Design Reuse Method of Corn Picking Device Based on Case-Based Reasoning

Rongjian Tai,[a] Bin Li,[a] Zhimin Sun,[b] Qingjiang Li,[b] Rongqing Liang,[a,]* and Bo Zhong,[b,]*

In order to shorten the design cycle of corn snapping mechanism, a case reuse design method of snapping devices based on user requirements was proposed. A matter-element model is used to build a case matter-element database and parametric model library together to form a case database; the case attributes are divided, the retrieval scope is narrowed through the matching of core parameters, and the similarity of matching parameters and performance evaluation parameters is calculated by using analytic hierarchy process and deviation maximization method to realize the retrieval of similar cases. The transformation relationship between the design requirements and the main driving parameters of the parametric model is established by using the rule association method to realize the case's modification. The engineering discrete element method is used to simulate the reuse case, and an improved method is proposed according to the simulation results. The improved device is verified by simulation and field experiments. The results show that the operating performance of the improved snapping device is improved, and the feasibility and effectiveness of the design reuse method are verified, which can provide technical reference for the intelligent design of agricultural machinery and equipment.

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Contact information: a: College of Energy and Machinery, Dezhou University, Dezhou, 253023, China; b: Shandong Academy of Agricultural Machinery Sciences, Jinan, Shandong Province 250100, China;
** Corresponding author: jjtai_sdau@163.com*

INTRODUCTION

Agricultural machinery and equipment is an indispensable tool to improve the technical level and production efficiency of agricultural production, realize the effective utilization of resources, improve the conditions of agricultural production and operation, and promote the sustainable development of agriculture. It plays a very important role in ensuring the safety of national grain production, promoting agricultural production and efficiency, changing the way of increasing farmers' income, and promoting rural development.

At present, various countries in the world are trying to change the design status of agricultural machinery and equipment. Digital design, reliability design, and other methods are being applied to the research and development of agricultural machinery and equipment. In recent years, with the increasing support of agricultural machinery and agricultural mechanization technology innovation, some progress has been made in the design of agricultural machinery and equipment.

Preliminary breakthroughs have been made in the digital design, reliability and test monitoring of agricultural machinery and equipment, such as parallel collaborative digital design, virtual design, and virtual prototype simulation environment construction, which has improved the digital design and manufacturing level of agricultural machinery and equipment manufacturing industry. However, the systematic research on the digitization, intelligence and modularization of agricultural machinery equipment and the reuse of agricultural equipment design knowledge are still unavailable, which restricts the improvement of the design and manufacturing level of agricultural machinery equipment in the world and the improvement of product R & D ability and speed.

The world's rural cultivated land is quite different, and the demand for agricultural machinery in different regions is different. In the face of people's increasingly personalized and diversified demand for agricultural machinery products, accelerating the overall process speed of products, improving the efficiency of product design, shortening the product development cycle, and meeting the rapidly changing market demand are the necessary ways to improve the competitiveness of agricultural equipment production enterprises in various countries. In the research and development of mechanical equipment, the design and development of new products are mostly based on the existing design knowledge and achievements, and the innovative design is often concentrated on one or several key components. According to statistics, more than 90 % of the product design process is adaptive design and variant design (Liu *et al.* 2019). By modifying the existing design to meet the current new design requirements, even if the new design can also learn from the existing products to start work. It can be seen that applying the existing design knowledge and design results to the product design and development process can avoid a lot of repetitive design, shorten the product design cycle, and improve the ability of enterprises to cope with the rapidly changing market demand. However, in the traditional agricultural equipment research and development process, in order to meet the design requirements of the whole machine, in addition to the innovative research and development of key components, designers also need to repeatedly consult the standard manual, draw the rest of the standard parts and general parts, and need a lot of repetitive work, which increases the workload of designers, leads to a long product development cycle, and reduces the market competitiveness of enterprises. Therefore, it is of great significance to apply the existing product design knowledge to the design process of new products to meet the new design requirements (Zhou 2013; Wang *et al.* 2017).

As one of the essential methods of design reuse, case-based reasoning (CBR) can effectively retrieve design cases that are consistent or similar to the design requirements of new models in the product case database. This method has been widely used in various fields of product design. Scholars at throughout the world have conducted in-depth and extensive research on case-based reasoning methods in the field of product design and have achieved certain results (Jiang *et al.* 2009; Li *et al.* 2009; Yang *et al.* 2009; Pahl *et al.* 2010; Chen *et al.* 2011; Chen *et al.* 2013; Wang *et al.* 2017; Wen *et al.* 2017; Zhao *et al.* 2017). Song *et al.* (2013) realized the rapid design of tracked harvesting machinery transmission system using the hybrid reasoning method based on case-based and rule-based reasoning. Xu *et al.* (2014) studied the intelligent design method of machine tool guide rail by case-based reasoning. Based on VB.NET intelligent design platform and SolidWorks 3D software, Zhang *et al.* (2008) realized the intelligent design of bridge crane by reusing the previous mechanical product design scheme. To avoid the complexity of case attribute description, Zheng *et al.* (2009) realized the modular rapid design of mechanical products by combining the case reasoning method on the basis of module division of mechanical products. Claudiu *et al.* (2010) used the decision support method of case-based reasoning to realize the rapid design of the countercurrent reactor model. Cabanillas *et al.* (2013) developed an injection mold design decision system based on computational argumentation and case-based reasoning. Chu and Hsu (2006) proposed a shape feature compensation search method in the similarity evaluation of three-dimensional mechanical parts, which solved the problem of feature crossover inherited by the feature-based method and applied this method to the design reuse of mechanical parts. Leake and Wilson (2001) integrated the case-based design support framework with interactive tools and used the case-based reasoning method to retrieve cases to realize the design reuse of aerospace products. Vong *et al.* (2002) applied the case-based reasoning method to the design of hydraulic circuits and solved the problems in the design of mechanical hydraulic circuits by reusing existing design experience.

Currently, case-based reasoning needs a unified knowledge expression form combining qualitative and quantitative. After completing similar case retrieval, there is also a need for more effective case evaluation and modification methods, which limits the accuracy and optimization of new product development. The research on knowledge-based intelligent design methods in the field of machinery is concentrated in the fields of automobiles, aircrafts and ships, while the research on the design of agricultural machinery products is in its infancy. At the same time, current agricultural machinery is based on tracking and imitation. Traditional design methods have problems such as long development cycles, low efficiency, poor knowledge inheritance and reuse. Although the current agricultural machinery enterprises have established different degrees of digital design platforms and accumulated a certain amount of design resources and knowledge. Because of the lack of a systematic and structured knowledge utilization system, they cannot achieve effective integration of design and knowledge, bringing the difficulties in meeting the agricultural machinery customization, and diversifying design requirements. Therefore, it is urgent to study the intelligent design method based on user needs, the combination of crop agronomic conditions and machine technical requirements to improve the design efficiency and operation quality of agricultural machinery products.

As the core component of the harvester, the performance of the corn ear picking device directly affects the performance of the harvester (Chen 2014; Zhang 2014; Alarcón *et al.* 2010; Herman *et al.* 2011; Zhang *et al.* 2019). The design process contains a wide range of knowledge and complex knowledge in the field, and the design and development of most agricultural equipment have been using traditional experience or experimental design methods, which directly leads to low design efficiency and long development cycle. However, the domestic corn planting agronomy, landform, and climate are more complicated than in foreign countries. Direct tracking and imitation or experimental improvement of advanced models make it difficult for the harvester to adapt to changes in corn traits and agronomy, resulting in harvest losses.

This paper takes the corn snapping device as the research object, uses the matter-element to express the design knowledge of the corn snapping device qualitatively and quantitatively, constructs the design reuse case library of the corn snapping device, studies the case retrieval and evaluation method, and explores the case modification method based on rule association. By combining case-based reasoning with matter-element, the reuse of design knowledge of snapping devices is realized, and the design efficiency and quality of corn harvester are improved, which provides a method reference for the intelligent design of other types of agricultural equipment.

EXPERIMENTAL

Design Reuse Process and Reuse Method Framework of Snapping Device

Design reuse process

In the design process of the snapping device, a large number of design standards, design experience, experimental data, and design cases are needed. In the design process, the existing design knowledge is expressed in an appropriate form, and then stored in the knowledge database. The case model is stored in the model database according to certain rules.

Through the retrieval of the existing case knowledge in the knowledge database, the existing cases similar to the design requirements are obtained. According to the corresponding relationship between the knowledge database and the model database, the case model is called, simulated, and analyzed, and the design is improved according to the analysis results, so as to meet the new design requirements, realize the effective use of design knowledge, and avoid a lot of repetitive design work. In order to realize the design of snapping device based on the case-based reasoning method, the case-based reasoning design process shown in Fig 1 is established, including case database, case retrieval, case call and modification, evaluation analysis, and modification.

(1) Case database. The existing product design knowledge is expressed as matter-element and converted into the instance in the case database. The instance in the case database is retrieved, called, and modified to meet the new design requirements.

(2) Case retrieval. In case of retrieval, designers need to input retrieval parameters and thresholds according to design requirements. The thresholds specify the similarity between the acquired component cases and the user design requirements. The designer uses the analytic hierarchy process to determine the subjective weight of each retrieval parameter. The similarity matrix is obtained through the matching calculation of each case parameter in the matter-element database.

Through the similarity in the similarity matrix, the objective weight of each retrieval parameter is calculated based on the deviation maximization multi-attribute weighting method. Combined with the subjective and objective weights, the multiplicative synthesis method is used to determine the combined weight of the retrieval parameters, and the weighted similarity of each case in the similarity matrix is calculated. Design cases that do not meet the threshold requirements are abandoned, and the recommended cases are placed in descending order of weighted similarity. If there is no design case to meet the threshold requirements, it is possible to modify the retrieval parameters, threshold re-retrieval or new design, until a design case has been put together than meets the user needs.

(3) Evaluation analysis and modification. Model, analyze, and simulate the retrieved case or the modified instance to test and evaluate whether it can meet the performance requirements under the current operation object and determine whether further improvement design can be made. If improvements are made, then they are designed in detail by the designer to obtain the final design. If there is no need to improve the design, then it is directly used as the final design scheme to complete the case-based design process.

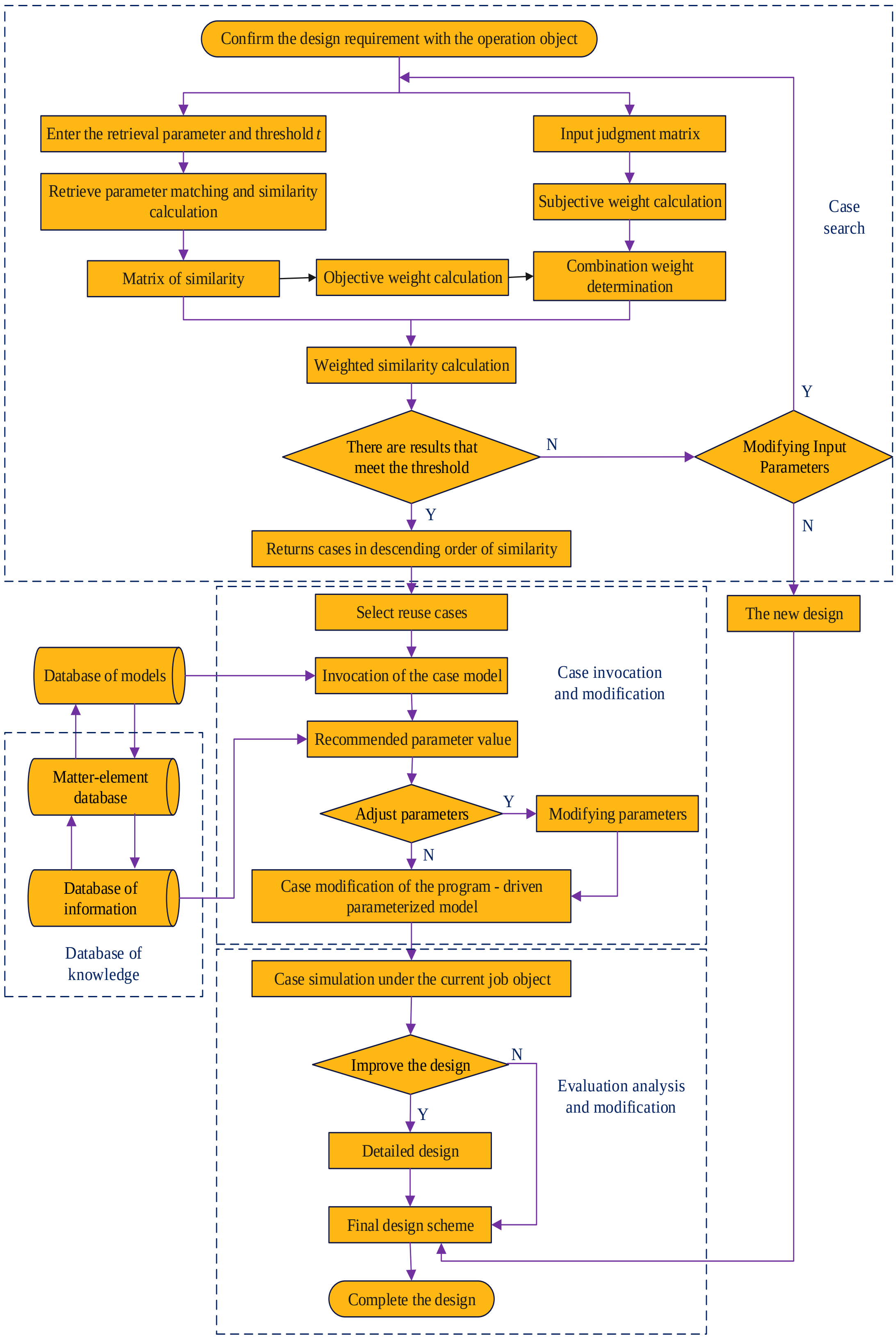


Fig. 1. Case-based reasoning design process of snapping device based on user requirements

Design method framework of snapping device based on case-based reasoning

Through the analysis of the design process characteristics and current design patterns of the snapping device, the framework of the case-based reasoning design method of the snapping device is established, as shown in Fig. 2, which provides a clear construction idea for the establishment of the case design system of the snapping device. The design framework is divided into four levels: user management layer, interactive interface layer, function layer, and data resource layer.

User management.

User management includes snapping device designers and system administrators. A large number of knowledge, experience, and model resources are involved in the design process of the snapping device. The design knowledge and case model are collected, sorted and classified by the designers and system administrators. The sorted design knowledge and model are stored in the knowledge database and model database according to certain rules, which can be called, modified, stored and maintained during design.

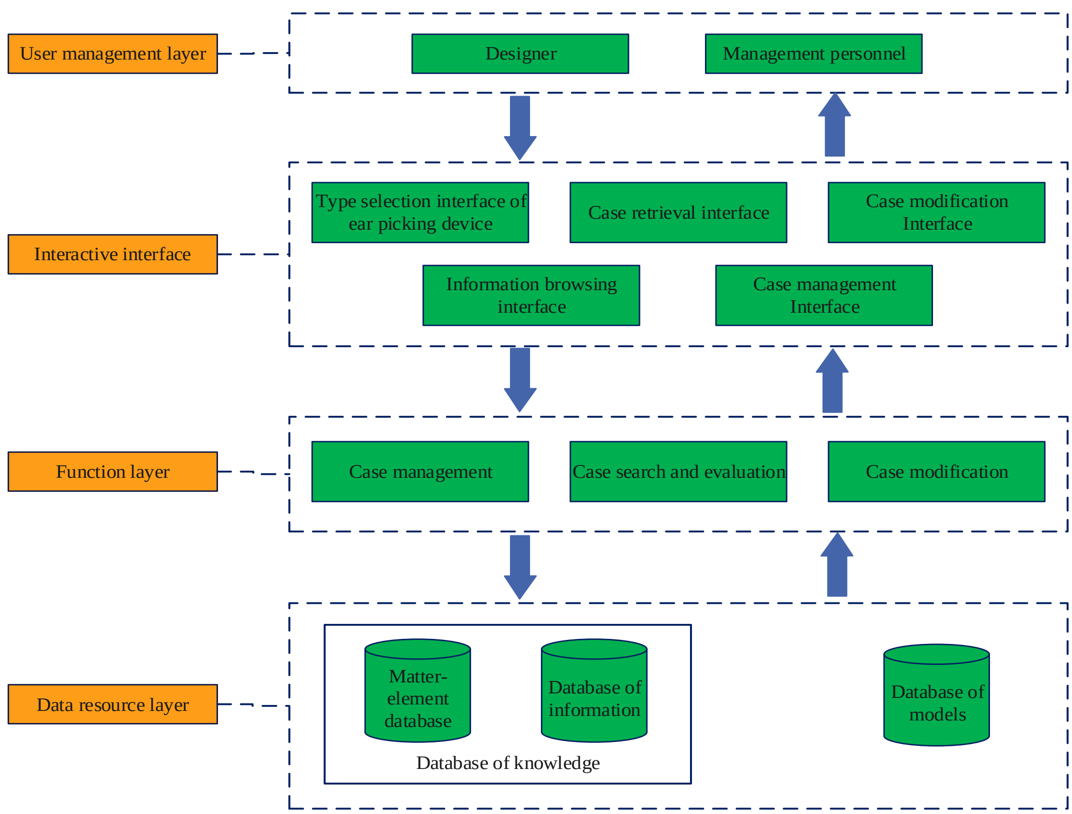


Fig. 2. Case-based reasoning design process of snapping device based on user requirements

Interactive interface layer

According to the expected function of the case-based reasoning design system of snapping devices, the man-machine interface of the system is designed. It mainly includes picking device type selection interface, case retrieval interface, case modification interface, information browsing interface and case management interface. The human-computer interaction interface can realize the selection of the type of ear picking device, the retrieval and evaluation of cases in the matter-element database, the call and modification of the model and other functions. Among them, the information browsing interface is used to learn the working principle and characteristics of the ear picking device, the interaction mechanism between the ear picking device and the crop, and provide a reference for designers to modify the design case. The knowledge management interface is mainly used to manage and maintain system data resources.

Functional layer

The function layer is the solution to the specific technical problems needed to realize the design system of snapping devices based on case-based reasoning. According to the functional requirements of the design system, the relevant programs are written in the corresponding interactive interface and development environment to realize the retrieval, call and modification of the design knowledge and case model in the data resource layer, which is the specific technical means to realize the case-based reasoning design system.

Data resource layer

The data resource layer is composed of knowledge database and model database. Knowledge database includes matter-element database and information database, which provides knowledge support for case design system of snapping device. The data resource layer stores the design knowledge of the snapping device that is collected and classified. Among them, the matter-element database contains the performance, structural size parameters, key component materials and other information of the snapping device that has been retrieved and reused. The information database stores the design principle, working mechanism and picture knowledge of the picking device. The model database stores a three-dimensional model of the working parts of the snapping device.

Case Representation and Case Database Construction

Representation of case knowledge

According to the type diversity and structural complexity of the snapping device, there are still some limitations in using frame representation, object-oriented representation, and other methods to represent its design cases. When new design requirements appear or a part structure needs to be modified, the case modification process will be very cumbersome and difficult to meet the requirements. To express the case, case parameters and parameter values in a simple and unified way, a case expression form combining qualitative and quantitative is formed, and the relationship between assembly and size change between parts is established. The matter-element theory is introduced to represent the case knowledge, so as to facilitate the construction of a knowledge database, digital three-dimensional model, and model database of ear picking device design reuse system.

The matter-element expression (M) of the case expresses the relationship between the name, parameters, values, and internal parameters of the case and its parts in the form of matter-element. For a case or case part O_{m}, if it has C_{mi} (i=1, 2,......,n) parameters, the value V_{mi} corresponding to the parameter C_{mi} can be a value, a value interval, a functional relationship between the internal parameters of the part and a descriptive statement for the parameters, and the corresponding value of m for C_{mi} is v_{mi} (i = 1, 2,..., n), which can be expressed as,

$$M_m = (O_m, C_m, \ V_m) = \begin{bmatrix} O_m & c_{m1} & v_{m1} \\ & c_{m1} & v_{m1} \\ & \cdot & \cdot \\ & \cdot & \cdot \\ & \cdot & \cdot \\ & c_{mn} & v_{mn} \end{bmatrix} \tag{1}$$

where O_m is the name of the case and case parts. m is the case and case part identification. n is the number of case attributes, $n \in$ N.

Because the design of the ear picking device is based on a combination of user needs and agronomy, changes in the object of operation and the environment will inevitably cause changes in the corresponding values of the relevant components of the ear picking device. Therefore, the case relationship matter element (R) is used to represent the relationship between the physical parameters of the crop and the parts.

$$R_{ij} = (M_i, M_j, V_{f(ij)}) = \begin{bmatrix} M_i & M_j & V_{f(ij)} \\ c_{i1} & c_{j1} & v_{f(ij1)} \\ c_{i2} & c_{j2} & v_{f(ij2)} \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ c_{ik} & c_{jk} & v_{f(ijn)} \end{bmatrix} \tag{2}$$

In the matrix 2, M_i and M_j represent crops and components that are interrelated. i, j are parts and crop identification; k is the number of related attributes, $k \in$ N.

For the case parts M_i and M_j, the number of attributes k can be different; $v_{f(ij)}$ is the corresponding relationship between attributes. $V_{f(ij)}$ can be equations, inequalities, functions, and relational expressions.

Representation of case database

The case database of corn ear picking device is composed of case matter-element database and Siemens NX software parametric case model database. Among them, the case matter-element database is used to store case feature attributes, values and other information, that is, the case is converted into a matter-element expression and stored in the SQL Server database. 3D model cases stored in the parameterized model database are used to call and modify the case model.

Due to the significant differences in the structure of different types of snapping devices, the basic hierarchical structure is divided by the type of snapping device, and the organization structure of the case database of the snapping device is established as shown in Fig. 3. This organizational structure is conducive to the retrieval and reuse of cases, and also makes the re-storage of cases rule-based, and provides convenience for the management and maintenance of case databases. The case model uses Siemens NX software-related modules for parametric modeling. Firstly, the dimensions and assembly relationships between parts are defined, that is, some case relationship matter elements are contained in the case model, so that the parts are no longer isolated individuals, fully reflecting the overall characteristics of the product.

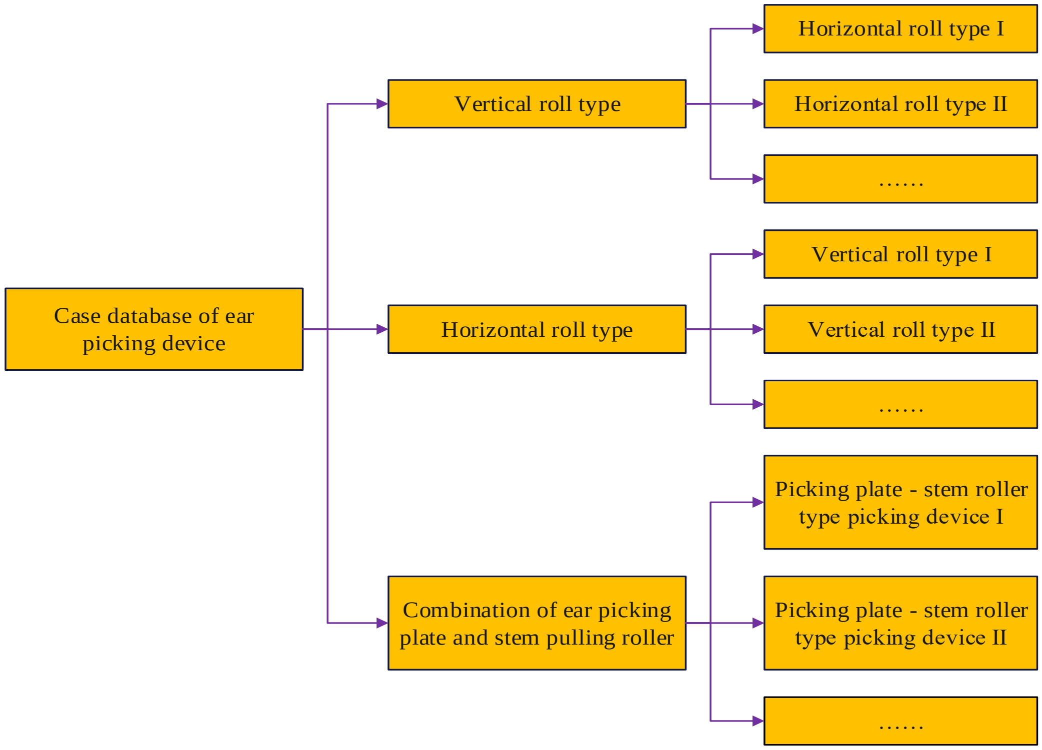


Fig. 3. Case database organization structure diagram

Design Retrieval Method of Corn Picking Device Based on Case Reasoning

Case retrieval is the core part of case-based reasoning. The goal is to quickly and accurately obtain cases similar to design requirements from existing cases is the key to case-based reasoning. In order to reduce the amount of calculation in the case retrieval process and improve the speed and accuracy of case retrieval, this paper classifies the case feature attributes of the snapping device, and it initially determines the scope of case retrieval. According to the similarity comparison, invalid cases are removed, and the case retrieval space is reduced. The nearest neighbor algorithm is used to calculate the size similarity and performance similarity of the case, so as to determine the most matching case.

Division of retrieval parameter categories

Case retrieval is the core part of case-based reasoning. It determines how to quickly and accurately obtain cases similar to design requirements from existing cases is the key to case-based reasoning. In order to reduce the amount of calculation in the case retrieval process and improve the speed and accuracy of case retrieval, this paper classifies the case feature attributes of the snapping device, and initially determines the scope of case retrieval. According to the similarity comparison, invalid cases are removed, and the case retrieval space is reduced. Then the nearest neighbor algorithm is used to calculate the size similarity and performance similarity of the case, so as to determine the most matching case.

The common characteristics of similar cases are the basis for case retrieval. In the design process of the picking device, not only the geometric dimensions such as the diameter and length of the picking roller of the picking device and the matching dimensions between the picking rollers, but also the operating performance of the harvester should be considered. In order to quickly and accurately obtain the snapping device with similar structure size and better snapping performance and quality from the case database, the attribute parameters of the snapping device are divided into core parameters, matching parameters and performance evaluation parameters.

(1) The core parameter is a parameter that can limit the search scope of the case. Due to the large difference in the structure of different types of snapping devices, the retrieval parameters are also different. There are differences in the operating performance of the same snapping device at different snapping roller (stem pulling roller) speeds. Limiting the speed will cause repeated retrieval and recommendation. Therefore, this paper will take the type of snapping device and the speed of snapping roller (stem pulling roller) as the core parameters of retrieval.

(2) Matching parameters can reflect the similarity with design requirements. For example, the diameter of the existing roller of the roller snapping device, and the diameter of the existing snapping roller in the database only need to be close to the design requirement value, and the absolute value of the difference of the snapping roller can reflect its similarity.

(3) Performance evaluation parameters can reflect the quality of operation performance. For example, the damage rate of harvested corn to ear is less than the design requirement in the matter-element database, and the greater the difference, the better the operation performance. Conversely, the worse the performance.

Case retrieval method

(1) Matching of core parameters

The core parameters of the snapping device include the type of the snapping device and the speed of the snapping roller (stem roller). Its primary function is limiting the retrieval range of matching and evaluation parameters. The type of snapping device in the core parameters is determined by interface selection. For the rotation speed of the header picking device, although the picking device under the same type has different operating performance at various operating speeds, its retrieval parameters are not affected by the operating speed. Therefore, the retrieval range of the picking device under different operating speeds is controlled by writing conditional control statements.

(2) Similarity algorithm of matching parameters

The parameter that reflects the degree of similarity to the design requirements. The closer the value is, the greater the similarity between the two cases is, and vice versa. In the design based on case-based reasoning, in order to obtain the design case with better cost performance from the matter-element database, under the premise of determining the basic parameters, it is necessary to calculate the matching parameters corresponding to the design requirements and the existing cases in the matter-element database. This paper calculates the similarity of matching parameters by modifying and improving the nearest neighbor algorithm.

Suppose the case set $M = \{M_1, M_2, \cdots, M_j, \cdots, M_m\}$, then each case has a parameter $C = \{c_1, c_2, \cdots, c_i, \cdots, c_n\}$. The number values corresponding to the ci parameter of the demand case M_q and the case M_j are $v_{qi} = [a_{i1}, a_{i2}]$ and $v_{ji} = [b_{i1}, b_{i2}]$, respectively. The distance between M_q and the parameter c_i corresponding to M_j can be expressed as:

$$dist(M_{qi}, M_{ji}) = \left|\frac{b_{i1} - a_{i1}}{2}\right| + \left|\frac{b_{i2} - a_{i2}}{2}\right| \tag{3}$$

For the matching parameters, only the similarity between the demand case and the case value in the case database is needed, without considering the positive and negative distance. Because different parameter dimensions are often different, in order to eliminate the influence of different dimensions, normalization processing is needed to obtain its superiority algorithm:

$$sim(M_{qi}, M_{ji}) = 1 - \frac{|b_{i1} - a_{i1}| + |b_{i2} - a_{i1}|}{2(\max(v_i) - \min(v_i))} \tag{4}$$

where max(v_i) and min(v_i) are the maximum and minimum values corresponding to the parameter *i*. When max(v_i)=min(v_i), sim (M_{qi},M_{ji})=1.

(3) Similarity algorithm of performance evaluation parameters

There are differences in their operating performance for similar cases, such as structural size. These parameters can reflect the advantages and disadvantages of different cases. In order to evaluate the performance of a case, in addition to determining the criteria for judging the performance of the case, it is also necessary to be able to quantitatively describe the quality of the case.

The performance evaluation parameters of the ear picking device mainly include the ear damage rate and the corn grain loss rate during the operation process. For these two indicators, the smaller the parameter value should be, the better the ear picking performance is. The calculation method is as follows.

$$sim(M_{qi}, M_{ji}) = \frac{(b_{i1} - a_{i1}) + (b_{i2} - a_{i2})}{2[\max(v_i) - \min(v_i)]} \tag{5}$$

where max (v_i), min (v_j) are the maximum and minimum values corresponding to the *i* th parameter. When sim (Mqi,M_{ji}) > 0, the parameter values corresponding to the case meet the design requirements. The larger the value, the better the performance. When sim (M_{qi},M_{ji}) = 0, the parameter value corresponding to the case is in a critical state. When sim (M_{qi},M_{ji}) < 0, the parameter value corresponding to the case cannot meet the design requirements, and the smaller the value, the worse the performance. When max (v_i) = min (v_j), sim (M_{qi},M_{ji}) = 0.

(4) The calculation method of retrieval parameter weight

In order to distinguish the influence degree of each parameter on decision-making, it is necessary to determine the weight of each case parameter. The case retrieval of snapping device design is a multi-attribute decision-making problem. It is essential to assign weights to each parameter and determine the relative importance of each parameter. Whether the weight is reasonably assigned directly affects the correctness of the search results. Therefore, the reasonable determination of weights is the core of multi-attribute decision-making problems.

Because the subjective weighting method and the objective weighting method have their advantages and disadvantages, based on the application of the two methods, the analytic hierarchy process and the subjective and objective comprehensive weighting method based on the combination of the maximum deviation multi-attribute weight determination are used to determine the weight, avoiding the limitations of a single weighting method.

(1) Determination of parameter weight based on analytic hierarchy process

The analytic hierarchy process decomposes the decision-making problem into different components, and determines the importance of the factors by comparing the different factors, and then constructs the judgment matrix and obtains the parameter weight. If each case of the case set $M=\{M_1,M_2,\cdots,M_m\}$ has n parameters, then the weight determined by the designer using the analytic hierarchy process according to the importance of each parameter is $W^{(1)}=\{w_1^{(1)},w_2^{(1)},\cdots,w_i^{(1)},\cdots,w_n^{(1)}\}$.

(2) Determination of multi-attribute weights based on deviation maximization

If each case of case set $M=\{M_1,M_2,\cdots,M_m\}$has n parameters, then the objective weight determined by the influence of data information on decision-making is $W^{(2)}=\{w_1^{(2)},w_2^{(2)},\cdots,w_i^{(2)},\cdots,w_n^{(2)}\}$. If the similarity of the c_i parameter between the design target case M_q and the case database case M_j is recorded as S_{ji}, then M_q and all case parameters in case set M can form a similarity matrix $\boldsymbol{S}$, as shown in Equation (6).

$$S=\begin{bmatrix} S_{11} & S_{12} & \cdots & S_{1i} & \cdots & S_{1n} \\ S_{21} & S_{22} & \cdots & S_{2i} & \cdots & S_{2n} \\ . & . & & . & & . \\ . & . & & . & & . \\ . & . & & . & & . \\ S_{j1} & S_{j2} & \cdots & S_{ji} & \cdots & S_{jn} \\ . & . & & . & & . \\ . & . & & . & & . \\ . & . & & . & & . \\ S_{m1} & S_{m2} & \cdots & S_{mi} & \cdots & S_{mn} \end{bmatrix} \tag{6}$$

If the similarity S_{ji} (j = 1, 2,..., m) of the i-th parameter c_i has little difference, it shows that the parameter c_i has less decision-making effect on the case, and its parameters can be given smaller weights; if c_i makes a large difference in the similarity of all cases, it shows that it plays a greater role in the ranking of decision-making schemes, and a larger weight should be given in the design process. D^{ji} ($W^{(2)}$) is used to represent the i-th parameter similarity deviation between the example M_j and all other cases, and Equation (7) is:

$$D_{ji}\left(W^{(2)}\right)=\sum_{k=1}^{m}\left|w_i^{(2)}s_{ji}-w_i^{(2)}s_{ki}\right| \tag{7}$$

For the parameter c_i, the total similarity deviation between all cases and other cases is:

$$D_i\left(W^{(2)}\right)=\sum_{j=1}^{m}\sum_{k=1}^{m}\left|w_i^{(2)}s_{ji}-w_i^{(2)}s_{ki}\right| \tag{8}$$

The total deviation between all cases under all parameters is:

$$D_i\left(W^{(2)}\right)=\sum_{i=1}^{m}\ \sum_{j=1}^{m}\sum_{k=1}^{m}\left|w_i^{(2)}s_{ji}-w_i^{(2)}s_{ki}\right| \tag{9}$$

The selection of weight $W^{(2)}$ should maximize the total deviation between cases under all parameters, so solving weight $W^{(2)}$ is equivalent to solving the following optimization model:

$$\begin{cases} \max D\left(W^{(2)}\right) = \sum_{i=1}^{m}\sum_{j=1}^{m}\sum_{k=1}^{m}\left|w_{ji}^{(2)} - w_{ki}^{(2)}\right| \\ s.t. \sum_{i}^{n}(w_i^{(2)})^2 = 1, w_i^{(2)} \geq 0, i = 1,2,3,\cdots,n \end{cases} \tag{10}$$

According to the optimization model in Equation (10), the final parameter weight is obtained by normalization:

$$w_i^{(2)} = \frac{\sum_{j=1}^{m}\sum_{k=1}^{m}\left|s_{ji} - s_{ki}\right|}{\sum_{i=1}^{n}\sum_{i=1}^{m}\sum_{k=1}^{m}\left|s_{ji} - s_{ki}\right|} \tag{11}$$

Case Revision

In the process of product design reuse, existing cases similar to the current design requirements can be obtained through retrieval, but they may not fully meet the design requirements, or even if the current design requirements are met, their performance can be further improved through optimization and improvement. Therefore, it is generally necessary to further modify the retrieved cases. This paper uses the method based on rule association to modify the case.

Rule association refers to the quantitative description relationship between the case structure size parameters and the design requirements or the strong correlation with the performance in the design requirements. The rule association between the design requirements and the case structure size parameters is shown in Fig. 4. The size parameters of the case structure include the main driving parameter *P* and the driven parameter *U*. The main driving parameters are directly related to the design requirements or play a decisive role in the overall structure and performance of the case, such as the inclination angle of the picking device and the horizontal plane operation, the diameter of the harvested corn stalk, and the diameter of the large end of the harvested ear. The driven parameters are regularly associated with the main drive parameters and change with the main drive parameters. According to the design requirement *Q*, the case can be quickly modified by adjusting the main drive parameters.

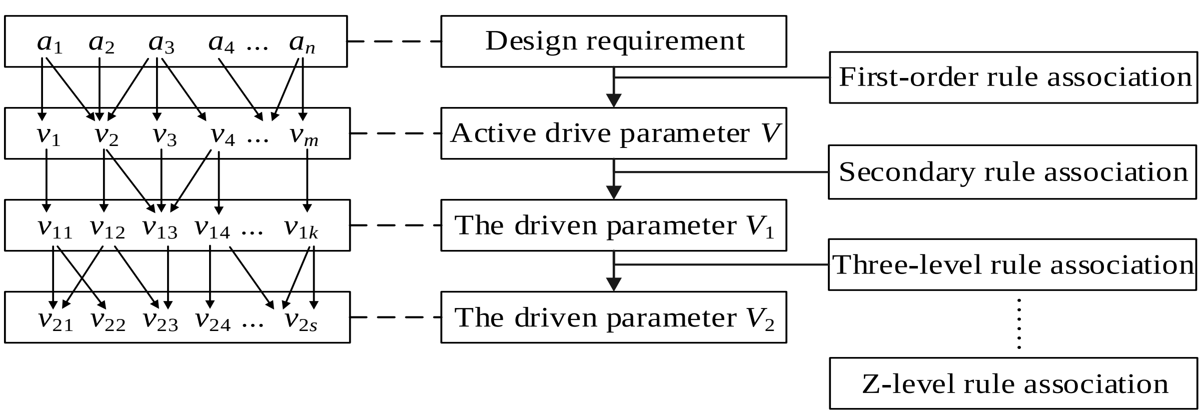


Fig. 4. The design requirements are associated with the case structure size parameter rules

The matter-element expression of the case modification process based on rule association is:

$$T^*M_0 = T^*\begin{bmatrix} O_0 & c_{01} & v_{01} \\ & c_{02} & v_{02} \\ & \cdot & \cdot \\ & \cdot & \cdot \\ & \cdot & \cdot \\ & c_{0j} & v_{0j} \\ & \cdot & \cdot \\ & \cdot & \cdot \\ & \cdot & \cdot \\ & c_{0n} & v_{0n} \end{bmatrix} = \begin{bmatrix} O_0^{'} & c_{01} & v_{01}^{'} \\ & c_{02} & v_{02}^{'} \\ & \cdot & \cdot \\ & \cdot & \cdot \\ & \cdot & \cdot \\ & c_{0j} & v_{0j}^{'} \\ & \cdot & \cdot \\ & \cdot & \cdot \\ & \cdot & \cdot \\ & c_{0n} & v_{0n}^{'} \end{bmatrix} = M_0^{'} \tag{14}$$

Among them, $T^* = \{T_1, T_2, \cdots, T_n\}$,

where T* is the set of modified methods. M_o is the matter element of the case before modification. O_0 is the modified case or case parts. M'_o is the new case matter element obtained after modification; c_{oj} is the modified case element attribute. v'_{oj} is the value of the modified case matter-element attribute.

There is a rule association between the case matter element M_o and the case matter elements in the case matter element set $M^{'} = \{M_1, M_2, \cdots, M_m\}$, and the relationship matter element set $R^{'} = \{R_{01}, R_{02}, \cdots, R_{0m}\}$ indicates that the expression of the case matter element change caused by the modification of M_0 is:

$$\{M_1, M_2, \cdots, M_m\} \xrightarrow{T^*M_0 + R^{'}} \{M_1^{'}, M_2^{'}, \cdots, M_m^{'}\} \tag{15}$$

Implementation of Case-based Reasoning Retrieval Method

The key to the realization of the design reuse method of corn snapping device is the connection of the instance matter-element database and the call and modification of the three-dimensional model in the instance Siemens NX parametric model library.

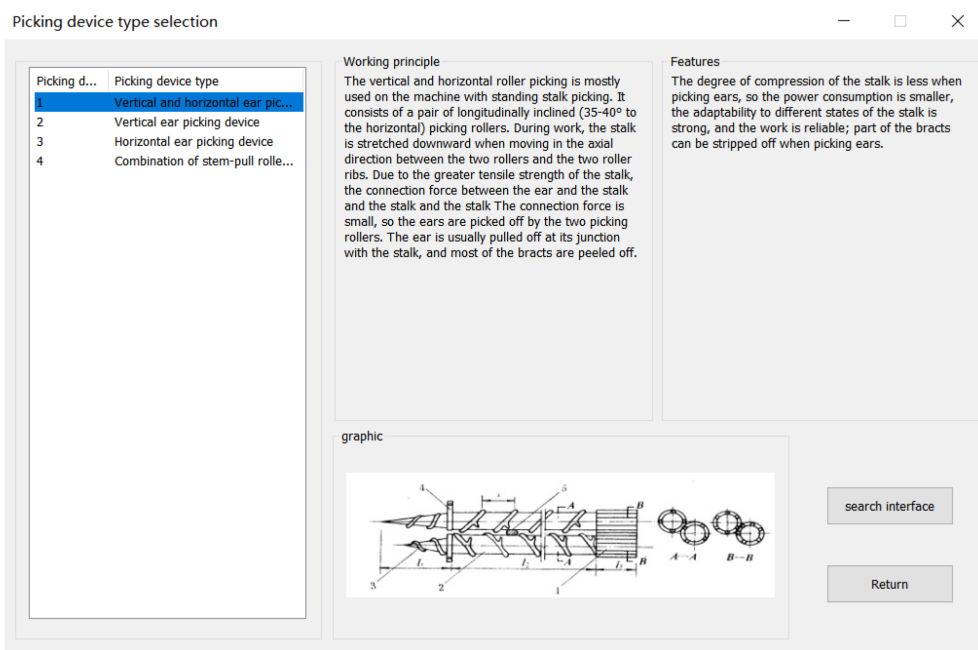


Fig. 5. Selection interface of picking device type

In the process of design reuse of corn snapping device, SQL Server database is used to store the case parameters of the snapping device.

(1) Type selection

According to the retrieval strategy, the type of the snapping device needs to be determined first when the case-based reasoning design is carried out. This process selects the type through the interface guidance. Through this interface, in addition to determining the type of reusable components, the structure, working principle and characteristics of the components can also be preliminarily understood. As shown in Fig. 5, the type selection interface of the snapping device is shown.

(2) Case retrieval

When retrieving the design example of the snapping device, it is necessary to determine the required retrieval parameters. The retrieval parameters of different types of components are different, and the content of the retrieval interface is also different. For example, the vertical and horizontal snapping device needs to consider the diameter, length, and inclination angle of the snapping roller. In addition to determining the parameters required for component retrieval, the weight of each parameter needs to be determined and input. As shown in Fig.6, the case retrieval interface of the vertical and horizontal roller snapping device is shown. According to the relative importance of each retrieval parameter, the designer inputs the judgment matrix in the retrieval interface, uses the analytic hierarchy process to calculate the subjective weight, clicks the ‘retrieval evaluation’ button, searches the instances in the database, obtains the similarity matrix, calculates the objective weight and the combined weight, and then calculates the weighted similarity of each instance to obtain the available instances.

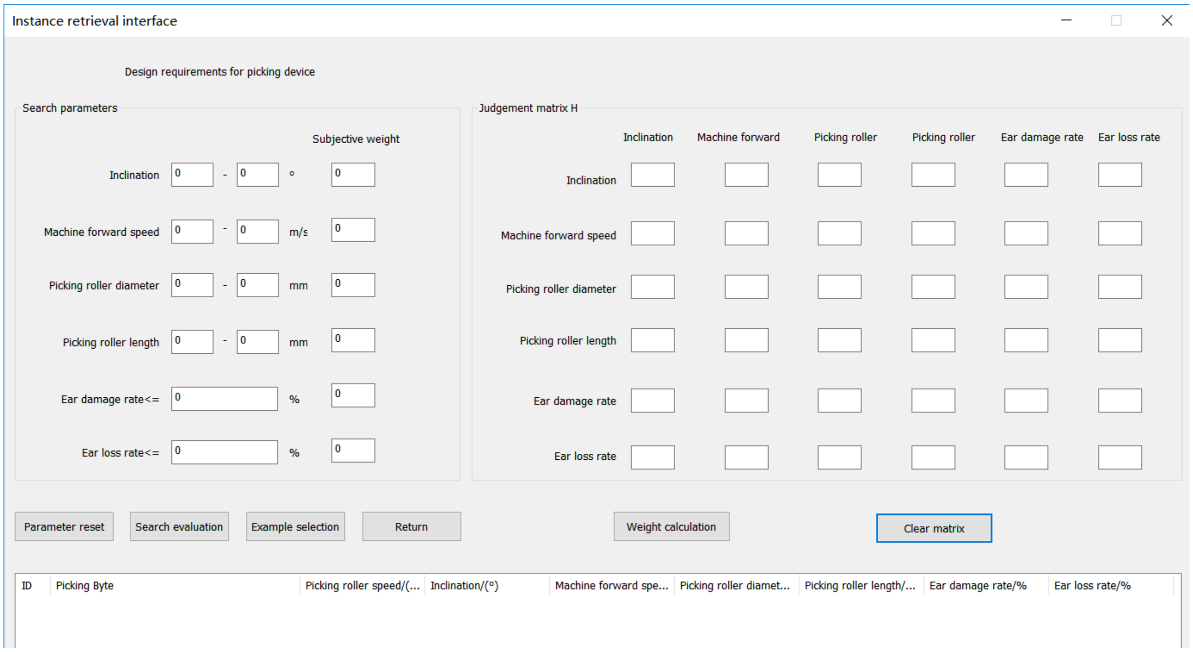


Fig. 6. Snapping device retrieval interface

(3) Case adaptation

Through case retrieval, one or more similar design case schemes may be obtained. The designer determines the final design requirement instance according to the actual demand, and calls its model from the model library. There are some differences between examples and requirements in the case base. Designers modify the selected examples with professional knowledge to improve the performance of product operations. As shown in Fig.7, the interface of the vertical and horizontal picking device is modified. The interface includes the main driving parameter, the rotation speed of the picking roller and the driven parameter, the length of the picking roller, the diameter of the picking roller, the inclination angle and the forward operation speed. The rotation speed of the snapping roller affects the changes of other driven parameters. Click ‘parameter confirmation’, and its value will change with the change of main drive parameters.

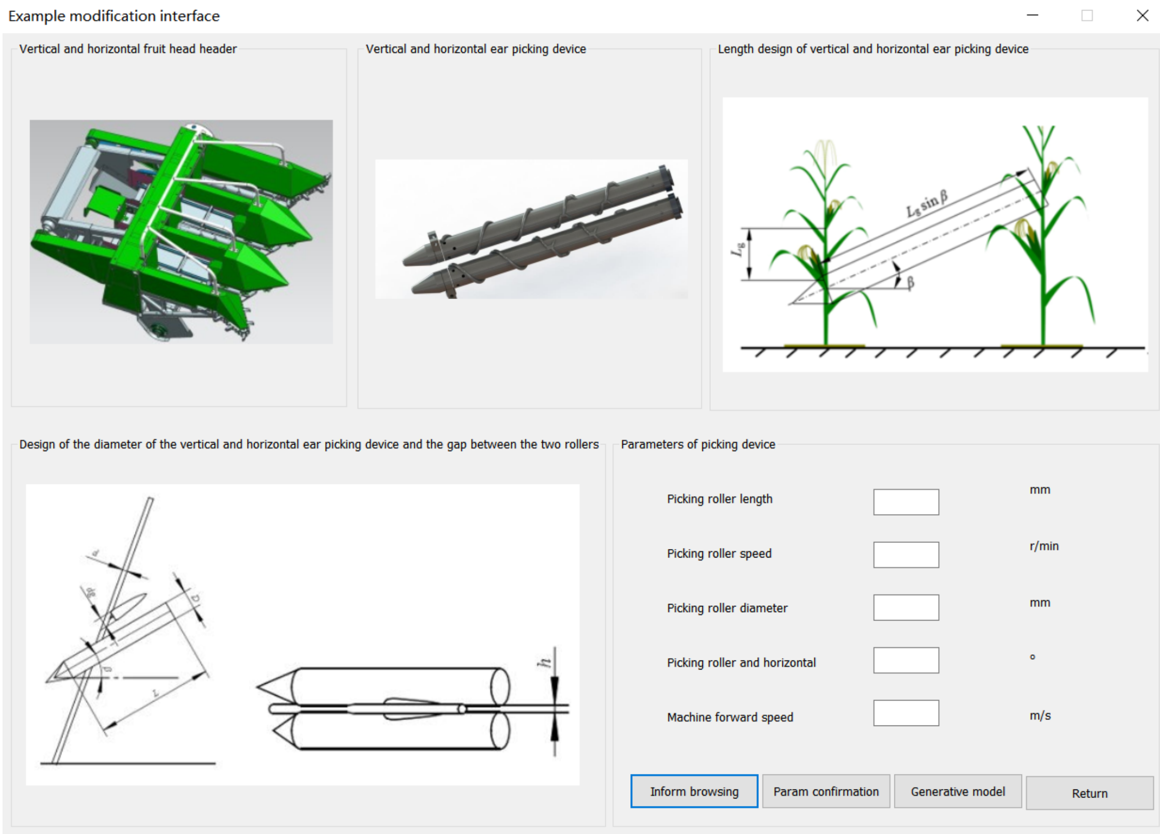


Fig. 7. Stripper device case modification interface

RESULTS AND DISCUSSION

Case Analysis and Numerical Simulation

Determination of operation object and design parameters

In the case study, Hongyu 168 was used as the working object, and the five-point method was used to measure and count the active objects in the field. The average physical characteristics are shown in Table 1.

Table 1. Statistics of Maize Plant Physical Parameters of Hongyu 168

Item	Natural Plant Height/ mm	Minimum Ear Height/ mm	Cluster Length/ mm	Diameter of Big End of Ear/ mm	Root Stem Diameter /mm	Stem Diameter at earing/ mm	Top stem diameter/ mm
Minimum Value	2948	988	220	60	41	28	8
Maximum Value	3285	1395	268	74	52	38	13
Average Value	3013	1177.63	243.17	67.10	44.70	32.87	11.03

Before the design of the picking device based on real case reasoning, it is necessary to determine the type of the designed picking device, the structural size of the key parts, the working matching parameters, and the main operating performance indicators. The core parameter is the vertical and horizontal picking device. The rotation speed of the picking roller of the picking device is 800 r/min. The specific case requirements are shown in Table 2. According to the design requirements, the matter-element Mq of the demand case is established. If there are similar cases in the case database, the retrieval parameters of the ear picking device are classified. The core parameters are the type of ear picking device and the forward speed of the harvester. The matching parameters are the diameter and length of the ear picking device and the inclination angle between the ear picking device and the horizontal plane. The performance evaluation parameters are the ear damage rate and grain loss rate of the ear picking device. Through matching core parameters, the case of vertical and horizontal roller snapping device with a speed of 800 r/min can be retrieved.

$$M_q = \begin{bmatrix} Earpicking device & Type & Horizontal rolltype \\ & Speed & 800 r/\min \\ & Angle & 30° \sim 35° \\ & Speedofadvance & 2m/s \sim 2.5m/s \\ & Diameter & 70mm \sim 90mm \\ & Length & 1100m/s \sim 1300m/s \\ & Damagerateofear & \leq 1\% \\ & Grainlossrate & \leq 1\% \end{bmatrix}$$

Table 2. Retrieval Parameters of Snapping Device

Spike Picking	Rotating Speed of Picking Roller (pulling roller)/(r/min)	Tapping Roller and Horizontal Plane Inclination (°)	Harvester Forward Speed (m/s)	Picking Roller Diameter (mm)	Length of Snapping Roller (mm)	Ear Damage Rate (%)	Grain Loss Ratio (%)
Vertical Horizontal Roller Snapping Device	800	30~35	2.0~2.5	70~90	1100~1300	≤1	≤1

Case retrieval

The threshold value of 0.5 is set. According to the user's needs, the attribute weight of the performance index of the corn picking device required by the user is obtained by the analytic hierarchy process. According to the different importance of the matching parameters and the performance evaluation parameters, the discriminant matrix ***D*** is constructed by the analytic hierarchy process.

$$D=\begin{bmatrix} 1 & \frac{8}{25} & \frac{4}{15} & \frac{2}{3} & \frac{8}{15} & \frac{4}{5} \\ \frac{25}{8} & 1 & \frac{5}{6} & \frac{25}{12} & \frac{5}{3} & \frac{5}{2} \\ \frac{15}{4} & \frac{6}{5} & 1 & \frac{5}{2} & 2 & 3 \\ \frac{3}{2} & \frac{12}{25} & \frac{2}{5} & 1 & \frac{4}{5} & \frac{6}{5} \\ \frac{15}{8} & \frac{3}{5} & \frac{1}{2} & \frac{5}{4} & 1 & \frac{3}{2} \\ \frac{5}{4} & \frac{2}{5} & \frac{1}{3} & \frac{5}{6} & \frac{2}{3} & 1 \end{bmatrix}$$

The weight $W^{(1)}$={0.08,0.25,0.3,0.12,0.15,0.1} is obtained by the sum product method, and the similarity matrix S is calculated according to the Equation (2) to (7).

$$S=\begin{bmatrix} 0.5 & 0.7 & 1 & 0.5 & 0.69 & 0.15 \\ 0.5 & 0.02 & 0.8 & 0.575 & 0.08 & 0.37 \\ 0.5 & 1 & 0.3 & 0.75 & 0.17 & 0.28 \\ 0.9 & 0.7 & 0 & 0.5 & 0.28 & 0.7 \\ 0.5 & 0.7 & 0 & 0.75 & 0.03 & 0.06 \end{bmatrix}$$

The weight $W^{(2)}$={0.2221,0.2388,0.1608,0.2221,0.0459,0.1103}is calculated by Eqs. (8) to (13), and the final weight W = { 0.1043,0.3506,0.2833,0.1565,0.0405,0.0648 } is calculated by Eq. 13. The similarity of each case 1, 2, 3, 4 and 5 calculated by Eq. 14 is {0.6921, 0.3910, 0.6108, 0.4261, 0.4054}. As shown in Table 3, the similarity of cases is 1 > 3 > 4 > 5 > 2. According to the input threshold conditions, cases 1 and 3 meet the threshold conditions and are recommended to users in descending order of similarity. Case 1 is the most similar case, which can be used as a preferred design case.

(1) Case parameter modification

Select the case a with the highest similarity in the table as the design reuse object. In order to improve the working performance of the ear picking device, the active parameters of the ear picking device can be modified as follows: According to the physical characteristics of the plant of the maize variety Hongyu 168, the average stem diameter at the earing site is 32.87 mm, the minimum is 28 mm, and the maximum is 38 mm. The average diameter of the large end of the ear is 67.1 mm, the minimum is 60 mm, and the maximum is 74 mm. According to the design knowledge operation, the range of the diameter of the picking roller can be determined. Within the allowable range of the design, the average diameter of the picking roller is determined to be 85 mm. In order to ensure the harvest quality, the working speed is proportional to the inclination angle of the picking roller and the ground when the speed of the picking roller is constant.

Table 3. Recommended Cases of Snapping Device

Case	Kernel Parameter		Matching Parameters				Performance Evaluation Parameter		Similarity
	Spike picking	Revolution Speed (r/min)	Dip angle (°)	Forward Speed (m/s)	Picking Roller Diameter (mm)	Length of Snapping Roller/mm	Ear Damage Rate (%)	Grain Loss Ratio (%)	
1	Vertical horizontal roller type a	800	35	2.1	80	1300	0.31	0.85	0.6921
2	Vertical horizontal roller type b	800	35	1.76	84	1115	0.92	0.63	0.3910
3	Vertical horizontal roller type c	800	30	2.25	94	1150	0.83	0.72	0.6108
4	Vertical horizontal roller type d	800	33	2.4	100	1100	0.72	0.30	0.4261
5	Vertical horizontal holler type e	800	30	2.4	100	1250	0.97	0.94	0.4054

Table 4. Comparison of Picking Device Parameters Before and After Modification

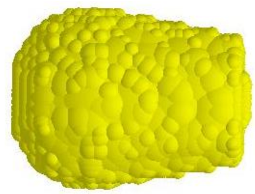
Vertical Horizontal Roller Snapping Device	Picking Roller Diameter *D* (mm)	Length of Snapping Roller *L* (mm)	Dip Angle β/°	Operating Speed v_m/(m/s)
Before Modification	80	1300	35	2.1
After Modification	85	1225	35	1.2

At this time, $k = v_m/v \sin\beta = 0.7$ to 1.1 is satisfied. In this range, the working speed is changed to 1.2 m/s. The parameters of the picking device before and after modification are shown in Table 4.

Virtual simulation and improvement

The discrete element simulation of the modified snapping device was carried out by EDEM software, and the Hertz-Mindlin with Bonding model was selected as the contact collision model (Hertz 1882; Hu *et al.* 2010; Han *et al.* 2017). According to the shape and three-dimensional size information of maize, the grain is modeled by selecting the common tooth-shaped grain and the cone-shaped grain in the maize ear. According to the obtained position coordinates of the filling particles of maize grain, mandrel and stem, the manual particle filling is carried out respectively, and the filling models are obtained respectively, as shown in Fig 8.

(a) Horse-tooth grain filling model



(b) Ball cone grain filling model

(c) Filling model of mandrel

(d) Stem filling model

Fig. 8. Manual filling model of corn kernels, cobs and stems

According to the position of corn kernels manually filled with particles, the position coordinates of corn kernels are generated using the grain filling plane coordinate system, and the particle replacement file is written by the programming software Visual Studio. The text file generated by the particles is mainly the three-dimensional position coordinates and the number of particles generated by the kernels relative to the mandrel during the particle replacement. The final corn filling model is shown in Fig. 9.

Fig. 9. Corn ear filling model

After field measurement and literature review, the basic physical property parameters and bonding parameters set by the discrete element model of Hongyu 168 maize were established, as shown in Tables 5 and 6.

Table 5. Basic Physical Parameters of Corn and Picking Board

Site	Poisson Ratio	Density (kg/m^3)	Shear Modulus (Pa)
Haulm	0.24	1020	7.3×10^8
Bunch	0.40	1246	1.37×10^8
Snapping Plate	0.25	7200	4.5×10^{10}

Table 6. Calibration of Connection Parameters

Site	Normal Stiffness (N/m^2)	Shearing Rigidity (N/m^2)	Tensile Strength (Pa)	Shearing Strength (Pa)	Contact Diameter (mm)
Stem and Ear	1.5×10^{10}	1.0×10^{10}	2.8×10^7	1.4×10^7	4
Grain and Mandrel	4.5×10^9	3.0×10^9	1.5×10^7	4.0×10^6	4

According to the requirement of the speed of the picking device in the matter-element of the demand case, the virtual simulation of the operation of the picking device at the speed of 800 r/min was carried out. The simulation results showed that the ear damage rate was 0.29% and the grain loss rate was 0.81%, which met the design requirements.

To determine whether the design parameters of the ear picking device are the optimal design parameters of the operating object, the diameter of the stem pulling roller, the length of the ear picking roller, the inclination angle between the ear picking roller and the horizontal plane and the forward operating speed are taken as the experimental factors, and the grain loss rate and the ear damage rate are taken as the evaluation indexes. The orthogonal analysis of 4 factors and 5 levels tested the influence of the interaction of working parameters on the ear damage rate and the grain loss rate. The experimental factors were coded as shown in Table 7. According to the field sampling measurement, the five-point method was used to select 10 Hongyu 168 varieties of corn at maturity as the basic parameters for establishing the corn simulation model, and the corn discrete element model was established. The established 10 discrete element models were selected for simulation in each group.

The simulation results show that the ear damage rate and grain loss rate are the smallest when the diameter of the picking roller is 85 mm, the length of the picking roller is 1220 mm, the inclination angle is 35º, and the operating speed is 1.4 m/s. The ear damage rate is 0.26%, and the grain loss rate is 0.80%. The modified parameters of the case are not optimal due to the extensive design range of design experience data. In case modification, the design calculation is modified according to the measurement of corn physical characteristic data and the design experience of the corn harvester header. In the calculation process, the average value of the design range is taken as the final selection data, which leads to the lack of a certain theoretical basis in selecting optimal parameters. Only the optimal interval of parameters can be determined, and the optimal parameter combination cannot be determined.

Table 7. Experimental Factors Coding Table

The Level of Coding	Picking Roller Diameter *D* (mm)	Length of Snapping Roller *L* (mm)	Tapping Roller and Horizontal Plane Inclination *β* (°)	Operating Speed (v_m/(m/s))
-2	79	1215	33	0.8
-1	82	1220	34	1
0	85	1225	35	1.2
1	88	1230	36	1.4
2	91	1235	37	1.6

Simulation verification

Whether the operation performance of the improved corn snapping device has been improved needs further verification. The discrete element simulation of the improved snapping device operation process is carried out by EDEM software. In order to determine the availability of the improved snapping device, the performance of the snapping device at 600 to 1000 r/min was simulated. The simulation results are shown in Table 8.

Table 8. Simulation Results of Header Snapping Device at Different Speeds

Rotating speed of picking roller/(r/min)	Corn ear damage rate (%)	Corn grain loss rate (%)	Total loss rate (%)
600	0.49	0.88	1.37
650	0.40	0.86	1.26
700	0.32	0.84	1.16
750	0.26	0.83	1.09
800	0.26	0.80	1.06
850	0.29	0.82	1.11
900	0.30	0.84	1.14
950	0.40	0.83	1.23
1000	0.45	0.89	1.34

From the simulation results of Table 8, the change trend of the modified ear picking device on the ear damage rate and grain loss rate is first decreased and then increased, and the change range is 0.26 to 0.49% and 0.80 to 0.89%, respectively. The total loss rate is the smallest when the speed is 800 r/min, the ear damage rate is 0.26%, and the grain loss rate is 0.80%, and its operating performance is relatively improved.

Field Test

Test equipment and test conditions

To verify the availability of the case picking device after retrieval and modification, a field experiment was conducted in Lingcheng District, Dezhou City, Shandong Province, China in October 2022. The growth of maize plants in the selected test area was relatively uniform and good, there was no lodging phenomenon of maize plants, and there was no obvious drooping of ears. The maize variety in the test site was Hongyu 168. The moisture content of maize grain was 28.56 to 2.53 %, and the moisture content of maize plant was 75.38 to 78.41%. The case picking device was processed and installed on a three-row self-propelled horizontal roller corn harvester for field trials. The test site is shown in Fig 10.

Fig. 10. Field test site

Test scheme and result analysis

The harvester's corn ear damage rate and grain loss rate were used as evaluation indexes to evaluate the harvesting quality of the picking roller speed in the range of 600 to 1200 r/min. Each group of test time is 10 minutes. After the test and calculation statistics, the results are shown in Table 9.

Table 9. Field Experiment Results

Rotating Speed of Picking Roller/(r/min)	Corn Ear Damage Rate (%)	Corn Grain Loss Rate (%)	Total Loss Rate (%)
600	0.47	0.92	1.39
650	0.36	0.92	1.28
700	0.32	0.83	1.15
750	0.28	0.84	1.12
800	0.26	0.81	1.07
850	0.28	0.84	1.12
900	0.32	0.85	1.17
950	0.43	0.84	1.27
1000	0.49	0.92	1.41

The field test results were basically consistent with the simulation results for the same speed and range. The maximum relative error of the total loss rate of corn was 0.07 %, the maximum relative error of the ear damage rate was 0.04 %, and the maximum relative error of the grain loss rate was 0.06 %. The reason for the error may be that the corn ear feeds into the cutting table with various postures, there are certain differences in the height of the corn stalk, and there is a certain fluctuation in the forward speed of the harvester. After field experiments, it was verified that its performance was improved compared with that before improvement, and its working performance was within the allowable range required by the retrieval case.

CONCLUSIONS

1. The design reuse process of corn snapping device can be divided according to knowledge database, model database, case retrieval, case call and modification, evaluation analysis and modification, which meets the requirements of design reuse

process. This approach is conducive to the modular development of design reuse system and improves the efficiency of system development.

2. The unified representation of the case knowledge of corn snapping device by using the matter-element expression form and relation matrix including case name, parameter, and value can realize the combination of qualitative and quantitative description of design knowledge, so that the representation of design knowledge is complete, specific, clear and standardized, which is conducive to the effective use of design knowledge.
3. The retrieval parameters of snapping device are divided into core parameters, matching parameters and performance evaluation parameters. Through the matching of core parameters, the scope of retrieval can be reduced, the amount of calculation in the retrieval process can be reduced, and the retrieval efficiency can be improved. By calculating the similarity between the matching parameters and the performance evaluation parameters, the quantitative evaluation of the structural size and advantages and disadvantages of the snapping device can be realized, and the accuracy of the retrieval can be improved. The built-in rules of the design reuse system of the snapping device can give the recommended modification parameters according to the comparison between the design and reuse examples and combine the program-driven parametric model structure size change to improve the modification efficiency of the snapping device.
4. The proposed design reuse method of corn header snapping device can quickly obtain and modify the current snapping device similar to the design requirements, improving the snapping device's design efficiency. Based on the case, the field experiment was conducted on the reused ear picking device. When the rotation speed of the ear picking device was 800r / min, the ear damage rate, corn grain loss rate and total loss rate of the reused ear picking device were 0.26%, 0.81%, and 1.07%, respectively. The harvest performance was within the allowable range. Compared with the case before modification, the grain loss rate and ear damage rate were reduced, which demonstrated the practicability and effectiveness of the design reuse method.

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