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Evaluation of open-architecture product adaptability using quantitative measures

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ABSTRACT
Open architecture provides a sustainable product framework for the mass personalized production with features of adaptability and upgradability. Open-architecture products (OAPs) can support the product change to meet users' requirements in the product life time. A typical OAP would consist of common platforms, add-on modules and public interfaces. The add-on modules include known functional modules at the product development stage and unknown modules to meet the need of the product change in the future. A product open index is proposed in this paper to measure the adaptability of OAPs in their life time. The measures are qualitative for the performance evaluation of OAPs. The evaluation process includes the representation and quantitative measures of product technical factors. Based on the structure of OAPs in product platforms, modules and interfaces, three key technical indicators, namely compatibility of platform, life cycle of modularity, and openness of interface are proposed to evaluate the OAPs adaptability. An industrial painting machine is designed using the open architecture in a case study to verify the proposed method.

KEYWORDS
Open-architecture product; Product open index; Evaluation model; Product life cycle

1. Introduction

Market competition and economic globalization have been the driving force of product innovation to meet variant consumer requirements. Effective design methods and right product architecture are essential to meet demands of today's global marketplace in product quality, productivity and sustainability [3]. A variety of strategies and methods have been proposed to achieve cost-effective solutions in the product development. An appropriate structure or architecture can enable products to meet different requirements of manufacturers and users. Product architecture affects the product configuration to meet operation functions, upgrading ability and flexibility to respond to the market change. Therefore, product design using appropriate architecture is vital to meet requirements of product changes in the process of product development and applications. Industrial products have experienced the development stages of mass production and mass customization. The personalized product is a trend to meet preference of the individual user in the global competition [15]. Personalized products require the changeability of product functions and users' involvement in the product design and implementation.

Adaptability is a special feature of product to meet changing requirements of users in the product life time, which demands the product to be flexible enough either in the development stage or applications to allow changes made in the original product to upgrade the product function with the minimum cost [7]. Product adaptability includes the ability of a design method to be able to adopt the existing design knowledge in the new product design, and the ability of a product to make changes meeting the changing requirement of users during the product application. There are three key elements in an adaptable product including the function independence, modular components and public interfaces [7, 8].

Open architecture is proposed as a new product structure to allow the product function to be upgraded by adding or replacing personalized functional modules in the original product [15]. An open-architecture product (OAP) can continuously meet user requirements in the product life time. An OAP consists of three types of functional product modules that are common platform modules, customized modules and personalized modules [18]. The OAP allows the third-party vendors to develop new add-on modules for the product to use these modules through the product public interfaces. OAPs promise

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features of adaptability, upgradability, extendibility and sustainability that need to be measured by designers and users to know performance details of an OAP compared to products that use the traditional structure.

However, there is limited research on the measure of OAPs. Most of the existing OAP research considers either strategies or guidelines for the OAP design and module planning [12], or interfaces for the connection of different functional modules [13]. There is not an effective method to measure the performance of OAPs for their adaptability to meet user demands in the product life time [31]. It is therefore difficulty for designers to evaluate design solutions of OAPs, or for users to choose OAPs to meet their requirements.

A product open index is introduced in this paper to measure the adaptability of OAPs in their life time, which provides qualitative measures for the performance evaluation of OAPs. The measures are used at the product design stage to evaluate an OAP potential to accommodate changing requirements for a product in its life time. Based on the structure of OAPs in common platforms, functional modules and interfaces, three key technical indicators of quantitative measures, namely compatibility of platform (COP), life cycle of modularity (LCM) and openness of interface (OOI), are proposed to evaluate the OAP adaptability as shown in Fig. 1. An industrial painting machine is developed in a case study to verify the proposed method.

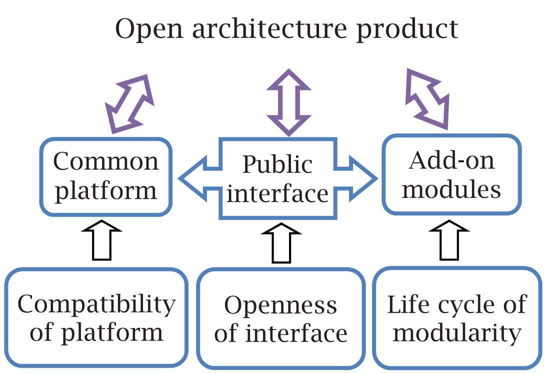


Figure 1. Evaluation indicators of OAP.

Following parts of the paper are organized as follows. The next section reviews related research on modular design, adaptable design, open-architecture product and evaluation methods. Section 3 introduces the proposed method to evaluate the OAP adaptability. Section 4 is a case study of an industrial painting machine design to verify the evaluation methods, and the improvement of the product open index for adaptability, followed by conclusions and further work in Section 5.

2. Related research

Different methods have been proposed to increase the product adaptability, such as modular design, adaptable design, design for upgradability, and design for product life cycle. Compared to the integral product structure, modular products can quickly be assembled by manufacturers to meet different user requirements. Modular design allows components, assemblies, and final products to fulfill various functions through the combination of modules [14]. Ulrich and Tung [25] defined characteristics of modular products using the similarity of physical and functional architecture for the minimization of incidental interactions between physical components. Gao et al [11] used a product platform for the product modularization applied in hydraulic press products.

Adaptable design is an approach to develop products for adaptability. Gu et al [8] proposed the adaptable design to make products to be changed or adapted for the structure reconfiguration or function upgrading to satisfy different requirements of customers. Fletcher et al [5] developed a method for designers to analyze adaptability and to make objective design decisions based on information in the design process. The method was primarily for the analytical exploration of an adaptable product framework by comparing the actual structure of the product with its ideal structure that can be easily changed. Cheng et al [4] suggested a structure-based approach to evaluate product design by measuring essential adaptability and behavioral adaptability. The essential adaptability looks the relation of function requirements and function modules based on the axiomatic design and adaptability of interfaces. The behavioral adaptability measures the performance of adaptable requirements after the adaptation measured based on the Kano model. Li et al [16] introduced measures for the adaptability evaluation considering the extendibility of functions, upgradeability of modules, and customizability of components based on different design candidates in the identification of the optimal adaptable design.

Design for upgradability was discussed by Umeda [26] to allow a product to be easily upgraded. A major aim of the product upgradeability is to make a long-term upgrading plan for multi-generations of a product during its use or remanufacturing stage and to assist designers to derive a suitable design solution for the product [27]. Effects of the structural configuration on system upgradeability were studied by Pridmore et al [20]. They investigated the favorable configuration forms for rapid prototyping of the application-specific signal processor, which enables both hardware and software to be reused with open interface standards. Umeda et al [28] developed a design method for upgradable products by using function-behavior-state modeling to examine and configure functional and structural interactions among components of a product.

Design for product life cycle mainly considers the improvement of product design and manufacturing process for sustainability with the lowest level of impact to the environment [21]. The existing method evaluates product impacts through consuming materials and energy in different stages of the product life cycle, including raw material production, manufacturing, distribution, product use and disposal [10, 30]. The suggested solutions are normally very high in cost for manufacturers to implementation based on the existing product and product structure [19].

The existing methods improve the design solution and manufacturing process mainly for the product developers. For example, the modular design allows manufacturers to develop products using pre-prepared modules to quickly install a customized product in mass production such as the production process in an assembly line of passenger cars. There is a lack of research to consider the user involvement in product changes to meet requirements of the individual product user.

Personalization is an emerging manufacturing paradigm to meet the personalized need of product users. Design for mass personalization searches for cost-effective solutions of the personalized product development [24]. OAPs were proposed to use personalized function modules to meet the individual requirement based on the existing production format in the mass personalization [15]. OAPs allow personalized function modules to be adopted in an original product to improve the product function for the individual need. As shown in Fig. 2, an OAP is considered as the product with common platforms and public interfaces where different add-on modules from different sources can be used in the product to satisfy individual user requirements. OAPs include following features [32].

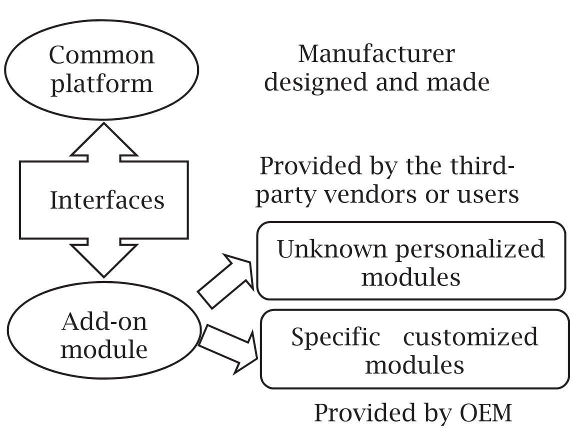


Figure 2. Open-architecture product.

(1) OAPs use common platforms, add-on modules and public interfaces for the product flexibility to meet different requirements of users in the product life time.
(2) Specifications and constraints of the public interfaces are open to product users and other manufacturers.
(3) The platform and add-on modules are connected through public interfaces to meet functional requirements through defined input and output parameters.
(4) Add-on modules can be specific modules that are designed during product development stage and unknown modules that may be designed during product life time to meet the future need.
(5) Add-on modules can be provided by both the original equipment manufacturer (OEM) and the third-party vendors.

Aziz et al [2] believed that open architecture can help the collaborative product development and knowledge management for small and medium-sized enterprises by improving non-customizable data models and inter-enterprise integration in product life cycle management. The OAP combines commonality and modularity in product design, which can bring benefits of availability and upgradability for many durable assets and reduced inventory cost as described by Ferrer [6]. One of the important features of OAPs is their interfaces open to public. Product components made by other manufacturers can be applied to OAPs [22].

Because the concept of using open architecture is new for the product structure, the research and applications of OAPs are limited. The existing research on OAPs is mainly in the areas of conceptual design and structure planning using the modular design methods to decide the product modules and interfaces. For example, Zhao et al proposed methods for planning OAP modules [34]; Hu et al proposed the interface design and evaluation for OAPs using the function correlation matrix, morphologic and fuzzy logic analyses [12]; Zhang et al considered using a cost-based method to decide the use of OAPs [33].

These methods provided limited solutions for the OAP development and applications; especially there is not a general method to decide the feasibility of OAPs for product developers and users. It is necessary to have a measure in the evaluation of OAPs for product developers and users to know detailed performance of an OAP, which will guide the implementation and applications of OAPs.

This research proposes key technical indicators of OAPs to measure the OAP performance in the compatibility of product platforms to accommodate personalized user modules, use ability of modules in the product life time, and openness of interfaces for public users to meet the requirement changes for the product adaptability. Mathematical models of the quantitative measures are established to evaluate of the adaptability of OAPs in the product life time to satisfy the individual user need.

3. Product open index

Adaptability of OAPs is constrained by the product platform, functional modules, and interfaces. Users can apply OAPs to meet their needs by using related functional modules connected to the platform through public interfaces in the product life time. A product open index, including three key technical indicators, namely compatibility of platform (COP), life cycle of modularity (LCM), and openness of interface (OOI), is proposed in this research to measure the adaptability of OAPs.

3.1. Compatibility of platform (COP)

OAPs meet different functional needs by integrating modules into the product common platform. When a new function or improvement is proposed from user requirements into the engineering metrics domain, the platform compatibility will decide the fitting level of an existing product to meet new requirements and to accommodate the change, which reflects the degree of agreement or distance between the existing and expected product function and performance. The higher value of the compatibility of platform, the more compatible the platform is to meet the function change.

Quality Function Deployment (QFD) is a tool in product design for analyzing needs by mapping customer requirements, engineering metrics and component specifications [1]. A product can be represented as a set γ_i (i = 1, 2 . . . , n), where$\gamma$is an engineering metric of the product and n stands for the number of engineering metrics. In the life time of a product, a new function requirement is represented as γ_i^e in the existing engineering metricγ_i^c, this engineering metric of the new generation product to meet the new requirement is denoted asγ_i^e. Assuming thatγ_i^e is always better than γ_i^c in terms of functionality, a mathematic model of the compatibility of platform *(COP)* can be represented in Eqn. (1). Where$\tau_i$is the normalization of a real-valued vector for the *ith* engineering metrics to represent the magnitude and direction of an improvement, a positive *t* designates the improvement or increase of the current value, while a negative *t* stands for the opposite direction. The coefficient *k* valued as 0.1, 0.3, 0.5, 0.7, or 0.9 represents the ascending level of difficulty or significance of the improvement [29].

$$COP_i = \exp[-I], \quad i = 1, 2, \ldots, \mathrm{n} \tag{1}$$

$$\text{Where} \quad I = -k_i \frac{\gamma_i^e - \gamma_i^c}{\tau_i}, \quad i = 1, 2, \ldots, \mathrm{n} \tag{2}$$

Based on the function analysis and the functional correspondence to the fulfilment of identified customer requirements, using the method of an analytic hierarchy process (AHP) [17], the weight of engineering metrics to the functionality of a product can be obtained as shown in Eqn. (3). COP_{sys} is modeled as the aggregation of a weighted *COP* for all engineering metrics.

$$COP_{sys} = \sum_{i=1}^{n} w_i COP_i, \quad \sum_{i=1}^{n} w_i = 1 \tag{3}$$

Where, $w_i$is a weight of the functional importance assigned based on the contribution of the *ith* EM to the overall functionality of the product.

According to ways that COP_i and COP_{sys} are measured, engineering metrics are used to represent the characteristics of a product platform in the function domain of product design, which shows the adaptability of the current parametrical setting in the product platform. In the process to have a product meeting the demand of an individual user, the more demand of functions will result in more changes in product engineering characteristics. A lower level of COP_{sys} will reduce the compatibility of a platform and increase the difficulty of the product adaptability.

3.2. Life cycle modularity (LCM)

Add-on modules of OAPs can be customized modules or personalized modules. The mass customized modules are designed during product development by original equipment manufacturers (OEMs). The personalized modules can be designed and used in the future provided by any manufacturers. The life cycle of modularity (*LCM*) is to assess the OAP ability to meet user requirements through the variant module design, module upgrading or replacing in the product life time. The mathematic formula of the *LCM* is proposed as follows.

$$LCM = \sum_{l=1}^{R} \sum_{i=1}^{C} w_l d_{li} \left(1 + \sum_{h \neq i}^{C} j_{ih} \right) \tag{4}$$

Where *R* is the total number of user needs; *C* is the total number of add-on modules; w_l is the weight of the *lth* need obtained by the analytic hierarchy process (AHP); δ_{li} is the influence degree of the *lth* need to the *ith* module obtained by a correlation analysis; j_{ih} is the change degree caused by the *ith* module change under the effect of the *lth* demand, which is obtained by the correlation analysis [23].

3.3. Openness of interface (OOI)

Public interfaces in an OAP are used to connect add-on modules onto the platform for different function requirements. Compared to a closed architecture product, the public interfaces in the OAP are featured by their openness to support the personalized module in OAPs. The interface openness has an important effect on upgrading OAPs in disassembly and assembly of personalized modules in the OAPs. Criteria proposed for the quantitative assessment of the interface open feature are the interface standardization, interactions and constraints of the interface as listed in Tab. 1.

Table 1. Criteria of the interface openness [19].

Level	Description	Grade
1	Standardized connections from industrial society. Interactions and constraints are classified and proved;	0.8 ~ 1
2	Connections developed by a manufacturer and/or its suppliers. Interactions and constraints are classified.	0.6 ~ 0.8
3	Single type of regular geometric profile/indirect interface. Single type of interaction and constraint/indirect interaction.	0.4 ~ 0.6
4	Compound profile of regular geometric elements Compound interactions and constraints.	0.2 ~ 0.4
5	Unique fitting between two modules. Highly specialized interactions and constraints.	0 ~ 0.2

The interface openness is represented using Eqn. (5) to measure the module connection and operation ability of public interfaces and personalized modules for the module replacing or upgrading.

$$OOI = \frac{1}{n}\sum_{i=1}^{n} w_i \tag{5}$$

Where n is the number of open interfaces in a product; wi is the importance degree of the *ith* open interface.

3.4. Product open index (POI) for adaptability

In order to evaluate the complete performance of the OAP adaptability, above-introduced three measures are combined for the measure of OAP performance with weighted factors based on the compatibility of platform, life cycle of modularity, and openness of interface. A specific product adaptability index is introduced to include these measures using a dimensionless measure. The weighted factors can be selected based on importance of each factor in a product. The product open index (*POI*) has a value range from 0 to 1. There will be no open feature in a product when $POI = 0$. It will be a complete open product when $POI = 1$. A higher value of POI indicates a better performance of the product adaptability. The mathematic model of the POI is represented as follows.

$$POI = w_1{}^*COP + w_2{}^*LCM + w_3{}^*OOI \tag{6}$$

Where $w_1 + w_2 + w_3 = 1$. The proposed measure supports a detail evaluation of the open feature of OAPs, which also indicates the improvement area for an OAP after the evaluation.

3.5. Improvement of the product open index (POI) for adaptability

The compatibility of platform (*COP*) is related to the engineering metrics. The more engineering metrics of a product are affected by functional changes during upgrading product, the lower level of COP_{sys} will become and the more difficult for the product to meet OAPs. If the engineering metrics have the "expected values" identified as being significantly different from their current parametrical settings, the COP_{sys} will be a lower level. Consequently, it suggests that a great effort may be needed to bridge such "gaps" between the two sets of values.

The life cycle modularity (*LCM*) consists of the need effect to the module and the module change caused by the change of other modules. It directly reflects the fitness of the product structural configuration to meet requirements of remanufacturing. Weak intra-module links and enhanced module independence are highly important to the need of OAPs. Apparently, the more important a module is, the greater the impact will be on the product *LCM*. The module contributions to the ultimate OAP are directly related to the function importance of the product, which can be identified through mapping user requirements to functional parameters.

The openness of interface (*OOI*) is decided by the standardization of interfaces, interactions and constraints of the interface. The higher standardized interface with simpler interactions and constraints will result in a better adaptability. Using the *POI* measure of the product adaptability, an industrial painting machine is evaluated for its adaptability, and is then improved for the problem found in the evaluation to meet the OAP requirement.

4. Case study

The industrial painting machine is used in the toy industry to paint surfaces of toys made from plastic or metal materials as shown in Fig. 3. The machine is designed using the open architecture concept to meet different function requirements of the machine operation through replacing or upgrading personalized modules in the original machine [7]. Adaptability of the industrial painting machine is evaluated using the proposed measure *POI*.

4.1. Compatibility of platform (COP)

A QFD matrix of the machine is developed based on the analysis of the existing product market by consulting the related enterprise and the survey of users. Tab. 2 shows the user demands, current values and expected values of the engineering metric of the industrial painting machine. The values of the COP and COP_{sys} in Eqns (1) and (3) can be calculated as follows:

$$
\begin{aligned}
COP_{sys} &= w_1 * COP_1 + w_2 * COP_2 + w_3 * COP_3 \\
&\quad + w_4 * COP_4 + w_5 * COP_5 + w_6 * COP_6 \\
&\quad + w_7 * COP_7 + w_8 * COP_8 + w_9 * COP_9 \\
&\quad + w_{10} * COP_{10} \\
&= 0.141 * 0.69 + 0.102 * 0.74 + 0.122 * 0.70 \\
&\quad + 0.114 * 0.73 + 0.065 * 0.78 + 0.084 * 0.42 \\
&\quad + 0.104 * 0.86 + 0.099 * 0.90 + 0.112 * 0.79 \\
&\quad + 0.054 * 0.77 \\
&= 0.74.
\end{aligned}
$$

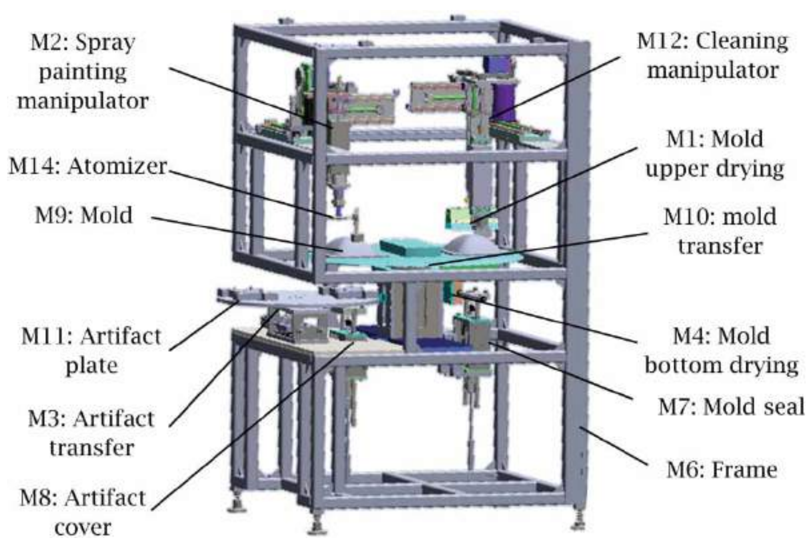


Figure 3. The industrial painting machine.

Table 2. QFD of the industrial painting machine.

	Spraying area	Spray granulating diameter	Spraying speed	Cleaning speed	Dry wind speed	Exhaust	Color number	Adjust gear number	Dose adjusting range	nose
Spraying range	X									
Spraying precision		X								
Spraying speed			X							
Cleaning speed				X						
quick drying					X					
Environmental protection						X				
Spraying color							X			
Spray Angle								X		
Dose adjustment									X	
noise small										X
Weight	0.141	0.102	0.122	0.114	0.065	0.084	0.104	0.099	0.112	0.054
unit	cm^2	mm	mm/s	mm/s	cm/s	M^3/h	EA	EA	ML/min	dB
g^c	216	1	300	216	3.5	400	1	3	30	85
g^e	432	0.5	400	432	4	450	3	5	50	70
t_i	175	−0.5	27.5	67.5	0.2	17.5	4	2	25	−17.5
κ	0.3	0.5	0.1	0.1	0.1	0.3	0.3	0.1	0.5	0.3
COP_i	0.69	0.74	0.70	0.73	0.78	0.42	0.86	0.90	0.79	0.77

Hu et al planned modules of the open-architecture painting machine with 14 main modules [9]. They are mold upper drying (M1-G), spray-painting manipulator (M2-C), artifact transfer module (M3-G), mold bottom drying (M4-C), waste gas treatment module (M5-C), frame (M6-G), mould seal module (M7-C), artifact cover module (M8-C), mould (M9-P), mold transfer module (M10-G), artifacts plate module (M11-P), cleaning manipulator (M12-C), cleaning fluid supply (M13-G), and atomized spray module (M14-P). The module planning method is implemented for the painting machine to decide the type, layout and interaction of modules. The machine modules and relations are shown in Fig. 4, where nodes represent modules, data in the node are module numbers and types (G-common module, C– customized module, P-personalized module), the link indicates a connection through the interface between modules.

4.2. Life cycle modularity (LCM)

In order to evaluate the life cycle of modules, Tab. 3 uses the mapping method based on the user demand for the effect degree of modules and module changes caused by the change of other modules with a value range of (0,1]. The weight of user demand is listed on the table left, the table top parts are user demands for the effect degree of modules, and the table bottom parts are module changes caused by the change of other modules. The modules considered in Tab. 3 are customized modules and personalized modules of the painting machine. The LCM of the machine can then be calculated as a value of 0.11 using Eqn. (4).

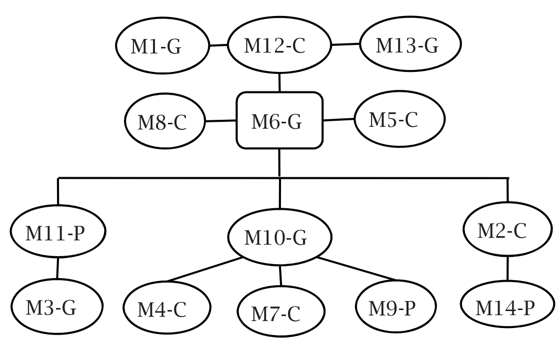


Figure 4. Modules and relations of the painting machine.

4.3. Openness of interface (OOI)

According to the result of the module planning, modules M9, M11 and M14 are personalized modules. The interfaces between M9 and M10, M11 and M3, M12 and M14 are required to be the public interfaces. Hu et al designed the painting machine with the function correlation matrix, morphologic and fuzzy logic analyses considering adaptable interfaces [6]. The openness of interface can be obtained based on criteria of the interface listed in Tab. 1. For example, pins are used to ensure the accuracy of positioning. The screw and gasket are used to clamp the connection and to meet needs of the module replacement in assembly and disassembly between M11 and M3, and the connection was developed by the manufacturer. Tab. 4 shows connections of these three personalized modules with their interfaces in the painting machine, and grades of the interfaces. The openness of painting machine interfaces can then be calculated based on Eqn. (6) and Tab. 4, as $OOI = (0.7 + 0.8 + 0.9)/3 = 0.80$.

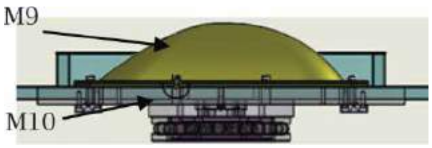
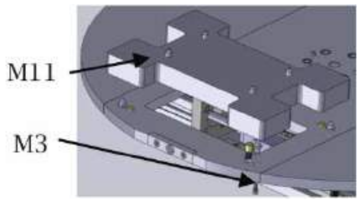
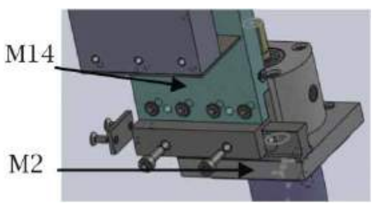
4.4. Product open index (POI) for adaptability

It is assumed that the effect degree of each index for the machine is same in this case study. The adaptability

Table 3. Module weights and effect of changes.

Weight	Modules	M2	M4	M5	M7	M8	M9	M11	M12	M14
0.17	Spraying range	0.8				0.1		0.3		
0.25	Spraying precision	0.3					0.3			0.8
0.21	Spraying speed	0.6						0.3		0.1
0.11	Cleaning speed				0.3				0.8	
0.09	Quick drying		0.8							
0.03	Environmental protection			0.8			0.1			0.1
0.06	Spraying color				0.1					0.3
0.04	Spray Angle	0.3								
0.03	Dose adjustment									0.3
0.02	Noise small	0.6	0.3						0.6	
weight	Customer demand	M2	M4	M5	M7	M8	M9	M11	M12	M14
	M2									0.3
	M4			0.1						
	M5									
	M7						0.1			
	M8				0.1					
	M9		0.1		0.3					
	M11									
	M12				0.1					
	M14	0.1								

Table 4. Examples of interfaces and modules.

NO.	example	Description	Grade
M9 & M10		• Standardized connections from industrial society • Static interaction with screw constraints	0.7
M11 & M3		• Connections developed by a manufacturer and/or its suppliers. • Indirect interaction with pin and spring constraints	0.8
M2 & M14		• Standardized connections from industrial society • Static interaction with bolt constraints and slot	0.9

of the painting machine can be obtained as $POI = w_1{*}COP + w_2{*}LCM + w_3{*}OOI = 0.33{*}0.74 + 0.33{*}0.89 + 0.33{*}0.80 = 0.80$.

4.5. Improvement of adaptability of the painting machine

Based on the evaluation result, the adaptability of the painting machine is relatively high, but some areas are identified in the evaluation that can be improved. The compatibility index of platform is 0.73. As the "expected values" of some important features of engineering characteristics are different from their current parametrical settings. To improve the compatibility of platform (*COP*), the "gaps" between the two sets of values should be narrowed. For example, if the painting manipulator can increase the spraying area to 400 cm^2 from 216 cm^2 , and increase the spraying speed to 400mm/s from 216mm/s in Tab. 2. The COP_1 and COP_4 in Eqns (1) and (2) can be calculated as $COP_1 = exp\,[-0.3{*}(432 - 400)/175] = 0.95$, $COP_4 = exp\,[-0.1{*}(432 - 400)/67.5] = 0.95$. Then, the value of the COP_{sys} will be improved to 0.80 as follows:

$$
\begin{aligned}
COP_{sys} = {} & w_1 * COP_1 + w_2 * COP_2 + w_3 * COP_3 \\
& + w_4 * COP_4 + w_5 * COP_5 + w_6 * COP_6 \\
& + w_7 * COP_7 + w_8 * COP_8 + w_9 * COP_9 \\
& + w_{10} * COP_{10}
\end{aligned}
$$

$$
\begin{aligned}
= {} & 0.141 * 0.95 + 0.102 * 0.74 + 0.122 * 0.70 \\
& + 0.114 * 0.95 + 0.065 * 0.78 + 0.084 * 0.42 \\
& + 0.104 * 0.86 + 0.099 * 0.90 + 0.112 * 0.79 \\
& + 0.054 * 0.77 = 0.80.
\end{aligned}
$$

The life cycle modularity (*LCM*) is 0.89, which suggests that the independence of modules can meet user needs through replacing or upgrading the module. For the openness of interface (*OOI*), the index value of M9 and M10 is relevant low as the screw fastening is used to connect modules of M9 and M10. The interface connection may be improved to simplify the assembly and disassembly operations in the module upgrading. Screw fastening can be replaced by other fasteners for efficient operations.

Through improving areas identified in the evaluation, the machine adaptability can be improved to better meet the demand of individual users. The *POI* of the machine can be recalculated as $POI = w_1{*}COP + w_2{*}LCM + w_3{*}OOI = 0.33{*}0.80{+}0.33{*}0.89 + 0.33{*}0.83 = 0.83$. The adaptability of the painting machine is increased.

5. Conclusions

The open architecture provides an adaptable product structure for personalized products to meet changing requirements of product functions in the product life time. The performance measure plays an important role in the design and implementation of OAPs for designers and users. This paper proposed a quantitative evaluation method using the product open index to measure the adaptability of a product. The proposed product open index POI ranges from 0 to 1, a high value of POI closed to 1 indicates the good performance of product adaptability. The paper introduced the key factors that affect the product adaptability. Models and representations of the proposed quantitative measures were described. Three key technical indicators including the compatibility of platform, life cycle of modularity, and openness of interface were suggested to evaluate the product platforms, modules and interfaces.

The proposed method has been used in the evaluation and improvement of an OAP industrial painting machine. The solution can be used to identify and improve the machine commonality and operations to meet personalized demands. Further research is to include the cost factor in the evaluation of OAPs and to apply the proposed measures to different products for the method improvement.

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