Comprehensive evaluation and analysis of design scheme of automatic feeding and discharging device for freeze-drying system

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Abstract. In order to improve the reliability of the design scheme, objective design scheme evaluation methods were selected to the optimal scheme. According to the existing problems of the automatic feeding and discharging device prototype for the freeze-drying system, operator's actions which included disassembling and cleaning the device were simulated by the software of Siemens Tecnomatix Jack. The analysis results were verified and guided the design direction. Analytic hierarchy process, grey correlation analysis method, and combination of the above two methods were applied. Design scheme was determined according to the evaluation results. The results obtained schemes, design evaluation. According to the evaluation results, the first scheme was selected. It can be seen that gray correlation analysis is applied, and more objective manner is used to provide a reference.

1. Introduction

The freeze-drying system uses vacuum freeze-drying technology, which is a process system for drying substances under vacuum, aseptic and low temperature conditions. It is widely used in medicine, bioengineering, food and other fields. Automatic feeding and discharging device is an important part of freeze-drying system. The function is automatically pushing the substance into a lyophilizer to avoid operators contacting directly and to meet the aseptic conditions of the lyophilization process. The current market requires high requirements for the appearance and operation convenience of pharmaceutical equipment. In order to respond to the increasingly fierce competition in the international pharmaceutical market, the idea of industrial design needs to be introduced into the design and manufacture of pharmaceutical equipment to make it more satisfied with market demands. There are multiple factors that affect the choice of design options. Therefore, the paper uses the analytic hierarchy process and the grey correlation analysis method to effectively compensate for the shortcomings of using the single factor analysis to determine the optimal solution.

Generally, choosing the best scheme is completely determined by the subjective views of experienced experts. In order to avoid this kind of phenomenon, the paper introduced the software of Siemens Tecnomatix Jack to analysis and verify rationality of the design and used AHP and gray correlation analysis to choose the optimal solution objectively with the fixed automatic feeding and discharging device for freeze-drying system of Shanghai Tofflon Science & Technology Co., Ltd. as an example. According to the actual situation, the device was designed and analyzed comprehensively. The optimal program was selected in an objective manner.
2. Analysis of design objects

1) Environmental impact: The automatic feeding and discharging device of aseptic workshop of pharmaceutical factory requires high cleanliness. Thus the designed product surface should avoid uncleaned corners as much as possible.

2) The influence from operators: When operators perform conventionally maintenance or repair on the device, it should ensure that outer casing is easy to disassemble and damage of operator's body should be reduced.

3) Aesthetic influence: Automatic feeding and discharging device has good stability under working conditions, but market competitiveness is reduced due to the monotonous and tedious appearance. The prototype is only a simple cuboid, as shown in Figure 1. The product cannot change its raw materials because of the particular environment. It needs to change its shape through the lines to enhance design.

4) Other influence: In the design process, it is necessary to consider the difficulty of the actual production process and the difference of produced device between actual and expected effect.

3. Ergonomics simulation

Siemens Tecnomatix Jack software was used to analyze the action of disassembling and wiping the shell of device to make the design meet the requirements of the employees from pharmaceutical factory. According to the results of human body motion analysis, the prototype was designed to enhance aesthetics and more suitable for human operation. Rationality of the design scheme was verified.

3.1 Building human body models

Software of Siemens Tecnomatix Jack includes human body sizes of many countries. Most of the dismantling and maintenance work is done for men and the cleaning work is mostly for women at pharmaceutical factory. In order to meet the operational needs of most employees, the 95th percentile Chinese adult male and female body models were selected for analysis. At the same time, the model prototype was imported into the software.

3.2 Human analysis of operating the device

3.2.1 Action analysis of disassembling the shell of device

The automatic feeding and discharging device is connected to the barrier system through the left connecting plate. The operator's process of disassembling the shell is divided into two actions. In the first step, an operator stands at the right end of the device and pulls the casing to the right. In the second step, the operator presses the right end casing downward with the hand and the body. By analyzing the strength of main joints of the human body in the action of disassembling the outer casing, it was known that the average force received by the operator's waist was higher than other parts and the waist movement range was relatively large. In the subsequent design, it was necessary to consider the effect of the disassembling action on operator’s waist and the amplitude of waist should be minimized.
3.2.2 Action analysis of cleaning the shell of device
The software analyzed the operator's cleaning process, which used the palm as the analysis object to obtain the palm reachable domain. According to the analysis results, the cleaning area was much larger than the palm touching area. Thus the action of cleaning shell needed to be constantly changed. When the lower of the shell was cleaned in a kneeling position, the strength of the waist was relatively large in the force of body’s each part. In the design process, according to the analysis results, a part of the space can be cut to reduce the operating frequency and the cleaning time so that the cleaning work can be completed more efficiently and easily.

3.3 Design scheme and analysis

3.3.1 Design scheme
The original device has a lot of free space, because there are only push rods and motors inside. Therefore, the shell shape can be optimized based on the results of simulation and internal structure of the device. It can be seen that bottom right corner of the device can be changed.

When the space in the right corner was removed, the palm can be directly contacting the added surface, which reduced the fatigue of the operator's palm. By the fixed position where the palm was placed on the shell, bending angle of waist and waist damage caused by the disassembling action can be reduced. The amount of cleaning time in a kneeling position was reduced, which reduced damage to the waist. The total area of the outer casing was reduced, which also reduced operator movement.

Four schemes of automatic feeding and discharging device were designed. There were still some differences between the four design schemes in terms of satisfying the two factors of easy maintenance and easy cleaning. Due to the work state of device should be stable and smooth, the design of the scheme was based on the design concepts of “simple”, “stable”, “dynamic” and “scientific sense of technology”. Option 1 has enough internal space for moving pushing rods. The feeling of overall design has a delicate and full feeling by using round chamfer. Option 2 changes the position of the device’ leg and uses the flow curve to show the sense of movement. Option 3 shows the sense of stability of the equipment with a tough line. Option 4 cancels the device’ leg and connects directly to the left support plate, but the shortcoming of this scheme is weak stability. The design modeling presents different styles with great sense of design.

3.3.2 Design analysis and verification
Four designs were validated to ensure that waist stress had been reduced. The four schemes were imported into the software, and the motion simulation analysis was performed on disassembling the device. When the operator disassembled the prototype shell of the device, the average maximum force of the trunk flex was 400 Nm. After the improvement, the average maximum force of the trunk flex is 300 Nm as shown in Figure 2. It can be seen that the four design schemes enhance the protection of the operator's waist, so the four design schemes meet the operational requirements.

4. Comprehensive evaluation of design scheme
It is necessary to comprehensively consider the influence of the four factors in selecting the optimal program which includes aesthetics, easy production, easy maintenance and easy cleaning. However, each factor has different influence level with different experts’ opinions on the selection of the optimal solution. Therefore, the evaluation of the scheme adopted analytic hierarchy process, grey correlation analysis and combination of the above two methods. Another method was used for the evaluation of the program. In order to ensure comparability of the results, the four comparison methods had the same relative score because of same attitude for each influencing factor and scheme. Five experts in relevant fields were invited to use the different methods to evaluate the design schemes including two experts specializing in industrial design, two mechanical design experts who designed the structure of automatic feeding and discharging device, and one middle leader of production department, recorded as B={B₁, B₂, B₃, B₄, B₅}.
4.1 Analytic hierarchy process

The problem can be analyzed by multiple objective decision making in the analytic hierarchy process. The factors affecting the evaluators were regarded as the decision criterion, and the optimal plan was regarded as the decision objective.

4.1.1 Establish a hierarchical structure model of the system

Selecting optimal plan was based on five experts’ opinions. Five experts had their own opinions on the importance of the four influencing factors. The four factors affected selection result. The model of hierarchical structure shown in Figure 3 was established.

4.1.2 Obtaining the weight coefficient of the influencing factors

In the evaluation, the five experts had the same weight for selecting the optimal solution, and the judgment matrix was constructed from the second level. The 1-5 scale ratio method was used to construct the judgment matrix of each expert on the importance of the influencing factors. According to the method, the judgment matrices were normalize. The matrix $F_i$ was obtained.

$$q_{ij} = \frac{E_{ij}}{\sum_{i=1}^{5} E_{ij}}$$

In equation (1), $E_{ij}$ is the score from the expert for the i-th factor compared with the j-th factor, and $q_{ij}$ is the normalized value of the matrix.
The eigenvector of the calculation matrix $F_i$ was $G_i=(0.4768, 0.2262, 0.1076, 0.1895)^T$. In order to ensure the rationality of the evaluation results, matrix consistency was judged, and used the formula (2) to calculate the maximum characteristic root $\lambda_{max}=4.2191$ of the judgment matrix.

$$\lambda_{max} = \frac{1}{m} \sum_{i=1}^{n} (AG)_{ii}$$  \hspace{1cm} (2)

In the formula, $(AG)_{ii}$ is the product of the eigenvector and the judgment matrix. According to looking up the table, the fourth-order matrix consistency index is $RI=0.89$, and the formula (3) was used to judge whether the $CR$ satisfies less than 0.1, $CR_1=0.0821<0.1$.

$$CR = \frac{CI}{RI}$$  \hspace{1cm} (3)

In the formula, $CI$ is $CI = \frac{\lambda_{max} - n}{n - 1}$.

In the same way, the eigenvectors of the five experts for the evaluation of each influencing factor were obtained, and the values all meet the consistency requirements.

$G_2=(0.4745, 0.0904, 0.1561, 0.2791)^T, \lambda_{max}=4.2483, CR=0.0930<0.1$
$G_3=(0.1833, 0.3998, 0.3038, 0.1131)^T, \lambda_{max}=4.2490, CR=0.0933<0.1$
$G_4=(0.3472, 0.2361, 0.3333, 0.1579)^T, \lambda_{max}=4.1181, CR=0.0442<0.1$

Then the weighting coefficients of the four influencing factors to the four schemes by the five experts were obtained.

### 4.1.3 Hierarchical ordering and consistency check

Using the formulas (1), (2), and (3), the results got the evaluation results of the aesthetics about the four schemes from five experts, the maximum eigenvalue $\lambda_{max}$ of the judgment matrix, and the consistency test. The results are shown in Table 1. The eigenvector of the first expert of the other three factors were got.

H1=(0.5117, 0.2378, 0.1725, 0.0780)^T, $\lambda_{max}=4.1050, CR=0.0393<0.1$
H2=(0.4118, 0.2930, 0.1872, 0.1080)^T, $\lambda_{max}=4.0709, CR=0.0266<0.1$
H3=(0.4231, 0.1225, 0.2272, 0.2272)^T, $\lambda_{max}=4.0104, CR=0.0039<0.1$

Table 1. The evaluation of aesthetic design from five experts

|       | B1   | B2   | B3   | B4   | B5   |
|-------|------|------|------|------|------|
| D1    | 0.0736 | 0.0994 | 0.1413 | 0.1951 | 0.3708 |
| D2    | 0.1715 | 0.2101 | 0.3937 | 0.1951 | 0.1514 |
| D3    | 0.2840 | 0.3452 | 0.2325 | 0.4915 | 0.3708 |
| D4    | 0.4709 | 0.3452 | 0.2325 | 0.1184 | 0.1069 |
| $\lambda_{max}$ | 4.0514 | 4.0611 | 4.0607 | 4.0607 | 4.0613 |
| CR    | 0.0192 | 0.0229 | 0.0227 | 0.0227 | 0.0230 |

In the same way, the evaluated results of the four design schemes, multiply the weight coefficients of each influencing factor and the corresponding evaluation indicators were got. The arithmetic mean was obtained by the expert's hierarchical ranking of the four design schemes. The results are shown in Table 2.

Table 2. Total hierarchy permutation of each scheme

|       | B1   | B2   | B3   | B4   | B5   |
|-------|------|------|------|------|------|
| D1    | 0.2753 | 0.1903 | 0.2376 | 0.2968 |
| D2    | 0.223  | 0.1687 | 0.2409 | 0.2503 |
| D3    | 0.2947 | 0.2605 | 0.2459 | 0.1989 |
According to the results, the obtained evaluation results of each scheme by the analytic hierarchy process were $K_1=0.31>K_3=0.2572>K_4=0.2054>K_2=0.204$. The obtained results from this method showed that the optimal solution was the first scheme.

4.2 Grey correlation analysis
There are many factors that influence the choice of the optimal design, and the accumulation of various factors will interfere with the choice of the program. The gray correlation analysis method was used to obtain the optimal scheme through obtaining the correlation degree among the influencing factors.

4.2.1 Grey correlation analysis to determine weight coefficient
Five experts scored 1-9 points for each factor according to the requirements, recorded as $L_i$. The best scores of each influencing factor were used as reference sequences, recorded as $L_0=\{8, 9, 9, 9\}$. The raw datas were made indexes being dimensionless. Since there was no obvious up-and-down trend between the datas, the datas were calculated by the homogenization method through the formula (4).

$$L'_i = \frac{L_i(k)}{\frac{1}{n-1} \sum_{j=1}^{n} L_j(k)}$$ (4)

The reference sequence after the above processing was $L'_0=\{0.9143,1.0286, 1.0286, 1.0286\}$, and the comparison sequence was $L'_1=\{L'_{11}, L'_{12}, \ldots, L'_{1n}\}$, $i=1, 2, \ldots, m$, $j=1, 2, \ldots, n$. By calculating the difference between the reference sequence and the comparison sequence, the maximum difference $\Delta_{(\text{max})}=0.7060$ and the minimum difference $\Delta_{(\text{min})}=0.0052$ between the two sequences were obtained. To avoid the reference difference of the data gap was too large, the $\rho=0.2$ was taken. The obtained weights of the influence factors above were taken to the formula(5) to get the correlation coefficient.

$$R_q(k) = \frac{\min \min \left| X_q(k) - X_i(k) \right| + \rho \cdot \max \max \left[ X_i(k) - X_q(k) \right]}{X_q(k) - X_i(k) + \rho \cdot \max \max \left[ X_q(k) - X_i(k) \right]}$$ (5)

The degree of association was represented by decentralized datas. In order to make its information appear in a more concentrated form, the correlation $R_q(k)$ between the comparison series and the reference series was calculated by using equation (6). Based on the obtained degree of correlation, the weighting factors of the impact factors were determined as $O=\{0.6317, 0.3609, 0.4453, 0.6747\}$, as shown in Table 3.

$$R_q(k) = W_i^k \frac{1}{n} \sum_{i=1}^{n} R_i(k)$$ (6)

| $R_q(k)$ | $W_i^k \frac{1}{n} \sum_{i=1}^{n} R_i(k)$ |
| --- | --- |
| $C_1$ | $C_2$ | $C_3$ | $C_4$ |
| $B_1$ | 0.6317 | 0.3609 | 0.4453 | 0.6477 |
| $B_2$ | 0.3502 | 0.1747 | 0.3336 | 0.1415 |
| $B_3$ | 0.4066 | 0.226 | 0.2797 | 0.1394 |
| $B_4$ | 0.4066 | 0.226 | 0.2797 | 0.1394 |
| $B_5$ | 0.3335 | 0.2595 | 0.5730 | 0.4932 |
| $B_6$ | 0.3335 | 0.4030 | 0.4683 | 0.5886 |
| $B_7$ | 0.3335 | 0.4030 | 0.4683 | 0.5886 |
| Weight Coefficient | 0.6317 | 0.3609 | 0.4453 | 0.6477 |

4.2.2 Grey correlation analysis method to choose the best scheme
The correlation coefficient was the product of the correlation degree of each design scheme under the influence of each factor by five experts times the weight coefficient corresponding to each factor. The evaluation results of each scheme obtained by the gray correlation analysis
method were $P_1=0.1913>P_4=0.1781>P_2=0.1670>P_3=0.1618$. The results showed that the optimal solution was the first scheme.

4.3 Combination of analytic hierarchy process and grey relational degree analysis
The evaluation was combined with the above analytic hierarchy process and gray correlation analysis to obtain the weight coefficient of each factor, and then calculated the optimal scheme.

4.3.1 Analytic hierarchy process to obtain weight coefficient
The weight coefficient of each factor can directly adopt the above weight coefficient $G_{ij}$ and the optimal scheme can be selected by the results of the gray correlation degree analysis. The data was calculated according to the formulas (4), (5), and (6), and the correlation coefficient and the degree of association were obtained.

The analytic hierarchy process calculated the weight coefficients. The above results combined with the gray correlation analysis method. The evaluation results of each scheme were $S_1=0.1011>S_4=0.0931>S_2=0.0777>S_3=0.0770$. The results showed that the optimal solution was the first scheme.

4.3.2 Grey correlation analysis method obtains weight coefficient
The weight coefficient $O=[0.6317, 0.3609, 0.4453, 0.6477]$ was obtained by applying above result of the gray correlation analysis. The analytic hierarchy process was used to select the optimal solution. The results are shown in Table 4.

Table 4. Evaluation results of weight coefficient obtained by grey correlation analysis

|      | D1     | D2     | D3     | D4     |
|------|--------|--------|--------|--------|
| B1   | 1.4524 | 0.8288 | 0.8633 | 0.8555 |
| B2   | 1.1108 | 0.6667 | 0.7457 | 0.7055 |
| B3   | 1.2054 | 0.9979 | 0.9385 | 0.8582 |
| B4   | 1.5112 | 0.6995 | 1.2141 | 0.5753 |
| B5   | 1.5795 | 0.8333 | 1.004  | 0.5832 |
| Evaluation Results | 1.3718 | 0.8052 | 0.9531 | 0.7155 |

According to the results, the evaluation result obtained by this method was $T_1=1.3718>T_3=0.9531>T_2=0.8052>T_4=0.7155$. The optimal solution was the first scheme.

4.4 Comparative analysis of evaluation results
Comparing the four evaluation results, we can see that although the four evaluation methods indicate that the first one is the optimal design but the evaluation of the other three design schemes is different, as shown in Table 5. There may be some reasons below caused the phenomenon. First, raw datas obtained by the analytic hierarchy process are comparison values. The obtained datas by the grey correlation analysis are the evaluation value of each element by the evaluator. Differences in the evaluation datas between the two methods may result in differences. Second, the original datas are evaluated by experts according to their own experience. In the evaluation, only 5 experts are invited. Number of datas are limited. Third, the evaluation is based on the same weight of evaluation by experts. However, due to the different levels of experience of the experts, there will be some differences in the recognition of the weight of evaluation.

The obtained comparative datas by the analytic method are more subjective. Therefore, gray correlation analysis can be applied to increase the objectivity of the results.

Table 5. Comparison of evaluation results obtained by four Methods

|      | 1       | 2       | 3       | 4       |
|------|---------|---------|---------|---------|
| AHP  | $K_1=0.3100$ | $K_2=0.2572$ | $K_3=0.2054$ | $K_4=0.2040$ |
| Grey correlation analysis | $P_1=0.1913$ | $P_2=0.1781$ | $P_3=0.1670$ | $P_4=0.1618$ |
| Evaluation results of weight coefficient obtained by AHP | $S_1=0.1011$ | $S_2=0.0931$ | $S_3=0.0777$ | $S_4=0.0770$ |
Evaluation results of weight coefficient obtained by grey correlation analysis

|  | T₁=1.3718 | T₂=0.9531 | T₃=0.8052 | T₄=0.7155 |

5. Conclusion
At the first, the factors were analyzed to select scheme of automatic feed and discharge device. Then, the software of Siemens Tecnomatix Jack was used to analyze and verify the design direction and the rationality of the human-related factors. Finally, the selecting optimal scheme had used AHP, gray correlation analysis and combination of the two methods. The following conclusions were obtained through the design of the device and the selection of the optimal scheme.

1) Four evaluation methods indicate that the first option is the best one.
2) The subsequent design direction can be obtained to analyze the prototype of the product using human-machine simulation software of Siemens Tecnomatix Jack.
3) The study comprehensively evaluates and analyzes the design in a quantitative manner. The application of grey correlation analysis can minimize the interference of individual subjective factors on the program determination.
4) The study does not cover all the influencing factors that affect the design of automatic feed and discharge device in the actual design and production process. There is less raw data. The weight of evaluators are the same. Therefore, the reason of different results can be further discussed.

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