performance, and constraints) [14]. These products information serve as a basis for improvement during the enhanced design phase [15].

Design knowledge in medium and small enterprises relies heavily on informal and personal interaction. If the knowledge representing the developers is embedded in the constructed CAD model, it can improve people's understanding of the product and better reuse of the product model [16-18]. CAD models are a visual representation of the product design process, but the knowledge used in the design process should be the wealth of the enterprise. 3D annotations, as a carrier of design knowledge, are an effective mechanism for exchanging design knowledge. They not only contain numerical structured data but also capture the interaction of design information.

Our proposed method aims to provide a basis for establishing a knowledge base within enterprises and even industries by capturing the design knowledge of engineers and embedding it into CAD models, as well as reusing design models to transfer design knowledge and shorten the design cycle. The process is illustrated in Fig.1. This article focuses on representing and storing design knowledge, achieving interaction between CAD models and conceptual design processes.

The main contributions of this paper can be summarized as follows.

(1) The improved axiomatic design theory is established at the product conceptual design stage by introducing design knowledge domains into axiomatic design. Based on the conceptual design process of designers in engineering, design knowledge in the conceptual design process is defined as professional knowledge, design decisions, necessary dimensions, and working principles.

(2) Design knowledge is annotated in the 3D model of the conceptual solution, and an integrated view of the 3D model and annotations is established as the primary form of design knowledge storage, effectively connecting the product conceptual design process.

(3) A Model Knowledge Base (MKB) based on parsed 3D models and their annotations is developed to achieve intelligent storage and retrieval of product design knowledge.

The remainder of this paper is organized in the following manner. Section 2 reviews the related works. Section 3 introduces the construction process of design concepts and CAD annotation. Section 4 presents a general framework of the proposed method. Section 5 verifies the feasibility of the proposed method in a case study. The conclusion and further research are described in Section 6. Additionally, an open-source software tool for CAD model storage and retrieval has been developed.

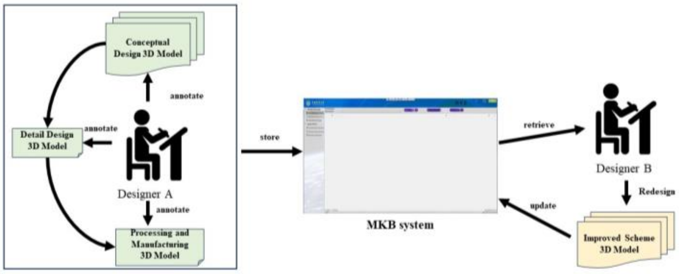

Figure 1: Proposed method for aiding design knowledge reuse.

2 RELATED WORK

2.1 Generation of Design Concepts

Concept generation in practical engineering design problems is a highly personalized process in which designers or teams of designers work together to develop practical and unconventional solutions [19]. In recent years, scholars have developed a variety of design methods to provide designers with a way to explore conceptual solutions for new design problems (where there is no recognized solution) and redesign problems (where past solutions can simply be improved to meet design goals) [20].

Data-driven conceptual design is rapidly becoming a powerful approach to leverage external knowledge (such as patent texts, Wikipedia, scientific papers, etc.) to generate novel and meaningful ideas, especially in the early design phase [21-22]. Xu & Dang [23] proposed a method to mine solution knowledge from data and recommend the best solution to problem solvers to solve quality problems efficiently and with high quality. Liu et al. [9] developed a novel Functional Structural Conceptual Network (FSCN) that explores functional and structural information associations to generate innovative ideas. Liu et al. [24] proposed a function-based patent knowledge retrieval tool to acquire and integrate cross-domain patent knowledge, recommend cross-domain patent texts to designers, and inspire designers to generate more innovative design ideas. Liu et al. [25] proposed a new analogy retrieval tool based on a structure-mapping functional model (SMFM) to support conceptual design innovation. Under the stimulation of external knowledge, intelligent design methods generate design solutions with high novelty, while by contrast, their feasibility is poor.

TRIZ theory provides a set of methods and approaches for product innovation and is a suitable catalyst for increasing the efficiency of product innovation design and improving the methodology. TRIZ theory is integrated with other product design methods to form a structured and more operational model of the product design process [26,27]. Design is a knowledge-intensive process with heterogeneous design knowledge from multiple sources; therefore, it requires problem-solving logic to derive effective solutions [28].

Axiomatic design [29-30] divides the design space into four domains, i.e., requirements, functional, structural, and process domains, based on the design sequence. Conceptual solutions are formed through a sawtooth mapping process between adjacent domains. Gero [31] proposed a function-behavior-structure model for mapping function to structure. Subsequently, many scholars [32-33] have proposed the situated function-behavior-structure framework based on environmental constraints, function-behavior-effect-structure (FBES) model integrating the effects in TRIZ with FBS, to develop FBS framework. These methods can be used to represent transformational design knowledge. Based on the axiomatic design method, designers' implicit design knowledge is described as product structure. However, other than the designer himself, it is difficult for others to understand the design process solely from the product structure. Therefore, this article expands the domain of design knowledge and establishes an extended axiomatic design.

During the design process of a part or product, in addition to data from retrieval, designers make many design decisions based on various factors, such as existing design methodologies or the designer's experience. Many of these decisions are based on tacit knowledge and thus cannot be understood by other designers, making it difficult to reuse the design knowledge. As a tool for documenting the conceptual design solution, CAD software has no information transmission with the early design process. Still, text annotation is an effective tool for embedding the design methodology used by the designer into the CAD model.

2.2 CAD Annotation

A key factor in the difficulty of reusing design knowledge in engineering is the absence of design knowledge, that is to say, there is a lack of information on designers using specific design methods. CAD annotations are an effective mechanism for exchanging design knowledge. CAD has invested much effort in researching how annotations directly support design methods, such as capturing the design process, retrieving basic principles, and supporting and integrating with other engineering tools [34].

Product Lifecycle Management (PLM) aims to connect product communication information among multiple stakeholders throughout the product lifecycle, from the initial concept to the end of the lifecycle [35]. CAD files are the key product data for PLM systems, so semantically rich CAD models are essential for system interoperability. However, for a longer product lifecycle, due to personnel management issues, it is difficult or even impossible for late-stage CAD engineers to infer the original design information from CAD models containing only geometric information [36]. Annotated 3D models are intended to convey interrelated messages with a long lifecycle [16].

The Model-Based Definition (MBD) is the key to PLM, whose central concept embodied is that a 3D product model is the most appropriate tool for documenting all the detailed information about the product during the product delivery cycle [37]. The MBD plugin typically provides CAD annotation functionality. Annotated 3D models can provide details for specific downstream operations such as manufacturing planning, production simulation, and material sourcing [6].

CAD annotations are divided formally into text documents and structured data. Structured data is typically annotated by the dimensioning module in CAD software, and text data is annotated by the annotation module [38]. 3D annotations allow design knowledge and fundamentals to be shared with other users directly through the 3D model in a manner similar to the way that software engineers and programmers annotate source code [39].

The lack of a standard set of rules to manage information content has led to inconsistent annotation practices, which has implications for using annotations in industrial environments. Huet et al. [40] proposed a Context-Aware Cognitive Design Assistant embedded in CAD software, which aims to structure design rules and contextual information into a computable knowledge graph and retrieve applicable design rules. Plumed et al. [34] built a speech annotation system integrating 3D models with design knowledge. However, speech-described design knowledge is difficult to retrieve in a standardized way, especially for companies that may keep many design plans, which can be confusing and lead to difficulties in achieving knowledge reuse. Qin et al. [41] proposed an ontology-based multi-mode retrieval approach for heterogeneous 3D part models using semantic web theory and information retrieval theory to facilitate engineers in the detailed design phase. Murat & Roy. [42] established a product information model that combines the product design process with 3D models to manage the product lifecycle from a functional-structure perspective. However, PLM focuses more on data relationships and information integration after generating the model and ignores the management and integration of the product conceptual design process. Camba et al. [38] implemented an annotation manager that can explicitly communicate geometric design intent to reduce the confusion of annotation views in 3D models. Company et al. [16] divided text annotations into four different functional types: objectives, requirements, rationale, and intent, and established a global view of the design structure with text annotations. Annotations are simple text elements in 3D space, and the user operates planar views to carry the annotations. Therefore, some annotations may become visually unavailable when the user changes viewpoint.

The context of design knowledge in the conceptual design phase can be defined as that requirements are the origin of design knowledge and that 3D models are the carriers of design knowledge. In the conceptual design phase, multiple design solutions are generated, but after evaluation and refinement, only one solution is put on the market, and the other abandoned solutions may not be realized due to technological constraints, high cost, and so on. However, as technology advances and the competitiveness of the products brought to market decreases, the original design solution can be reused to reduce design costs. The foundation for reusing a model is to understand its function, and the shape of an object alone is insufficient to understand its function.

Most studies based on CAD annotation focus on the detailed design stage, and no studies combine the product conceptual design process with CAD annotations. Hence, this paper focuses on non-geometric design knowledge annotation, the basis for model storage and retrieval, related to the product conceptual design process. Generally, annotations are attached to the global CAD model rather than sub-assemblies or parts (namely components). The current annotation method is modified to annotate the non-geometric design knowledge to the exploded view by calling the exploded view module in CAD software. At the same time, due to version issues, annotation semantics may be lost. In order to achieve efficient storage, retrieval, and reuse of design knowledge, the MKB system is established. Annotated CAD models are created to record the results of mapping from function to structure and are stored as design knowledge in the MKB system.

3 IMPLEMENTATION OF THE PROPOSED METHOD

The implementation of the proposed method focuses on two fundamental aspects: design knowledge representation and design knowledge storage, as shown in Fig.2. In practice, this process covers the following three steps.

Step 1: A wide range of user requirements are collected, from which practical requirements using natural language processing methods are extracted. Then, through the improved axiomatic design, conceptual design solutions are generated, and the mapping from structure to design knowledge is achieved.

Step 2: A functional model of the conceptual solution is developed by the function analysis (FA). Based on functional analysis, a functional model is established to partition the model components. In the CAD software, exploded views are created, and then the design knowledge gained from the improved axiom design process is annotated in the appropriate components of the CAD model.

Step 3: The MKB system is constructed and used to import and identify the annotated models, store components, and store the corresponding design knowledge.

3.1 Generation of Design Concepts

Product design quality depends heavily on effectively aggregating customer requirements (CRs) to determine functional requirements (FRs).CR is commonly used in the product design process to guide designers in determining the function and structure of a product [43-44]. Understanding customer requirements is critical to new product development and customer-centric product design [45]. Thus, the integration of requirements analysis and design methods is expected to improve the feasibility of conceptual design. Intelligent analysis tools are combined with traditional design methods, and design experience is combined with external knowledge, which are effective ways to reduce design costs and improve the design success rate.

3.1.1 Requirement acquisition and problem analysis

There are two steps to obtain CR: a customer needs survey and a definition of CR by analyzing customer reviews on shopping websites. Currently, most research focuses on analyzing customer reviews [46], but products in the early stage of the product lifecycle cannot find enough reviews on websites. Meanwhile, CRs obtained from reviews usually contain some unnecessary and unimportant information, which may affect their accuracy, and questionnaires are the most direct and accurate way to obtain CRs. The questionnaire method is used to conduct a comprehensive survey of customers.

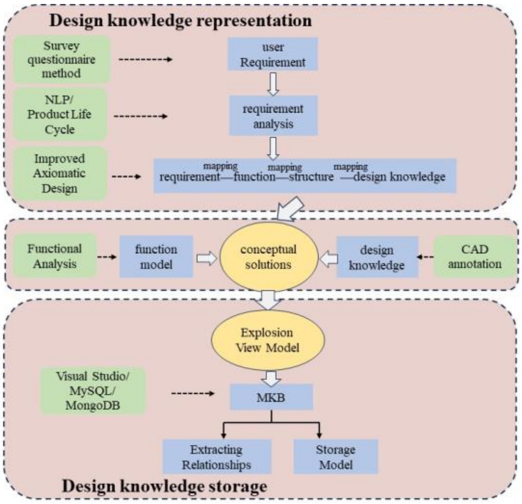

Figure 2: Framework of design knowledge representation and storage.

Existing CR definition methods include subjective and intelligent clustering methods. Analyzing data manually is very time-consuming. Intelligent customer requirement analysis using Python enables efficient extraction of key data to identify the leading CR. The code was established on GitHub at XuDuoDu/Requirement-survey-and-analysis (github.com).

Since the questionnaire export is saved in a .xlsx file, the raw text data needs to be processed in 4 steps into recognizable data to mine the hidden information in customer needs. Fig.3 shows the text analysis process.

Step 1: Sentences are segmented by line breaks, and each requirement in the questionnaire is listed. In Chinese, some words have no real meaning and must be deleted. Python-jieba package is used for Chinese word segmentation and removal of stop words.

Step 2: Text data is unstructured data that needs to be converted into digital information for computers to recognize and compute. A Python module (sklearn. feature_extraction.text) converts the processed text into TF-IDF feature vectors.

Step 3: K-means clustering is a typical clustering algorithm, and its simplicity and efficiency make it the most widely used of all clustering algorithms. The number of clusters k is determined by the elbow method, and the K-means algorithm iteratively divides the data into k clusters based on the distance function.

Step 4: The stage of the design product lifecycle is determined, and the corresponding requirements after clustering are extracted after clustering. Customer requirements vary at different stages of the product lifecycle. Fig.4 presents the specific requirements for each stage.

3.1.2 Improved Axiomatic Design

Axiomatic design is a mapping tool for different design domains. The process is represented by a matrix [29]. The first step in axiomatic design is to define the system's FRs. Functional requirements are decomposed into a set of sub-requirements, and FRs must satisfy the principle of minimum independent set. Mapping these FRs to the physical domain is conceiving a design implementation plan. For product improvement design, design parameters (DPs) generally refer to physical parameters. Nevertheless, for new product concept design, DPs are typically parts or components since there is no reference to the initial product. In mapping from FRs to DPs, an intermediate tool such as function-oriented search [47] retrieves the structure corresponding to the function. Usually, many options for structures satisfy the corresponding function, which are combined to travel multiple conceptual design solutions. Fig. 5 shows the mapping between different design domains in axiomatic design.

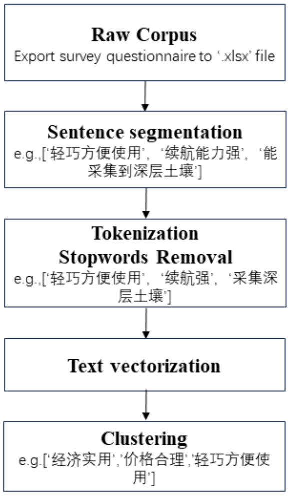

Figure 3: Flow diagram for processing original text of requirements.

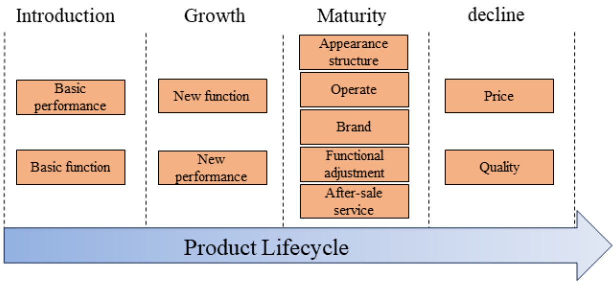

Figure 4: Demand distribution at each stage of the product lifecycle.

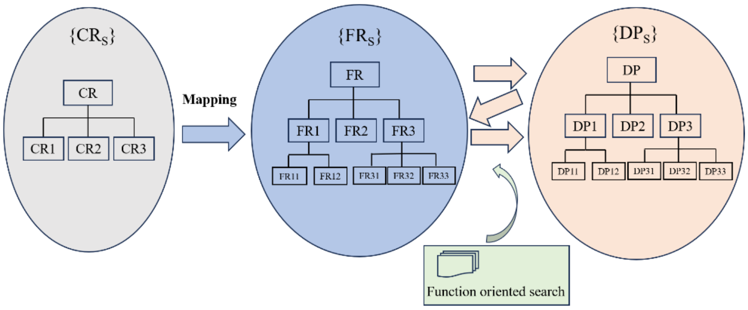

Figure 5: Three domains of the design world. {X} are characteristic vectors of each domain.

The mapping matrix relationship between FRs and DPs can be represented by the design equation shown in Eq. (1), where $[A]$ is called the design matrix.

$$\{FR\} = [A]\{DP\} \tag{1}$$

The independence axiom is mainly used to elucidate the relationship between FR and DP and to maintain the independence among the functional requirements to produce the minimum functional requirements that satisfy the design goal characteristics and the most straightforward design product structure. In the mapping process, the design should fulfill the independence axiom, i.e., the matrix $[A]$ in Eq. (1) must be a diagonal or triangular matrix as follows.

$$[A] = \begin{bmatrix} A_{11} & 0 & 0 \\ 0 & A_{22} & 0 \\ 0 & 0 & A_{33} \end{bmatrix} \tag{2}$$

$$[A] = \begin{bmatrix} A_{11} & 0 & 0 \\ A_{21} & A_{22} & 0 \\ A_{31} & A_{32} & A_{33} \end{bmatrix} \tag{3}$$

The information axiom states that among the design solutions that satisfy the independence axiom, the best solution is the one with the lowest information content. The information axiom is mainly used to evaluate and compare design solutions [48-49].

However, regarding the conceptual design of new products, the limitation of axiomatic design is that the final solution is only a combination of design schemes. In enterprises, simply designing solutions is often challenging to understand, and cannot effectively communicate and transfer knowledge among different designers. Therefore, it is necessary to introduce design knowledge domains into axiomatic design to improve its comprehensibility and reusability.

The design knowledge (DKs) domain is introduced in axiomatic design, which only has a mapping matrix relationship with the final mapping structure of the physical domain (i.e., parts or components). It can be represented by the design equation shown in Eq. (4), where $[B]$ is called the design matrix. DK represents professional knowledge, design decisions, necessary dimensions, and working principles of parts or components.

$$\{DP\} = [B]\{DK\} \tag{4}$$

The matrix $[B]$ is a non- square matrix, i.e., m ≠ n. The elements of the design matrix $[B]$ shown in Eq. (5) are represented by "1" and "0": "1" means that DPs and DKs are related, and "0" means that DPs and DKs are related.

$$[B] = \begin{bmatrix} B_{11} & B_{12} & \cdots & B_{1n} \\ B_{21} & B_{22} & \cdots & B_{2n} \\ B_{31} & B_{32} & \cdots & B_{3n} \\ \cdots & \cdots & \cdots & \cdots \\ B_{m1} & B_{m2} & \cdots & B_{m3} \end{bmatrix} \tag{5}$$

In the stage of axiomatic design, designers generate rich design knowledge, which is difficult to store in a practical form. However, the design scheme generated at this stage can be visually represented in the CAD model, introducing design knowledge into the CAD model as annotations. A 3D model introduced with DKs not only increases the comprehensibility of the design scheme but also improves the reusability of DKs through effective storage.

3.1.3 Establishing a functional model for a conceptual solution

Anatomy of the product is a key step in aligning design knowledge with specific components [19]. In the previous stage, the customer requirements have been translated into a product design solution. The product is analyzed based on its function, components, and their relationship. From the global perspective, function analysis is building a functional model of a technical system. The various components of the technical system, subsystems, and related supersystems are identified, and the interrelationships among the components are described [50-51]. The basic process and an example of it (cycling) are shown in Fig.6.

Step 1: A component list is created to describe the system composition and the hierarchy of components. The supersystem, which interacts with the technological system, is the necessary external environment for the technological system to realize its function.

Step 2: Component analysis is to describe the interactions between components.

Step 3: Functional modeling, using the functional specifications, reveals the interactions among all the components of the technical system, subsystems, and supersystems and how the system's functions are realized.

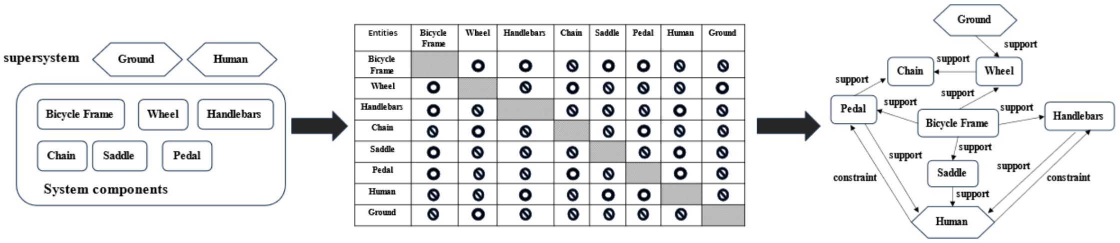

Figure 6: The function analysis process of cycling.

3.2 CAD Annotation

An effective way to supplement design knowledge is to introduce annotations into 3D models. However, the annotation interface is chaotic due to rich content or view changes. In addition, in a fixed view, some occluded structures in the 3D model are often invisible and, accordingly, cannot be annotated. Motivated by annotated issues, CAD software (SolidWorks) exploded view module is used.

Exploded view is a commonly used form of assembly representation in engineering design, which disassembles 3D models to facilitate the exchange of design knowledge between designers and clients or designers. The relationship between product functions and parts is often not one-to-one correspondence. Using the exploded view module of the CAD software (SolidWorks), the designer can customize the annotated structure (subassembly or parts) based on their function analysis. The design knowledge gained from product disassembly is stored in the MKB system.

4 EXPERIMENTAL STUDY

Soil sample collection and analysis of its physical and chemical properties are widely used in scientific research in environmental science, geography, ecology, agronomy, and other fields, as well as in industrial and agricultural production practice. Currently, the sampling method is based on the manual collection of soil samples, which is labor-intensive and inefficient. A tractor-based soil sampling device has been developed.

4.1 Requirement Analysis of Automatic Soil Sampling Device

Requirements are the essential force that drives the evolution of an engineering system toward idealization. A questionnaire was used to obtain extensive requirements, collecting 83 suggestions, which were exported to a .xlsx file. The methodology given in Fig. 3 was applied for requirement text analysis. Using Python, the required text was preprocessed, and the text was clustered using the K-Means algorithm. An open repository was established on GitHub at XuDuoDu/Requirement-survey-and-analysis (github.com). It contains the .xlsx files exported from the survey questionnaire, the text processing code, and the analysis results.

Code	*Description*
CR1	work credibility
CR2	store soil samples
CR3	adjust sampling depth
CR4	automation
CR5	install simply
CR6	collect soil samples
CR 7	power provided by the tractor
CR 8	efficiently collect
CR 9	don’t damage the surrounding soil layer in the collection process
CR 10	replace simply soil sampling components

Table 1: CRs of tractor-based automatic soil sampling device.

Table 1 lists the 10 most popular requirements after clustering. Combined with the market survey, the tractor-based automated soil sampling device was in the infant stage of the product lifecycle, and its main functional requirements were identified as FR1 Automated soil sampling, FR2 Store soil samples, FR3 Adjust sample depth, and FR4 Power provided by the tractor.

4.2 Conceptual Design Solution and CAD Annotation

The actuator can achieve FR1(Automated soil samples) and FR2(Stored soil samples). The control system operates FR3(Adjust sample depth), and the tractor power system provides power. In this case, the actuator was used as an example, and the focus was on the design solution that would enable the collection and preservation of soil samples. The axiomatic design approach presented in Fig. 5 was used to design the tractor-based automated soil sampling device. In the first step, an axiomatic design was applied, and the results of the requirements analysis were formed. A hierarchy of major functional requirements was formed, and a high-level mapping between the functional requirements and the design parameters was established. According to the independence axiom, a set of functional requirements was mapped to the corresponding design parameters at the same design level. Function-oriented search retrieves the structure through the behavior to present design knowledge beyond the memory of the designer's expertise. Each FR can be searched through a function-oriented search to obtain the DP. The significant functions were decomposed into functional elements. The mapping was repeated in a "Z" approach until all the functional requirements were satisfied, as shown in Figure 7.

As shown in Fig.8 and Fig.9, the two conceptual design solutions of the tractor-based automatic soil sampling device were generated. This paper details the implementation process of the improved AD theory-based scheme design with the design of an automatic soil sampling device. Appendix 1 and Appendix 2 show the mapping of the DP and DK for the two designs of automatic soil sampling devices. Function analysis of the two conceptual design solutions was constructed (Fig.10 and Fig.11). Based on the functional model and design knowledge, exploded views with the annotations for the two conceptual solutions were generated, as shown in Figures 12 and 13.

4.3 MKB System Construction

Design knowledge must be available for the entire product lifecycle, and designers are often reluctant to accept archiving and annotating the design knowledge with another tool. However, for long-term preservation, storing the model in one or more separate annotation files rather than embedding them directly into the original geometric model would be a better solution [52]. Therefore, applications are needed to capture and archive design knowledge from designers operating CAD software.

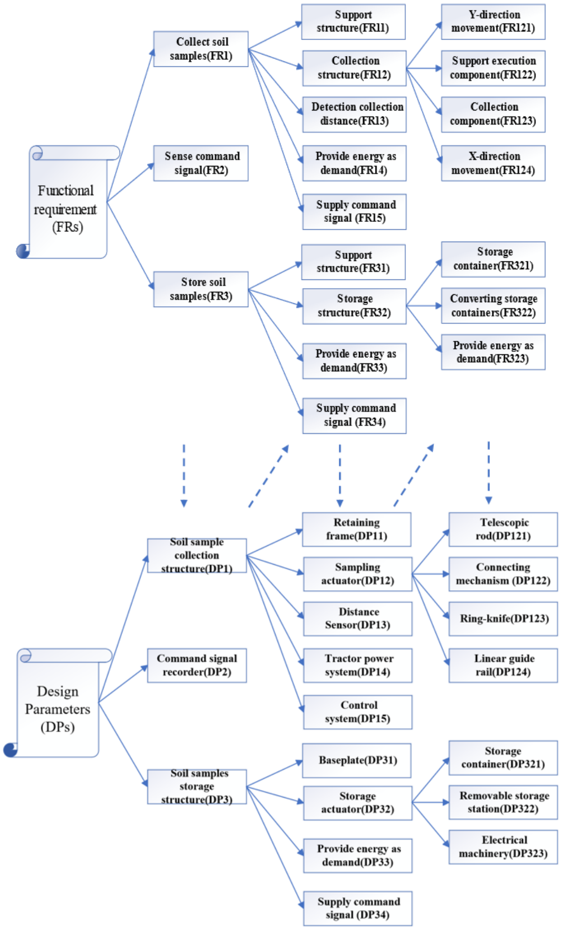

Figure 7: Domain mapping based on the axiomatic design of the tractor-based automatic soil sampling device.

Figure 8: Conceptual Design-1 of the tractor-based automatic soil sampling device.

Figure 9: Conceptual Design-2 of the tractor-based automatic soil sampling device.

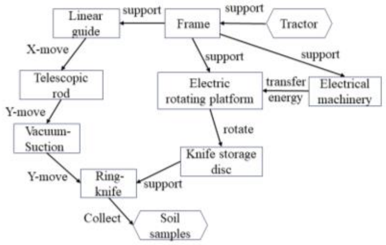

Figure 10: Function analysis of conceptual Design-1.

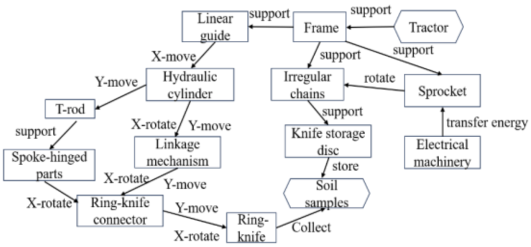

Figure 11: Function analysis of conceptual Design-2.

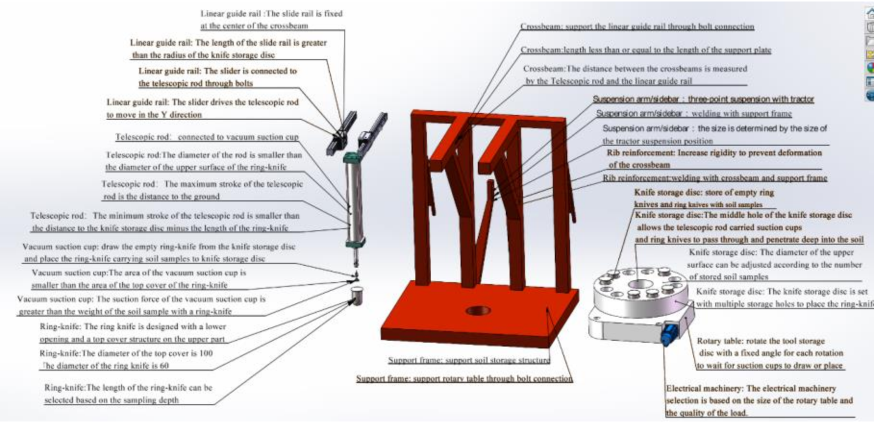

Figure 12: Exploded view with the annotations of conceptual Design-1.

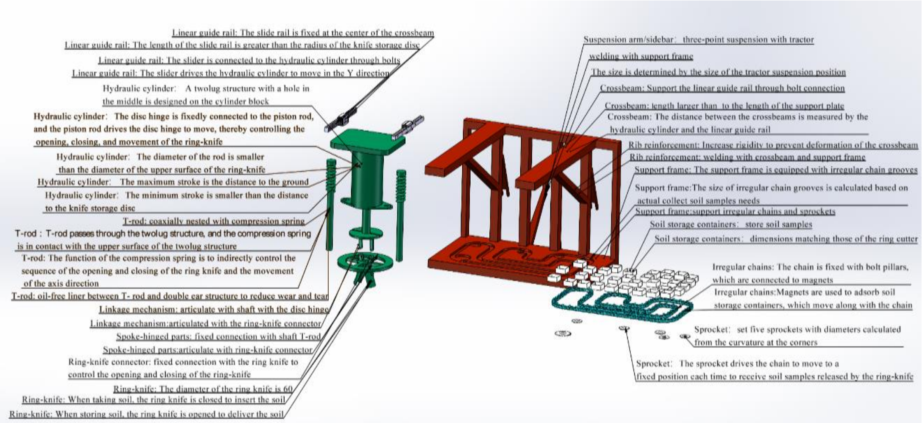

Figure 13: Exploded view with the annotations of conceptual Design-2.

To intelligently analyze and store design data, a Model Knowledge Base (MKB) tool was developed using Visual Studio, MySQL, and MongoDB, with the interface shown in Fig.14. The MKB client, as a standalone program, calls the SolidWorks API to read models and annotations, and also can use a third-party open-source interface NPOI to parse. xlsx files.

Firstly, the user creates a new design project in the “Concept Design Data Entry” module. Under this project, the “Analyze Model” tab can parse the design requirement .xlsx file, which then saves in the submodule 'Design Requirement,' and insert the AD mapping process image in the “DR-CP” submodule. The next step is to create a new design scheme under the “DK annotations” submodule. The next step is to create a new design scheme under the “DK annotations” submodule. Then, the “Start or connect SolidWorks” tab automatically captures the annotations of the design scheme model and stores the components. The annotated components are stored in the MongoDB database, and the interrelationships are stored in the MySQL relational database. Next, users can insert the function analysis diagram under the “Component relationships” submodule and reviewers’ improvement suggestions under the "Modification suggestions" submodule.

As products go through iterations, there is a high risk that the designer turnover will result in a loss of context for the product. When a new designer joins the project, he/she knows little about the pre-production phase of the project and will have to consult various unstructured sources or communicate orally to get the information he/she needs. However, the design knowledge communicated orally may have been missing for a long time. Compared to traditional design knowledge recording and communication, MKB can save design knowledge and record the design process in the same software. For knowledge reuse, storing design knowledge originally recorded in different software in a knowledge base is advantageous. The concept design module of MKB has been tested in the company's R&D department, and several designers have discussed the system. Designers generally believe this system has a positive outlook and provides an effective platform for capturing and storing enterprise knowledge. The designers further suggest the possibility of classifying annotations referencing the same component, which then can be folded or expanded; functionality to link corresponding components in the “Component relationships” submodule to their 3D model and annotations in the “DK annotations” submodule.

4.4 Discussion

To validate the proposed MKB system, we conducted a one-hour training and practice seminar for 20 designers and researchers. All participants already have a solid foundation in using SolidWorks or other CAD software packages. Each designer is required to annotate their 3D model during the practical phase, use MKB to parse and store it in the software, and then add review comments to the models and design knowledge uploaded by other participants in the software.

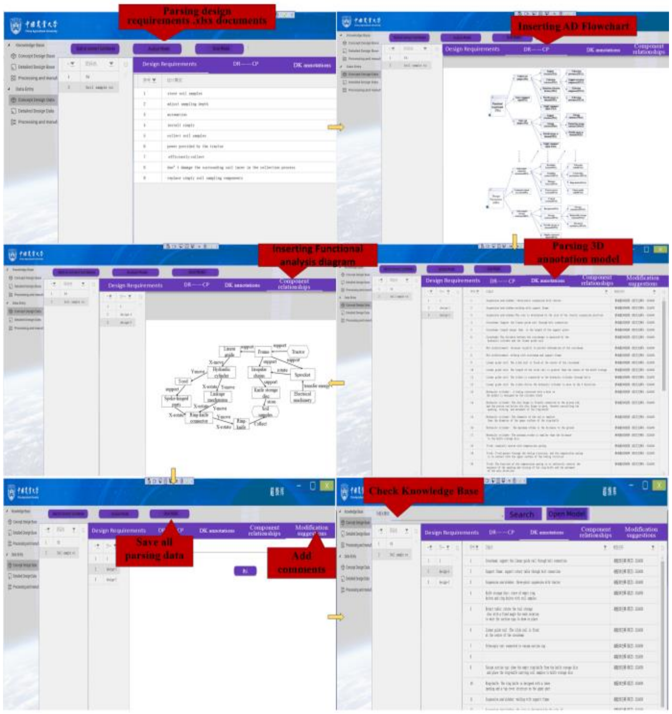

Figure 14: Introduction to MKB System Interface.

Twenty designers received a survey questionnaire within a week of training. The survey questionnaire was designed based on Kirkpatrick's evaluation method [53], which is divided into four levels: (1) Response: evaluating the satisfaction level of the trainees; (2) Learning: measuring the learning acquisition degree of the trainees; (3) Behavior: examining the knowledge application level of the trainees; and (4) Result: calculating the economic benefits of the training output.

Fifteen questionnaires were actually received, with three designers exceeding the survey time limit. Two team managers gave feedback face-to-face, believing MKB can effectively manage designers' design intentions. As managers, they have really felt the frequent turnover of personnel, especially in recent years, which has further hindered subsequent projects. They believe that MKB integrates design knowledge generated by different divisions of labor in the project and strengthens the collaborative design. Besides, a manager suggested adding more interactive features to the software, such as assigning tasks, checking task progress, etc.

According to the results of the survey questionnaire, the evaluation of four levels of the Kirkpatrick Model is described here:

Response: Only 1 out of 15 designers expressed reluctance to use MKB, believing that the software would increase their workload. He also pointed out that the lack of specialized usage specifications, e.g., component names, makes it difficult to reuse knowledge in the future.

Learning: All designers believed that the MKB interface classification was clear and after one hour of training and practicing, they had become proficient in operating the MKB system.

Behavior: Many designers believe MKB will be convenient for their future work. One of the engineers who made design improvements expressed great willingness to use this software because he found a 2014 design plan as a reference, but he did not know why the designers at that time made such a design plan.

Result: The designers generally believe that MKB can enable new personnel to quickly understand the product, achieve technical inheritance and iteration, and accelerate project development progress. Simultaneously, data sharing is beneficial for collaborative design and improves the efficiency of team collaboration.

5 CONCLUSIONS AND FURTHER WORKS

The main task of knowledge management in manufacturing enterprises is to explore the available design knowledge, represent and store the knowledge, achieve knowledge sharing and full utilization, and ultimately achieve the purpose of adding value to the enterprise [52]. Out of several conceptual designs, only one will ever get commercialized, and the remaining designs are often discarded. However, discarded design solutions also contain the designer's design knowledge, so it is necessary to represent and store it.

Our proposed method for representing and storing intelligent design knowledge consists of two phases: "conceptual design" and "CAD annotation". The methodology was validated with the design of the tractor-based automatic soil sampling device. In this case, improved AD is proposed to achieve the FR-DP-DK mapping process. A 3D model of the conceptual design scheme and DK annotations were built in CAD software as the primary form of design knowledge storage. The Model Knowledge Base (MKB) tool was developed to intelligently capture and store the annotated components in the 3D model. The approach enables design knowledge storage and transformation by integrating product conceptual design with CAD annotations, and capturing design decisions, which ultimately makes knowledge readable, understandable, and reusable.

The future work will focus on the following two aspects: (1) 3D models contain rich data, such as material information, styles, annotations, manufacturing process data and cost data, and other design document features. The development of the detailed design module in MKB can automatically recognize this information as the stored content of the enterprise's knowledge base, which provides a reference for subsequent improvement. And 3D drawings with annotations make it easier to protect corporate intellectual property (patent applications). At the same time, the development of the knowledge base establishes a design environment with knowledge support functions for designers, making it easy for designers to use effective design methods to achieve a higher level of design. (2) Currently, MKB applications heavily rely on servers, such as downloading/uploading files and long-term archiving, thus consuming a large amount of server internal memory. To address this issue, CAD models are stored in a lightweight format, or the repository is transferred to a cloud drive. Using cloud storage services allows all users exercising MKB applications to freely download the required models, thereby facilitating the improvement of model reusability and design efficiency.

Appendix 1: The mapping of the DP and DK for the first design of automatic soil sampling device

DP		DK
DP11 Retaining Frame DP31 Baseplate	DP111 Suspension arm DP112 Sidebar	DK111 -1 three-point suspension with tractor
		DK111-2 welding with support frame
		DK111-3 The size is determined by the size of the tractor suspension position
	DP113 Crossbeam	DK113 -1 supports the linear guide rail through bolt connection
		DK113 -2 length less than or equal to the length of the support plate
		DK113 -3 The distance between the crossbeams is measured by the telescopic rod and the linear guide rail.
	DP114 Rib reinforcement	DK114 -1 increases rigidity to prevent deformation of the crossbeam
		DK114 -2 welding with crossbeam and support frame
	DP115 Support frame	DK115 -1 support rotary table through bolt connection
		DK115 -2 support soil storage structure
		DK1211-1 connected to vacuum suction cup

DP121 Telescopic rod	DP1211 Telescopic rod	DK1211-2 The diameter of the rod is smaller than the diameter of the upper surface of the ring-knife
		DK1211-3 The maximum stroke of the telescopic rod is the distance to the ground
		DK1211-4 The minimum stroke of the telescopic rod is smaller than the distance to the knife storage disc minus the length of the ring-knife
DP122 Connecting mechanism	DP1221 Vacuum suction cup	DK1221-1 draw the empty ring knife from the knife storage disc and place the ring knife carrying soil samples to the knife storage disc
		DK1221-2 The area of the vacuum suction cup is smaller than the area of the top cover of the ring-knife
		DK1221-3 The suction force of the vacuum suction cup is greater than the weight of the soil sample with a ring knife
DP123 Ring-knife	DP1231 Ring-knife	DK1231-1 The ring knife is designed with a lower opening and a top cover structure on the upper part
		DK1231-2 The diameter of the top cover is 100. The diameter of the ring knife is 60
		DK1231-3 The length of the ring knife can be selected based on the sampling depth
DP124 Linear guide rail	DP1241 Linear guide rail	DK1241-1 The slide rail is fixed at the center of the crossbeam
		DK1241-2 The length of the slide rail is greater than the radius of the knife storage disc
		DK1241-3 The slider is connected to the telescopic rod through bolts
		DK1241-4 The slider drives the telescopic rod to move in the Y direction
DP321 Storage container	DP3211 Knife storage disc	DK3211-1 store of empty ring knives and ring knives with soil samples
		DK3211-2 The middle hole of the knife storage disc allows the telescopic rod carrying suction cups and ring knives to pass through and penetrate deep into the soil
		DK3211-3 The diameter of the upper surface can be adjusted according to the number of stored soil samples
		DK3211-4 The knife storage disc is set with multiple storage holes to place the ring-knife
DP322 Removable storage station	DP3221 Rotary table	DK3221-1 rotate the tool storage disc with a fixed angle for each rotation to wait for suction cups to draw or place
DP323 Electrical machinery	DP3231 Electrical machinery	DK3231-1 The electrical machinery selection is based on the size of the rotary table and the quality of the load

Appendix 2: The mapping of the DP and DK for the second design of the automatic soil sampling device

DP		DK
DP11 Retaining Frame DP31 Baseplate	DP111 Suspension arm DP112 Sidebar	DK111 -1 three-point suspension with tractor
		DK111-2 welding with support frame
		DK111-3 The size is determined by the size of the tractor suspension position
	DP113 Crossbeam	DK113 -1 supports the linear guide rail through bolt connection
		DK113 -2 length larger than the length of the support plate
		DK113 -3 The distance between the crossbeams is measured by the telescopic rod and the linear guide rail.
	DP114 Rib reinforcement	DK114 -1 increases rigidity to prevent deformation of the crossbeam
		DK114 -2 welding with crossbeam and support frame
	DP115 Support frame	DK115 -1 The support frame is equipped with irregular chain grooves
		DK115 -2 The size of irregular chain grooves is calculated based on actual collected soil sample needs
		DK115 -3 support irregular chains and sprockets
DP121 Telescopic rod	DP1211 Hydraulic cylinder	DK1211-1 A two lug structure with a hole in the middle is designed on the cylinder block
		DK1211-2 The disc hinge is fixedly connected to the piston rod, and the piston rod drives the disc hinge to move, thereby controlling the opening, closing, and movement of the ring knife
		DK1211-3 The diameter of the rod is smaller than the diameter of the upper surface of the ring-knife
		DK1211-4 The maximum stroke of the telescopic rod is the distance to the ground
		DK1211-5 The minimum stroke of the telescopic rod is smaller than the distance to the knife storage disc
DP122 Connecting mechanism	DP1221 T-rod	DK1221-1 coaxially nested with compression spring
		DK1221-2 T-rod passes through the two lug structures, and the compression spring is in contact with the upper surface of the two lug structure

		DK1221-3 The function of the compression spring is to indirectly control the sequence of the opening and closing of the ring knife and the movement of the axis direction
		DK1221-4 oil-free liner between T- rod and double ear structure to reduce wear and tear
	DP1222 Linkage mechanism	DK1222-1 articulate with shaft with the disc hinge
		DK1222-2 articulated with the ring-knife connector
	DP1223 Spoke-hinged parts	DK1223-1 fixed connection with shaft T-rod
		DK1223-2 articulate with ring-knife connector
	DP1224 Ring-knife connector	DK1224-1 fixed connection with the ring knife to control the opening and closing of the ring knife
DP123 Ring-knife	DP1231 Ring-knife	DK1231-1 The diameter of the ring knife is 60
		DK1231-2 When taking soil, the ring knife is closed to insert the soil
		DK1231-3 When storing soil, the ring knife is opened to deliver the soil
DP124 Linear guide rail	DP1241 Linear guide rail	DK1241-1 The slide rail is fixed at the center of the crossbeam
		DK1241-2 The length of the slide rail is greater than the radius of the knife storage disc
		DK1241-3 The slider is connected to the hydraulic cylinder through bolts
		DK1241-4 The slider drives the hydraulic cylinder to move in the Y direction
DP321 Storage container	DP3211 Soil storage containers	DK3211-1 store soil samples
		DK3211-2 dimensions match those of the ring cutter
DP322 Removable storage station	DP3221 Irregular chains	DK3221-1 The chain is fixed with bolt pillars, which are connected to magnets
		DK3221-2 Magnets are used to adsorb soil storage containers, which move along with the chain
	DP3222 Sprocket	DK3222-1 The sprocket drives the chain to move to a fixed position each time to receive soil samples released by the ring-knife
		DK3222-2 set five sprockets with diameters calculated from the curvature at the corners
DP323 Electrical machinery	DP3231 Electrical machinery	DK3231-1 The electrical machinery selection is based on the size of the sprocket and the quality of the load

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