Identification of the Optimal Design Based on Evaluation of Product Configurations Considering Specific Product Adaptabilities

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Abstract
Adaptable design is a new design approach to create products that can be easily adapted to satisfy the changed functional requirements. Adaptable design approach can reduce the environment impact as well as to improve product competitiveness by replacing multiple products with a single adaptable product. In this research, a method to evaluate adaptabilities of mechanical products based on configurations of these products is introduced. In this method, different functional requirements are described by adaptation tasks. Each adaptation task is achieved by a product whose configuration is modeled by a number of modules based on modular design approach. Adaptation from one product to another one is conducted by changing modules (i.e., adding new modules and removing existing modules) of this product. Adaptabilities of a product to change to other products considering the adaptation tasks are obtained based on the required costs to change from configuration of this product to the configurations of the adapted products. An industrial application is provided to show the effectiveness of the introduced method.

Keywords:
Adaptable Design, Product Platform, Gear Cutting Machine Tool

1 INTRODUCTION

Adaptable design is a new design paradigm with both economical and environmental benefits [1]. The fundamental principle of adaptable design is the ability of a design or a product to be adapted to a new one based on the changed requirements by reusing some of the components in the existing design or product in the new one. Adaptable design approaches can reduce the costs of customers by replacing multiple products with a single adaptable product as well as to reduce the effort of manufacturers by reusing the knowledge in the existing design. Adaptable design approaches can also be used to improve the environment by reducing the number of totally manufactured products.

Adaptability is defined as the ability for a design or product to be adapted to other ones. Two types of adaptabilities are considered in adaptable design: design adaptability and product adaptability [1]. Design adaptability is the capability of an existing design to be adapted to create a new or modified design based on the changed requirements. Product adaptability is the capability of a physical product to be adapted to satisfy the changed requirements. Since design adaptability can be achieved by developing knowledge-based systems, this research focuses on adaptable design considering product adaptability.

Since the introduction of the adaptable design concept, many design methods and processes have also been developed to identify the adaptable products [2]. Some traditional design methodologies can also be used to design the adaptable products. For example, the reconfigurable design method can be used to create a reconfigurable machine to achieve functions of several machines by reconfiguration of the components of this machine [3]. The modular, product platform, and product family/portfolio design methods can be used to improve the structures of products, so these products can be changed easily to achieve different functions [4]. Various kinds of multi-functional machine tools have been developed and used to satisfy the specific demands of customers [5]. However, a systematic methodology to design configurations of the machines considering adaptability has not been introduced. Due to the increasing demands on multi-functional machine tools, more effort must be devoted to develop a scientific methodology for the design of these multi-functional machine tools with high efficiency and quality.

Because many design candidates can be achieved in adaptable design, evaluation of these candidates considering their product adaptabilities needs to be conducted to identify the best design from all these candidates. In adaptable design, product adaptabilities are classified into specific product adaptabilities and general product adaptabilities, depending on whether planned information for specific adaptations is available [1]. When certain adaptabilities and their probabilities can be predicted, the product can be designed to accommodate these specific product adaptabilities. For accommodating some unpredictable requirements and changes, the product can be designed to have some general product adaptabilities by its product architecture and interfaces.

For achieving specific product adaptabilities, Gu et al. developed a method to measure specific product adaptability by comparing the relative efforts of product adaptation and new product creation [1]. Li et al. extended this specific product adaptability evaluation method by considering three types of product adaptation tasks: extendibility of functions, upgradeability of modules and customizability of components [6]. Fletcher et al. developed a method to quantify general product adaptability by comparing the actual product structure with its ideal product structure that can be easily changed [7]. In addition, modularity, commonality [8], customizability

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[9], etc. used in modular, product platform, and product family/portfolio design methods can also be employed to evaluate product adaptabilities.

The research presented in this paper focuses on the development of an evaluation method to measure specific product adaptabilities considering the contributions of the modules to different configurations of the required adaptable products. A design process is introduced to create a family of products where each product in this family can be easily adapted to other products in the same family. The developed specific product adaptability evaluation method has also been employed in the design of a heavy-duty gear cutting machine.

2 A METHOD TO EVALUATE SPECIFIC PRODUCT ADAPTABILITIES

2.1 Specific Product Adaptability

Gu et al. [1] developed a method to measure specific product adaptability by comparing the relative efforts of product adaptation with new product creation. Suppose Tp_i is the i-th adaptation task, the effort for this task, according to the information axiom in axiomatic design theory [10], can be modeled by its information content described by $Inf(Tp_i)$. Cost is usually used for modeling the effort. When S_1 is the current state of the existing product, AS_2 is the state after adaptation, the effort for this adaptation is then described by $Inf(S_1 \rightarrow AS_2)$. In the same way, the effort to develop a new product from scratch is described by $Inf(ZERO \rightarrow IS_2)$, where $ZERO$ is the state to design a new product from scratch, and IS_2 is the state of product to satisfy only the new requirements. The relative saving of effort is modeled as adaptable factor, $AF(Tp_i)$.

$$AF(Tp_i) = \begin{cases} 1 - \dfrac{Inf_{(S_1 \rightarrow AS_2)}}{Inf_{(ZERO \rightarrow IS_2)}}, & Inf_{(ZERO \rightarrow IS_2)} > Inf_{(S_1 \rightarrow AS_2)} \\ 0, & Inf_{(ZERO \rightarrow IS_2)} \le Inf_{(S_1 \rightarrow AS_2)} \end{cases} \quad (1)$$

When less effort is required to adapt a product than to develop a new one, the $AF(Tp_i)$ is described by a measure between 0 and 1. When it takes more effort to adapt a product than to develop a new product (i.e., $Inf(S_1 \rightarrow AS_2) \ge Inf(ZERO \rightarrow IS_2)$), product adaptation should not be considered ($AF(Tp_i) = 0$). When no additional effort is required for product adaptation (i.e., $Inf(S_1 \rightarrow AS_2) = 0$), the product is a perfect adaptable product ($AF(Tp_i) = 1$).

When n product adaptation tasks, Tp_i $(i = 1,2,\ldots,n)$, and their probabilities, $Pr(Tp_i)$, are considered, the specific product adaptability is then modeled by:

$$A(P) = \sum_{i=1}^{n} \left[\Pr(Tp_i) AF(Tp_i) \right] \quad (2)$$

2.2 Modeling of Configurations of Adaptable Products

Modular design is a popular method for obtaining adaptable products. In modular design, similar components are grouped into modules according to their functions, technologies or physical structures [4]. Since the modules are relatively independent, these modules can be disassembled non-destructively from the product as units. For an adaptable product created using modular design, the modules can be attached, detached, modified, relocated and replaced easily for achieving the changed design functional requirements.

Suppose for an existing product, P, n adaptation tasks are described by $Tp=\{Tp_1, Tp_2, \ldots, Tp_n\}$, and these adaptable tasks are achieved by products AP_j $(j=1,2,\ldots,n)$ through adding new modules to the existing product, removing modules from the existing product, and replacing the modules of the existing product by new modules. The probabilities of these adaptation tasks are described by $Pr = \{Pr(Tp_1), Pr(Tp_2), \ldots, Pr(Tp_n)\} = \{Pr_1, Pr_2, \ldots, Pr_n\}$.

Since each product created in adaptable design is composed of modules, product adaptability can then be achieved by sharing modules among the products. Suppose each of the n products AP_j $(j=1,2,\ldots,n)$ is modeled by a configuration with a number of modules, and a total of m modules, $M=\{M_1, M_2, \ldots, M_m\}$, are used to describe the n products AP_j $(j=1,2,\ldots,n)$, configurations of these n products AP_j $(j=1,2,\ldots,n)$ can then be modeled by the m modules M_i $(i=1,2,\ldots,m)$ by the following matrix.

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ a_{m1} & a_{m2} & \cdots & a_{mn} \end{bmatrix} \quad (3)$$

where each element a_{ij} $(i=1,2,\ldots,m;\ j=1,2,\ldots,n)$ is described by a Boolean value of either 1 or 0.

- $a_{ij}=1$: product AP_j is composed of the module M_i.
- $a_{ij}=0$: product AP_j is not composed of the module M_i.

Configuration of the existing product P is modeled by

$$B = \begin{bmatrix} b_1 & b_2 & \ldots & b_m \end{bmatrix}^T \quad (4)$$

where b_i $(i=1,2,\ldots,m)$ is described by a Boolean value of either 1 or 0.

Costs of these m modules are modeled by:

$$C = \begin{bmatrix} c_1 & c_2 & \ldots & c_m \end{bmatrix}^T \quad (5)$$

2.3 Calculation of Specific Product Adaptabilities

Suppose IP_j $(j=1,2,\ldots,n)$ represents the ideal product to achieve the functions specified in Tp_j. Based on equation (1), adaptable factor considering the change from the product P to the product AP_j $(j=1,2,\ldots,n)$ can be modeled by:

$$AF(Tp_i) = \begin{cases} 1 - \dfrac{Inf_{(P \rightarrow AP_j)}}{Inf_{(ZERO \rightarrow IP_j)}}, & Inf_{(ZERO \rightarrow IP_j)} > Inf_{(P \rightarrow AP_j)} \\ 0, & Inf_{(ZERO \rightarrow IP_j)} \le Inf_{(P \rightarrow AP_j)} \end{cases} \quad (6)$$

In equation (6), $Inf(ZERO \rightarrow IP_j)$ $(j=1,2,\ldots,n)$ describes the effort to create the ideal product IP_j from scratch to satisfy the functions given in the adaptation task Tp_j, while $Inf(P \rightarrow AP_j)$ $(j=1,2,\ldots,n)$ describes the effort to change from the existing product P to the product AP_j considering the adaptation task Tp_j.

In this work, cost is employed to model the effort given in equation (6). For example, the effort to produce product AP_j from scratch is obtained by adding all the costs of the individual modules of the product AP_j using:

$$Inf(AP_j) = \sum_{i=1}^{m} c_i a_{ij} \quad (7)$$

Since many modules are used in this research to build the products by sharing these modules in different configurations, the cost to create the ideal product IP_j is approximated by the cost to create the product AP_j from scratch to achieve the same functional requirements. Therefore the $Inf(ZERO \rightarrow IP_j)$ in equation (6) is calculated by:

$$Inf(ZERO \rightarrow IP_j) \approx Inf(ZERO \rightarrow AP_j) = \sum_{i=1}^{m} c_i a_{ij} \qquad (8)$$

Inf(P→AP$_j$) in equation (6) is obtained by adding the costs of the modules which are added to *P* to form the *AP$_j$* using:

$$\begin{aligned} Inf(P \rightarrow AP_j) &= Inf(AP_j) - Inf(P \cap AP_j) \\ &= \sum_{i=1}^{m} c_i a_{ij} - \sum_{i=1}^{m} c_i b_i a_{ij} \qquad (9) \\ &= \sum_{i=1}^{m} \left(c_i (1 - b_i) a_{ij} \right) \end{aligned}$$

By replacing the *Inf(ZERO→IP$_j$)* and *Inf(P→AP$_j$)* in equation (6) using the results calculated by equations. (8) and (9), the adaptable factor considering the change from the product *P* to the product *AP$_j$* (*j*=1,2,...,*n*) can be calculated by:

$$AF(Tp_j) = 1 - \frac{Inf(P \rightarrow AP_j)}{Inf(ZERO \rightarrow IP_j)} = 1 - \frac{\sum_{i=1}^{m} \left(c_i (1 - b_i) a_{ij} \right)}{\sum_{i=1}^{m} c_i a_{ij}} \qquad (10)$$

When *n* product adaptation tasks, *Tp$_i$* (*i* = 1,2,...,*n*), and their probabilities, *Pr$_i$* (*i* = 1,2,...,*n*), are considered, based on equation (2), the specific product adaptability is calculated by:

$$\begin{aligned} A(P) &= \sum_{j=1}^{n} \left[\Pr(Tp_j) AF(Tp_j) \right] \\ &= \sum_{j=1}^{n} \left[\Pr_j \left(1 - \frac{\sum_{i=1}^{m} \left(c_i (1 - b_i) a_{ij} \right)}{\sum_{i=1}^{m} c_i a_{ij}} \right) \right] \qquad (11) \end{aligned}$$

When many design candidates can be achieved, the optimal design of the product, *P**, with the maximum specific product adaptability can be identified based on evaluations of all design candidates in terms of their specific product adaptabilities.

3 AN ADAPTABLE DESIGN PROCESS BASED ON SPECIFIC PRODUCT ADAPTABILITIES

The major advantage of adaptable design is the use of an adaptable product to replace a number of products which are demanded based on different customer requirements. By employing a modular design approach, a product can be changed to another one by adding new modules to the existing product, removing modules from the existing product, and replacing the modules of the existing product by new modules.

When an adaptable product is designed to achieve multiple functions from different customer requirements, evaluation of each configuration of the product considering the efforts to adapt to other configurations is required. When multiple candidate adaptable products can be created to satisfy the same adaptation tasks, the one with the best average specific product adaptability considering the adaptation from any configuration of this adaptable product to its other configurations is selected as the optimal design.

This adaptable design process is composed of 4 steps as shown in Figure 1.

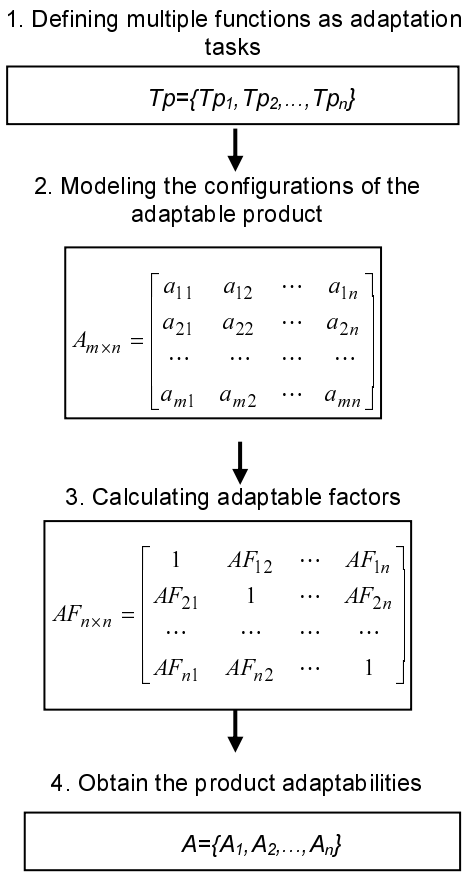


Figure 1: An adaptable design process.

(1) Defining multiple functions as adaptation tasks.

In this step, the *n* different functions of the customer requirements are defined by *n* adaptation tasks *Tp$_j$* (*j*=1,2,...,*n*).

(2) Modeling the configurations of the adaptable product.

A total of *m* modules, *M$_i$* (*i*=1,2,...,*m*), are used to model the *n* configurations of the adaptable product, *AP$_j$* (*j*=1,2,...,*n*), for achieving the *n* adaptation tasks. Each configuration is composed of modules selected from the *m* modules. An *m* by *n* matrix, A_{mxn}, is constructed to show what modules have been used for each of the *n* configurations using equation (3).

(3) Calculating adaptable factors.

For any two configurations, *AP$_i$* and *AP$_j$* (*i*=1,2,...,*n*; *j*=1,2,...,*n*), calculate the adaptable factor, *AF$_{ij}$*, based on equation (10) to establish an *n* by *n* matrix *AF$_{nxn}$*.

(4) Obtain the product adaptabilities.

Based on equation (11), the *n* product adaptabilities, *A$_j$* (*i=1,2,...,n*), for the *n* configurations of this adaptable product are then obtained.

4 AN INDUSTRIAL APPLICATION

Heavy-duty gear cutting machines are mainly used for manufacturing large gears, including spur gears and helical gears with internal and external gear teeth, through the manufacturing processes of milling (roughing), hobbing (semi-finishing) and teeth grinding (finishing). A

traditional gear cutting machine is primarily designed for a specific type of gear machining process. Such a machine cannot be adapted to satisfy the changed functional requirements of a new type of gear process. Therefore the development of an adaptable product using an adaptable design method is necessary. Based on market analysis, product family planning and module planning, the adaptability evaluation method for a variety of products derived from the modular design platform is used in this research to identify the best adaptable product by prioritizing the different design candidates.

Each gear cutting machine in the product family is composed of modules. Since the same modules are shared by different machines in this product family, a machine in this family can be adapted to other ones in the same product family by adding new modules to the existing machine, removing modules from the existing machine, and replacing the modules of the existing machine by new modules. By evaluating product adaptability of each product derived from the same product family, the product family with the maximum adaptability is selected as the optimal design.

4.1 Identification of the Adaptable Tasks

The gear cutting machines considered in this application are designed according to different requirements which are shown in Table 1. These gear cutting machines are classified into two categories considering whether the workpiece or the cutting tool is moved in the manufacturing process. When different processes are used, different tools with different tool holders have to be considered. Therefore the employment of an adaptable design method in the design of the tool turrets in this application is not considered. To support different sizes of workpieces, the table of the machine needs to be adapted to different sizes. Even though these work tables are different in size, the structures of these work tables are similar. Therefore adaptable design can be considered for the design of work tables.

Requirement	Variations
Maximum gear diameter	1200 mm - 3,000 mm
Maximum gear modulus	16 mm - 35 mm
Maximum gear width	400 mm - 600 mm
Maximum table load	15 t - 40 t
Gear type	Internal , external
Process	Milling, hobbing

Table 1: Variations of Requirements for Gear Cutting Machines

In this application, the considered adaptation activities include two kinds of processes (i.e., milling and hobbing), two types of gears (i.e., gears with internal teeth and gears with external teeth), three maximum sizes of workpieces (i.e., 1,200 mm, 2,000 mm and 3,000 mm), and so on as shown in Table 2. As hobbing can only be used for cutting external teeth, a total of 9 sets of product specifications are created. These specifications are defined as adaptation tasks as shown in Table 2.

4.2 Modeling of Product Configurations in Different Product Families

Modular design approach is employed in this work to design the structure of this adaptable machine. First each adaptable task is achieved by a configuration of the adaptable product. When a different adaptable task is required, the existing configuration is then adapted to a different configuration to achieve the new adaptable task.

Adaptation task	**TP_1**	**TP_2**	**TP_3**	**TP_4**	**TP_5**	**TP_6**	**TP_7**	**TP_8**	**TP_9**
Gear type	internal	internal	internal	external	external	external	external	external	external
Process	milling	milling	milling	milling	milling	milling	hobbing	hobbing	hobbing
Maximum gear diameter (mm)	1,200	2,000	3,000	1,200	2,000	3,000	1,200	2,000	3,000
Maximum gear module (mm)	16	25	35	16	25	35	16	25	35
Maximum gear width (mm)	400	500	600	400	500	600	400	500	600
Maximum table Load (Tons)	15	30	40	15	30	40	15	30	40

Table 2: Adaptation Tasks for Gear Cutting Machines

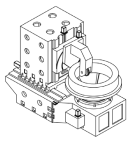
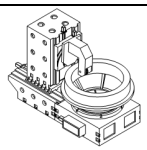
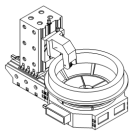
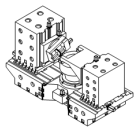
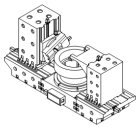
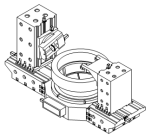
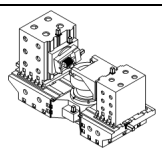
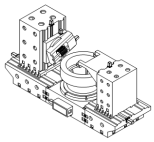
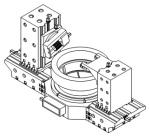
Product Category	Features	Maximum gear diameter (mm)		
		1,200	2,000	3,000
Trunk-type milling head for internal teeth	Internal milling			
Hob frame for external teeth	External milling			
	External milling			

Table 3: Configurations in Product Family I

Tasks/adaptable factors	TP_1	TP_2	TP_3	TP_4	TP_5	TP_6	TP_7	TP_8	TP_9
TP_1	1.00	0.30	0.30	0.90	0.30	0.30	0.90	0.30	0.30
TP_2	0.25	1.00	0.25	0.25	0.89	0.25	0.25	0.89	0.25
TP_3	0.20	0.20	1.00	0.20	0.20	0.89	0.20	0.20	0.89
TP_4	0.90	0.30	0.30	1.00	0.30	0.30	0.94	0.30	0.30
TP_5	0.25	0.90	0.25	0.25	1.00	0.25	0.25	0.94	0.25
TP_6	0.20	0.20	0.90	0.20	0.20	1.00	0.20	0.20	0.95
TP_7	0.90	0.30	0.30	0.94	0.30	0.30	1.00	0.30	0.30
TP_8	0.25	0.89	0.25	0.25	0.94	0.25	0.25	1.00	0.25
TP_9	0.20	0.20	0.90	0.20	0.20	0.94	0.20	0.20	1.00

Table 4: Adaptable Factors for Product Family I

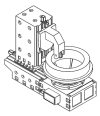
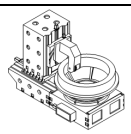
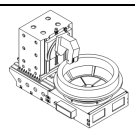
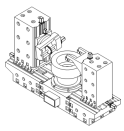
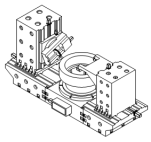
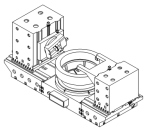
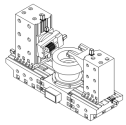
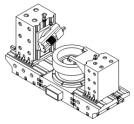
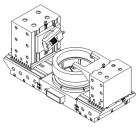
Product Category	Features	Maximum gear diameter (mm)		
		1,200	2,000	3,000
Trunk-type milling head for internal teeth	Internal milling			
Hob frame for external teeth	External milling			
	External milling			

Table 5: Configuration in Product Family II

Tasks/adaptable factors	TP_1	TP_2	TP_3	TP_4	TP_5	TP_6	TP_7	TP_8	TP_9
TP_1	1.00	0.30	0.30	0.88	0.30	0.30	0.88	0.30	0.30
TP_2	0.20	1.00	0.20	0.20	0.89	0.20	0.20	0.89	0.20
TP_3	0.12	0.12	1.00	0.12	0.12	0.91	0.12	0.12	0.91
TP_4	0.88	0.31	0.31	1.00	0.31	0.31	0.94	0.31	0.31
TP_5	0.21	0.90	0.21	0.21	1.00	0.21	0.21	0.94	0.21
TP_6	0.12	0.12	0.92	0.12	0.12	1.00	0.12	0.12	0.95
TP_7	0.88	0.30	0.30	0.94	0.30	0.30	1.00	0.30	0.30
TP_8	0.21	0.89	0.21	0.21	0.94	0.21	0.21	1.00	0.21
TP_9	0.12	0.12	0.92	0.12	0.12	0.95	0.12	0.12	1.00

Table 6: Adaptable Factors for Product Family II

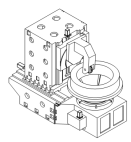
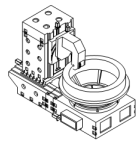
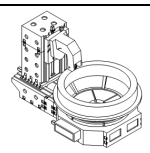
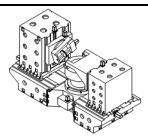
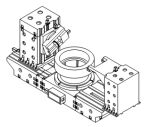
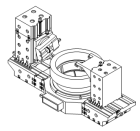
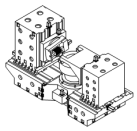
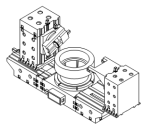
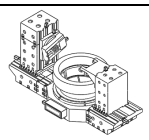
Product Category	Features	Maximum gear diameter (mm)		
		1,200	2,000	3,000
Trunk-type milling head for internal gear	Internal milling			
Hob frame for external gear	External milling			
	External milling			

Table 7: Configurations in Product Family III

Tasks/adaptable factors	TP_1	TP_2	TP_3	TP_4	TP_5	TP_6	TP_7	TP_8	TP_9
TP_1	1.00	0.56	0.56	0.90	0.56	0.56	0.90	0.56	0.56
TP_2	0.42	1.00	0.42	0.42	0.90	0.42	0.42	0.90	0.42
TP_3	0.34	0.34	1.00	0.34	0.34	0.90	0.34	0.34	0.90
TP_4	0.90	0.56	0.56	1.00	0.56	0.56	0.94	0.56	0.56
TP_5	0.43	0.90	0.43	0.43	1.00	0.43	0.43	0.95	0.43
TP_6	0.35	0.35	0.91	0.35	0.35	1.00	0.35	0.35	0.95
TP_7	0.90	0.56	0.56	0.94	0.56	0.56	1.00	0.56	0.56
TP_8	0.42	0.90	0.42	0.42	0.94	0.42	0.42	1.00	0.42
TP_9	0.35	0.35	0.91	0.35	0.35	0.95	0.35	0.35	1.00

Table 8: Adaptable Factors for Product Family III

By analyzing the functions of the 9 adaptable tasks, 3 gear cutting machine families are identified as shown in Tables 3, 5 and 7. In Family I, shown in Table 3, the width of the bed is fixed, and the size of the table can be changed. In Family II, shown in Table 5, since the bed is integrated with the table, sizes of both the table and the bed can be changed. In Family III, as shown in Table 7, the width of the bed is fixed, and the column and the bed can be adapted to different travel lengths.

4.3 Calculation of the Adaptable Factors

By using the configuration information provided in Tables 3, 5 and 7, the costs of the modules, and equation (10), adaptable factors from the *i*-th product ($i=1,2,\ldots,9$) to the *j*-th product ($j=1,2,\ldots,9$) considering all 9 products in each product family can be achieved as shown in Table 4, 6, and 8.

4.4 Calculation of the Product Adaptabilities

From Tables 4, 6 and 8, the specific product adaptability from the *i*-th product to all other products in the same product family can be achieved using equation (11). The

specific product adaptabilities for all of the products in the three product families are shown in Table 9. In this case study, the probabilities of all 9 of the adaptable tasks are selected as 1s, since all these adaptable tasks have to be satisfied. From this table, Product Family III is selected as the one with the maximum measure of the average product adaptability. The product platform is then selected to build the 9 configurations of the adaptable product in this product family.

Tasks/ Family	Product family I	Product family II	Product family III
TP_1	4.61	4.57	6.15
TP_2	4.29	4.00	5.35
TP_3	3.98	3.54	4.86
TP_4	4.66	4.65	6.21
TP_5	4.35	4.07	5.40
TP_6	4.06	3.59	4.95
TP_7	4.65	4.65	6.20
TP_8	4.34	4.07	5.39
TP_9	4.06	3.59	4.94
Average	4.33	4.08	5.49

Table 9: Evaluation of Product Adaptability Considering All Three Product Families

5 SUMMARY

A new method to measure specific product adaptabilities is introduced in this work. In this method, different requirements are described by adaptation tasks. By using modular design, each adaptation task can be achieved by a configuration of the adaptable product which is modeled by a number of modules. Adaptation from one configuration to another one is conducted by changing the modules of this product. Adaptabilities of a product to other products considering the adaptation tasks are achieved based on the required costs to change from configuration of this product to the configurations of the adapted products. An industrial application has been provided to show the effectiveness of the introduced method.

The characteristics of this adaptable design approach can be summarized as follows.

1. Modular design is an effective approach to improve product adaptabilities in adaptable design by developing relatively independent modules according to the functions of these modules in the adaptable product.
2. The introduction of a new specific product adaptability measure considering product configuration is effective to evaluate how easily a product can be adapted to other products based on the costs for achieving these adaptation tasks.
3. The industrial application demonstrates that the newly introduced approach can be employed in industrial equipment design to replace multiple products with a single adaptable product to reduce the environment impact as well as to improve product competitiveness.

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7 REFERENCES

[1] Gu, P., Hashemina, M., and Nee, A.Y.C., 2004, Adaptable Design, CIRP Annals – Manufacturing Technology, 53(2): 539-557.

[2] Gu, P., Xue, D., and Nee, A.Y.C., 2009, Adaptable Design: Concepts, Methods and Applications, Proceedings of the Institution of Mechanical Engineers, Part B, Journal of Engineering Manufacture, 223(11): 1367-1387.

[3] Landers, R.G., Min, B.K., and Koren, Y., 2001, Reconfigurable Machine Tools, CIRP Annals – Manufacturing Technology, 50(1): 269-274.

[4] Simpson, T.W., Siddique, Z., and Jiao, J., eds., 2007, Product Platform and Product Family Design, Methods and Applications, Springer Science and Business Media , LLC.

[5] Moriwaki, T., 2008, Multi-functional Machine Tool. CIRP Annals - Manufacturing Technology, 57(2): 736-749.

[6] Li, Y., Xue, D., and Gu, P., 2008, Design for Product Adaptability, Concurrent Engineering – Research and Applications, 16(3): 221-232.

[7] Fletcher, D., Brennan, R.W., and Gu, P., 2009, A Method for Quantifying Adaptability in Engineering Design, Concurrent Engineering – Research and Applications, 17(4): 279-289.

[8] Fixson, S.K., 2007, Modularity and Commonality Research: Past Developments and Future Opportunities, Concurrent Engineering – Research and Applications, 15(2): 85-111.

[9] Jiao, J., and Tseng, M.M., 2004, Customizability Analysis in Design for Mass Customization, Computer-Aided Design, 36(8): 745-757.

[10] Suh, N.P., 1990, The Principles of Design, Oxford University Press.