Design for Product Adaptability

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Abstract: Adaptable design is a new design paradigm to create designs and products that can be easily changed to satisfy different requirements. Adaptable design aims at identifying the designs and products considering functionality, manufacturing efforts, customization, and environment friendliness. This research focuses on adaptable design considering product adaptability. In this work, product adaptability is evaluated by three measures including extendibility of functions, upgradeability of modules, and customizability of components. Various design candidates created in adaptable design are evaluated by different life-cycle evaluation measures including product adaptability of design, part and assembly costs of manufacturing, and operationability of customers. Since different evaluation measures are modeled in different units, the grey relational analysis method is employed to integrate these measures for prioritizing different design candidates. A case study is given to demonstrate the effectiveness of the introduced adaptable design approach.

Key Words: adaptable design, product adaptability, design evaluation, grey relational analysis method.

1. Introduction

Adaptable design is a new design paradigm with both economical and environmental benefits [1]. The underlying philosophy of adaptable design is the ability of a design or a product to be adapted to new requirements and the reuse of a design or a product when requirements are changed. Adaptable design is usually achieved through replacement of multiple products by one adaptable product with a set of add-on attachments.

Two types of adaptabilities are considered in adaptable design: design adaptability and product adaptability [1]. The design with design adaptability can be modified by manufacturer to generate new designs to improve variety of products. The product with product adaptability can be changed by user in a usually reversible and simple procedure to achieve different functions or usages. Design adaptability helps the manufacturer reuse the existing design and manufacturing equipments, which usually cost less than to create new designs and manufacturing equipments. Product adaptability allows the user to utilize the same product under different conditions, by replacing with different functional parts or upgrading existing parts. Both adaptabilities are also beneficial to the environment because they can reduce the total production volumes and extend the products’ life spans. This research focuses on the product adaptability aspect.

Although adaptable design is a relatively new concept, many existing design methods, including modular design, product platform and family design, and mass customized design, can be used and improved for creating adaptable products that can be easily modified to satisfy different requirements [1,2].

Modular design is an approach to create a product using groups of components called modules [3,4]. Since these modules are relatively independent, they can be easily disassembled from the product for upgrading, repairing, recycling, or reusing. Many methods have been developed to cluster components into modules based on similar of functions, technologies, and structures. Gershenson et al. [5] classified the modular design methods into four main categories: checklist methods, design rules, matrix manipulations, and step-by-step measure and re-design methods. Modularity measures have also been developed to evaluate modular designs [6].

Platform design is another approach, by grouping the common components for a number of products in a product family, as the platform to be shared by these products [2]. In the past decade, considerable effort has been devoted to product platform and family design [7,8]. Product platforms can be classified into two categories: modular platforms and scalable platforms [2]. A modular platform is a collection of components to be shared by all the products in a product family. Different functions in this family are achieved by adding, removing, or substituting attachment modules to/from the platform [9]. A scalable platform is modeled...
by scalable variables that can be changed to satisfy different requirements [10]. Parametric design can be used for achieving a scalable platform. Commonality measures have also been introduced to evaluate product platform and family design [6].

Mass customization is a manufacturing approach to produce customized products based on requirements of individual customers with near mass production efficiency [11]. Many methods and sophisticated software systems have been developed in recent years to design customized products based on customer requirements [2]. Jiao and Tseng [12] introduced the customizability measure to evaluate mass customized designs and their impact to customers and manufacturers. Siddique and Boddu [13] developed an information system to integrate design and manufacturing activities in mass customization. Concurrent engineering approach was also used in mass customization by integrating design, manufacturing, customer requirements, service requirements, etc. into the same environment [14,15]. In addition, modular design, platform design and product family design methods have also been used in mass customization [2].

Since the introduction of the adaptable design concept by Gu et al. [1], many new methodologies have been developed to achieve the objectives of adaptable design. Sand and Gu [16] developed modularization and upgrade planning techniques for adaptable design. A computer system, called AdaptEx, was implemented based on the introduced methods. Fletcher et al. [17] proposed methods for measuring general adaptability of products. Xu et al. [18] applied adaptable design methods in the design of gantry-type CNC machines. Shao et al. [19] extended the adaptable design approach into product family-based adaptable design. Li et al. [20] developed a guideline for achieving product adaptability through the adaptable design process. By following this guideline, the design engineers may achieve different design candidates, which all are adaptable and fulfill the design requirements. Many existing methodologies, including modular design, product platform design and product family design, have also been used and improved in the development of adaptable design methods.

Despite the progress, evaluation of adaptable design is still not well studied due to the complex nature of this new design approach. Since many design candidates can be identified to achieve the adaptable design requirements, quantitative evaluation measures need to be developed to evaluate these candidates. In the research presented in this article, three new product adaptability evaluation measures, including extendibility of functions, upgradeability of modules, and customizability of components, are introduced. In addition, other product life-cycle aspects are also considered in this research for identifying the optimal design.

2. Product Adaptability in Adaptable Design

2.1 Product Adaptability

Product adaptability is the ability of a created or purchased product to be adapted by users to achieve various functions or to enhance its performance [1]. For example, the 2003 Ford Freestyle FX concept car adds a new feature to convert a SUV into a pickup truck, as well as to convert it back. This vehicle is equipped with an electric-powered track for moving the trunk module forward and backward. This structure allows for future additions of passenger seats, provides extra space for possible future use, and the electric-powered track greatly facilitates the adaptation task for users.

Product adaptabilities can be classified into specific product adaptabilities and general product adaptabilities depending on whether predicted information for specific adaptions is available [1]. When particular adaptabilities and their probabilities can be predicted, the product can be designed to accommodate these specific product adaptabilities. For example, when the AGP video cards were first introduced, the PCI video cards were still primarily used as default video cards for most computers. Since it was predicted that more users would change to the AGP video cards in the future, many motherboards of these computers provided the AGP slots for future upgrading. Therefore, the adaptability for the AGP video card is a specific adaptability. On the other hand, when the new requirements cannot be predicted, the product can be designed to have some general product adaptabilities by its product architecture and interfaces. For example, many HDTV terminal boxes provide the USB interfaces, although no actual plans have been created on how these USB interfaces will be used in the future. The adaptability of USB for HDTV terminal boxes is a general adaptability. This research focuses on the specific product adaptabilities.

2.2 Measures for Evaluating Specific Product Adaptabilities

In this research, three evaluation measures are introduced to evaluate specific product adaptability: extendibility of functions, upgradeability of modules, and customizability of components.

2.2.1 EXTENDIBILITY OF FUNCTIONS

Extendibility of functions is achieved by designing a product with potential extension of functions. Extendibility is a kind of product adaptabilities to adapt the product from one function to another function with the minimum effort of the user. Extendibility of functions can be obtained from the existing parts designed with versatile functions, or by adding/replacing parts and assemblies of the existing products.
In this research, functions of an adaptable design are classified into two categories: fundamental functions and adaptable (optional) functions. Suppose the probability to adapt the current product with an adaptable function $T_{pi}$ (i.e., the $i$-th target adaptation) in the future is defined as $Pr(T_{pi})$, the effort to adapt the current product to the new adaptable function $T_{pi}$ is described by $Inf(S_1 \rightarrow AS_2)$, and, the effort to create a completely new product with the same function is described by $Inf(ZERO \rightarrow IS_2)$. The extendibility factor, $EF(T_{pi})$, is then defined by:

$$EF(T_{pi}) = 1 - \frac{Inf(S_1 \rightarrow AS_2)}{Inf(ZERO \rightarrow IS_2)}, \quad 0 \leq EF(T_{pi}) \leq 1$$  \hspace{1cm} (1)

When all $n$ possible adaptable functions are considered, the extendibility of the existing product is defined by:

$$E(P) = \sum_{i=1}^{n} [Pr(T_{pi})EF(T_{pi})]$$ \hspace{1cm} (2)

In this method, the costs are usually selected to describe the efforts for adapting an existing product or for creating a new product. In Equation (1), the efforts for adapting an existing product or for creating a new product are defined by:

- $S_1$: the current state of the existing product
- $AS_2$: the modified state with the additional adaptable function
- $ZERO$: the state to design a new product from scratch
- $IS_2$: the state with only the required adaptable function
- $Inf()$: information change (i.e., efforts) from one state to another state

From Equation (1), when the effort for adapting an existing product is greater than the effort for creating a new product, the extendibility factor is calculated as 0. In this case, no adaptation is required. When the effort for adapting an existing product is less than the effort for creating a new product, the extendibility factor is calculated as a value between 0 and 1. In this case, adaptation of the existing product should be considered. When no extra effort is required to achieve the adaptable function from the existing product, the extendibility factor of this product is 1. For example, considering an LCD computer monitor with adaptable function of HDTV monitor, $T_{p1}$. When the cost to create a new HDTV monitor is $800$, and the cost to add the HDTV function to an existing LCD computer monitor is $500$, the extendibility factor, $EF(T_{p1})$, is calculated as

$$EF(T_{p1}) = 1 - \frac{Inf(S_1 \rightarrow AS_2)}{Inf(ZERO \rightarrow IS_2)} = 1 - \frac{500}{800} = 0.375$$

Since the extendibility factor is calculated as a value between 0 and 1, it is cheaper to adapt the computer monitor with the HDTV function than to create a new HDTV monitor. In this case, adaptation of the existing product should be considered. When the cost to create a new HDTV monitor is $800$, and the cost to add the HDTV function to an existing LCD computer monitor is $1000$, the extendibility factor, $EF(T_{p1})$, is calculated as

$$EF(T_{p1}) = 1 - \frac{Inf(S_1 \rightarrow AS_2)}{Inf(ZERO \rightarrow IS_2)} = 1 - \frac{1000}{800} = -0.25$$

According to Equation (1), the extendibility factor is obtained as 0, representing that it is more expensive to adapt the computer monitor with the HDTV function than to create a new HDTV monitor. In this case, adaptation of the existing product should not be considered. When the cost to create a new HDTV monitor is $800$, and no additional cost is needed to add the HDTV function to an existing LCD computer monitor, the extendibility factor, $EF(T_{p1})$, is calculated as

$$EF(T_{p1}) = 1 - \frac{Inf(S_1 \rightarrow AS_2)}{Inf(ZERO \rightarrow IS_2)} = 1 - \frac{500}{800} = 0.375$$

In this case, design of the monitor with both the computer monitor function and the HDTV function must be considered.

### 2.2.2 Upgradeability of Modules

With the advances of technologies and changes of user requirements, the existing products need to be upgraded to accommodate new technologies and requirement changes. Upgradeability is another kind of product adaptabilities to achieve better performance or advanced technologies to meet new needs.

Suppose the probability to upgrade the current part with an upgraded part $U_{pi}$ (i.e., the $i$-th target adaptation) in the future is defined as $Pr(U_{pi})$. The effort to provide the upgrading function in the current part is described by $Inf(P_1 \rightarrow U_{pi})$, and, the effort to create current part without upgrading capability is described by $Inf(P_1)$. The upgradeability factor, $UF(U_{pi})$, is then defined by:

$$UF(U_{pi}) = 1 - \frac{Inf(P_1 \rightarrow U_{pi})}{Inf(P_1)}, \quad 0 \leq UF(U_{pi}) \leq 1$$  \hspace{1cm} (3)

When all $n$ possible upgrading parts are considered, the upgradeability of the existing product is defined by:

$$U(P) = \sum_{i=1}^{n} [Pr(U_{pi})UF(U_{pi})]$$ \hspace{1cm} (4)

In this method, costs are usually selected to describe the efforts for providing the upgrading function and for
creating the part without upgrading function. Generally, the cost for providing upgrading function is calculated by the cost of interface which allows for the upgrading of new modules. In Equation (3), the effort for providing upgrading function is defined by:

\[ P1: \text{the state of the module without upgrading function} \]

\[ UP1: \text{the state of the module with upgrading function} \]

From Equation (3), when the effort for adding an interface to an existing part is greater than the effort for creating this part, the upgradeability factor is calculated as 0. In this case, no upgrade is required. When the effort for adding the interface to an existing part is less than the effort for creating this part, the upgradeability factor is calculated as a value between 0 and 1. In this case, upgrade of the existing part should be considered. When no extra effort is required to achieve the upgrade from the existing part, the upgradeability factor of this part is 1.

2.2.3 CUSTOMIZABILITY OF COMPONENTS

Customizability of components is the easiness of product adaptation based on requirements and preferences of individual customers. The product design with customizability can be easily reconfigured to different product configurations by combining standard components and modules based on the customer requirements. In this work, the customization mainly focuses on part customization.

Same as the upgradeability, suppose the probability to customize the current part by another part with the same function \( C_{pi} \) (i.e., the \( i \)-th target adaptation) in the future is defined as \( Pr(C_{pi}) \), the effort to provide the customization function to customize the current part to another part \( C_{pi} \) is described by \( Inf_{(P1 \rightarrow CP1)} \) and, the effort to create current part without the customizability is described by \( Inf_{(P1)} \). The customizability factor, \( CF(C_{pi}) \), is then defined by:

\[ CF(C_{pi}) = 1 - \frac{Inf_{(P1 \rightarrow CP1)}}{Inf_{(P1)}}, \quad 0 \leq CF(C_{pi}) \leq 1 \] (5)

When all \( n \) possible customization parts are considered, the customizability of the existing product is defined by:

\[ C(P) = \sum_{i=1}^{n} [Pr(C_{pi})CF(C_{pi})] \] (6)

In this method, costs are usually selected to describe the efforts for providing the customization function and for creating the part without customization function.

In Equation (5), the effort for providing customization function is defined by:

\[ P1: \text{the state of the part without customization function} \]

\[ CP1: \text{the state of the part with customization function} \]

When the selected customization part is also an upgradeable part and they can share the same interface, there is no extra effort required to achieve the customization from the existing part.

2.2.4 SPECIFIC PRODUCT ADAPTABLE INDEX

The specific product adaptability index is achieved based on three measures: (1) extendibility of functions, (2) upgradeability of modules, and (3) customizability of components. To define the specific product adaptability using these three different evaluation measures, these measures should be first converted into dimensionless evaluation measures. The normalized measure for extendibility of functions is calculated by:

\[ NE(P)_i = \frac{E(P)_i}{E(P)_{\text{max}}} \] (7)

where, \( E(P)_i \) and \( E(P)_{\text{max}} \) are the extendibility of functions for the \( i \)-th design candidate and the maximum value of extendibility of functions considering all the compared design candidates, respectively.

In the same way, the upgradeability of modules and customizability of components can be calculated by:

\[ NU(P)_i = \frac{U(P)_i}{U(P)_{\text{max}}} \] (8)

\[ NC(P)_i = \frac{C(P)_i}{C(P)_{\text{max}}} \] (9)

These three values can then be combined into an overall specific product adaptability index by assigning weighting factors. The specific product adaptability index for the \( i \)-th design candidate is calculated by:

\[ A(P)_i = I_E NE(P)_i + I_U NU(P)_i + I_C NC(P)_i \] (10)

where \( I_E \), \( I_U \), and \( I_C \) are weighting factors. In this research, these three weighting factors are selected with the same value, 33.3%, representing the equal importance of these evaluation aspects.

The specific product adaptability index \( A(P)_i \) of each design candidate ranges from 0 to 1. When \( A(P)_i = 0 \), there is no specific product adaptability. When \( A(P)_i = 1 \), the design candidate has complete specific product adaptability.
3. Evaluation of Design Candidates Considering Product Adaptability

In adaptable design, the same design requirements can usually be achieved by different candidates. Therefore identification of the best candidate has to be conducted for subsequent production. Since a product with better adaptability usually requires more efforts of design and manufacturing due to its variety and complexity [21], evaluation of the design candidates considering all relevant life-cycle aspects is required.

3.1 Evaluation Measures

In this research, four evaluation measures, including specific product adaptability, total part cost, total assembly cost, and operationability of customers, are selected for evaluating design candidates.

3.1.1 SPECIFIC PRODUCT ADAPTABILITY

The fundamental functions and adaptable functions of a product are identified by the forecasting information at the marketing stage, and then the product is designed to accommodate these product adaptabilities. Such product adaptability is called specific product adaptability. The measures for evaluating specific product adaptability, including extendibility of functions, upgradeability of modules, and customizability of components, are introduced in Section 2.2. The specific product adaptability is calculated using Equation (10).

3.1.2 TOTAL PART COST AND TOTAL ASSEMBLY COST

Total part cost for each product candidate is the sum of the costs of all parts. Assembly cost is the cost for all assembly activities. Different product architectures usually require different assembly costs. The part cost and assembly cost can be described by dollars.

3.1.3 OPERATIONABILITY

The operationability of a product is evaluated based on convenience of interface, degree of difficulty to adapt to different functions, and feelings of customers. Because the operationability is evaluated in terms of evaluation measures such as good, fair, and poor in this research, this operationability evaluation measure is qualitative in nature. Operationabilities are rated on scales between 0 and 5, where 0 and 5 represent totally unsatisfactory and totally satisfactory, respectively.

3.2 Grey Relational Analysis Approach

Design candidate selection through evaluation to these candidates considering different evaluation measures is a typical multiple criteria decision-making problem. Since decision to select the design candidate is conducted at early design stage, the information of design candidates is usually limited, incomplete, and uncertain. The relationships among various evaluation measures are also unclear. In this case, the analysis using classical statistical methods for multiple criteria decision-making may not be acceptable or reliable without large data sets. For example, three parameters were used by Prasad to model the costs of variety considering number of options in a product variety, how much the product is away from its finish stage, and effort to change from one variety to another [21]. Identification of these parameter values, however, is difficult especially at early design stage.

The grey relational analysis is a method in the grey theory [22] to compare evaluation measures quantitatively. This method is used to establish the relations among different evaluation measures by comparing the evaluation measures of a particular design candidate with the best evaluation measures considering all the design candidates. The grey relational analysis approach needs less data and requirements on data distributions to overcome the disadvantages of traditional statistical analysis methods. The grey relational analysis has been demonstrated as a simple and effective approach for analyzing relationships among different decision parameters (e.g., performance and costs) in multiple criteria decision-making problems [23].

This research employs the grey relational analysis approach to integrate the different evaluation measures for prioritizing different design candidates. The evaluation is conducted through the following six steps.

1. Establish comparative series and standard series.

The comparative series is composed of the evaluation measures for the adaptable design candidates:

\[ A_i = (x_{i1}, x_{i2}, \ldots, x_{in}), \quad i = 1, 2, 3, \ldots, m \]  

These \( n \) evaluation measures for the \( m \) adaptable designs form an \( m \) by \( n \) decision matrix, \( D \). The standard series is the target series modeled by:

\[ A_0 = (x_{01}, x_{02}, \ldots, x_{0j}, \ldots, x_{0n}) \]  

The standard series is composed of the best values for each of all the evaluation measures.

2. Generate the normalized decision matrix \( K \) (dimensionless).

To compare the different evaluation measures, these measures should be first converted into the dimensionless evaluation measures through the following three steps.

\[ K_{ij} = \frac{x_{ij}}{C_0/C_1}, \quad i = 1, 2, 3, \ldots, m, \quad j = 1, 2, 3, \ldots, n \]  

3. Convert the dimensionless decision matrix into a grey relational coefficient matrix.

4. Calculate the grey relational grade of each candidate.

5. Prioritize the candidates.

6. Determine the selected design candidates.

The grey relational analysis approach is a useful tool for evaluating design candidates considering all relevant life-cycle aspects.
(a) If the evaluation measure is of the larger-the-better type (e.g., the adaptability), the normalized measure is calculated by:

\[ x^*_ij = \frac{x_{ij} - \min x_{ij}}{\max x_{ij} - \min x_{ij}} \quad (13) \]

(b) If the evaluation measure is of the smaller-the-better type (e.g., the cost), the normalized measure is calculated by:

\[ x^*_ij = \frac{\max x_{ij} - x_{ij}}{\max x_{ij} - \min x_{ij}} \quad (14) \]

(c) If the evaluation measure is of the nominal-the-best type (e.g., the output voltage of a voltage converter), and the target value is selected as \( x_{obj} \), the normalized measure is calculated by:

\[ x^*_ij = \frac{|x_{ij} - x_{obj}|}{\max x_{ij} - x_{obj}} \quad (15) \]

The standard series should be converted into \( A^*_0 = (x_{01}^*, x_{02}^*, \ldots, x_{0j}^*, \ldots, x_{0n}^*) \) in the same manner.

3. Obtain the differences between the comparative series and the standard series.

To discover the degree of the grey relationship, the differences, \( \Delta_{0ij} \), between the normalized decision matrix \( K \) and the normalized standard series \( A^*_0 \) are achieved by:

\[ \Delta_{0ij} = |x^*_0ij - x^*_ij| \quad (16) \]

4. Calculate the grey relational coefficients.

The grey relational coefficients, \( \gamma_{0ij} \), indicate the contiguous grades between the comparative series and the standard series. A relational coefficient with higher value represents a closer relationship with the best evaluation measure considering all design candidates. The grey relational coefficient is calculated by:

\[ \gamma_{0ij} = \frac{\Delta \min + \zeta \Delta \max}{\Delta_{0ij} + \zeta \Delta \max} \quad (17) \]

where, \( \Delta \max \) and \( \Delta \min \) are obtained by:

\[ \Delta \max = \max_i \max_j \Delta_{0ij} \quad (18) \]

\[ \Delta \min = \min_i \min_j \Delta_{0ij} \quad (19) \]

\( \zeta \) is called a distinguished coefficient, only affecting the relative value without changing the priority. Generally, \( \zeta \) is selected as 0.5.

5. Determine the degree of relation with the standard series.

To achieve the degree of relation with the standard series (i.e., the ideal design), the weighting factors of the evaluation measures must first be decided. These weighting factors can be determined by expert experience or marketing strategies in the firm. The degree of relation with the standard series for a design candidate is calculated by:

\[ \Gamma_{0i} = \sum_{j=1}^{n} [w_j \times \gamma_{0ij}] \quad (20) \]

where, \( w_j \) is the weighting factor for the \( j \)-th evaluation measure satisfying:

\[ \sum_{j=1}^{n} w_j = 1 \quad (21) \]

6. Prioritize the design candidates.

From the degrees of relation between the comparative series and the standard series, the design candidates can be prioritized. The design candidate with a larger \( \Gamma_{0i} \) can better satisfy the requirements considering different product life-cycle aspects.

This grey relational analysis approach treats each design candidate as a comparative series. The degree of relation between the comparative series and the standard series for each design candidate is then calculated. At the end, the best design can be selected based on the rankings of all the design candidates.

4. A Case Study Example

A case study example of a stand mixer design is given in this section to illustrate the effectiveness of the introduced adaptable design method.

4.1 Problem Statement

Various electric-motor-driven small appliances are used for processing different types of foods in the kitchen. These appliances include stand mixers, blenders, and meat grinders. Since most of them use similar power driven and control systems, similar functions can be found in these food processing appliances. In this research, we focus on redesign of a stand mixer to make it adaptable for other functions found in blender and meat grinder.

4.2 Two Design Configurations

Through the process of adaptable design following the guidelines introduced in our previous work [20],
two design configurations, as shown in Figure 1(a) and (b), were identified to fulfill the requirements of a stand mixer with the potential to be adapted to other types of food processing appliances. Both design configurations provide the functions of a stand mixer together with the functions of blender and meat grinder. For the first design configuration, when only the function of the stand mixer is selected as the fundamental function of the product, and the functions of blender and meat grinder are selected as adaptable (optional) functions of the product, the part and assembly costs of this product are usually low, compared with a product with all three functions selected as the fundamental functions. The adaptability of the product with all the three functions is high, since no extra efforts are required to achieve any of the required food processing functions.

In this case study, four product candidates with different fundamental and adaptable functions are selected considering each of these two design configurations. These eight product candidates are summarized in Table 1.

### 4.3 Four Measures for Evaluating the Adaptable Designs

In this work, adaptability of product, total part cost, total assembly cost, and operationability are selected as the evaluation measures considering design, manufacturing and operation life-cycle aspects of the products.

#### 4.3.1 ADAPTABILITIES OF PRODUCTS

Adaptability of a product represents its capability of being adapted with additional functions, which are usually initiated by changes in market demand, customer preferences, operating environment of the product, and reuse of components of a product at the end of its life-cycle.

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**Figure 1.** Two design configurations: (a) design configuration 1, (b) design configuration 2.

<table>
<thead>
<tr>
<th>Design configuration</th>
<th>Candidate</th>
<th>Stand mixer</th>
<th>Grinder</th>
<th>Blender</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design configuration 1</td>
<td>Candidate 1</td>
<td>✓</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td></td>
<td>Candidate 2</td>
<td>✓</td>
<td>○</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>Candidate 3</td>
<td>✓</td>
<td>✓</td>
<td>○</td>
</tr>
<tr>
<td></td>
<td>Candidate 4</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Design configuration 2</td>
<td>Candidate 5</td>
<td>✓</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td></td>
<td>Candidate 6</td>
<td>✓</td>
<td>○</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>Candidate 7</td>
<td>✓</td>
<td>✓</td>
<td>○</td>
</tr>
<tr>
<td></td>
<td>Candidate 8</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

Note: ✓ indicates the function is a fundamental function in the candidate. ○ indicates the function is an adaptable function in the candidate.
In this case study, the probabilities of using different food processing functions were identified as:

\[ \text{Pr}(\text{Stand Mixer}) = 100\%, \quad \text{Pr}(\text{Grinder}) = 20\%, \quad \text{Pr}(\text{Blender}) = 95\% \]

Table 2 (Panel A) shows the costs of parts for design configuration 1. When the function of the stand mixer is selected as the fundamental function of the product (i.e., candidate 1 in Table 1), the total part cost for this product is then calculated as $56. Based on the stand mixer in design configuration 1, the costs for achieving the adaptable functions of a meat grinder and a blender are identified as $10 and $8, respectively. Table 2 (Panel B) gives the costs of parts for design configuration 2.

When the costs for creating new products of meat grinder and blender are selected as $35 and $60, the extendibility of functions for candidate 1 is then calculated using Equation (2).

\[
E(P_1) = 100\% \cdot (1 - 0) + 20\% \cdot \left(1 - \frac{10}{35}\right) + 95\% \cdot \left(1 - \frac{8}{60}\right) = 1.97
\]

The extendibilities of all other candidates for design configurations 1 and 2 can be calculated in the same manner.

From Table 2, we can find out that some parts are selected as upgradeable parts and customizable parts. The cost to upgrade or customize the current part to another part is given in a bracket and modeled using the unit cost. In this case study, we assume that all of the selected parts will be upgraded or customized in the future. The upgradeability of candidate 1 considering motor and controller parts is then calculated using Equation (4).

\[
U(P_1) = 100\% \cdot \left(1 - \frac{3}{15 - 3}\right) + 100\% \cdot \left(1 - \frac{2}{10 - 2}\right) = 1.5
\]

The upgradeabilities of all other candidates for design configurations 1 and 2 can be calculated in the same manner.

Since some parts are selected as both the upgradeable parts and the customizable parts, they can use the same interfaces to be upgraded or to be customized. If the interface cost has been calculated considering the upgradeability, the cost for customization of the same part will be selected as 0, because both measures are achieved using the same interface. In this case study, the motor, the controller, and the color of the frame...
are customized. The customizability of candidate 1 is then calculated using Equation (6).

\[
C(P_1) = 100\% \cdot \left(1 - \frac{0}{15-3}\right) + 100\% \cdot \left(1 - \frac{0}{10-2}\right) + 100\% \cdot \left(1 - \frac{0}{10}\right) = 3.0
\]

The customizabilities of all other candidates for design configurations 1 and 2 can be calculated in the same manner.

The results of extendibility, upgradeability and customizability of all the eight product candidates are summarized in Table 3.

To use these three different measures to evaluate the eight product candidates, these three measures should be first converted into dimensionless evaluation measures. The normalized measures for extendibility of functions, upgradeability of modules and customizability of components are calculated using Equations (7)–(9), respectively. These three normalized values can then be used to calculate the specific product adaptability index. The specific product adaptability index of the \(i\)-th design candidate is calculated by Equation (10). In this case study, the weighting factor of each adaptability evaluation measure is defined equally as 33.3%, because extendibility of functions, upgradeability of modules, and customizability of components are considered the same important. The adaptabilities of all the eight product candidates are summarized in Table 3.

### 4.3.2 TOTAL PART COSTS

Total part cost for each product candidate is calculated by adding the costs of all its composing parts. For example, the total part cost of candidate 1 is calculated by:

\[
C(P_1) = C(Motor) + C(Controller) + C(Reduce Gear) + C(Frame) + C(Bowl) + C(Flat Beater) + C(Wire Whip) + C(Dough Hook)
\]

\[
= \$15 + \$10 + \$5 + \$10 + \$10 + \$2 + \$2 + \$2 = \$56
\]

The total part costs of other product candidates are calculated in the same way, as shown in Table 3.

#### 4.3.3 ASSEMBLY COSTS

Assembly cost is the cost for all assembly activities. Different product architectures usually require different assembly costs. In this case study example, the assembly costs of the eight selected product candidates are given in Table 3.

As more parts are used in a product, the assembly cost usually increases. Since the assembly activities do not require considerable effort in the process of manufacturing, the differences among assembly costs of different candidates are not significant. From Table 3, we can see that product configuration 2 requires a higher assembly cost compared with the design configuration 1, due to its complex architecture.

#### 4.3.4 OPERATIONABILITIES

The operationability of product is based on convenience of interface, degree of difficulty to adapt to different functions, and the feelings of customers. Operationabilies are rated on scales between 0 and 5, from totally unsatisfactory to totally satisfactory. The operationabilies of the eight product candidates are also given in Table 3.

#### 4.4 Selection of Weighting Factors for Different Evaluation Measures

The weighting factors of the four different evaluation measures are determined from expert experience and marketing strategies. These weighting factors are identified as follows.

\[
\begin{align*}
W_{\text{adaptability}} &= 45\%, \ W_{\text{part–cost}} = 20\%, \ W_{\text{assembly–cost}} = 20\%, \ W_{\text{operationability}} = 15\%
\end{align*}
\]

Since this research focuses on adaptable design, a high weighting factor is selected for the adaptability evaluation measure.

<table>
<thead>
<tr>
<th>Design candidate</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adaptability</td>
<td>1.97</td>
<td>2.09</td>
<td>2.02</td>
<td>2.15</td>
<td>1.98</td>
<td>2.09</td>
<td>2.04</td>
<td>2.15</td>
</tr>
<tr>
<td>evaluation</td>
<td>1.5</td>
<td>1.8</td>
<td>1.5</td>
<td>1.8</td>
<td>0.75</td>
<td>0.75</td>
<td>0.75</td>
<td>0.75</td>
</tr>
<tr>
<td>measures</td>
<td>3.0</td>
<td>3.0</td>
<td>3.0</td>
<td>3.0</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Product</td>
<td>0.917</td>
<td>0.991</td>
<td>0.924</td>
<td>1.000</td>
<td>0.668</td>
<td>0.685</td>
<td>0.677</td>
<td>0.694</td>
</tr>
<tr>
<td>life-cycle</td>
<td>56</td>
<td>64</td>
<td>66</td>
<td>74</td>
<td>54</td>
<td>71</td>
<td>64</td>
<td>81</td>
</tr>
<tr>
<td>evaluation</td>
<td>10</td>
<td>10</td>
<td>12</td>
<td>12</td>
<td>13</td>
<td>13</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>measures</td>
<td>4.5</td>
<td>4.5</td>
<td>4.5</td>
<td>4.5</td>
<td>5.0</td>
<td>5.0</td>
<td>5.0</td>
<td>5.0</td>
</tr>
<tr>
<td>Evaluation result</td>
<td>0.724</td>
<td>0.792</td>
<td>0.576</td>
<td>0.692</td>
<td>0.591</td>
<td>0.485</td>
<td>0.484</td>
<td>0.442</td>
</tr>
<tr>
<td>Ranking</td>
<td>2</td>
<td>1</td>
<td>5</td>
<td>3</td>
<td>4</td>
<td>6</td>
<td>7</td>
<td>8</td>
</tr>
</tbody>
</table>
4.5 Prioritization of Product Candidates

Prioritization of the product candidates using the grey relational analysis approach is conducted as follows:

1. Establish the decision matrix \( D \).

\[
D = \begin{bmatrix}
0.917 & 56 & 10 & 4.5 \\
0.991 & 64 & 10 & 4.5 \\
0.924 & 66 & 12 & 4.5 \\
1.000 & 74 & 12 & 4.5 \\
0.668 & 54 & 13 & 5.0 \\
0.685 & 71 & 13 & 5.0 \\
0.677 & 64 & 15 & 5.0 \\
0.694 & 81 & 15 & 5.0 \\
\end{bmatrix}
\]

2. Obtain the standard series.

\[ A_0 = \begin{bmatrix} 1 & 54 & 10 & 5 \end{bmatrix} \]

3. Generate the normalized decision matrix \( K \) and the standard series \( A_0^* \).

\[
K = \begin{bmatrix}
0.750 & 0.926 & 1.000 & 0.000 \\
0.973 & 0.630 & 1.000 & 0.000 \\
0.771 & 0.556 & 0.600 & 0.000 \\
1.000 & 0.259 & 0.600 & 0.000 \\
0.000 & 1.000 & 0.400 & 1.000 \\
0.051 & 0.370 & 0.400 & 1.000 \\
0.027 & 0.630 & 0.000 & 1.000 \\
0.078 & 0.000 & 0.000 & 1.000 \\
\end{bmatrix}
\]

\[ A_0^* = \begin{bmatrix} 1 & 1 & 1 & 1 \end{bmatrix} \]

4. Calculate the differences between the comparative series and the standard series.

\[
\Delta_0 = \begin{bmatrix}
0.250 & 0.074 & 0.000 & 1.000 \\
0.027 & 0.370 & 0.000 & 1.000 \\
0.229 & 0.444 & 0.400 & 1.000 \\
0.000 & 0.741 & 0.400 & 1.000 \\
1.000 & 0.000 & 0.600 & 0.000 \\
0.949 & 0.630 & 0.600 & 0.000 \\
0.973 & 0.370 & 1.000 & 0.000 \\
0.922 & 1.000 & 1.000 & 0.000 \\
\end{bmatrix}
\]

\[ \Delta_{\text{max}} = \begin{bmatrix} 1 & 1 & 1 & 1 \end{bmatrix} \]

\[ \Delta_{\text{min}} = \begin{bmatrix} 0 & 0 & 0 & 0 \end{bmatrix} \]

5. Determine the grey relational coefficients.

\[
\gamma_0 = \begin{bmatrix}
0.667 & 0.871 & 1.000 & 0.333 \\
0.949 & 0.574 & 1.000 & 0.333 \\
0.686 & 0.529 & 0.556 & 0.333 \\
1.000 & 0.403 & 0.556 & 0.333 \\
0.333 & 1.000 & 0.455 & 1.000 \\
0.345 & 0.443 & 0.455 & 1.000 \\
0.339 & 0.574 & 0.333 & 1.000 \\
0.352 & 0.333 & 0.333 & 1.000 \\
\end{bmatrix}
\]

6. Determine the degrees of relations with the standard series.

Using the weighting factors and Equation (20), the degrees of relations for all the eight product candidates are obtained as follow.

\[
\Gamma_{01} = 0.724; \quad \Gamma_{02} = 0.792; \quad \Gamma_{03} = 0.576; \quad \Gamma_{04} = 0.692 \\
\Gamma_{05} = 0.591; \quad \Gamma_{06} = 0.485; \quad \Gamma_{07} = 0.484; \quad \Gamma_{08} = 0.442 
\]

7. Prioritize the eight product candidates.

From the ratings of the product candidates, candidate 2 is selected as the best one, considering all the relevant life-cycle evaluation measures. Compared with candidate 1, candidate 2 can provide one more often-used functions (i.e., blender) with minor additional cost. Compared with candidate 2, candidate 4 provides only one more function (i.e., meat grinder), which is seldom used, with considerable additional cost.

As the result, the design candidate 2 with functions of stand mixer and blender is selected as the commercial product. The parts for function of meat grinder are sold separately as accessories.

5. Conclusions

The characteristics of this design for product adaptability method are summarized as follows:

- Three measures, including extendibility of functions, upgradeability of modules, and customizability of components, were developed to model the specific product adaptability. These measures are effective to evaluate adaptability of product quantitatively and to decide whether an existing product should be adapted or a new product should be created.
- A new method to evaluate and prioritize different design candidates in adaptable design was introduced based on the grey relational analysis approach.
In addition to the adaptability of a product, other life-cycle aspects of a product including production costs, operationability, etc. can also be considered to evaluate the different design candidates for identifying the optimal design considering these relevant product life-cycle aspects.

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