Research Article

Reconfigurability Evaluation of Multifunctional Intelligent Boom Sprayer Based on Fuzzy Comprehensive Evaluation

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Multifunctional intelligent boom sprayer is a development direction of boom sprayers, and it could satisfy needs of precision and variable spraying and achieve aims of sustainable development of pesticide spraying, ecological protection, and efficient plant protection by reconfiguring its structures. Therefore, the evaluation of multifunctional intelligent boom sprayer reconfigurability has a role in improving product reconfigurability while reducing product function redundancy and production costs and reducing product function redundancy and production cost. In order to comprehensively evaluate the reconfigurability of a multifunctional intelligent boom sprayer, this paper established an evaluation index system and realized the evaluation process by using fuzzy comprehensive evaluation, analytic hierarchy process, and validity test. The evaluation result would avail to directly and effectively guide product optimization and upgrade process in accordance with quantitatively analyzed evaluation indexes of intelligent boom sprayer reconfigurability by using mathematical methods such as analytic hierarchy process and validity test in evaluation process. The index system was formed from six components, which were key design information, quality, cost, efficiency, intelligence, and operational capability. Index weights were calculated by the analytic hierarchy process. Finally, a multifunctional shiftable boom intelligent sprayer was evaluated for product reconfigurability improvements by using the evaluation method. Reconfigurability evaluation result of the multifunctional shiftable boom intelligent sprayer belonged to "good" evaluation interval by the calculation of formulas. There was further room to improve product reconfigurability, as the membership degree in the "good" evaluation interval was below 0.5. The study could provide a scientific basis for improving the reconfigurability, technical performance, and operation quality of products in intelligent boom sprayer design. In addition, it may be possible to decrease the arbitrary nature of subjective design factors and support economic and ecological goals when businesses upgrade products.

1. Introduction

Reconfigurable system is the one that can change its configuration dynamically in response to changes in conditions in order to achieve operational requirements [1]. Reconfigurable systems can help to improve the versatility and adaptability of agricultural machinery in complex, diverse operating environments. With the adjustment of the scale structure of farmland in China, the proportion of boom sprayers used to prevent and control large-scale crop pests and diseases has increased to meet pest control and defoliant spraying needs [2]. Therefore, it is a development trend about boom sprayers, which is to develop an intelligent boom sprayer that can meet the individual needs of farmers, realize the intelligence of boom sprayers, and achieve the

requirements of the reconfigurable system. IBS, intelligent boom sprayer, should be able to adapt to the precise, variable pesticide, water, and fertilizer application requirements associated with various working environments and objectives through the reconfiguration of its software/hardware modules. IBS adapts to the requirements of the reconfigurable system and pays attention to the sustainable development of the ecological environment while reducing the total cost of products and improving the economic benefits of the products. There are boom-transformable sprayers, variable spray boom sprayers, profiling sprayers, unmanned sprayers, and so on, belonging to IBS with various degrees of intelligence. Therefore, IBS is to use new intelligent technologies to improve and develop the existing boom sprayers to achieve product reconfiguration. The reconfigurability of

IBS is a key index to realize its capabilities. The research on the IBS reconfigurable system assessment can provide a new research idea and executable method to evaluate the reconfigurability of IBS and provide technical support for the IBS rapidly improving development.

At present, boom sprayer evaluation is focused primarily on its adaptive evaluation [3] and considers the effects of specific boom sprayer functions [2, 4–10]. In contrast, there are relatively few studies that consider boom sprayer reconfigurability and engineering.

Therefore, this paper seeks to develop an IBS reconfigurability evaluation index that considers the external application effects, internal structural engineering, product economics, etc. to provide a comprehensive, objective, and scientific evaluation system. Meanwhile, the evaluation index system should achieve the requirement which can help people in different fields related to IBS, especially product users, to participate in the evaluation process, so that the product can adapt to market changes. The IBS reconfigurability evaluation may be achieved by applying fuzzy comprehensive evaluation to the evaluation index system. In the process, the index weight could be decided by using the analytic hierarchy process. We would use a validity test to ensure the validity of the evaluation results. The evaluation results could clearly reflect the probability value of reconfigurability evaluation in different result domains by using the mathematical methods such as analytic hierarchy process and validity test of the evaluation process. The study can provide a scientific basis for improving the reconfigurability of IBS and also provide directing guidance for enterprises to optimize the product process. It could avoid fuzzy or qualitative evaluation results and lead designers to optimize and upgrade a product module in ambiguous judgement environment. Finally, it is proposed to establish an IBS reconfigurability evaluation system for evaluating and improving products reconfigurability.

2. Analysis of Reconfigurability Evaluation Index on IBS

In order to comprehensively and scientifically evaluate the reconfigurability of IBS, the IBS reconfigurability evaluation index system needs to be constructed for researching the scientific and reasonable evaluation method. In the process, the validity test and index weight determination would be studied.

2.1. Business Impact Analysis Model of Brownfield Process.
BfP, Brownfield Process, is a product development approach for modular product families that focuses on product configuration and emphasizes reuse of existing resources and standardized applications while rationalizing product diversity [11]. BfP considers key engineering concepts comprehensively while other design methods consider them only partially or in various combinations. These key engineering concepts include partitioning logic, set of modules, interfaces, architecture, and configuration knowledge. These are indispensable for modular product family development

[12]. BIA, business impact analysis, describes the interrelationships between key engineering concepts, supports the guidelines and mechanisms for the rationalization of manufacturing industrial product diversity and general manufacturing processes, and reflects the maximum benefit evaluation of modular systems in BfP [11]. In order to reflect the completeness of key product design information, the IBS reconfigurability evaluation index system was constructed based on BIA.

2.2. Construction of IBS Reconfigurability Evaluation Index System.
The evaluation index system comprehensively reflects the IBS reconfigurability based on the principles of comprehensiveness, comparability, scientificity, and practicability. The IBS reconfigurability evaluation index was constructed by combing with the relevant standards of boom sprayers [13–16] and the connotation of IBS and the BIA model, which is based on the evaluation index of the existing boom sprayers. It has focused on standardization and resource reuse. The reconfigurability evaluation indexes also focused on the concept of standardization and resource reuse in enterprises. The IBS reconfigurability evaluation index architecture model was divided into three layers. The target layer was IBS reconfigurability evaluation. The criterion layer (first-level index) included six components, key design information (partitioning logic, set of modules, interfaces, architecture, and configuration knowledge), quality, cost, benefit, intelligence, and operational capability. The relevant program layer content (secondary-level index) is shown in Figure 1, and the relevant technical indexes are explained in Table 1.

2.3. Fuzzy Comprehensive Evaluation Process and Analytic Hierarchy Process.
In systems engineering, fuzzy comprehensive evaluation is a practical method designed to quantify empirical results in complex systematic evaluation conditions by combining multiple indexes with quantitative and qualitative results [13]. Index weights are determined via an analytic hierarchy process. The evaluation process is as follows [18–26]:

(1) $F = \{F_1, F_2, \ldots, F_i\}$, and the established factor domains are a set of evaluation indexes which indicate that F_i, the first-level indexes, needs to be evaluated. In this context, $i = 1, 2, \ldots, n$. At the same time, the secondary indexes included in each F_i are represented by C_{ij}, where $j = 1, 2, \ldots, m$.

(2) $E = \{E_1, E_2, \ldots, E_k\}$ represents the established result domains, which includes a set of evaluation levels. In order to avoid excessive invalidation of the evaluation grade division granularity, $E = \{$very good, good, general, bad$\}$ is taken as the result domain for IBS reconfigurability evaluation and $k = 1, 2, \ldots, 4$. The "very good" percentile interval is [90, 100], the "good" percentile interval is [75, 90], the "general" percentile interval is [60, 75], and the "bad" percentile interval is [0, 60] [25].
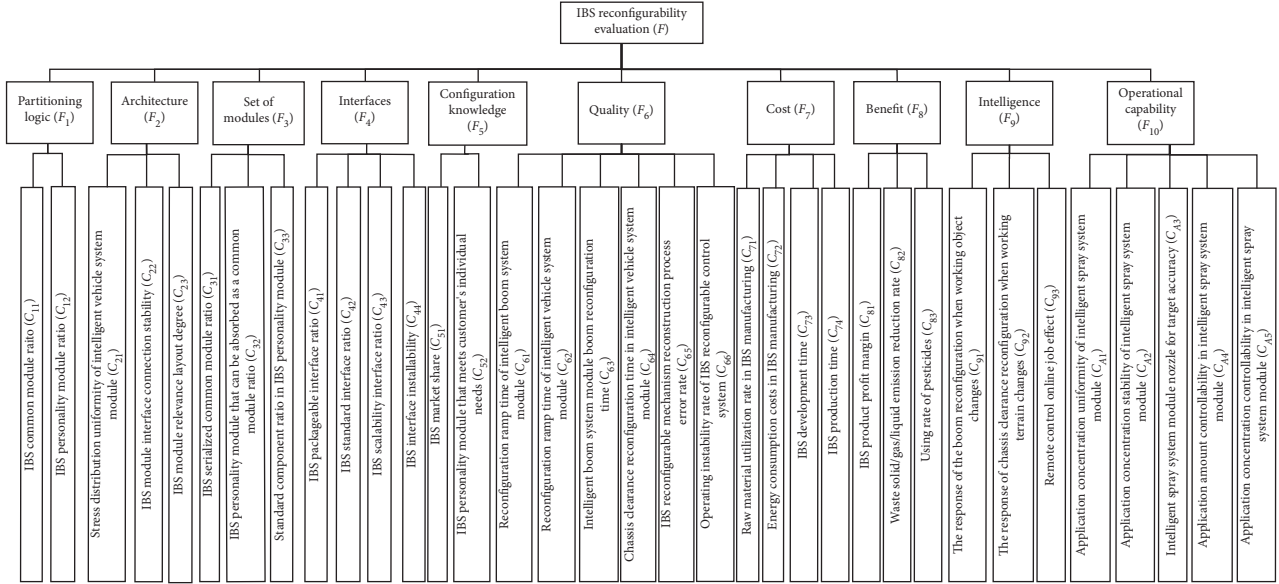
FIGURE 1: Evaluation index system. The evaluation index system includes target, criterion, and program layers.

(3) $R = \{R_1, R_2, \ldots, R_i\}^T$ is the established membership matrix. $r_{ijk} = (E_{ijk}/n)$ in $R_i = (r_{ij1}, r_{ij2}, \ldots, r_{ijk})$, membership degree, is the mean of the probability that the n evaluation subjects achieve rating E_k in terms of C_{ij} and $\sum_{k=1}^{4} r_{ijk} = 1$, where n is the number of experts.

(4) T is the evaluation index weight and is established using analytic hierarchy process. A is the comparison matrix and is established by applying Delphi method to the evaluation system hierarchy model. The scoring rules are determined in accordanc with the importance of the former relative to the latter. A score of 1 indicates the same importance, a score of up to 9 indicates that the former is more important than the latter, and a score of less than 1 indicates that the latter is more important than the former. a_{st} is the score value in A. $W_i = (W_1, W_2, \ldots, W_s)^T$, the hierarchical single sort result, is determined by equations (1) and (2), the maximum eigenvalue λ_{max} is determined by equation (3), and the consistency check is determined by equations (4) and (5).

$$W_s = \frac{w_s}{\sum_{s=1}^{j} (w_s)}, \qquad (1)$$

$$w_s = \sqrt[j]{\prod_{t=1}^{j} a_{st}} \quad s = 1, 2, \ldots, j, \qquad (2)$$

$$\lambda_{max} = \frac{1}{j} \sum_{s=1}^{j} \frac{(AW)_s}{W_s}, \qquad (3)$$

$$CI = \frac{\lambda_{max} - j_{max}}{j_{max} - 1}, \qquad (4)$$

$$CR = \frac{CI}{RI} < 0.1. \qquad (5)$$

RI is the average random consistency index. CI is the consistency index. CR is the consistency ratio. If CI = 0, the comparison matrix is completely consistent; if CI $\neq$ 0, but equation (5) is satisfied, the matrix has satisfactory consistency, and the comparison matrix is acceptable. If equation (5) is not satisfied, the comparison matrix must be modified until equation (5) becomes satisfied. RI can be selected according to Table 2 [16]. j_{max} is the total number of secondary indexes under the first-level indexes F_i. Finally, a consistency check of the resulting total hierarchical ranking is performed such that the inspection process is consistent with the single-level consistency test. After passing the test, the evaluation index weight T, $T = (T_1, T_2, \ldots, T_i)$, can be obtained. When calculating the weight of the first-level indexes, j takes the value i, and j_{max} is the maximum value of i in equations (1)–(4).

(5) Fuzzy comprehensive evaluation includes evaluation of target level, first-level index, and second-level index. First, the secondary index levels should be evaluated, and the percentage of the secondary indexes $V_{C_{ij}}$ should be determined by equation (6). E_{mid} is the mean value of percentile intervals in E. Second, the comprehensive evaluation vector B_i of the first-level index is obtained using equation (7). Finally, the comprehensive evaluation vector B of the target level is obtained using equation (8). The comprehensive evaluation vector identifies indexes that need to be improved. Corresponding improvement plans can be formulated to avoid blind optimization and upgrade of products and improve the reconfigurability and quality of IBS.

Table 1: Interpretation of indexes.

Target	First-level index	Secondary-level index	Paraphrase
IBS reconfigurability evaluation (F)	Partitioning logic (F_1)	IBS common module ratio (C_{11})	C_{11} = number of common modules/total number of modules; this reflects the impacts of existing resources on the product structure
		IBS personality module ratio (C_{12})	C_{12} = number of personality modules/total number of modules; this reflects the impacts of customer personality requirements on product structure
		Stress distribution uniformity of the intelligent vehicle system module (C_{21})	This reflects the rationality of the module load distribution
	Architecture (F_2)	IBS module interface connection stability (C_{22})	This reflects the patency of energy and information transfer between modules and the robustness of the connections between modules
		IBS module relevance layout degree (C_{23})	This reflects the extent to which the module is laid out by relevance
		IBS serialized common module ratio (C_{31})	C_{31} = number of serialized modules/total number of modules; this reflects the degree of module serialization
	Set of modules (F_3)	IBS personality module that can be absorbed as a common module ratio (C_{32})	C_{32} = number of personality modules that can be absorbed as common modules/total number of modules; this reflects the development trend of customer personality needs
		Standard component ratio in IBS personality module (C_{33})	C_{33} = number of standard components in personality modules/total number of components in personality modules; this reflects the reuse of existing resources in the development of personality modules
		IBS packageable interface ratio (C_{41})	C_{41} = number of packageable interfaces/total number of interfaces; this reflects the quality of the interface
	Interfaces (F_4)	IBS standard interface ratio (C_{42})	C_{42} = number of standard interfaces/total number of interfaces; this reflects the reuse of existing resources in the interface
		IBS scalability interface ratio (C_{43})	C_{43} = number of scalability interfaces/total number of interfaces; this reflects the degree of functionality scalability
		IBS interface installability (C_{44})	This reflects the ease of operation such as module replacement and maintenance
	Configuration knowledge (F_5)	IBS market share (C_{51})	The percentage of market share in similar products that reflect the degree of response to market changes
		IBS personality module that meets customers' individual needs (C_{52})	This primarily reflects the response of product to market changes
		Reconfiguration ramp time of intelligent boom system module (C_{61})	This reflects the time from the completion of boom reconfiguration to the stabilization operation
		Intelligent boom system module boom reconfiguration time (C_{62})	This reflects the time from the completion of chassis reconfiguration to the stabilization operation
		Reconfiguration ramp time of intelligent vehicle system module (C_{63})	This reflects the time required for the boom to move from one configuration to another
	Quality (F_6)	Chassis clearance reconfiguration time in intelligent vehicle system module (C_{64})	This reflects the time for the chassis to go from one height to another
		IBS reconfigurable mechanism reconstruction process error rate (C_{65})	C_{65} = number of scalability interfaces/total number of interfaces; this reflects the probability of a fault or problem during the reconfiguration of the boom
		Operating instability rate of IBS reconfigurable control system (C_{66})	The operational instability of the intelligent sprayer is reflected primarily in the droplet drift performance during IBS operation. C_{66} = (spraying the total mass of the droplet – amount of precipitation)/spraying the total mass of the droplet
	Cost (F_7)	Raw material utilization rate in IBS manufacturing (C_{71})	C_{71} = usage amount of raw materials and existing materials/total usage amount of materials; this reflects the use of raw materials and the reuse of existing materials
		Energy consumption costs in IBS manufacturing (C_{72})	This reflects the consumption of energy and the utilization of existing process equipment
		IBS development time (C_{73})	This refers primarily to the time spent on developing designs and reflects the reuse of existing design files
		IBS production time (C_{74})	This refers primarily to the time spent on manufacturing and reflects the reuse of existing processes
		IBS product profit margin (C_{81})	The ratio of IBS product profit to total cost
	Benefit (F_8)	Waste solid/gas/liquid emission reduction rate (C_{82})	C_{82} = (previous waste discharge amount – current waste discharge amount)/previous waste discharge amount; this reflects the degree of contribution by the IBS to reducing environmental pollution and greenhouse gas emissions
		Using rate of pesticides (C_{83})	C_{83} = amount of pesticide deposited on crops/total amount of pesticide use × average leaf area with pesticides/average leaf area; this reflects the extent to which IBS contributes to ecological conservation by improving overall pesticide use and the effective pesticide utilization rate
		The response of the boom reconfiguration when working object changes (C_{91})	This reflects the ability of IBS to intelligently configure the boom to work normally when working objectives change
	Intelligence (F_9)	The response of chassis clearance reconfiguration when working terrain changes (C_{92})	This reflects to the ability of IBS that intelligently configurate the chassis to make it work properly as the topography changes
		Remote control online job effect (C_{93})	This reflects the ability of multiple IBS products to operate remotely under unmanned conditions during pesticide application
		Application concentration uniformity of intelligent spray system module (C_{A1})	$C_{A1} = 1 - \left(\sum_{i=1}^{N} |x_i - \overline{x}| / N\overline{x} \right)$; this reflects the degree of uniformity of pesticide in the application effect based on principle of variance calculation [17]. x_i is the ith pesticide coverage measurement value. $\overline{x}$ is the mean value of x_i. N is the number of test points
	Operational capability (F_{10})	Application concentration stability of intelligent spray system module (C_{A2})	This reflects the ability of the spray concentration to stabilize within a particular range during application
		Intelligent spray system module nozzle for target accuracy (C_{A3})	This reflects to the ability to apply pesticide only to the target
		Application amount controllability in intelligent spray system module (C_{A4})	This reflects to the ability to adjust the spray amount based on relevant disease, insect, or grass information during application
		Application concentration controllability in intelligent spray system module (C_{A5})	This reflects to the ability to adjust the spray agent concentration for various application targets such as diseases, worms, and grass when the application objective changes

TABLE 2: Average random index [16].

n	1	2	3	4	5	6	7	8	9	10	11	12	13	14
RI	0	0	0.52	0.89	1.12	1.26	1.36	1.41	1.46	1.49	1.52	1.54	1.56	1.58

$$V_{C_{ij}} = R_{ij} \cdot E_{\mathrm{mid}}^T, \tag{6}$$

$$B_i = W_i^T \cdot R_i, \tag{7}$$

$$B = T \cdot \left(B_1, B_2, \ldots, B_i\right)^T. \tag{8}$$

2.4. Validity Test Process. The maximum membership degree principle, which is typically followed during comprehensive evaluation vector processing, may be invalid under certain conditions [26]. Therefore, some mathematics researchers have proposed the maximum membership validity test method, as shown in the following equation [23–25, 27]:

$$\alpha = \frac{(n\beta - 1)}{(2\gamma(n-1))}. \tag{9}$$

In equation (9), α is the result of validity test. If $\alpha = +\infty$, the maximum membership degree principle is completely valid; if $1 \leq \alpha < +\infty$, the maximum membership degree principle is highly effective; if $0.5 \leq \alpha < 1$, the maximum membership degree principle is generally effective; if $0 \leq \alpha < 0.5$, the maximum membership degree principle is minimally effective; and if $\alpha = 0$, the maximum membership degree principle is completely invalid. In this equation, n is the elements number of E; β is the maximum membership degree in B; and γ is the maximum membership degree after β is removed from B.

The validity test is then quantified because the valuation result cannot be judged accurately when $\alpha < 0.5$ or $\alpha = 0$. The steps of quantification process are as follows [25]:

(1) The highest score, S_H, and lowest score, S_L, from the final comments are calculated, as shown in the following equations:

$$S_H = B \cdot E_{KH}, \tag{10}$$

$$S_L = B \cdot E_{KL}, \tag{11}$$

where E_{KH} and E_{KL} are the maximum and minimum in each percentile interval E_K.

(2) The interval length L is calculated as shown in the following equation:

$$L = S_H - S_L. \tag{12}$$

(3) The probability of the evaluation results in each percentile interval, P_K, is calculated as shown in equation (13). L_K evaluation result interval length for each percentile interval E_K.

$$P_K = \frac{L_K}{L}. \tag{13}$$

(4) The evaluation result based on $\max P_K$ is determined.

2.5. Index Weight Determination. The weights in the evaluation index system are calculated by using the content of process (4) in Section 2.3. A group of 13 researchers [27], who understood the concepts of IBS and reconfigurable theory participated in the index weight determination process by referencing the Delphi method. The first-level factors index weights could be confirmed in accordance with these researchers' opinions and process (4) in Section 2.3, as shown in Table 3.

In this manner, weights of other indexes were obtained. The calculation results are shown in Table 4.

3. Case Study

The multifunctional shiftable boom intelligent sprayer developed by the research group is a typical IBS that can meet the target operation requirements of field pest control for field crops, hedge crops, fruit trees, and forests. It can reconfigure the tractor chassis structure to meet plant protection requirements for various crop types and plant heights via dynamic adjustment of product operation parameters within a given range in response to changes in objectives or operating conditions. The multifunctional shiftable boom intelligent sprayer can solve the problem of mechanization, specialization, and intelligence of pest control in a variety of business models with limited scale of agricultural and forestry production land. It can perform multiple agricultural production functions to maximize product use efficiency. The multifunctional shiftable boom intelligent sprayer is shown in Figure 2 [28, 29]. The maximum spray width of the prototype is 9 m, the "U" frame has dimensions of 1.5×1.5 m, and the maximum lifting height is 3 m. At the same time, the prototype can realize shrinking and transporting state of boom. The boom has three types of working status, including shapes of "—," "U," and "∏." The prototype control system enables intelligent target spraying [30–32] and dynamically controls the number of nozzles activated in accordance with the presence of crops. The presence of crops could be identified by using an infrared optoelectronic sensor on the nozzles. The spraying system can also adjust the duty cycle of the solenoid valve to maintain spray system flow stability and pressure in order to meet agricultural production requirements. The working speed of the prototype is 2~6 km/h, application rate is 350 L/ha, comprehensive utilization rate of pesticide is ≥30%, pressure is 0.3 Mpa, and flow is 2 L/min/nozzle. The

Table 3: The scoring of first-level factors.

F	F_1	F_2	F_3	F_4	F_5	F_6	F_7	F_8	F_9	F_{10}	w_s	W_s
F_1	1	1	1	1	1	1/4	1/3	1/4	1/3	1/4	0.5296	0.043352625
F_2	1	1	1	1	1	1/4	1/3	1/4	1/3	1/4	0.5296	0.043352625
F_3	1	1	1	1	1	1/4	1/3	1/4	1/3	1/4	0.5296	0.043352625
F_4	1	1	1	1	1	1/4	1/3	1/4	1/3	1/4	0.5296	0.043352625
F_5	1	1	1	1	1	1/4	1/3	1/4	1/3	1/4	0.5296	0.043352625
F_6	4	4	4	4	4	1	2	1	2	1	2.2974	0.188063294
F_7	3	3	3	3	3	1/2	1	2	1	1/2	1.6161	0.13229263
F_8	4	4	4	4	4	1	1/2	1	1/2	1	1.7411	0.142525028
F_9	3	3	3	3	3	1/2	1	2	1	1/2	1.6161	0.13229263
F_{10}	4	4	4	4	4	1	2	1	2	1	2.2974	0.188063294
$\lambda_{\max} = 10.21247659$			CI = 0.023609				RI = 1.49				CR = 0.015845 < 0.1	

Table 4: The weights of evaluation indexes on IBS.

Index code	F_1	F_2	F_3	F_4	F_5	F_6	F_7	F_8	F_9	F_{10}
	0.0433526	0.04335262	0.0433526	0.0433526	0.0433526	0.188063294	0.132293	0.142525	0.132293	0.188063294
C_{11}	0.7500054									
C_{12}	0.2499946									
C_{21}		0.2000127								
C_{22}		0.39999365								
C_{23}		0.39999365								
C_{31}			0.296965							
C_{32}			0.5396151							
C_{33}			0.1634198							
C_{41}				0.4929715						
C_{42}				0.1954152						
C_{43}				0.1161981						
C_{44}				0.1954152						
C_{51}					0.6666667					
C_{52}					0.3333333					
C_{61}						0.035963014				
C_{62}						0.035963014				
C_{63}						0.139475789				
C_{64}						0.139475789				
C_{65}						0.324561197				
C_{66}						0.324561197				
C_{71}							0.125005412			
C_{72}							0.125005412			
C_{73}							0.374994588			
C_{74}							0.374994588			
C_{81}								0.142848652		
C_{82}								0.428575674		
C_{83}								0.428575674		
C_{91}									0.428575674	
C_{92}									0.428575674	
C_{93}									0.142848652	
C_{A1}										0.285706207
C_{A2}										0.285706207
C_{A3}										0.142862529
C_{A4}										0.142862529
C_{A5}										0.142862529

minimum and maximum boom heights are 3000 mm and 600 mm, respectively. MDCO nozzles are used.

A group of 13 researchers evaluated the multifunctional intelligent boom sprayer reconfigurability by using the IBS evaluation index system and process (4) in Section 2.3, for scientifically evaluating and optimizing the multifunctional shiftable boom intelligent sprayer and gradually meeting the IBS requirements. During evaluation, some indexes were determined by the simple testing method or subjective way, such as determination using a stopwatch or manual observation operation. This can aid in further research and aid users who participate in index evaluation. The

FIGURE 2: Reconfiguration images of the multifunctional shiftable boom intelligent sprayer. (a) The shape of "—." (b) The shape of "U." (c) The shape of "∩."

reconfigurability evaluation result was verified using validity testing.

The results from evaluating all the secondary indexes under F_i can be determined using equation (6). The index evaluation results are shown in Figure 3. The evaluation result of the first-level index F_i can be obtained using equation (7), and the index evaluation results are shown in Figure 4.

The evaluation result of target-level F can be obtained according to equation (8). Therefore, there was membership degree of $E = \{\text{very good, good, general, bad}\}$ of target-level F which was "0.276955, 0.420507, 0.203853, 0.098685," respectively. The α value could be determined using validity testing, as shown in the following equation:

$$\alpha = \frac{(4 \times 0.420507 - 1)}{(2 \times 0.276955 \times (4 - 1))} = 0.41. \tag{14}$$

According to $\alpha = 0.41 < 0.5$, the maximum membership degree principle was minimally effective. The evaluation result of target-level F should be judged accurately using the quantification process in Section 2.4. Thus, S_H, S_L, and L could be obtained using equations (10)–(12), as shown in the following equations:

$$S_H = (0.276955\ 0.420507\ 0.203853\ 0.098685)$$
$$\cdot \begin{pmatrix} 100 \\ 90 \\ 75 \\ 60 \end{pmatrix} = 86.75121, \tag{15}$$

$$S_L = (0.276955\ 0.420507\ 0.203853\ 0.098685)$$
$$\cdot \begin{pmatrix} 90 \\ 75 \\ 60 \\ 0 \end{pmatrix} = 68.69516, \tag{16}$$

$$L = S_H - S_L = 18.05605. \tag{17}$$

The S_H and S_L values were, respectively, located in good and general evaluation intervals. The boundary between good and general evaluation intervals occurs at 75.

Therefore, L_K could be calculated using equations (18)–(20). P_K could be calculated using equation (13), as shown in equations (21)–(23).

$$L_2 = S_H - 75 = 86.75121 - 75 = 11.75121, \tag{18}$$

$$L_3 = 75 - S_L = 75 - 68.69516 = 6.304836, \tag{19}$$

$$L_1 = L_4 = 0, \tag{20}$$

$$P_2 = \frac{L_2}{L} = \frac{11.75121}{18.05605} = 0.650819, \tag{21}$$

$$P_3 = \frac{L_3}{L} = \frac{6.304836}{18.05605} = 0.349181, \tag{22}$$

$$P_1 = P_4 = 0. \tag{23}$$

4. Results and Discussion

The probability values of different level indexes in different result domains could be obtained through the formula calculation from the fuzzy comprehensive evaluation, analytic hierarchy process, and validity test. Technicians can use these probability values to determine whether to perform further analysis of influencing factors. Reconfigurability evaluation result of multifunctional shiftable boom intelligent sprayer was belonged to good evaluation interval, owing to the max $P_K = P_2$. However, the membership degree within the "good" evaluation interval was below 0.5. Although the product achieved some reconfigurability, there was room for improvement.

In Figure 4, the evaluation result of F_9 was in the poor evaluation interval. When the product is optimized and upgraded, the index and its corresponding secondary-level indexes should be the areas of focus. The evaluation results of F_5 and F_6 fall within the "bad" interval. This type of index and its secondary indexes should be secondary concerns when optimizing and upgrading products. Although the evaluation results of F_1, F_2, F_3, F_4, F_7, and F_{10} were located in the "good" interval, their membership degree within the "good" evaluation interval was below 0.5. In addition, other first-level indexes have membership degree above 0.5 in
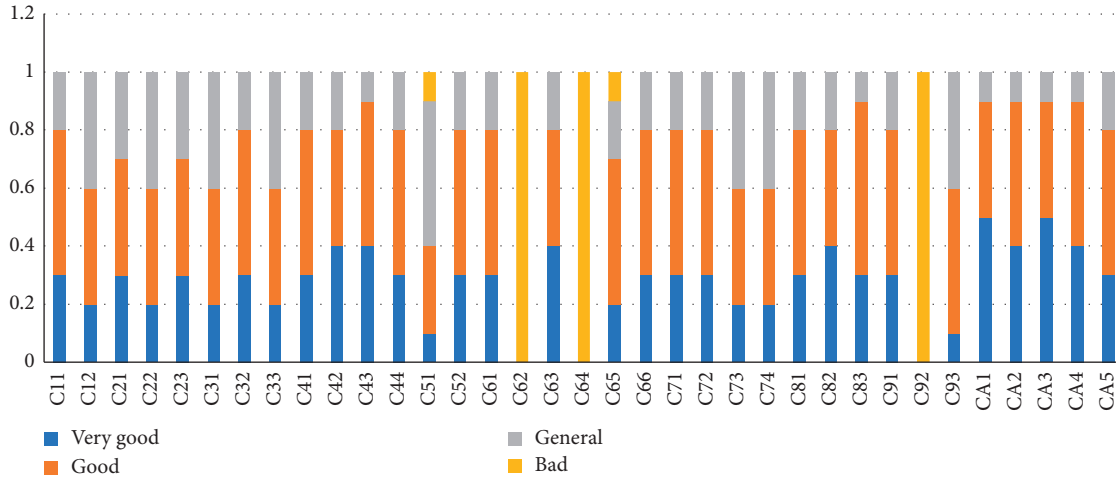
FIGURE 3: Evaluation results of the secondary indexes. The colour bars represent the evaluation results of secondary-level indexes in the result domain.
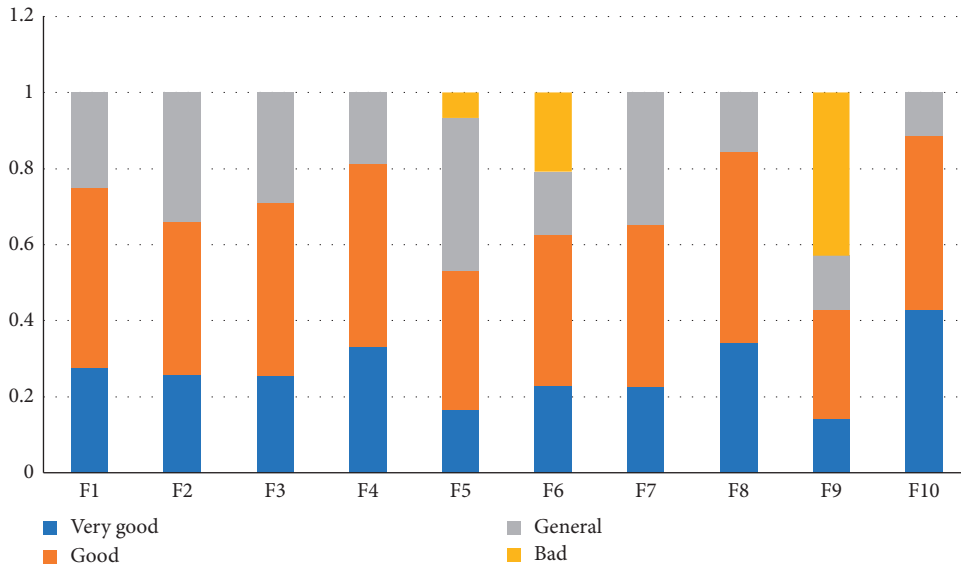

FIGURE 4: Evaluation results of the first-level indexes. The colour bars represent the evaluation results of first-level indexes in the result domain.

"good" evaluation interval. These can be appropriately optimized and improved in accordance with the existing resource conditions and market changes of the enterprise. Enterprises can formulate product optimization plans to meet market requirements via enterprise resource optimization and reconfiguration using analysis of these indexes. In the next evaluation cycle, the improved product would be evaluated and compared to previous evaluation results. From the comparison results, the customer satisfaction of the optimized product, the market's changing trend, and the applicability of the index system are analyzed. The evaluation cycle and indicator system revision cycle can be determined based on the product market cycle. Furthermore, this can lead to construction of a product periodic optimization mechanism to meet the requirements of market changes.

In Figure 3, the evaluation results of C_{62}, C_{64}, and C_{92} were located in the "bad" interval and their membership degree was 1. These three indexes should be prioritized for optimization, when optimizing its first-level index. Among the secondary indexes, the chassis-related indexes should be fully considered, when the product is optimised and upgraded, for improving the reconfigurability of the chassis. At the same time, it can be seen from C_{51} and C_{65} that product promotion should be strengthened. The secondary level-index is a further reflection of the first-level index. The secondary-level indexes could more accurately reflect the problems of products to assist designers in making optimization plans. And the first-level indexes and its secondary-level indexes should be implemented simultaneously during periodic product optimization.

Excessive pursuit of product advances should be avoided and both the enterprise and market development changes should be focused. The index evaluation results can provide decision support data for research and enterprise R&D personnel in product development and optimization. According to the evaluation of multifunctional intelligent boom sprayer, different optimization and improvement schemes can be formulated to reduce the interference of subjective factors on product optimization schemes and provide scientific basis for more scientific and objective guidance of product optimization. Therefore, this will assist R&D personnel determining design directions in the process of researching or optimizing products. It also reduces unnecessary product development and optimization waste. The index system effectiveness was verified by the site testing of the multifunctional intelligent boom sprayer. The index systems basically expressed various aspects of the multifunctional intelligent boom sprayer.

5. Conclusion

Evaluating IBS reconfigurability allows one to scientifically guide IBS reconfigurability and provides direct product optimization guidance. The IBS reconfigurability evaluation index system was constructed using the BIA model. A fuzzy comprehensive evaluation method was used to evaluate the process of the evaluation index system, and the weight of the index is determined by the hierarchical analysis method. The evaluation result was verified by the validity test.

As a typical IBS, the multifunctional shiftable boom intelligent sprayer developed by the research group was processed using the evaluation system to obtain the comprehensive evaluation result and evaluation results of each individual index. These results intuitively illuminated the overall product and all aspects of the indexes, thus providing a basis for designers to improve the product. The index system effectiveness was verified via the case study. The above research provides an objective, scientific, and complete evaluation method for evaluating IBS reconfigurability and supporting the achievement of corporate green manufacturing goals.

In future, the multifunctional shiftable boom intelligent sprayer would be improved based on this evaluation method. A few IBS would be produced for more researchers to participate in the evaluation process to improve the index systems. It is necessary to create a schedule and plan to update the index system and weights regularly to ensure index system effectiveness.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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