Title:
Evaluation of Open-architecture Product Adaptability Using Quantitative Measures

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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 [1]. 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 [6]. 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 [2]. 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 [2, 3].

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 [6]. 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 [7]. 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 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 [4], or interfaces for the connection of different functional modules [5]. There is not an effective method to measure the performance of OAPs for their adaptability to meet user demands in the product life time [9]. 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. An industrial painting machine is developed in a case study to verify the proposed method.

Main Idea:
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.

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 (*COP*), the more compatible the platform is to meet the function change. A mathematic model of the compatibility of platform (*COP*) can be represented in Eqn. (1).

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

Where COP_{sys} is modeled as the aggregation of a weighted *COP* for all engineering metrics. 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.

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.

$$LCM = \sum_{l=1}^{R} \sum_{i=1}^{C} w_l d_{li} \left(1 + \sum_{h \neq i}^{C} j_{ih}\right) \tag{2}$$

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* needs 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 [8].

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Openness of Interface (OOI)

The 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.

The interface openness is represented using Eqn. (3) to measure the module connection and operation ability of public interfaces and personalized modules for the module replacing or upgrading.

$$OOI = \frac{1}{n}\sum_{i=1}^{n} w_i \tag{3}$$

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

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.

$$POI = w_1 * COP + w_2 * LCM + w_3 * OOI \tag{4}$$

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.

Case Study:

An industrial painting machine used in the toy industry shown in Fig. 1 is developed in the case study. 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 [2]. Adaptability of the industrial painting machine is evaluated using the proposed measure *POI*.

Compatibility of Platform (COP)

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. 2, 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.

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. The user demands, current values and expected values of the engineering metric of the industrial painting machine are analyzed. The values of the *COP* and COP_{sys} in Eqns (1) are calculated.

Life Cycle Modularity (LCM)

In order to evaluate the life cycle of modules, the mapping method is used based on the user demand for the effect degree of modules and module changes caused by changes of other modules with a value range of (0,1]. The weight of user demand is decided for the analysis of effect degrees of the module, and module changes caused by the change of other modules. The modules considered are customized modules and personalized modules for the machine. The *LCM* of the painting machine can then be calculated using Eqn. (2).

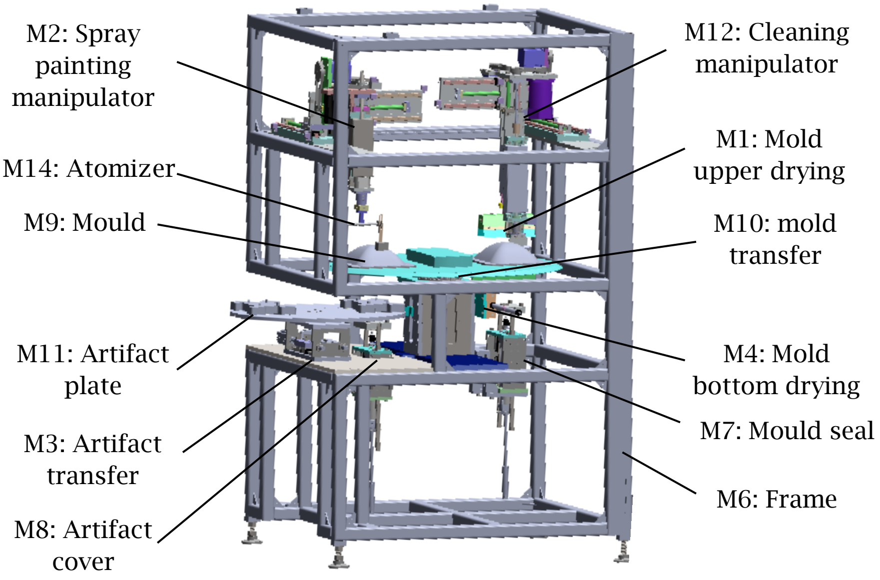

Fig. 1: The industrial painting machine.

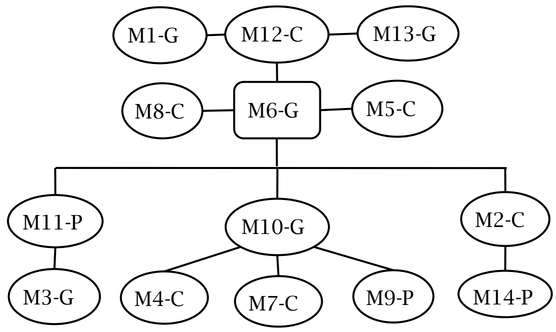

Fig. 2: Modules and relations of the painting machine.

Openness of Interface (OOI)

According to the result of the module planning, the interfaces between the platform and personalized modules are required to be the public interfaces. The openness of interfaces can be obtained based on criteria of the interfaces collected. 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 module assembly and disassembly. The connections were developed by the manufacturer. Based on connections of these personalized modules with their interfaces in the painting machine, and grades of the interfaces, the openness of painting machine interfaces can be calculated based on Eqn. (3).

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 of the painting machine can then be obtained. Through improving areas identified in the evaluation, the machine adaptability is improved to better meet the demand of individual users. The adaptability of the painting machine is increased.

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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