An intelligent design method and system for the silage harvester cutter

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Abstract. An intelligent design method is proposed to meet the requirements of multi-functional, customization and diversification of the silage harvester cutter. A reasoning model is built based on axiomatic design method. A hierarchical mapping structure and a design case library model are established. A precise search method classified by function is designed on the basis of the grey relational analysis. An intelligent design system for silage harvester cutter is developed according to axiomatic design and exemplary reasoning technology. A physical cutter is designed and manufactured. It turns out that the intelligent design system for silage harvester cutter works well. The intelligent design system can be used to design product efficiency and effectively.

1. Introduction
The cutter device is part of the most core components on the silage harvester. Its main function is tantamount to chop the material uniformly according to the pre-set length. At present, it is implemented mainly depends on the traditional design method. It is common to repeat the process of design, trial and error for many times, which is labor-intensive, time-consuming, and uneconomic [1-2]. Nowadays, to satisfy the requirements of user customization and diversification, it is particularly important to achieve the intelligent design for the cutter device of the silage feeder.

Axiomatic design is a scientific and systematic product design method. There is plenty of academic research achievements on intelligent design based on axiomatic design. Wang Tichun and others proposed a knowledge reuse method for design cases based on axiomatic design. Level case model was implemented with the reasoning of the case based on the retrieval algorithm [3]. Yang Jie et al. established a process decomposition model of the complex product design process under the axiomatic design framework, adopted a knowledge reuse retrieval algorithm based on similarity, and verified it with a case [4]. Therefore, with the advantages of the accumulated design experience and mature cases, the using of modern design theory and intelligent algorithms is feasible design method [5-12]. The application of axiomatic design theory for the intelligent design of agricultural machinery helps improve the accuracy and efficiency of design.

Therefore, this paper takes the silage harvester as a research object, applies the axiomatic design-based theories and methods to the intelligent design of the silage harvester, and develops an intelligent design system for the silage harvester.
2. Axiomatic design and case-based reasoning

2.1. A basic concept of axiomatic design

Axiomatic design (AD) [13] is a scientific and systematic product design method proposed by MIT Suh et al. Its purpose is to establish a scientific basis for different forms of design and to provide designers with an optimized design logically and rationally, including the concepts of domain, hierarchy, "Z" mapping, and two design axioms [14]. Axiomatic design summarizes design activities into a "Z" shape mapping between four domains (customer domains (CAs), functional domains (FRs), physical domains (DPs), and process domains (PVs)), as illustrated in Figure 1. Independent axioms guarantees the independence between sub-functions in the functional domain, while the axiom of information is that among all design schemes that meet the independent axiom, the one with the least amount of information is the optimal design scheme [15].

![Figure 1. Mutual mapping of domains in axiomatic design.](image)

![Figure 2. Intelligent design flow chart of cutter device.](image)
2.2. Intelligent design process of cutter device
According to the case-based reasoning technology based on axiomatic design, it is applied to the intelligent design of the cutter device of the silage machine, the reasoning process is illustrated in Figure 2.

3. Realization of cutter device case reasoning
According to the cutter intelligent design flow chart based on the axiomatic design, it’s easily to get product design methods for the cutter of the silage machine. Firstly, the case library of cutter design is constructed by case decomposition to obtain the functional requirement hierarchy table [16-18]; then a case retrieval algorithm is used to obtain the design case with the highest similarity by the case index.

3.1. Building cutter device library
According to the intelligent design flow chart of the cutter device, firstly based on the axiomatic design theory, the functional requirements of the cutter device design are decomposed to obtain the hierarchical structure of the functional domain, including productivity requirements (FR1) and cutting stability requirements (FR2) and cutting length requirements (FR3); the hierarchical structure of the functional domain, including three modules of moving knife (DP1), fixed knife (DP2), and roller (DP3). The mapping structure is illustrated in Figure 3.

According to the cutter device mapping structure model and design process, the design equation can be obtained:

\[
\begin{bmatrix}
FR1 \\
FR2 \\
FR3
\end{bmatrix} = \begin{bmatrix}
1 & 1 & 1 \\
1 & 1 & 1 \\
0 & 1 & 1
\end{bmatrix}\begin{bmatrix}
DP1 \\
DP2 \\
DP3
\end{bmatrix}
\]

(1)

Among them: "1" indicates that there is an association relationship, and "0" indicates that the association relationship is weak or can be ignored.

When the functional requirements of the cutter FR are used as a criterion, the FRs-DPs comparison matrix \(PM^1\) under the criterion is obtained by using the analytic hierarchy process (AHP):

When the design parameter DP of the cutter device is used as the criterion, the DPs-FRs comparison matrix \(PM^2\) under the criterion is obtained by using the analytic hierarchy process (AHP):

\[
PM^1 = \begin{bmatrix}
0.7314 & 0.1995 & 0.1153 \\
0.1414 & 0.7648 & 0.1464 \\
0.1547 & 0.1308 & 0.7351
\end{bmatrix}
\]

\[
PM^2 = \begin{bmatrix}
0.7309 & 0.0881 & 0.1435 \\
0.0992 & 0.7110 & 0.1364 \\
0.1665 & 0.1218 & 0.7384
\end{bmatrix}
\]

Then, the geometric average of \(PM^1\) and \(PM^2\) is geometrically averaged and normalized to obtain the correlation coefficient matrix \(PM\) between FRs and DPs:

\[
PM = \begin{bmatrix}
0.7371 & 0.1390 & 0.1374 \\
0.1122 & 0.7289 & 0.1323 \\
0.1502 & 0.1321 & 0.7303
\end{bmatrix}
\]

(3)

Among them:

\[
PM_{ij} = \sqrt[n]{\frac{pm^1_{ij}pm^2_{ij}}{\sqrt{pm^1_{ij}pm^1_{ij}pm^2_{ij}pm^2_{ij}pm^1_{ij}pm^2_{ij}pm^2_{ij}pm^2_{ij}pm^1_{ij}pm^2_{ij}pm^2_{ij}}}n}
\]

(4)

The domain experts score the FR and DP in the above design equations. The results are illustrated in Table 1:

Then through the formula [19]

\[
R = \prod_{i=1,n-1}^{i=1,n-1} \left[ 1 - \frac{(\sum_{k=1}^{K}PM_{ki}PM_{kj})^2}{(\sum_{k=1}^{K}PM_{ki})^2(\sum_{k=1}^{K}PM_{kj})^2} \right] \quad S = \prod_{i=1}^{n} \frac{|PM_{ij}|}{(\sum_{k=1}^{K}PM_{ki})^{1/2}}
\]

(5)

Calculate the intersection angle \(R = 0.9764\), the angle similarity \(S = 0.9071\), use Pareto's rule and set the correlation degree threshold value \(\delta = 0.8\). According to the experience of cutting device design experts, satisfy \(R \geq \delta\) and \(S \geq \delta\), and satisfy the independence. The axiom of the cutter device is feasible.
Therefore, according to the hierarchical map structure of the cutter device case decomposition illustrated in Figure 3, and the mapped physical case sub-case database model, the corresponding cutter machine case is established. A case library of crushing device design is illustrated in Figure 4.

### Table 1. Scoring matrix between functional requirement FR and design parameter DP.

| Criterion DP | FR1 | FR2 | FR3 |
|--------------|-----|-----|-----|
| DP1          | 1/3 | 1/7 | 1/9 |
| DP2          | 3   | 1   | 1/5 |
| DP3          | 7   | 5   | 1   |

| Criterion FR | FR1  | FR2  | FR3  |
|--------------|------|------|------|
| R1           | 1/8  | 1/3  | 1/4  |
| FR2          | 3/5  | 7    | 1    |
| FR3          | 2    | 1/5  | 8    |

**Figure 3.** Cutter device case decomposition hierarchical mapping structure.

**Figure 4.** Cutter device case library structure.

### 3.2. Case-based reasoning

Table 2 shows the attribute parameters of the roller module, moving knife module, fixed knife module, and target scheme in the sub-case library of the cutter device of the silage feeder. First, use the Formula (1) to normalize the attribute values of each case [20], and then use them. Equation (6) finds the similarity between the parameter value of the case sub-module and the corresponding parameter value of the target solution (see Table 3), and then uses Equation (7) to find the similarity of the m-level cases (see Table 3). Finally, use Equation (8) to find the similarity between the cutter device sub-module case and the corresponding device of the target solution as $S = (0.623, 0.535, 0.721)$. From this, it can be obtained that the cutter device of XDNZ2008 is most consistent with the new product solution design. The designer can then modify and improve the product design based on the actual needs of the product and the relevant knowledge base.

$$
\begin{align*}
\alpha_{EPI} &= \frac{\alpha_{TVI}'}{\alpha_{EPI}'} \quad \alpha_{TVI} \leq \alpha_{EPI} \\
\bar{\alpha}_{EPI} &= \frac{\alpha_{EPI}'}{\alpha_{TVI}'} \quad \alpha_{EPI} \leq \alpha_{TVI}
\end{align*}
$$

(6)
Where $\alpha_{EPI}$ is the case parameter value and $\alpha_{TVI}$ is the target solution parameter value.

$$s_j(\beta_{TVI}, \beta_{EPI}) = \frac{\min \min \sum_{i=1}^{\min} [1 - \alpha_{EPI} + \beta_{max} \max_{i=1}^{\max} 1 - \alpha_{EPI}]}{1 - \alpha_{EPI} + \beta_{max} \max_{i=1}^{\max} 1 - \alpha_{EPI}}$$  \hspace{1cm} (7)

Among them $\alpha_{TVI}$ is the attribute value of the jth sub-case library of the case, $\alpha_{EPI}$ is the parameter value of the target solution, $\beta$ is the resolution coefficient, and is generally taken as 0.5.

**Table 2.** Cutter device case parameter values and target scheme parameter values.

| Weights | Sub-module | Weights | Main design parameters | Cases | Target plan |
|---------|------------|---------|------------------------|-------|-------------|
| 0.189   | Drum module | 0.2     | Diameter               | JAGUAR900 | John Deere8500 | XDNZ2008 |
|         |            |         |                        | Parameter value | Parameter value | Parameter value |
|         |            |         |                        | Similarity | Similarity | Similarity |
|         |            | 0.3     | Width                  | 630     | 660        | 600 |
|         |            |         |                        | 0.966    | 0.881      | 0.933 |
|         |            | 0.5     | Rotating speed         | 750     | 800        | 780 |
|         |            |         |                        | 0.871    | 0.783      | 0.814 |
|         |            |         |                        | 1200    | 1150       | 1200 |
|         |            |         |                        | 0.730    | 0.775      | 0.730 |
|         |            |         |                        | 1000     |            |            |
| 0.537   | Moving knife module | 0.3 | Number of moving knives | 24       | 40         | 20 |
|         |            |         |                        | 0.730    | 0.474      | 1 |
|         |            | 0.4     | Moving blade angle     | 25       | 20         | 25 |
|         |            |         |                        | 1        | 0.692      | 1 |
|         |            |         |                        | 1        | 0.700      | 25 |
| 0.390   | Fixed knife module | 0.5 | Fixed knife configuration height | 10       | 80         | 80 |
|         |            |         |                        | 0.333    | 0.333      | 0.692 |
|         |            | 0.3     | Fixed knife cutting gap | 0.6      | 0.8        | 0.4 |
|         |            |         |                        | 0.759    | 0.783      | 0.512 |
|         |            |         |                        | 1        | 0.7        | 0.7 |

$$S_j = \sum_{k=1}^{r} \omega_{ij}^m * s_j$$  \hspace{1cm} (8)

$\omega_{ij}^m$ is the corresponding weight, which is determined by professional design and process designers.

**Table 3.** Cutter device sub module similarity.

| Sub module | JAGUAR900 | John Deere8500 | XDNZ2008 |
|------------|-----------|----------------|----------|
| Drum module | 0.820     | 0.799          | 0.796    |
| Moving knife module | 0.619     | 0.419          | 0.700    |
| Fixed knife module | 0.347     | 0.407          | 0.500    |

**Figure 5.** System structure.

4. **Realization of intelligent design system of cutter device**

Figure 5 shows the system architecture of the intelligent design system of the cutter device, including the interface layer, the function layer and the tool layer. The tool layer consists of SolidWorks, Visual
Studio, SQL Server, and a Web server, and they provide development tools and data support for system building.

The functional layer includes the detailed parameter design module of the cutter device, the drive parameter design module, the engineering drawing generation module and the knowledge management module. The interface layer is the spot where the user interacts with the system. The system obtains the design parameter requirements which is entered by the user in the user interface, recommends the historical case with the highest similarity through the case reasoning module, and guides the scheme modification through the internal logic and operational rules set of the system. In order to obtain the target solution, so the user can input customized and diversified design personnel in the user interface to obtain the corresponding product design solution.

The customized design requirements are entered in the intelligent design system of the silage harvester, and the three-dimensional model was designed through the system, and then automatically converted into processing drawings, and finally processed by the agricultural machinery manufacturer. The trial production is illustrated in Figure 6. The similarity with the design requirements is 0.721, which can satisfy the corresponding design requirements, functional requirements and installation requirements.

![Figure 6. Cutter device prototype.](image)

5. Conclusions

This paper used axiomatic design theory to decompose the instance information, construct a cutter device-mapping model and design an instance library can realize the expression of complex product design, reduce the strong coupling relationship between sub-modules, and thereby improve the performance of case reasoning.

Matching and evaluation of the basic design parameters of the cutter device were achieved through a precise search method. This method can make the results of the case reasoning more accurate.

An intelligent design system for silage harvesters was developed and verified. A prototype of a cutter device was designed and manufactured. The system matching similarity was 0.721, and it could meet the customer's functional and design requirements.

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