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One-Step QFD based 3D morphological charts for concept generation of product variant design

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ABSTRACT

This paper proposes a novel methodology, QFD based 3D morphological charts, to support variant design of simple and technically mature products. Customer's requirements are incorporated in developing the morphological charts through a holistic approach, *One-Step QFD*. In contrast to the traditional cascading deployment, members from marketing, design, and manufacturing teams concurrently derive the requirements from three different aspects. The charts driven by the deployment results produce design concepts of high feasibility through query by function, specification, and module of a product. They are presented in 3D assembly for better visual stimuli rather than clutter of 2D sketches. A computer-aided conceptual design system is implemented to realize the proposed ideas with computer mice as an example product. A design experiment is conducted to compare the quantity and quality of the concepts generated with and without the aid of the system. The results show that it promotes quick generation of innovative concepts while maintaining their manufacturability.

1. Introduction

More than 75% of design activities fall into the categories such as design modification, variant design, or case-based design (Regli & Circirello, 2000). Product Variant design involves the variation of the parameters of certain aspects of an existing product to generate a new design. It is commonly adopted in developing subsequent generations of a product in industry. One crucial task in product variant design is to modify the existing features of the current product based on the customers' feedback gained from product use. One of the often used tools is the morphological charts originally proposed by Zwicky (1969) in the 1960s. It is a method that lists all the possible solutions for non-quantitative multi-dimensional problems. The method was firstly used for the development of jet engines and missile launching systems. A typical morphological chart consists of indexes of product specifications followed by a list of relevant product components for each specification index. Fig. 1 shows an example of using morphological charts for the design of automotive doors (Miller, Brand, Heathcote, & Rutter, 2005). Morphological charts can be used at early stages of design and have become one of the most efficient methods for producing conceptual designs (Cross, 1994; French, 1985; Pahl, Beitz, Feldhusen, & Grote 2007; Ulrich & Eppinger, 2004).

However, morphological charts are constructed without any filtering mechanism. For example, in Fig. 2, the possible solutions for designing an automotive door are the product of multiplying the degree of freedom of each dimension and rows of listed components. The values can easily exceed one million. Such information overflow may confuse the designers. And often indeed, there may be only a few feasible solutions. For example, the morphological chart produced a total of 36,864 possible engine types in Zwicky (1969). Only two of them were manufacturable at the time at that time. Traditional morphological charts use 2D sample sketches for describing product concepts. The designers select desired component sketches and try to integrate them into a representation of the final product. The designers thus need to imaginatively form a complete 3D product based on the cluttered component images. This limits the use of morphological charts, despite the exhaustive process being carried out to derive them. A more flexible approach such as using 3D models to present the component data is desired to improve the usability of morphological charts.

On the other hand, quality function deployment (QFD) is well known for its ability to ensure that products meet customer expectations during product development. Originally proposed by Akao (1990), QFD collects the Voices of Customer (VOC) and establishes deployment results as the House of Qualities (HOQ), which transforms customer demands into technical requirements, including product specifications, design attributes, and ultimately to the manufacturing process parameters (Mizuno & Akao, 1994). QFD

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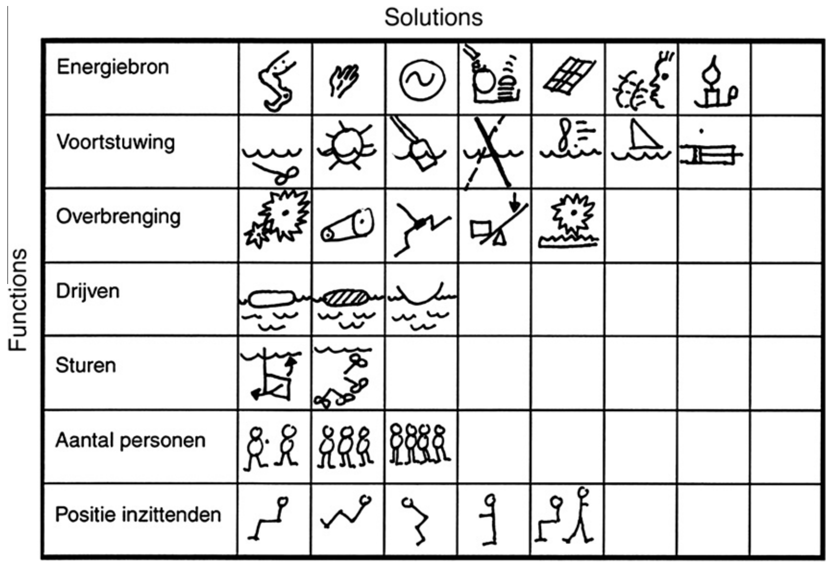


Fig. 1. Morphological chart for automotive door design (http://www.wikid.eu/index.php).

has been widely adopted in the development of various products (Chan & Wu, 2002). Chen (2009) proposed a modified approach to implementing QFD for the development of semi-conductors. The method integrates chip design and packaging processes and effectively reduces the time frames needed for completing the two processes in sequence. Tan and Neo (2002) utilized QFD and FEMA to trouble-shoot the malfunctioned calibrators. Partovi (2007) integrated QFD with AHP to define the optimized process for chemical reactions. Dikmen, Birgonul, and Kiziltas (2005) applied QFD to architecture design by transforming the customer requirements to design features such as colors, lighting, spatial layout. They showed that the HOQs used for construction industry are highly complex. The relationship matrix often yields hundreds of corresponding results. QFD has also been used in the software industry.

Those studies have verified the effectiveness of QFD on product development in practice. They have also indicated that the original QFD method needs to be adjusted according to different products or different types of product development. For example, the development of modern products usually involves incremental improvement to existing designs, rather than design from scratch. The transition from customer requirements to productions for a new variant resembles that of the previous ones, hence the possible simplification of the cascading approach in QFD. Chen, Chen, and Lin (2004) proposed a new methodology for processing and prioritizing customer demands in QFD for variant product design. Indeed the cascading deployment employed by QFD is one of its disadvantages (Armacost, Componation, Mullens, & Swart, 2004). The deployment results of the current stage are strongly affected by the results from previous stages. Any uncertainty in the decisions made earlier will be augmented during the deployment process and induce the concern of robustness in QFD (Kim & Kim, 2009).

This work proposes a new form of the morphological charts driven by systematic analysis of customer requirements derived from a holistic approach, One-Step QFD. The motivation is to solve the information overflow inherited by the traditional charts while improving the quality of the product concepts thus generated. In this approach, members of the development team from marketing, design, and manufacturing departments concurrently deploy the customer requirements to functions, specifications, and component modules of a product. The concurrent deployment is tailored to meet the needs of product variant design, particularly for mature and highly modulized products. The new charts present the product concept in 3D assembly for better visual stimuli. A computer-aided conceptual design system is developed to implement the proposed ideas, with computer mice as a sample product. A conceptual design experiment is conducted to validate the system. The results show that that it improves a designer's productivity in concept generation while maintaining the manufacturability and promoting innovation of his/her design.

2. Methodology

2.1. One-Step QFD

We propose a new QFD method for maximizing the use of the initial HOQs to avoid weakened connections between subsequent deployment stages in the traditional approach. This method starts with building three separated HOQs constructed from the following three aspects: product functions, product specifications, and components modules. We argue that it is not necessary to deploy HOQs in sequence for simple and technologically mature products. Particularly for the variant design of such products, there would not be a significant change in product specifications. A large portion of design functions should carry on to the next generation product development. New design features may evolve from previous products. For technically mature and highly modulized products, for example computer products and its peripherals, many product functions are readily offered by existing design modules (hardware and software) or standard components. Most manufacturing tasks are subcontracted to suppliers or replaced by direct sourcing. The traditional QFD approach needs to be tailored to meet those specific needs.

The three HOQs are built up based on the model proposed in Miller et al. (2005). As shown in Figs. 2–4, this particular type of HOQ emphasizes on the correlation matrix between customer requirements and technical parameters. The degree of correlation is denoted with a 5-point scale (1 – very weak, 3 – weak, 5 – neutral, 7 – strong, 9 – very strong). Each HOQ initiates a deployment thread and the three deployment threads proceed concurrently, hence the idea of "One-Step". Members of each deployment thread and the requirement aspect they work on are described as follows:

Correlation Matrix 1

		Product Functions		
		PF1	PF2	PF3
Customer Requirements	CR1			
	CR2			
	CR3			

Fig. 2. HOQ1: product functions deployed by marketing members.

Correlation Matrix 2

		Product Specifications		
		PS1	PS2	PS3
Customer Requirements	CR1			
	CR2			
	CR3			

Fig. 3. HOQ2: product specifications deployed by design engineers.

Correlation Matrix 3

		Component Modules		
		FM1	FM2	FM3
Customer Requirements	CR1			
	CR2			
	CR3			

Fig. 4. HOQ3: function modules deployed by production members.

2.1.1. HOQ1: transform customer requirements to product functions

The product functions here refer to the functions recognized by the end users, not the design functions from the engineering aspect. Members from the marketing department participate in this deployment thread as the representatives of end users. They have the experiences of investigating marketing trends and consumer needs. Their task here is to identify the requirement descriptions in the survey with corresponding functions provided by the product.

2.1.2. HOQ2: transform customer requirements to product specifications

Members from the design sectors like industrial designers, mechanical and electronic engineers accomplish the correlation based on the detailed specifications of a product. The aim of this deployment thread is to establish the links between the requirements and design specifications.

2.1.3. HOQ3: transform customer requirements to function modules

A functional module consists of components or sub-systems that work together to provide a specific function (or functions) of a product. Members of production sectors decide on whether these components and sub-systems can be manufactured within the production lines or need to be outsourced to other factories. They also provide feedbacks to the design engineers on the manufacturability of a product under the resource constraints like production costs and schedules. They take part in this deployment thread to transform customer requirements to corresponding component modules.

The three parameters deployed, product functions, product specifications, and component modules, are not independent in generic product development. However, for the variant design of a simple product like computer mice, most product functions have been well defined and are thus configurable by marketing or sales people. Instead of creating new specifications, the major task of the design team is to select specifications from the existing ones and to determine the attribute value(s) for each specification. For a technically mature product, standard software and hardware modules/components can mostly fulfill the chosen product functions and specifications. Thus we argue that the three deployments can be carried out at the same time.

We define a variable, *QMR*, to represent the degree of the correlations. Customers are requested to rank each requirement in terms of its importance. Given the requirement ranking data and the *QMR*s recorded in the correlation matrices, we can compute the design and production priorities of the technical parameters with the following steps using the HOQ1 as an example:

Step 1. For each *QMR*, multiply it with the corresponding requirement ranking score.

$$e_{mn} = RI_m \times QMR_{mn} \quad m = 1,2,3\ldots,M \quad n = 1,2,3\ldots,N \tag{1}$$

where m is the index of customer requirement, n is the index of the parameter to be correlated, $RI_m$is the ranking of the mth customer requirement, QMR_{mn} is the strength of the correlation between mth customer requirement and nth parameters, and e_{mn} is the product of the above two variables.

Step 2. The process in Step 1 results in a new matrix. The column sum of the e values recorded in the new matrix is then computed to obtain a total score of each listed product function (see Fig. 5).

Step 3. The scores are then sorted to decide the priority of producing each product function:

$$first = Max\left\{\sum_{m=1}^{M} e_{mn}, \quad \forall n = 1,2,3,\ldots,N\right\} \quad \text{where } m = 1,2,3,\ldots,M \tag{2}$$

e Matrix

			Product Functions				
			PF_1	PF_2	PF_3	…	PF_n
Customer Requirements	CR_1	RI	e_{11}	e_{12}	e_{13}	…	e_{1n}
	CR_2	RI	e_{21}			…	e_{2n}
	CR_3	RI	e_{31}			…	e_{3n}
	…	…	…			…	…
	CR_m	RIm	e_{m1}	e_{m2}	e_{m3}	…	e_{mn}
			Σe_{m1}	Σe_{m2}	Σe_{m3}	…	Σe_{mn}

Fig. 5. The resultant *e* matrix for HOQ1.

The above steps are repeated for the other two HOQs to obtain the priorities of producing each product specification and component module.

3. A case study – computer mice variant design

To validate the efficiency of product variant design facilitated by our method, we accomplish a real case study on the design of computer mice. The study was carried out with the procedures illustrated in Fig. 6. The following paragraphs will describe each step in detail.

3.1. Collect customer requirements

The target customers for computer mice in this case study are engineering students. We interviewed a total of 26 engineering students in university. Each interview lasted approximately 1 h. The semi-structural interview consists of three phases:

Phase 1: The interviewees are given a questionnaire to fill up with contact information. They are then asked to describe the purposes of using computer mice and whether they are satisfied with the current ones. They are also requested to point out, if any, the improvements of the current computer mouse that could be done.

Phase 2: Sample products of computer mice, including older models and those populated in the current market (see Figs. 7 and 8), are given to the interviewees to operate. The focus is to compare the differences between the two different product generations.

Phase 3*:* The interviewees are shown with images of computer mice (with manufacturer brands removed) in the current market. They are requested to identify the mice they prefer and provide the reason for their preferences.

3.2. Confirm the requirements

The interviewer analyzes the collected descriptions and extracts a list of specific requirements. The extracted requirements are documented and emailed to the interviewees for approval. If any of the extracted requirements does not correctly represent their needs, a further discussion with them is carried out to amend the listed requirements. After the confirmation process is completed, the requirements are sorted into a hierarchical list consisting of classes formed with similar requirements. In our case, we derive 11 main classes, in which 9 of them contain related subclasses. The hierarchical list of requirement classes is shown in Table 1. Another 50 engineering students are invited to rank the importance of each listed requirement using a 5-point scale (1: least important and 5: most important). The scores are then averaged to obtain the requirement rankings needed for the subsequent procedures.

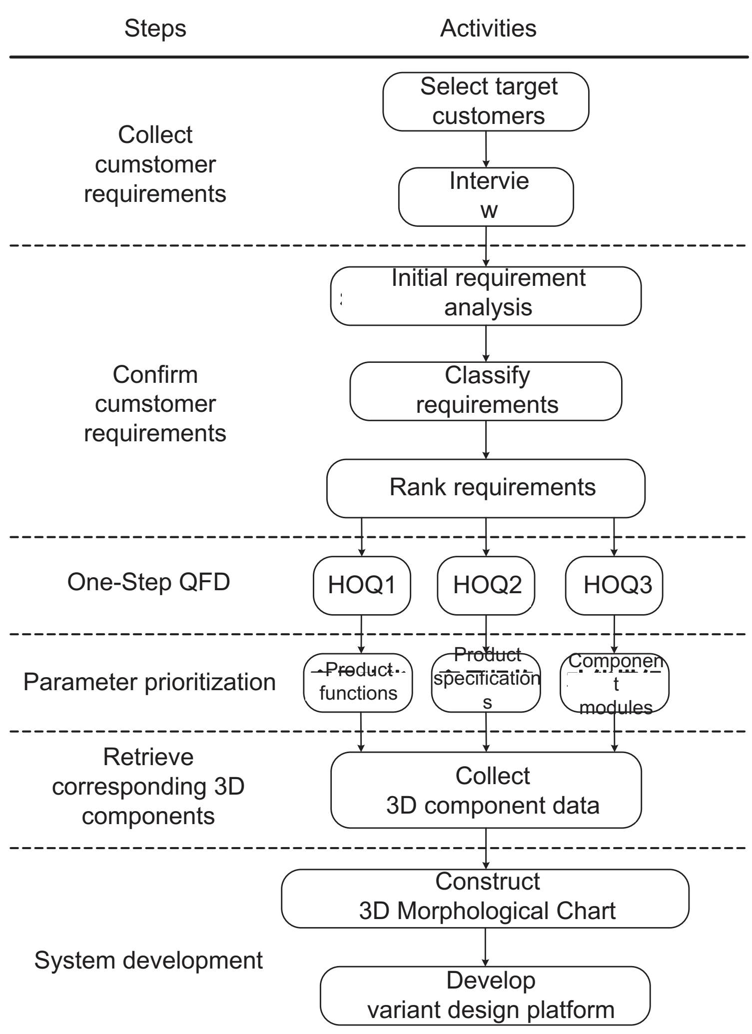


Fig. 6. Procedure of the design case study.

Fig. 7. Early models of computer mice.

Fig. 8. Current models of computer mice.

Table 1
Hierarchical list of customer requirements for computer mice.

Requirement classification			
Class no.	Main classes	Subclasses	Sub...
1	Frequency of use		
1.1		Casual users	
1.2		Competent users	
2	Hot buttons		
2.1		With hot buttons	
2.2		Hot button location	
3	Cursor		
3.1		Cursor lock	
3.2		Response time	
3.3		Pad materials	
4	Comfortable to hold		
4.1		Size	
4.2		Weight	
4.3		Materials	
4.4		Textures	
4.5		Shape	
5	Portability		
5.1		Wired mouse	
5.2		Wireless mouse	
6	Wheel and button		
6.1		Wheel-related	
6.2		Button-related	
6.2.1			Left
7	Wireless mouse power		
7.1		Battery	
7.2		Recharge	
8	Novel functions		
9	Appearance		
9.1		Ergonomics	
9.2		Symmetry	
9.3		Color	
9.4		Base shape	
10	Signal receiver		
10.1		Connection range	
10.2		Performance	
11	Miscellaneous		

3.3. Perform One-Step QFD

A global mouse manufacturer agreed to participate in our study anonymously. We invite the members from their marketing, engineering design, and production departments to build up the three corresponding HOQs of new mouse development. As described in the Section 2, the members of marketing team are responsible for building the HOQ of product functions. The design engineers work on the HOQ of product specifications. The members from production sector build up the HOQ of component modules.

3.4. Prioritize the design parameters

After the three HOQs have been built up, the design parameters are deployed according to the customer requirements of a mouse's functions, specifications, and component modules. With the requirement ranking data obtained in Section 3.2, we firstly calculate the *e* values according to Eq. (1), yielding three new matrices. The design and production priority scores of the design parameters are then computed with Eq. (2).

3.5. Retrieve the corresponding components

Due to the concern of business confidentiality, the manufacturer cannot provide us the direct access to the company's component database. However, the company is willing to provide physical samples of components corresponding to the highly-prioritized design parameters derived from the One-Step QFD process. These physical components are laser-scanned and processed with reverse engineering software to create the component database needed in this study. Fig. 9 shows the schematic of the morphological chart for computer mice variant design.

3.6. Framework of the prototype conceptual design system

The prototype design system is developed as a Web-based application. We utilize the *Model-View-Controller* (MVC) (Bergsten, 2003) architecture to construct the system. The system's architecture is illustrated in Fig. 10.

The Model layer consists of the component database described in the above section. The Controller part retrieves the components from the database with links established through the customer-driven morphological charts. Specifically, we develop JSP and Java-Servlet programs for the Controller part to query the component database based on the result obtained by the One-Step QFD method. The retrieved component models are converted into lightweight mesh data; these models are then automatically assembled according to the centroids of their bounding boxes (see Fig. 11). We use the APIs (Application Programming Interfaces) provided by the visualization software, SpinFire Professional, for the model conversion and calculating the relative position of each component for the assembling task. The bounding box assembling strategy is illustrated in Fig. 12. It generates a rough geometric layout for the assembled product. The main display task in the View layer is achieved by using SpinFire Reader. Users are able to interact with the system and manipulate 3D models via a client-side application.

3.7. Demonstration of the conceptual design system

The users start up the system with a Web browser such as Internet Explorer 6.0. A dialogue pops out for security check in the network environment. The quick message box then shows up to confirm that the user successfully logs into the platform (see Fig. 13). The interface of the system consists of four main blocks:

Block 1: In the Fig. 14, the block on the left displays the options for modules and components. The user can select the corresponding components to build up a product prototype.
Block 2: The assembled result, i.e. the product concept, is displayed in the central block.
Block 3: This block located at the top-right displays the production cost for current prototype.
Block 4: The user can further adjust the position of each component via the control buttons contained in this bottom block.

The user is allowed to right-click the mouse to get access to the SpinFire 3D manipulation functions. The menu provides navigating functions such as zoom, pan, rotate for the user to visually interact the prototype over the Internet (see Fig. 15).

4. Conceptual design experiment

A conceptual design experiment was conducted to validate that the prototype system can facilitate concept generation in product variant design. There were two conditions in the experiment. The experiment condition gives the participants access to the design system. Under the control condition, the participants, however, produce designs without the aid of the system. All of the participants were requested to express the design concepts of computer

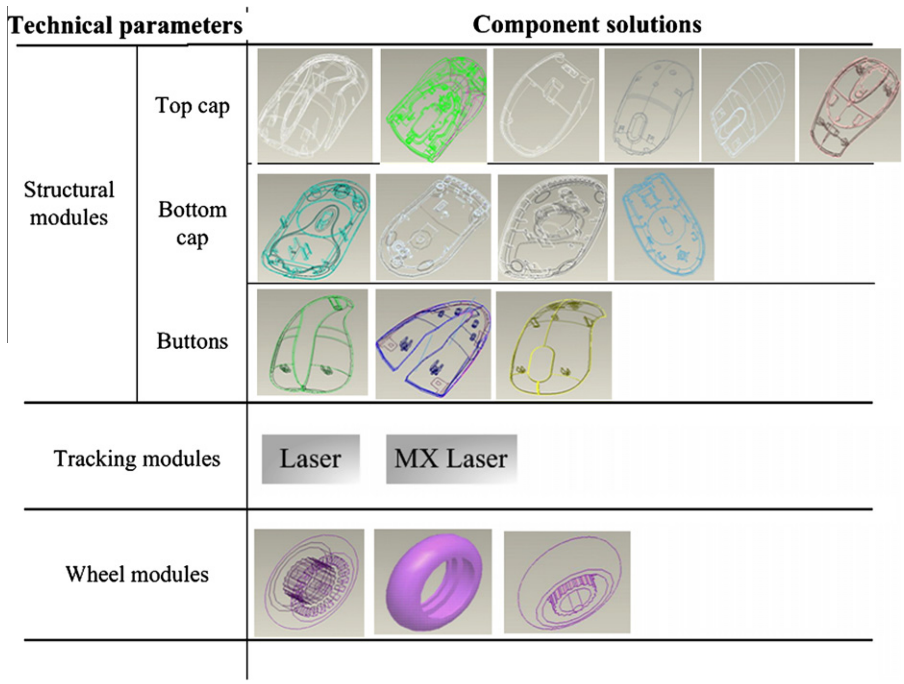


Fig. 9. 3D morphological chart for computer mice variant design.

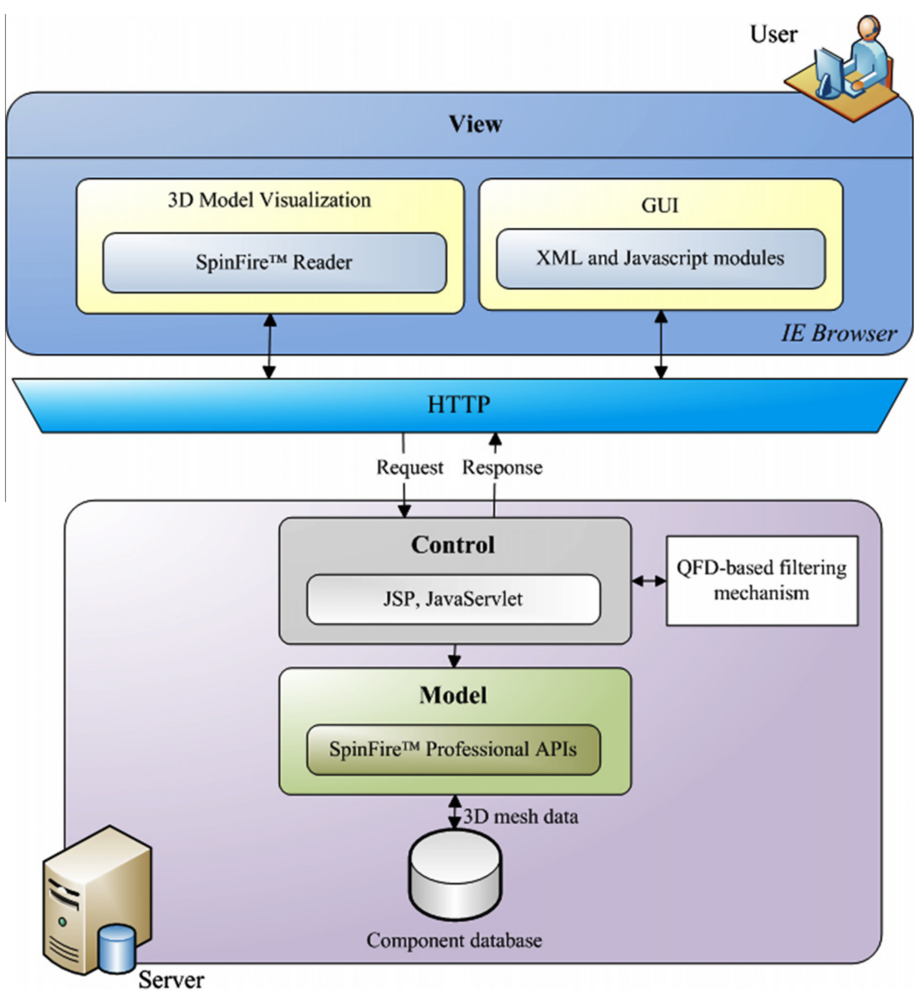


Fig. 10. Prototype system architecture.

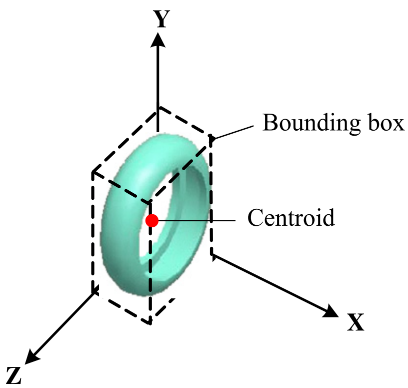


Fig. 11. The bounding box and centroid of a 3D component.

mice in sketches using pen and paper. They would be evaluated by experienced industrial designers both quantitatively and qualitatively.

4.1. Participant selection

The participants are undergraduate and graduate students of a major in product or industrial design. To reduce the individual differences, we carried out the Different Aptitude Tests (DATs) with a total of 60 students. Each of the 60 students took the Spatial Relationship test section of DATs. We set up a lower and upper threshold to pick the participants within a specific band of scores. For the lower threshold: their scores were compared against the average scores of senior high school students in Taiwan. If a student scored more than 30.97 for males, or, 26.92 for females, he or she was selected. For the upper threshold: their score distribution was evenly divided into nine bands as shown in Fig. 16, and the students with scores located from 5 to 7 were selected. A total of 32 participants were recruited to participant in the design experiment. The 32 participants were divided into two groups. The participants in the experimental group perform the design tasks with the aid of our One-Step QFD Morphological

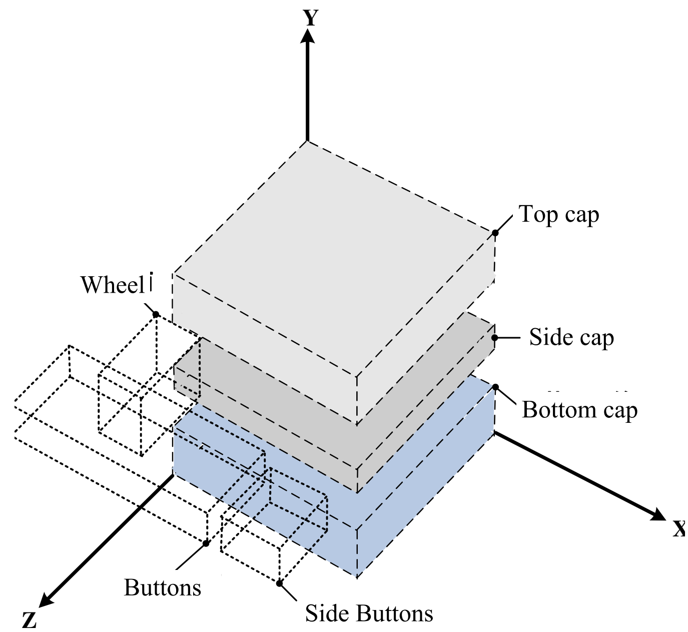


Fig. 12. Mouse components assembled with bounding boxes.

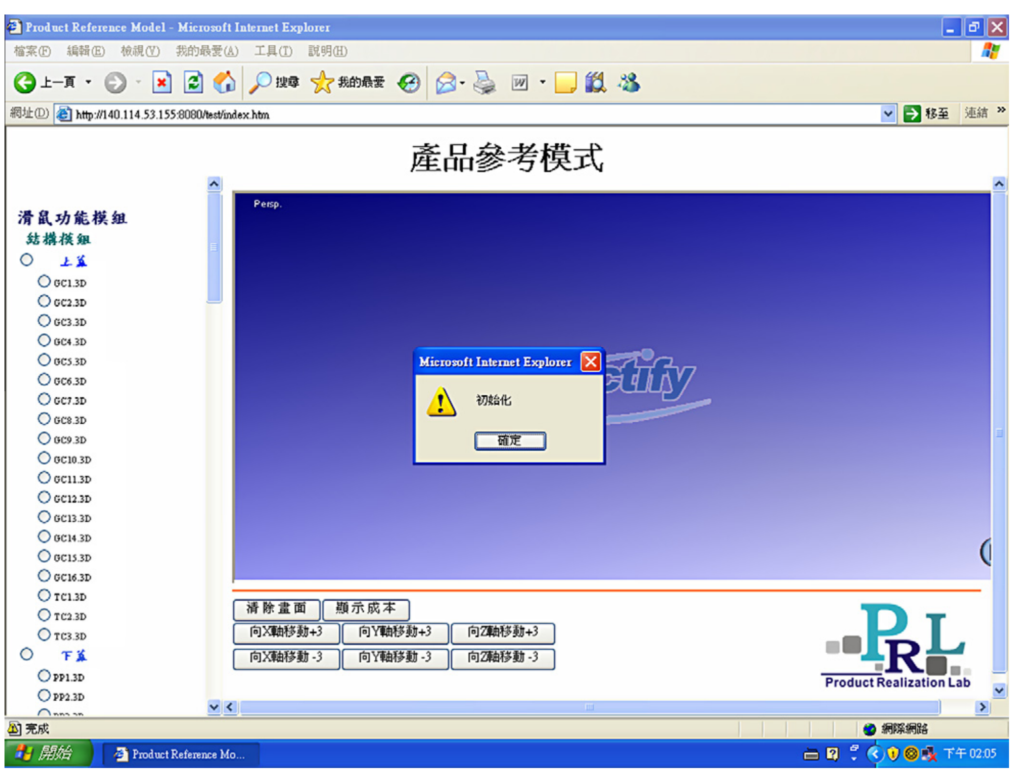


Fig. 13. System initialization.

Chart. The participants in the other group, the control group, perform the design tasks without it. The performances of the two groups were to be compared.

4.2. Procedures

Each group of participants was assigned to individual classroom to carry out the conceptual design task. The experimenters firstly explained the rules and the target product, computer mouse, to be designed during the experiment. They were told that a computer mouse manufacturer was seeking the new conceptual designs of the company's three main product lines: *versatile*, *casual*, and *portable*. The versatile line targets heavy users such as computer game players and 3D CAD software users. The casual line provides an affordable and reliable solution to common users. The portable line is designed for laptop users. Each participant was also given two

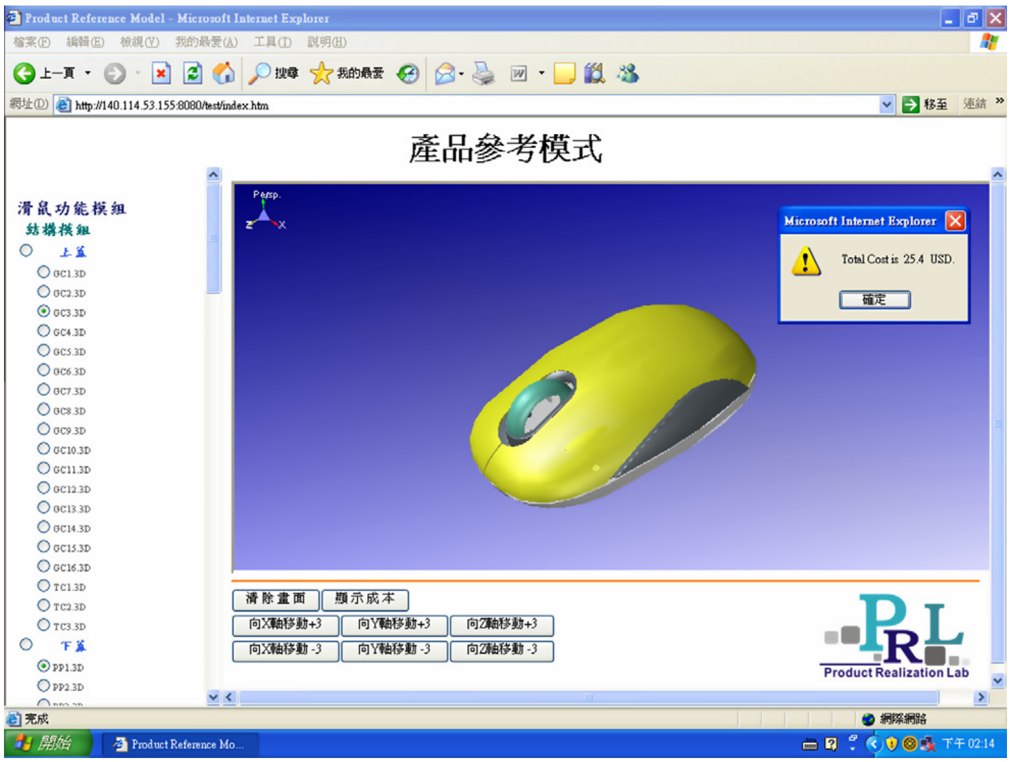


Fig. 14. System in operation.

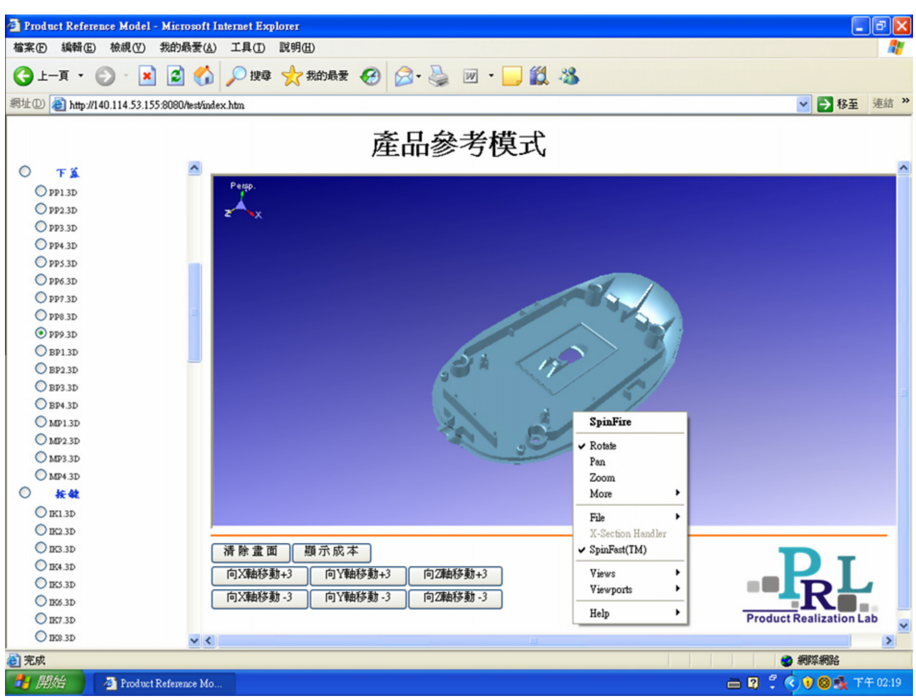


Fig. 15. 3D component navigation and manipulation.

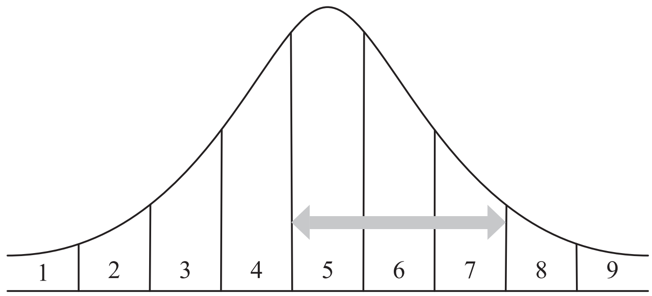


Fig. 16. Score distribution divided into nine bands.

specification sheets, one containing general specifications such as sizes and colors; and the other containing engineering-related specifications such as connection heads and the resolution of scrolling wheels (please see Appendices A and B for the details). For the experimental group, a 10-minute demonstration of using the variant design system is given to the participants. Both groups of participants were given 40 min to produce a number of conceptual sketches illustrating the new designs of the three lines of mouse product. The size of the paper used for sketching is standard B4. The participants were instructed that each piece of B4 paper should contain sketches of the perspective, side, and bottom views of a single mouse. The layout of the sketches is illustrated in Fig. 17.

5. Results and discussion

The sketches completed by the two groups of participants are reviewed by three senior industrial designers. The designs are evaluated both quantitatively and qualitatively:

5.1. Quantitative evaluation

(1) Each participant is requested to complete at least three design sketches.
(2) Each mouse prototype should not share the same components or similar shapes with each other, excluding the receivers.

The quantitative evaluation consists of two stages. In the first stage, individual reviewers evaluate the structural completeness of the designs assigned to them and judge whether the designs satisfies the requirements in the specification sheets. The designs that pass through this stage of evaluation are forwarded to the next stage. Based on the Gallery method, all three industrial designers evaluate the mouse prototype and decide which are better designed.

Table 2
The number of designs finished by the experimental and control groups.

Mouse types	Versatile	Casual	Portable	Total	Mean
Number of designs					
Experimental group	18	17	24	59	3.68
Control group	16	12	16	44	2.75

5.2. Qualitative evaluation

Two other industrial design experts, who have more than five-year experience of mouse development, are invited to be the final judges. They evaluate the designs based on the production cost, manufacturability, and potential popularity of the prototypes among engineering students.

The numbers of conceptual designs produced by the two groups of participants are shown in Table 2. Given the limited time, the experimental group produces averagely 3.68 conceptual designs. The control group produces averagely 2.75 conceptual designs. In addition, there are four participants in the control group who have not produced at least three designs. On the other hand, the participants in the experimental group all satisfy the least requirement of the quantitative evaluation. This finding supports our method in terms of improving the designer's productivity.

The conceptual designs are further evaluated by the industrial design experts. When considering only the manufacturability, the designs produced by the experimental group are judged to be easily manufacturable. Some of the designs produced by the control group, however, are difficult to be manufactured using existing technologies. For example, the two designs in Fig. 18 produced by two participants in the control group consist of outer shapes that may bring problems to the integration of other internal function modules.

The experimental group produces four satisfactory designs that fulfill the requirements of production cost, manufacturability, and styling at the same time, whilst the control group produces two satisfactory designs. Fig. 19 shows the four mouse prototype designed by the experimental group. The industrial design experts pointed out that not only did these designs fulfill the requirements

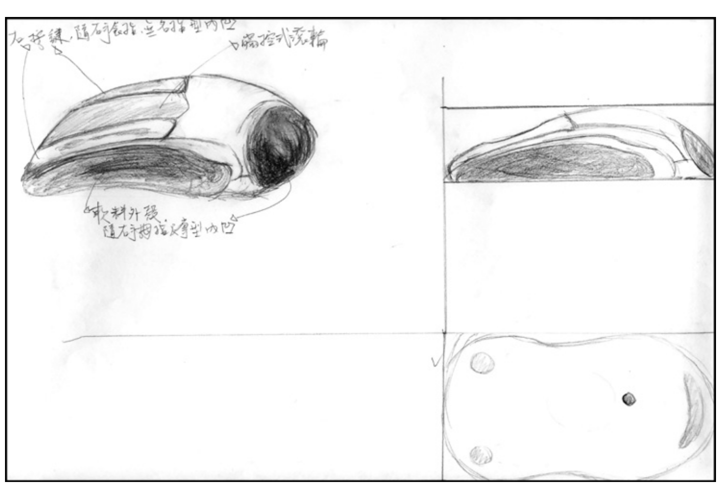


Fig. 17. The layout of sketch.

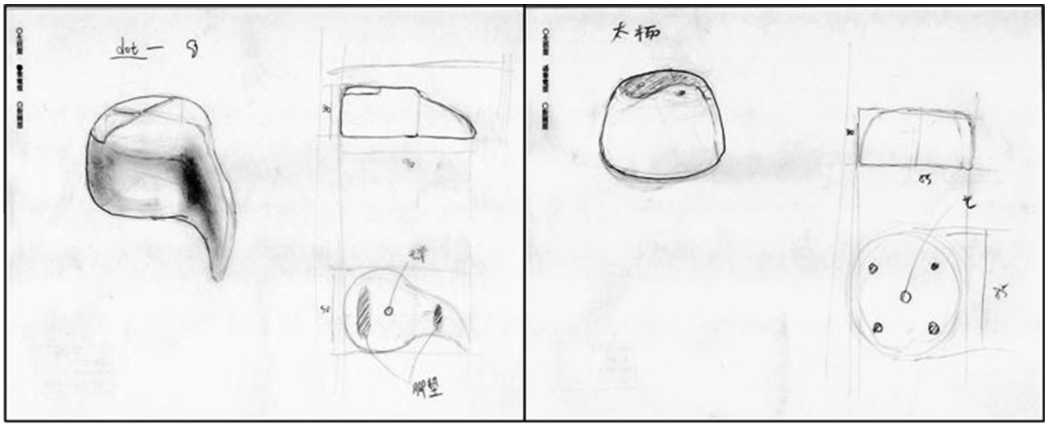


Fig. 18. Problematic designs produced by the control group.

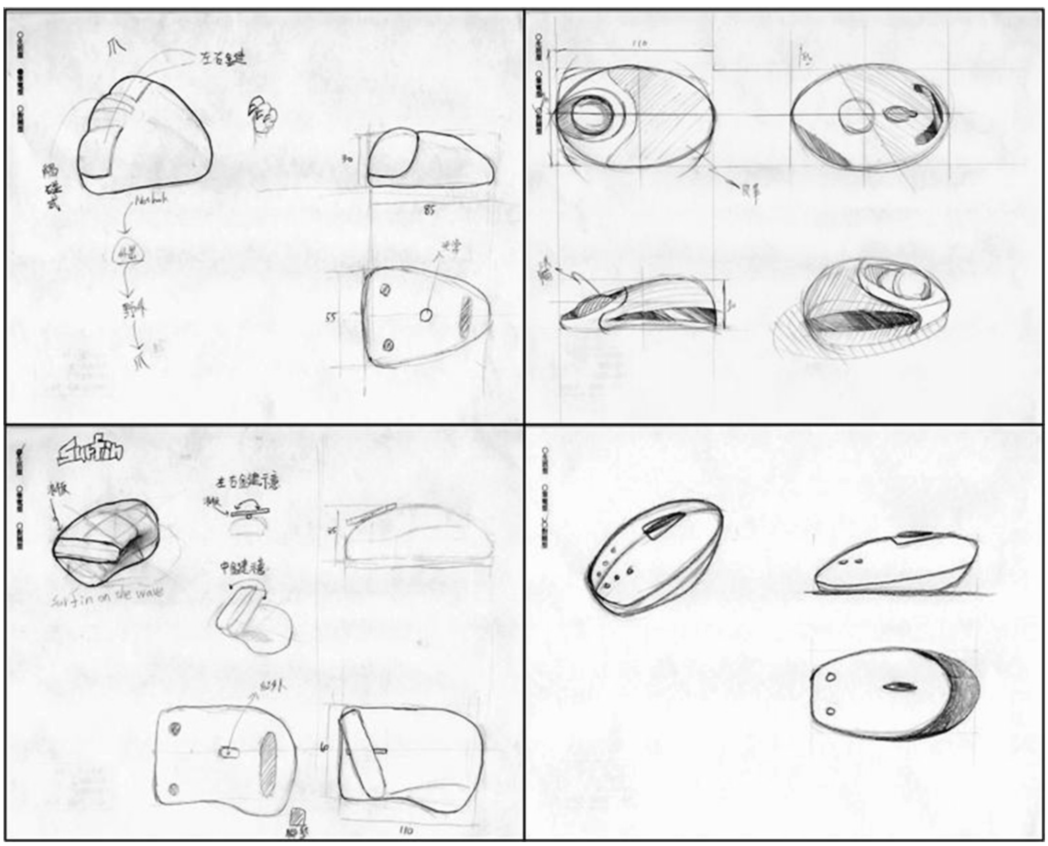


Fig. 19. Four of the mouse models designed by the experimental group.

of the three aspects, but also they presented innovations in terms of their design themes (e.g., the one at the bottom-left reflects the idea of "surfing" with the surfing-board-like buttons and scroll wheels).

6. Conclusion

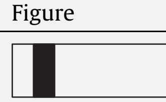
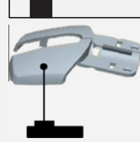
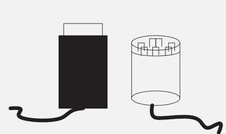
This paper presented a new methodology of concept generation in product variant design that incorporates QFD and Morphological Charts. A holistic approach, One-Step QFD, was developed to simplify the traditional cascading QFD process and thus meet the special needs of technically mature and highly modulized products. Members from marketing, design, and manufacturing teams simultaneously deploy the customer requirements to different technical aspects of a product. The deployment results serve as a screening mechanism in generation of product concepts, thus overcoming the information overflow inherited by the conventional charts. They also improve the quality of the product concepts thus generated in both innovation and manufacturing perspectives. The proposed methodology was implemented through a real case study of the development of computer mice. A computer-aided conceptual design system was implemented based on the proposed ideas. This system allows quick generation of product concepts assembled in 3D models through the query of product function, product specification, or component module. A conceptual design experiment was conducted to validate the system. The results showed that the participants in the group with the aid of the system produce better designs in terms of the variations, functions, manufacturability, and novelty. The proposed methodology improves the traditional

Appendix A. General product specification sheet

No.	Specification	Figure	Unit	Values
1	Versatile		cm	L: >11.5 W: >7 H:>3.5
2	Casual		cm	L:>10.5–11.5 W: >5–7 H: >3–3.5
3	Portable		cm	L: >8.5–10 W: <5 H:<3
4	Hot button location		Decided by ID[a]	
5	Soft grip		F[*]	>0.5
6	Key length		cm	⩾1/3L
7	Color		Decided by ID[b]	
8	Feet length		cm	>1
9	Feet diameter		cm	<1
10	Transparent feature			<2

[a] Friction measure of the soft grip.
[b] Industrial designer.

Appendix B. Engineering specification sheet

No.	Specification	Figure	Unit	Value
1	On/Off switch test		Lot	Pass, Yes/No
2	Key pressing gap		mm	1–3
3	Net weight		g	80–130
4	Scrolling res.		Pixel/s	1–4
5	Glossiness		F	<0.4
6	Connection port		Standard	USB/P2P

QFD by initiating three concurrent deployment threads with three HOQs. The resultant customer-driven morphological charts produce reduced but more essential design concepts. One of the possible extensions of this work is to combine the requirements captured by One-Step QFD directly with PDM systems. A potential application is customer-driven PDM System that tracks the history of product development related to customer requirements. One can also incorporate sophisticated methods such as AHP into One-Step QFD to obtain more comprehensive and possibly more accurate information of consumer needs.

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