www.cadanda.com Computer-Aided Design AND APPLICATIONS

Adaptable Interface Design for Open-architecture Products

Chonglin Hu[1], Qingjin Peng[2] and Peihua Gu[3]

[1]Shantou University, 11clhu1@stu.edu.cn
[2]University of Manitoba, Qingjin.Peng@umanitoba.ca
[3]Shantou University, peihuagu@stu.edu.cn

ABSTRACT

Increasing needs for personalized products in the market require the changeability of product functions and users' involvement in the product implementation. Open-architecture products (OAPs) allow changes of product functions by adding or replacing functional modules in products' original structure. OAPs can therefore support the product adaptability to meet user's requirements in the product life cycle. Interfaces connect functional modules of OAPs playing an important role in the product operation and maintenance when upgrading and replacing modules. Adaptable design (AD) provides the concept for the development of OAPs' modules and interfaces. Adaptable interfaces support the module replacement in the life cycle of OAPs. This research applies the AD concept to generate alternative plans of interfaces. The plans are evaluated for an optimal solution using the function correlation matrix, morphologic and fuzzy logic analyses. The design importance is ranked based on interface types, user requirements, and performance measures. The proposed method is applied in the design of an industrial painting machine.

Keywords: adaptable interface, open-architecture product, product design, fuzzy analytical hierarchy process.

1. INTRODUCTION

Industrial products have experienced in mass production, mass customization, and emerging personalization of development modes. The development of personalized products requires the changeability of product functions and users' involvement in the product design and implementation. The user involvement challenges the existing design and implementation of products. Open-architecture products (OAPs) allow adding or replacing functional modules to upgrade the initial product function [14]. OAPs consist of common functional modules, customized modules, and personalized modules for the product life cycle requirement [12]. The common modules and customized modules are designed and produced by original manufacturers, users can choose customized modules. The personalized modules are usually designed or purchased based on users' specific needs. Users may provide their own personalized module. Interfaces are key elements of OAPs to ensure the module updatability. Adaptable interfaces as bridges between modules ensure the final implementation of OAPs [17].

Interfaces use different physical structures to transfer flows of energy, motion and signal [11]. Adaptable interfaces have features of adaptability, stability and easy assembly. Products with adaptable interfaces are easy for module upgrading and replacing. There are different frequencies and probabilities for modules' upgrading or replacing in OAPs. Degrees of users' involvement in different design phases are also different. Therefore, the interface design should be determined according to the type of modules. Interfaces should be treated differently when linking different types of modules.

There is limited research on OAPs and their interfaces. Most of the existing research looks at only strategies or guidelines for the interface design. This research proposes a method of the adaptable interface design for OAPs. The interface is planned based on different types of modules as follows:

- Interfaces and design requirements are defined based on different types of modules.
- Interface plans are generated based on the importance and applications of interfaces.

Taylor & Francis
Taylor & Francis Group

- Measures of the interface performance are ranked using morphologic and fuzzy logic analyses.

An industrial painting machine is designed as an OAP using the proposed method.

2. RELATED RESEARCH

Diversification and personalization have become a trend of product development in today's competitive market. Besides advanced manufacturing technologies and production patterns, the innovative design plays an important role in the product development [8]. Koren et al proposed the concept of OAPs for users to participate in product design and implementation using personalized modules [14]. The personalized module can be upgraded or replaced on a common platform of the product for users' self-realization of special needs of the product. Interfaces connect different modules of OAPs. Design solutions of modules and interfaces affect duration and cost of the product development [10]. Adaptable interfaces enable flexibility and feasibility of the module combination for OAPs.

Compared to other functional modules, personalized modules demand more for the interface to fit different user requirements, which increases the complex of the interface design for OAPs. Existing research on interfaces are mainly for design guidelines and the interface evaluation. There is not a systematic method for the interface planning. For example, the MechBus concept proposed a three-step guideline to decide the functional structure of interfaces including the need identification, module selection and interface design [7]. Scalice et al summarized five standard interfaces through the function definition of interfaces with a conceptual design flowchart [18]. Chen and Liu suggested the interface strategy for modular products using concepts of external interfaces, internal interfaces and interface openness [3].

Conceptual design is an important process of interface planning. Research on the conceptual design is mainly for product design, such as the product conceptual design using a function-behavior-state (FBS) model [1], functional design based on the conceptual product structure and layered functions [5], and the product planning using a hybrid model of the behavior-function and behavior-structure [4]. Interfaces have to be abstracted from physical forms into analytical models to be described and evaluated. The existing interface representations use either a standard language or matrix. The related research is mainly for storing and matching of interface information to meet the need of design, compatible assembly and connection evaluation [6], [9], [15], [19], such as the method to represent interfaces of CAD/PDM systems [2], and the interface efficacy (IE) proposed for upgrading and replacing of product modules [11]. The IE is defined for the easy of assembly and disassembly of functional modules in the product. This method is constrained by the existing product structure. The adaptable interface should be considered at the stage of product design.

In summary, there is a lack of the systematic method for the interface design and planning. The less detail is found from literature for the interface design of OAPs. Most existing methods decide the product structure through the decomposition of product functions. The final solution depends on the experience of designers. This research proposes a method for the adaptable interface design of OAPs. Interface types and design requirements are defined according to the type of modules using a functional description method of interfaces. Interface design schemes are established based on interface functions and morphology matrices. A fuzzy analytical hierarchy process (FAHP) is applied to rank the design solutions based on the design requirement of interface types and evaluation measures. An optimal design scheme is planned based on the total score of ranking for the detail design of interfaces.

3. PROPOSED METHODS

Fig. 1 is a flowchart of the adaptable interface design proposed in this research for OAPs. A functional correlation matrix is established for product modules based on the module types planned in the modular design of OAPs. Functions in the matrix are detailed into functional units. Possible solutions of the function unit requirements are listed in a morphological

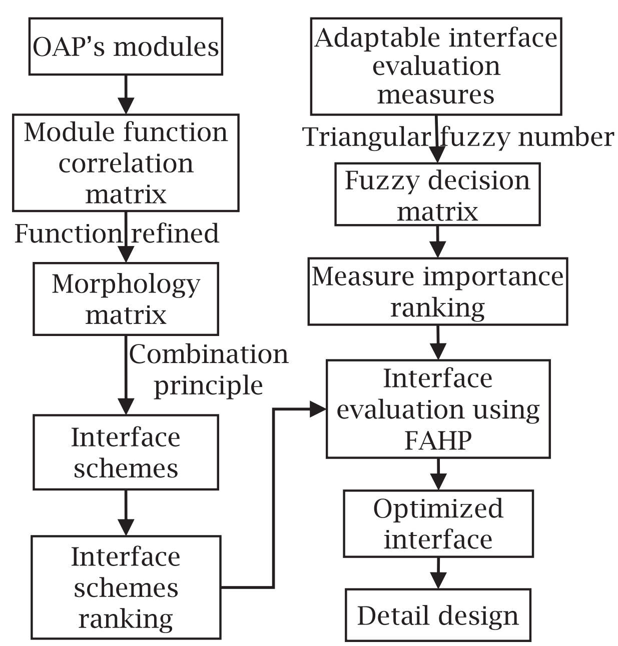

Fig. 1: OAPs' adaptable interface design.

matrix to form interface schemes based on the module structure and constraints. The interface schemes are then evaluated using the FAHP based on the performance measure of adaptable interfaces. The fuzzy decision matrix is formed using triangular fuzzy numbers for interface decision-making. The importance of the performance measures can then be ranked. The measures are scored based on the performance of interface schemes for the interface weight. A comprehensive measure is finally obtained by the FAHP for an optimal interface plan. Based on the optimal interface plan, the detail design of the interface can be conducted.

3.1. Acquisition of Interface Functions

Based on the module requirement of OAPs, the module type and components can be decided using the traditional planning method to establish a function correlation matrix of modules as shown in Fig. 2. Where C indicates the connection of modules, S represents the transmission of signals, M is the material flow, and E is for the energy transformation. A zero element in the matrix means no function relation for related modules. Function changes of product modules can be decided by the function correlation matrix.

Module	M1	M2
M1	1	C S M E
M2	C S M E	1

Fig. 2: Function correlation matrix of modules.

3.2. Planning and Evaluation of Adaptable Interfaces

A morphological matrix is used to help proposing multi-plans of an interface to overcome limitations of designers' experience [13]. Interactions of the interface between modules can be refined into specific functional units and listed in columns of the morphological matrix. All of the feasible solutions are listed in corresponding rows of the matrix based on combination rules and constraints of the interface. The feasible interface can then be obtained by combining a number of possible solutions.

As different types of modules are replaced or upgraded in different frequencies and probabilities during the product life cycle, different module interfaces should be considered differently. User requirements are therefore collected based on different types of modules to define interfaces types. The common module interface connects common modules. The customized module interface links customized modules, or customized modules and common modules. The personalized module interface connects a personalized module and other modules. The design requirements of these three types of interfaces are as follows.

- Common module interfaces: common modules are kept in constant in the product life cycle without changes, there is no need considering interfaces for the replacement of common modules.
- Customized module interfaces: customized modules are determined when a product is completed to deliver to the user. Customized module interfaces are operated by manufacturers, not by users. Therefore, its interface adaptability is not important for users.
- Personalized module interfaces: these interfaces are for users to upgrade or replace function modules in users' workplace. The interface should be designed for easy assembly and disassembly. As the change requirement of personalized modules varies for different users, the personalized module interface should be carefully designed to have adaptable features.

Therefore, the design evaluation should consider different interfaces and requirements. This research considers the interface adaptability for current and future needs to decide performance measures in manufacturing, assembling, operating, and cost for the interface evaluation. For product planning in the conceptual design phase without the structure of the interface detail, some performance in manufacturing can be simplified measured using cost or economy. According to summarized evaluation indicators of products [23], the proposed interface assessment criteria are listed in Tab. 1.

The importance level of these evaluation measures varies for different types of interfaces based on different requirements. Multiply evaluations can improve accuracy of the single-measure evaluation [16]. The hierarchical analysis method is a systematic hierarchical method using the combination of quantitative and qualitative analyses. The importance of measures can be ranked to guide the design of specific interfaces. It is difficult to determine the weight of measures using traditional methods based on experience or expert knowledge. This research uses a fuzzy analytic hierarchy process (FAHP) to decide the weight of measures and to evaluate interface solutions [20]. The relative weights are decided through a pairwise comparison of measures. The accuracy is ensured using the weight range based on triangular fuzzy numbers. Conventional ranking methods can only give a fixed value of the evaluation measure. This fixed value may sometime change within a range of values, which may result in a biased solution with the reduced accuracy in the evaluation. A triangular fuzzy number includes

Adaptability B1	Working performance B2	Assemblability B3	Economy B4
General adaptability C1	Stability C3	Structural complexity C7	Manufacturing complexity C10
Prediction adaptability C2	Reliability C4	Assemble complexity C8	Manufacturing error sensitivity C11
	Loading capacity C5	Operator skill proficiency C9	Function redundancy C12
	Adjustability C6		Energy efficiency C13

Tab. 1: Measures of adaptable interfaces.

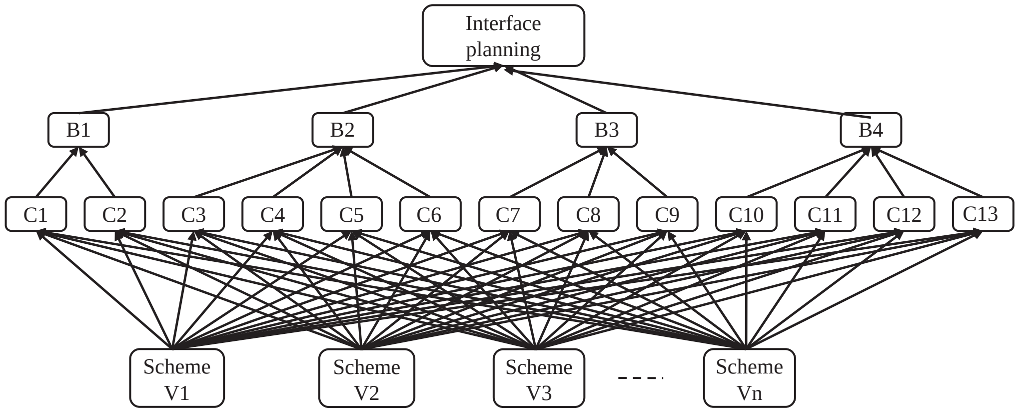

Fig. 3: Analytic hierarchy of interface planning.

not only the most likely measure value, but also the change range of measures [22].

The FAHP provides a comprehensive assessment to meet the design goal in the evaluation of different interfaces with five steps: the problem identification, model construction in the hierarchical structure, formation of the decision matrix, ranking the single-level hierarchy, and sorting the total hierarchy [10]. The FAHP objective is to search an optimal interface solution. An analytical hierarchy of the interface decision-making is shown in Fig. 3.

A triangular fuzzy number uses (l, m, u) to indicate its details, where m represents the middle value or median, l and u denote the lower and upper bounds of value changes. In the fuzzy decision matrix, m represents the most likely relationship based on a pairwise comparison. l and u are the upper and lower bounds of relationship changes of two measures. Scales of the median for triangular fuzzy numbers in the decision-making matrix is shown in Tab. 2 [22], where P_{ij} represents the median of triangular fuzzy numbers when comparing rows P_i and columns P_j in the matrix. P_i is more important than P_j when the comparison ratio is greater than 0.5, and P_i is less important than P_j when the ratio is less than 0.5.

The fuzzy decision matrix for the evaluation of different interfaces can be formed based on the discussion between designers and users. Matrices for personalized module interface planning based on

P_{ij}	Details
0.9	P_i is more important than P_j extremely
0.8	P_i is more important than P_j strongly
0.7	P_i is more important than P_j significantly
0.6	P_i is more important than P_j slightly
0.5	P_i and P_j are equally important
0.4	P_j is more important than P_i slightly
0.3	P_j is more important than P_i significantly
0.2	P_j is more important than P_i strongly
0.1	P_j is more important than P_i extremely

Tab. 2: Scales of fuzzy numbers.

measures in Tab. 1 and processes in Fig. 3 are formed in Tabs. 3 to 7, where column P represents weights of evaluation measures, other columns are triangular fuzzy numbers of the importance formed by the ratio of rows and columns.

Based on requirements of the personalized module interface and the discussion with the designers and product users, the personalized interface adaptability, assembly performance, working performance, and economy can be decided for the fuzzy matrix. Taking Tab. 3 as an example, elements in the matrix diagonal have the same value or importance as they are the comparison of same measures. Their median,

	B1	B2	B3	B4	P
B1	(0.5,0.5,0.5)	(0.5,0.5,0.6)	(0.4,0.5,0.5)	(0.5,0.55,0.6)	0.3320
B2	(0.4,0.5,0.5)	(0.5,0.5,0.5)	(0.35,0.45,0.5)	(0.45,0.5,0.55)	0.1219
B3	(0.5,0.5,0.6)	(0.5,0.55,0.65)	(0.5,0.5,0.5)	(0.55,0.6,0.65)	0.5233
B4	(0.4,0.45,0.5)	(0.45,0.5,0.55)	(0.35,0.4,0.45)	(0.5,0.5,0.5)	0.0228

Tab. 3: Fuzzy decision matrix of the interface evaluation.

	C1	C2	P
C1	(0.5,0.5,0.5)	(0.5,0.55,0.6)	0.7469
C2	(0.4,0.45,0.5)	(0.5,0.5,0.5)	0.2531

Tab. 4: Fuzzy decision matrix of adaptability.

the upper and lower limits of the range are 0.5 based on Tab. 2, therefore, triangular fuzzy numbers of the diagonal are (0.5, 0.5, 0.5). Using the comparison of elements in rows and columns of the fuzzy decision matrix, the sum of positive and negative comparison values of the measure is 1 in Tab. 2. Symmetric elements of the matrix diagonal have features of $B_{ij}(m) + B_{ji}(m) = 1$, and $B_{ij}(l) + B_{ji}(u) = B_{ij}(u) + B_{ji}(l) = 1$. Taking the interface B14 as an example, in order to meet future personalized needs of the product, if the increased cost is acceptable, the adaptability is set a slightly more important rate than the economy rate, 0.55. If the increased cost is not acceptable for adaptability of the personalized interface, the two criteria can be set equally important for a lower limit 0.5. Considering the acceptable cost level of both producers and users, for increasing adaptability without too much cost, the upper limit is set as 0.6. Therefore, triangular fuzzy numbers of B14 are set as (0.5, 0.55, 0.6), its symmetric element B41 is calculated as (0.4, 0.45, 0.5). Other data in the tables can be obtained using the same method.

The initial fuzzy weight of elements in the matrix can be determined by calculating the comprehensive fuzzy value of elements in the decision matrix. The calculation equation is as follows,

$$w_i = \frac{\sum_{j=1}^{n} a_{ij}}{\sum_{i=1}^{n}\sum_{j=1}^{n} a_{ij}} = \frac{\sum_{j=1}^{n} (a_{lij}, a_{mij}, a_{uij})}{\sum_{i=1}^{n}\sum_{j=1}^{n} (a_{lij}, a_{mij}, a_{uij})}$$

	C3	C4	C5	C6	P
C3	(0.5,0.5,0.5)	(0.45,0.5,0.55)	(0.5,0.5,0.55)	(0.45,0.45,0.55)	0.2313
C4	(0.45,0.5,0.55)	(0.5,0.5,0.5)	(0.5,0.5,0.55)	(0.45,0.45,0.55)	0.2313
C5	(0.45,0.5,0.5)	(0.45,0.5,0.5)	(0.5,0.5,0.5)	(0.4,0.4,0.5)	0.0531
C6	(0.45,0.55,0.55)	(0.45,0.55,0.55)	(0.5,0.6,0.6)	(0.5,0.5,0.5)	0.4842

Tab. 5: Fuzzy decision matrix of working performance.

	C7	C8	C9	P
C7	(0.5,0.5,0.5)	(0.4,0.45,0.55)	(0.35,0.4,0.5)	0.1223
C8	(0.45,0.55,0.6)	(0.5,0.5,0.5)	(0.4,0.45,0.55)	0.3376
C9	(0.5,0.6,0.65)	(0.45,0.55,0.6)	(0.5,0.5,0.5)	0.5401

Tab. 6: Fuzzy decision matrix of assemblability.

	C10	C11	C12	C13	P
C10	(0.5,0.5,0.5)	(0.4,0.5,0.6)	(0.4,0.45,0.5)	(0.45,0.45,0.55)	0.1331
C11	(0.4,0.5,0.6)	(0.5,0.5,0.5)	(0.4,0.45,0.5)	(0.45,0.45,0.55)	0.1331
C12	(0.5,0.55,0.6)	(0.5,0.55,0.6)	(0.5,0.5,0.5)	(0.5,0.5,0.55)	0.4329
C13	(0.45,0.55,0.55)	(0.45,0.55,0.55)	(0.45,0.5,0.5)	(0.5,0.5,0.5)	0.3010

Tab. 7: Fuzzy decision matrix of economy.

$$= \frac{\left(\sum_{j=1}^{n} a_{lij}, \sum_{j=1}^{n} a_{mij}, \sum_{j=1}^{n} a_{uij}\right)}{\left(\sum_{i=1}^{n}\sum_{j=1}^{n} a_{lij}, \sum_{i=1}^{n}\sum_{j=1}^{n} a_{mij}, \sum_{i=1}^{n}\sum_{j=1}^{n} a_{uij}\right)}$$

$$= \left(\frac{\sum_{j=1}^{n} a_{lij}}{\sum_{i=1}^{n}\sum_{j=1}^{n} a_{lij}}, \frac{\sum_{j=1}^{n} a_{mij}}{\sum_{i=1}^{n}\sum_{j=1}^{n} a_{mij}}, \frac{\sum_{j=1}^{n} a_{uij}}{\sum_{i=1}^{n}\sum_{j=1}^{n} a_{uij}}\right), \times i \in n \quad (1)$$

Where $a_{ij} = (a_{lij}, a_{mij}, a_{uij})$ is an element of the fuzzy decision matrix to represent the fuzzy value of the criteria i comparing with the criteria j, w_i represents the fuzzy weight of the assessment criteria i [21]. The fuzzy weight matrix in the first layer of the evaluation W_B can be formed using Eqn. (1):

$$W_B = (w_{B1}, \quad w_{B2}, \quad w_{B3}, \quad w_{B4})^{\mathrm{T}} = \begin{bmatrix} 0.2197 & 0.2562 & 0.2993 \\ 0.1965 & 0.2237 & 0.2789 \\ 0.2370 & 0.2687 & 0.3265 \\ 0.1965 & 0.2323 & 0.2721 \end{bmatrix}$$

A probability matrix can be generated based on the definition 2.4 in the literature as follows [21].

Assume $a = (a_l, a_m, a_u), b = (b_l, b_m, b_u)$,

$$p(a \geq b) = \lambda \max\left\{1 - \max\left(\frac{b_m - a_l}{a_m - a_l + b_m - b_l}, 0\right), 0\right\} + (1-\lambda)\max\left\{1 - \max\left(\frac{b_u - a_m}{a_u - a_m + b_u - b_m}, 0\right), 0\right\} \quad (2)$$

$p(a \geq b)$ is called the probability of $a \geq b$, where $\lambda \in [0, 1]$, here $\lambda = 0.5$.

$$P_B = \begin{bmatrix} 0.5000 & 0.7114 & 0.2924 & 0.8242 \\ 0.2886 & 0.5000 & 0.0974 & 0.6016 \\ 0.7060 & 0.9026 & 0.5000 & 0.9830 \\ 0.1758 & 0.3984 & 0.0170 & 0.5000 \end{bmatrix}$$

The probability matrix $P = (p_{ij})_{n\times n}$ can be formed based on the pairwise comparison of fuzzy weight w_{Bi} using Eqn. (2). P_B is a matrix with the size of 4×4 when $i = 4$ which is calculated by matrix W_B. Triangular fuzzy numbers can be converted into probabilities for ranking using the probability matrix. The ranking vector $Q = (q_1, q_2, \ldots, q_n)^T$ of probability P can be calculated using Eqn. (3).

$$q_i = \frac{1}{n}\left(\sum_{j=1}^{n} p_{ij} + 1 - \frac{n}{2}\right), \qquad i \in n \quad (3)$$

Where p_{ij} is the element in matrix P_B. The ranking vector $Q_B =$ (0.3320, 0.1219, 0.5233,0.0228).

W_c and P_C can be obtained using the same method. The ranking vector Q_P of evaluation measures for personalized module interfaces can be finally found as follows.

$Q_P = (q_{c1}, q_{c2}, q_{c3}, q_{c4}, q_{c5}, q_{c6}, q_{c7}, q_{c8}, q_{c9}, q_{c10}, q_{c11}, q_{c12}, q_{c13}) =$ (0.2480, 0.0840, 0.0282, 0.0282, 0.0065, 0.0590, 0.0640, 0.1767, 0.2826, 0.0030, 0.0030, 0.0099, 0.0069).

Where q_{ci} are different measures of product P_i shown in Tabs. 3 to 7, such as $q_{B1} = P_{B1}$ =0.3320, $q_{C1} = P_{B1} \times P_{C1}$ =0.3320*0.7469 = 0.2480. Evaluation measures for personalized module interfaces are ranked as follows:

$$q_{c9} > q_{c1} > q_{c8} > q_{c2} > q_{c7} > q_{c6} > q_{c3} = q_{c4} > q_{c12} > q_{c13} > q_{c5} > q_{c10} = q_{c11}$$

Therefore, weights of evaluation measures can be obtained for personalized module interfaces. The evaluation is normally conducted through a selection process based on the interface solutions. The quantitative evaluation uses a value of 1-9. Details of the values of 1-9 are {1- worst, 2-very poor, 3- worse, 4-poor, 5-fair, 6-good, 7-better, 8-very good, 9- excellent}. The final solution is selected based on the total score obtained for a specific interface. The highest score will be the optimal design solution. The adaptable interface can be formed after the detail design based on the optimal solution.

4. CASE STUDY

The proposed method is applied to the design of an industrial painting machine that is used for the body painting of toys made of plastic or metals. The machine function adjustment is commonly required in the operation for different colors, shapes, or sizes of toys. An OAP of the painting machine is able to meet these different requirements. Adaptable interfaces are necessary for the painting machine to allow users to replace and upgrade the machine functional module for the personalized need.

The module planning decides types, layout and interactions of modules. The machine module layout is shown in Fig. 4, where nodes represent modules, data in the nodes are module numbers and

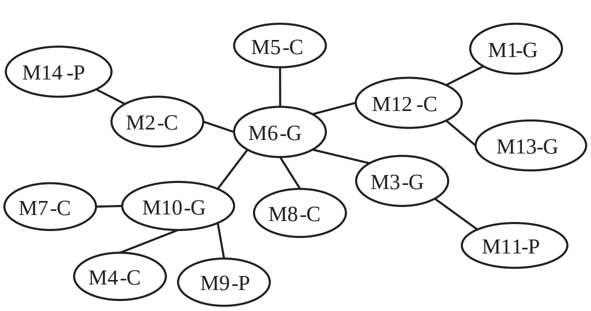

Fig. 4: Modules and interfaces of the painting machine.

Computer-Aided Design & Applications, 12(2), 2015, 156–165, http://dx.doi.org/10.1080/16864360.2014.962428

Module	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	M13	M14
M1	1				M		S					C S E	S	S E
M2		1				C								C
M3			1			C					C E			M E
M4				1			S			C		C		M E
M5	M				1	C							M	M
M6		C	C		C	1		C		C		C		
M7	S			S			1			C S		S	S	M E
M8						C		1	M		E			M E
M9								M	1	C	M			
M10				C		C	C S		C	1				M E
M11			C E					E	M		1			
M12	C S E			C		C	S					1	C S	
M13	S				M		S					C S	1	
M14	S E	C	M E	M E	M		M E	M E		M E				1

Fig. 5: Function relations of the painting machine modules.

types (G-common module, C–customized module, P-personalized module), the link indicates a connection between modules. The correlation matrix is formed based on functional interactions of modules in the painting machine as shown in Fig. 5. Where C represents connection, S represents signal, M represents material, E represents energy. In the matrix shown in Fig. 5, non-zero elements indicate related functions, and one in diagonal elements shows relations of related modules as defined in Fig. 2. Module details and connections of the painting machine are shown in Fig. 6. For introducing the design process of an adaptable interface, the interface between modules M3 and M11 is used as an example. As M3 is a common module and M11 is a personalized module, the interface between these two modules should meet the requirement of the personalized module interface.

The interface needs to provide functions of positioning, load supporting and buffering based on the analysis of interactions between the two functional modules. Constraints are used for positioning and limiting motion of connected parts. Using the morphological matrix proposed for the interface design, the interface functions and implementation are listed in the matrix shown in Fig. 7. There are six options to be applied for the interface between M11 and M3 using the principle of positioning and clamping based on the possible solutions listed in Fig. 7. They are as follows.

V1: Plane + plane + spring; V2: Plane + pin + rubber; V3: Pin + screw + spring; V4: Taper pin + pin + rubber; V5: Taper pin + pin + spring; V6: cylindrical pin + pin + spring.

These solutions are based on different methods of positioning, supporting and buffering. There are some similar methods in locating and supporting modes. In the detail design, some of them may be combined or modified based on details of the module connection, such as the plane shape and pin positions. These interface plans are evaluated based on the weights decided by the proposed method according to the interface performance in the value between 1 to 9 as shown in Tab. 8.

According to measures and weights of interface schemes in Tab. 8, the total score can be calculated. The weights of evaluation measures are the values of *Qp* in the proposed method. Such as the score of V1 is (0.2480*6 + 0.0840*5 + 0.0282*7.5

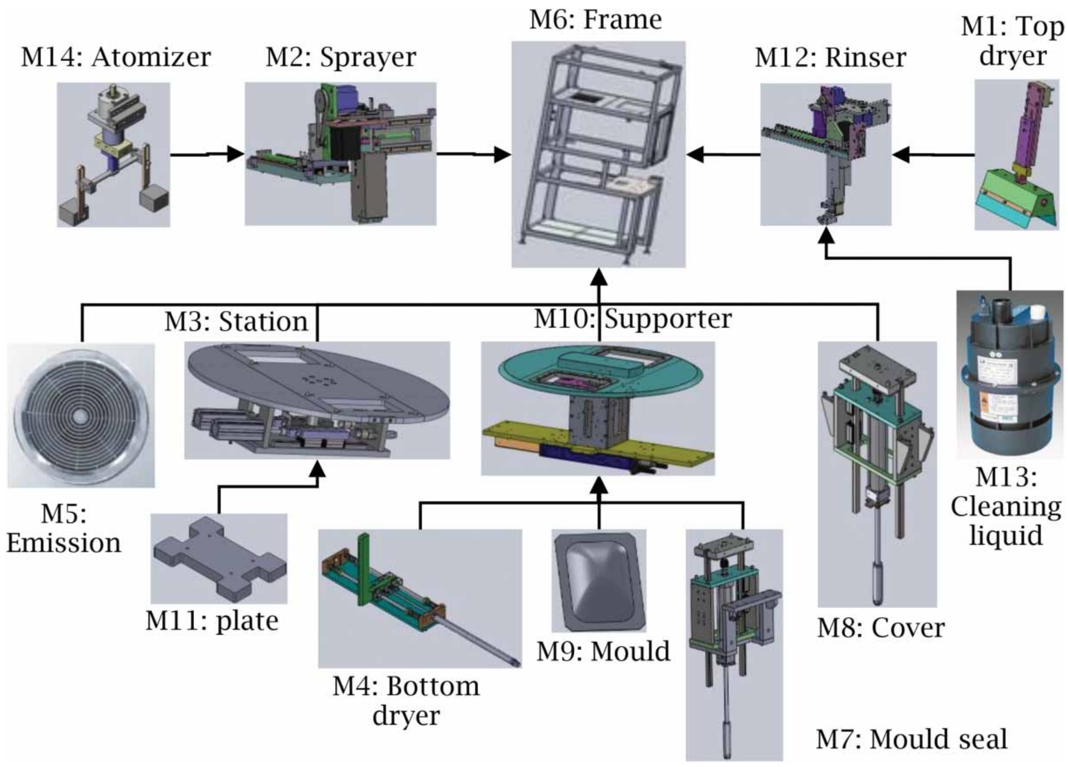

Fig. 6: Details and connections of the painting machine modules.

Need	Solutions				
Positioning	Combination of planes	Cylindrical pin	Taper pin	Combination of cylindrical	
Supporting	Combination of planes	Screw joint	Pin joint	Key joint	Spring
Buffering	Spring	Rubber	Foam	Air cylinder	Rubber baseplate

Fig. 7: Morphology matrix for interface solutions linking M11 and M3.

	Criterion	Details	Plans V1	V2	V3	V4	V5	V6
Interface schemes	Adaptability B1	General Adaptability C1	6	7	7	7	7	7
		Prediction Adaptability C2	5	6	7	7	7	6.5
	Working performance B2	Stability C3	7.5	7	7	6.5	7	7
		Reliability C4	7.5	7	6.5	7	7.5	7
		Carrying Capacity C5	7.5	7	7	7	7	7
		Adjustability C6	5	7	7	6.5	7	6.5
	Assemble performance B3	Structural Complexity C7	6	6.5	7	7	7	6
		Assemble Complexity C8	8	8	7.5	8	8	8
		Assembly Operator Proficiency C9	9	9	9	9	9	9
	Economy B4	Manufacture Complexity C10	7.5	7.5	8	8	8	6.5
		Manufacture Error Sensitivity C11	7.5	8	8	8	8	7
		Performance Redundancy C12	6.5	6	7.5	7	7.5	7
		Energy loss C13	8	8	8	8	8	8

Tab. 8: Interface schemes and measure weights of modules 11 and 3.

+ 0.0282*7.5 + 0.0065*7.5 + 0.0590*4 + 0.0640*6 + 0.1767*8 + 0.2826*9 + 0.0030*7.5 + 0.0030*7.5 + 0.0099*6.5 + 0.0069*8 = 7.1803). The final evaluation scores of 6 plans can be obtained using the weights in Tab. 8 for the interface performance measure as (7.1803, 7.6274, 7.6573, 7.7112, 7.7739,

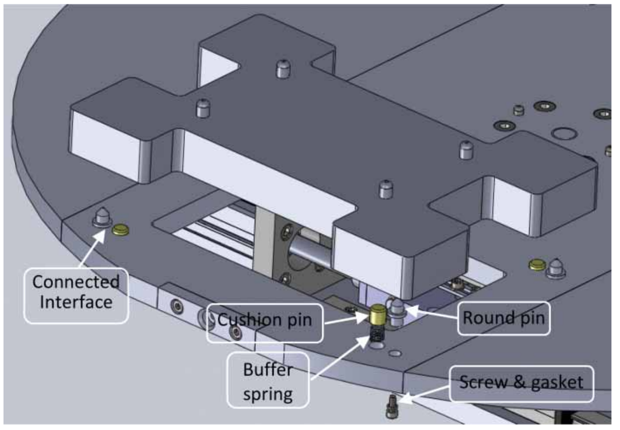

Fig. 8: Partial view of interface M3-M11.

7.6118). It can be found that plan 5 is the optimal design.

The detail design is then applied to plan 5 for the adaptable interface between modules M3 and M11 as shown in Fig. 8. Pins are used to improve the accuracy of positioning. The screw and gasket are used to clamp the connection and also to meet needs of the module replacement in assembly and disassembly. Module 11 is used to place the toy workpiece. As the variety of shapes and sizes of toys, there is a need to use different designs to meet the need of applications. M11 as a personalized module provides flexibility to users. The users can easily replace Module 11 based on their need in the workshop using the proposed interface.

5. CONCLUSIONS

This research proposed a systematic method for the adaptable interface design of OAPs. The modules and module types are decided using the method of module planning. Interface plans are formed based on the functional correlation matrix of modules. The morphological matrix is applied to form possible solutions of the interface. The triangular fuzzy numbers and fuzzy analysis hierarchy process are used to rank the importance of performance measures for the detail interface decision-making. An industrial painting machine is designed as an OAP using the proposed method with feasibility and effectiveness.

Current planning is a manual process. The calculation of the interface measure can be done automatically when the criteria rates are available in the database. There are many data and variables used in the proposed method, which may be difference from different products and user preferences. Further research will integrate the data collection and the design analysis using intelligent methods in data processing to improve the efficiency and accuracy of the application for the OAP design and implementation.

ACKNOWLEDGMENTS

The authors wish to acknowledge that this research has been supported by the Natural Sciences and Engineering Research Council (NSERC) of Canada and the National Natural Science Foundation of China (No.51375287).

REFERENCES

[1] Beek, T.; Mustafa, S.; Tetsuo, T.: Modular design of mechatronic systems with function modeling, Mechatronics, 20, 2010, 850–863. http://dx.doi.org/10.1016/j.mechatronics.2010.02.002

[2] Bettig, B.; Gershenson, J.: Module Interface Representation, ASME 2006 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference, 2006.

[3] Chen, K-M.; Liu, R-J.: Interface strategies in modular product innovation, Technovation, 25, 2005, 771–782. http://dx.doi.org/10.1016/j.technovation.2004.01.013

[4] Chen, X.; Lou, P.; Tang, D.; Zhu, R.; Yang, L.: Behavior-function and Behavior-structure hybrid mappings in mechanical conceptual design, Computer Integrated Manufacturing Systems, 6(7), 2010, 1363–1370.

[5] Deng, J.; Shao, M.: Method for Functional Design of Axiomatic Design Based on Connections, Chinese Journal of Mechanical Engineering-English Edition, 24(3), 2011, 364–371. http://dx.doi.org/10.3901/CJME.2011.03.364

[6] Godthi, V.; Yoo, J. J. W.; Arnold, C. B.; Simpson, T. W.; Kumara, S.: Product Design Using Interface-Based Module Description, Proceedings of the ASME 2010 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference, 2010.

[7] Gu, P.: Adaptable Design with Flexible Interface Systems, Journal of Integrated Design and Process Science, 8(3), 2004, 61–74.

[8] Gu, P.; Hashemian, M.; Nee, A-Y-C.: Adaptable design, CIRP Annals-Manufacturing Technology, 53(2), 2004, 539–557. http://dx.doi.org/10.1016/S0007-8506(07)60028-6

[9] He, B.; Feng, L-H.; Han, L-Z.; Liu, W-Z.: Research on Mechatronics Products Modular Interface Technology and Its Application in Robot, Computer and Automation Engineering (ICCAE), 2010 The 2nd International Conference on, 2, 2010, 523–527.

[10] Helmer, R.; Yassine, A.; Meier, C.: Systematic module and interface definition using component design structure matrix, Journal of Engineering Design, 21(6), 2010, 647–675. http://dx.doi.org/10.1080/09544820802563226

[11] Hu, C.; Peng, Q.; Gu, P.: Interface adaptability of an industrial painting machine, computer aided design and applications, 11(2), 2013, 182–192.

http://dx.doi.org/10.1080/16864360.2014.846089

[12] Hu, S. J.: Evolving Paradigms of Manufacturing: From Mass Production to Mass Customization and Personalization, Procedia CIRP 7, 2013, 3–8. http://dx.doi.org/10.1016/j.procir.2013.05.002

[13] Johan, Ö.; Björn, L.; Hampus, G.: A computerized optimization framework for the morphological matrix applied to aircraft conceptual design, Computer-Aided Design, 41, 2009, 187–196. http://dx.doi.org/10.1016/j.cad.2008.06.005

[14] Koren, Y.; Hu, S. J.; Gu, P.; Shpitalni, M.: Open-architecture products, CIRP Annals-Manufacturing Technology, 62(2), 2013, 719–729. http://dx.doi.org/10.1016/j.cirp.2013.06.001

[15] Liang, V-C.; Christiaan, J. J. P.: A Port Ontology for Conceptual Design of Systems, Journal of Computing and Information Science in Engineering, 4, 2004, 206–217. http://dx.doi.org/10.1115/1.1778191

[16] Liu, Z.; Deng, S.; Teng, H.: Survey on the evaluation methods of design schemes in a complicated engineering system, Systems Engineering and Electronics, 25(12), 2003, 1488–1491.

[17] Peng, Q.; Liu, Y.; Gu, P.; Fan, Z.: Development of an Open-architecture Electric Vehicle Using Adaptable Design, In Advances in Sustainable and Competitive Manufacturing Systems, Lecture Notes in Mechanical Engineering, Springer International Publishing, Switzerland, 2013, 79–90. http://dx.doi.org/10.1007/978-3-319-00557-7_7

[18] Scalice, R. K.; de Andrade, L. F. S.; Forcellini, F. A.: A Design Methodology for Module Interfaces, Collaborative Product and Service Life Cycle Management for a Sustainable World. Springer London, 2008, 297–304. http://dx.doi.org/10.1007/978-1-84800-972-1_28

[19] Singh, P.; Bettig, B.: Port-Compatibility and Connectability Based Assembly Design, ASME, 2003. http://dx.doi.org/10.1090/S0002-9947-02-03186-0

[20] Wang, H.; Zong, C.; Guan, Xin.; Xing, R.; Liu, L.: Method of Determining Weights of Subjective Evaluation Indexes for Car Handling and Stability Based on Fuzzy Analytic Hierarchy Process, J of Mech Engineering, 47(24), 2011, 83–90. http://dx.doi.org/10.3901/JME.2011.24.083

[21] Xu, Z.: A Method for Priorities of triangular fuzzy number complementary judgment matrices, Fuzzy Systems and Mathematics, 16(1), 2002, 47–50.

[22] Zhou, P.; Zhu, S.; Jiang, S.: Risk Management of Aeronautic Projects with Fuzzy Analytic Hierarchy Process, Computer Integrated Manufacturing Systems, 9(12), 2003, 1062–1066.

[23] Zou, H.: Tian, Y.: Guo, W.: Liang, Q.: Methodology for Conceptual Design of Mechanism System, Journal of Shanghai Jiaotong University, 37(5), 2003, 668–673.