An application of quality function deployment to functional modeling in a knowledge intensive design environment

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Abstract

Knowledge intensive design environments should assist designers with clear understanding of designers' intention. Therefore, relating functional information of a design object with the designer's intention is a crucial issue. We have already proposed the FBS (Function-Behavior-State) diagram as a framework for modeling function. An FBS diagram represents the information on function, behavior, and state of one design solution, but it cannot deal with design alternatives that are considered in a design process. This results in the FBS diagram being lacking the representation of the reasons why the designer selected one solution from alternatives. QFD (Quality Function Deployment) is a method for design review and allows the designer to evaluate a design object from view point of quality. This paper proposes an application of the QFD method to the FBS diagram to represent the designers' intention for decision making during design. We also describe a prototype system and illustrate an example design of a photocopier to demonstrate how a knowledge intensive design environment can contribute to guaranteeing and improving design quality.

Keywords

Functional modeling, Quality Function Deployment (QFD), Knowledge intensive engineering

1 INTRODUCTION

An intelligent CAD system is not only a set of intelligent design tools, but rather a knowledge intensive intelligent design environment (Tomiyama, 1991). This requests that it must be equipped with a large scale knowledge base in which design knowledge is intensively and systematically stored. This paper describes an attempt to incorporate various kinds of design knowledge into the knowledge base, in particular, knowledge for conceptual design.

Modeling function of a design object is of particular importance for assisting a designer in conceptual design. Therefore, we have proposed the FBS (Function-Behavior-State) diagram (Umeda *et al.,* 1990) for modeling function and developed the FBS modeler (Umeda *et al.,* 1992) that is a computational tool for representing and reasoning about FBS diagrams. This method, however, cannot deal with design process information that represents design alternatives or decision-making information, i.e., how and why the designer selected one particular solution from the alternatives.

In contrast, QFD (Quality Function Deployment) (Akao, 1990) that analyzes a design object from the view point of quality is a method for design review. QFD considers two types of quality. One is the customer requirement which represents market requirements (e.g., smoothness, fast speed, elegance, etc.). The other is the quality element which represents an attribute of the design object that affects quality of the design object (e.g., size, output voltage, etc.). By identifying the relationship between customer requirements and quality elements, the designer can review the design solution from the view point of customer's satisfaction. QFD is appropriate for enriching communication among designers and marketing officers.

We believe that the selection of a design solution from design alternatives is largely based on the market requirements. Because the QFD method can represent such requirements, the QFD and FBS methods can be combined to represent the designer's intention that plays a crucial role in decision-making during design. This paper proposes an application of the QFD method to the FBS modeler to describe the designer's intention and the decision-making information.

This paper is divided into five sections. After this introduction, Section 2 briefly reviews the FBS and QFD methods. Section 3 discusses how to integrate these two methods and propose a design method for conceptual design that takes design quality into consideration. Section 4 describes a prototype system based on the discussion in Section 3, illustrates an example of photocopier design, and compares our approach with related work. This prototype system demonstrates how such an intensive use of functional knowledge can guarantee and improve quality of design. It is also pointed out that in this way design process knowledge for decision-making can be systematized for sharing and reusing and the concept of knowledge intensive engineering can generate more added-value of design. Section 5 concludes the paper.

2 FUNCTIONAL REPRESENTATION

2.1 FBS modeling

Modeling function of a design object is of particular importance to assist the designer in conceptual design. We use the FBS (Function-Behavior-State) diagram (Umeda *et al.,* 1990) to represent functions (Figure 1). The FBS diagram consists of two types of relationship. One is the relationship between behavior and state. A state is described by entities, attributes, and relations among them. A behavior is a sequence of one or more changes of

Table 1 Definition of a functional prototype (Umeda *et al.*, 1992)

Item	Contents
Name	*verb + objectives*
Decomposition	networks of subfunctions
F-B Relationship	physical features

states. This relationship between behavior and state is called a *B-S relationship*. The other is the relationship between function and behavior. A function is a subjective description of behavior abstracted through human recognition of the behavior in order to utilize it. This relationship between function and behavior is called an *F-B relationship*, and gives physical semantics to a function.

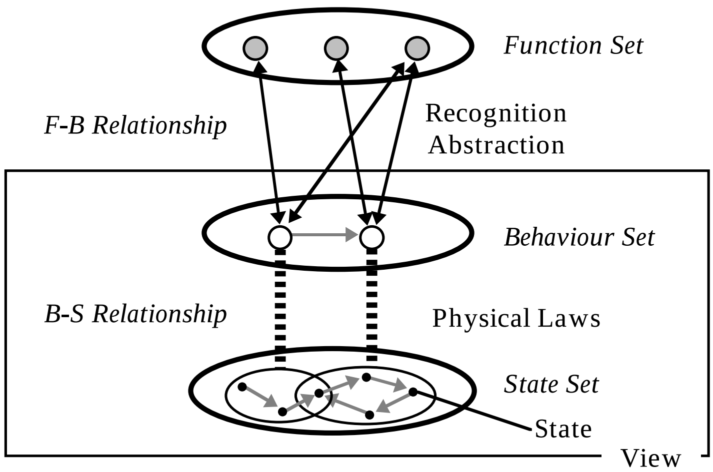


Figure 1 FBS diagram (Umeda *et al.*, 1990)

We have developed the FBS modeler (Umeda *et al.*, 1992) which is a computational tool for interactively building an FBS diagram of a design object in functional design. The FBS diagram is composed of functional prototypes that represent a functional hierarchy and F-B relationships. The FBS modeler represents behavior and state with physical features which are sets of physical phenomena and mechanism for invoking the phenomena. Table 1 shows the scheme of a functional prototype (Umeda *et al.*, 1992).

The designer uses the FBS modeler in two ways in functional design. One is function decomposition to decompose a function into subfunctions. The other is function synthesis in which physical features that can exhibit a desired function are searched for and instantiated. After instantiating physical features, the feasibility of function is tested against the specification by reasoning out the behavior of the design object. We use the qualitative physics reasoning system (Kiriyama *et al.,* 1991) to do so and to maintain the consistency of the B-S relationships.

2.2 Quality function deployment

Quality Function Deployment (QFD) is a method for design review that analyzes design objects from the view point of quality. QFD employs four types of deployment, i.e., quality deployment, technical deployment, cost deployment, and reliability deployment. Since this paper focuses on early stages of design, we briefly introduce two types of deployment (quality deployment and technical deployment).

Quality deployment translates market requirements to the vocabulary of designers. In this deployment, market requirements are customer requirements (e.g., smoothness, fast speed, elegance, etc.) and the vocabulary of designers is represented as quality elements that are attributes of design objects that affect the quality (e.g., weight, output voltage, size, etc.). This deployment is carried out as follows.

1. Marketing officers investigate the market and identify customer requirements with their Relative Importance (RI).
2. Designers and marketing officers compose a House of Quality Matrix (HQM) that represents the relationship between the customer requirements and the quality elements. Weight of Quality Elements (WQE) is calculated from RI and HQM and it denotes the importance of the quality elements.

   $$\overrightarrow{WQE} = ^t[HQM]\,\overrightarrow{RI}$$

3. Critical quality elements can be identified from WQE as those that have relatively large values.

Technical deployment is a process in which the designer specifies information about the mechanism and structure of the design object based on the information produced in quality deployment.

1. Designers identify functions of the design object.
2. The identified functions are decomposed into subfunctions and a functional hierarchy is created as a Function Deployment Table.
3. A matrix between the quality elements and the functions is composed. This matrix is called a Quality element and Function Matrix (QFM). Weight of Functions (WF) is calculated from WQE and QFM.

   $$\overrightarrow{WF} = [QFM]\,\overrightarrow{WQE}$$

4. Critical functions can be identified from WF as those that have relatively large values.
5. The decomposed subfunctions are embodied with mechanisms and a matrix between the functions and the mechanisms is composed. This matrix is a Function-Mechanism Matrix (FMM). Weight of mechanisms (WM) is calculated from WF and FMM.

   $$\overrightarrow{WM} = ^t[FMM]\,\overrightarrow{WF}$$

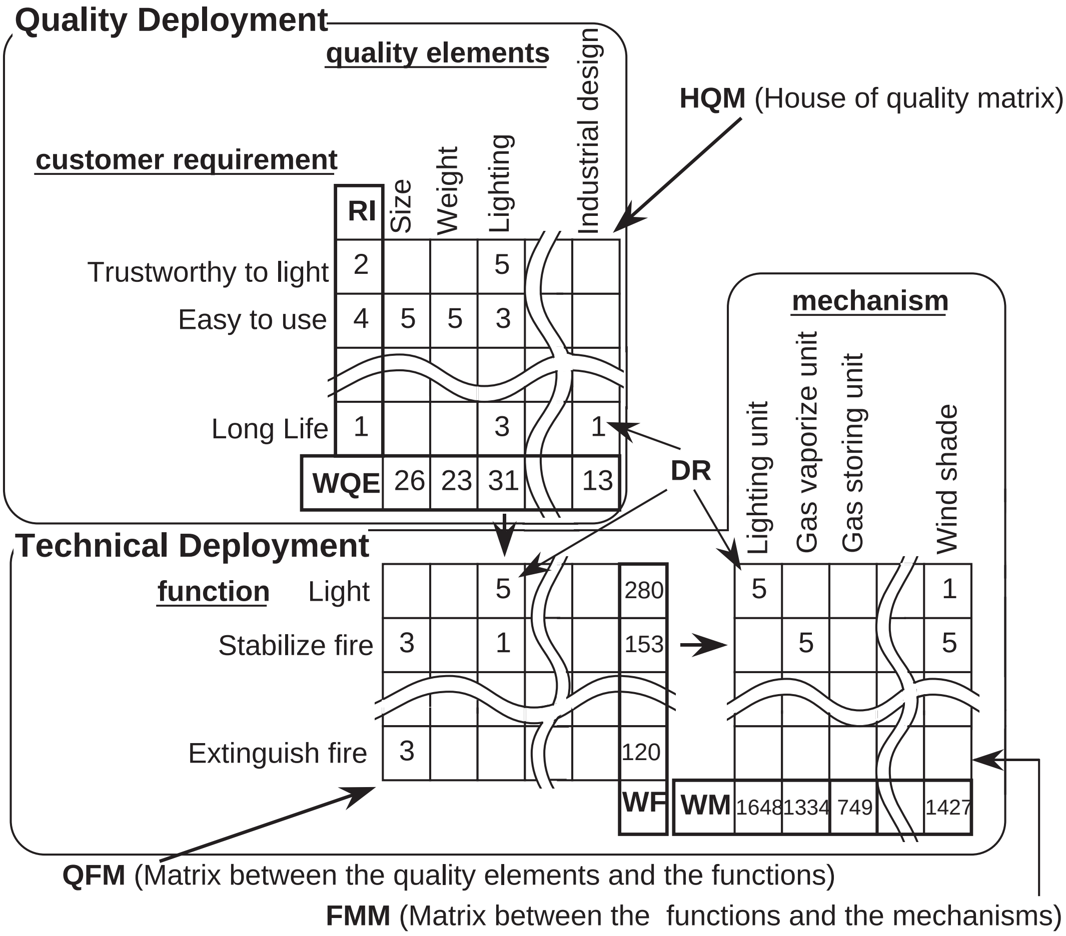


Figure 2 Matrices for quality deployment and technical deployment of the design of a lighter

6. Critical functions can be identified from WM as those that have relatively large values.

Figure 2 shows examples of QFD matrices (HQM, QFM, and FMM) generated in quality deployment and technical deployment of the design of a lighter. In these matrices, the degree of the relationship (DR) is represented by a number in the scale that 5 is strong, 3 is medium, and 1 is weak.

After these two types of deployment, the designers and marketing officers can review whether or not the design solution satisfies the market requirements by checking critical quality elements, functions, and mechanisms.

3 INTEGRATING THE FBS AND QFD METHODS

In the QFD method, a designer represents market requirements which, we believe, strongly influenced in decision-making on the designer's selection of one particular solution from various alternatives. This implies that QFD can be used to deal with the designer's intention. However, while QFD is good at analyzing results of design (e.g., comparing a design solution with the result of market research, quality assurance, etc.), it is not a synthetic method. To use the QFD method in conceptual design, it is requested to compose the three QFD matrices (HQM, QFM, and FMM) in accordance with the evolution of the design solution. Because HQM must be filled with quality elements which are hard to identify at the beginning of design, it is very difficult to use QFD in conceptual design. This suggests that we can arrive at a good design solution that will reflect market requirements with the QFD method, but to do so it must be combined with a method that can accommodate functional knowledge for conceptual design.

Therefore, we propose a new framework to integrate the QFD and FBS methods (Figure 3). In this new framework, we use HQM to represent market requirements and describe a reason for selecting one particular solution. The QFD tool composes HQM, QFM, and FMM corresponding to the evolution of the design object described with the FBS modeler, while the FBS modeler assists the designer in decomposing function and searching for design alternatives.

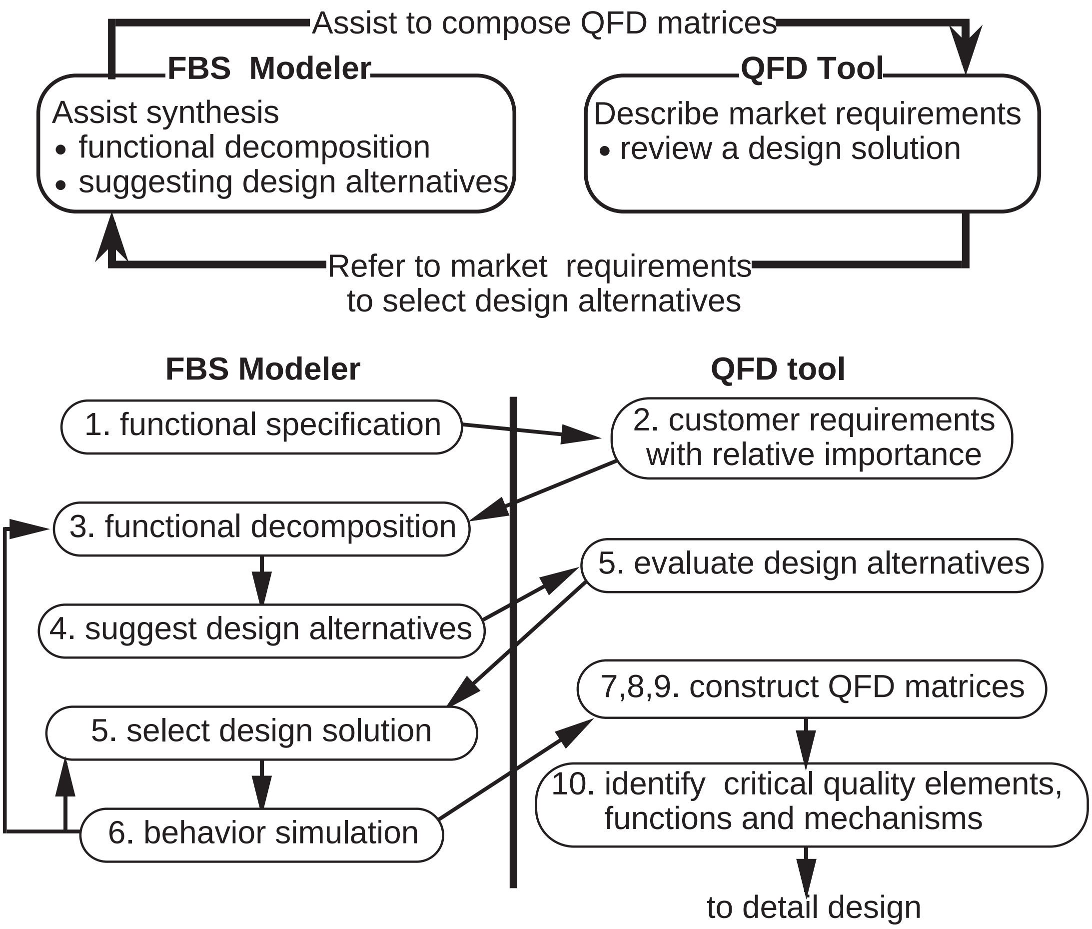


Figure 3 Design flow and the integrated system of FBS and QFD

Table 2 Definition of mechanism knowledge

Item	Contents
Name	name of physical feature
HQM	HQM for this mechanism
SD	SD for market requirements in HQM

To develop the framework, there involved two types of knowledge associated with mechanisms. First, we need to introduce *Satisfaction Degree* (SD) to evaluate how good a mechanism as a design alternative is with regard to customer's requirements. Second, it is necessary to describe knowledge for assisting the designer to compose QFD matrices corresponding to the evolution of design solution. Since a design solution evolves when a new physical feature, which is a set of a mechanism and physical phenomena to occur on the mechanism, is added to embody a subfunction in the FBS diagram, this knowledge should be associated with mechanisms.

Table 2 shows the definition of *mechanism knowledge* including SD and HQM for a mechanism. Figure 4 depicts an example of mechanism knowledge. Each element of SD corresponds to each of customer requirements of HQM for this mechanism and is represented in the scale between 1 (bad) and 5 (good).

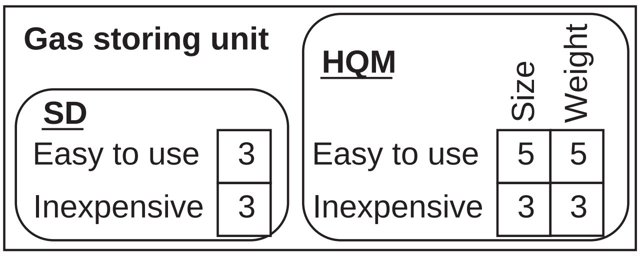


Figure 4 An example of mechanism knowledge

Figure 3 illustrates the design process on this framework that integrates QFD and FBS. The FBS modeler is used for decomposing function and suggesting design alternatives, while the QFD tool constructs QFD matrices for considering market requirements and reviewing design solutions from the point of view of quality. The design process proceeds in the following manner.

1. Functional specifications are described in the FBS modeler.
2. Market requirements as customer requirements are described with their Relative Importance (RI) by the Analytic Hierarchy Process method (Saaty, 1980). In this method RI is calculated as follows. First each market requirements is compared with all other requirements and given an Importance Degree (ID). If the i-th customer requirement

is more important than the j-th, ID_{ij} is assigned with a value that ranges 1 and 5, where 5 is very important, 3 is important, and 1 is the same. Then ID_{ji} is calculated with the following formulae.

$$
\begin{aligned}
ID_{ji} &= \frac{1}{ID_{ij}}, \quad \text{and} \\
ID_{ii} &= 1
\end{aligned}
$$

Second, RI is calculated with the following formulae.

$$
\begin{aligned}
X_i &= \sqrt[m]{\sum_{j=1}^{m} ID_{ij}^2}, \quad \text{and} \\
\overrightarrow{RI} &= \frac{\{X_1, \quad X_2, \quad \cdots, \quad X_m\}}{\sum_{i=1}^{m} X_i} \times 10,
\end{aligned}
$$

where m is the number of customer requirements.

3. The FBS modeler decomposes the required functions and builds a functional hierarchy using function prototype knowledge.
4. The FBS modeler then embodies each decomposed function by using function prototype knowledge base. This may results in design alternatives from which the designer has to choose to obtain a solution.
5. The designer evaluates Satisfaction Degree (SD) for each alternative with the mechanism knowledge. The Evaluation Result (ER) is calculated from satisfaction degree vector $\overrightarrow{SD}$ of the mechanism and $\overrightarrow{RI}$. If there is no satisfaction degree for a customer requirement in $\overrightarrow{RI}$, this degree is 0.

   $$ER = \overrightarrow{SD} \cdot \overrightarrow{RI}$$

   A design alternative which gets the highest evaluation result is selected as a design solution. Figure 5 is an example of this evaluation process. In this case “Flint stone lighting unit” is selected as a design solution.
6. Using the FBS modeler, behavior simulation verifies whether or not the functional specification is satisfied. If it fails, go back to Step 3 or Step 5.
7. A total HQM for each design solution is built from the mechanism knowledge. Figure 6 shows how to combine partial HQMs of “Flint stone lighting unit” and “Gas storing unit” to build HQM of the entire solution.
8. FMM is constructed based on the F-B relationships described in the FBS modeler. Since we believe the subfunction and the embodied mechanism are related strongly, the degree of relationship between the subfunction and the embodied mechanism is always 5. Figure 6 shows an example of combining the matrix for “Flint stone lighting unit”and “Gas storing Unit”.
9. The mechanism knowledge stores the mechanism’s partial HQM that lists quality elements. These quality elements are relevant to the mechanism’s subfunction that can be retrieved with the FBS modeler. Thus, the designer can identify elements of QFM which have valid relationships between the quality elements and subfunctions. In Fig-

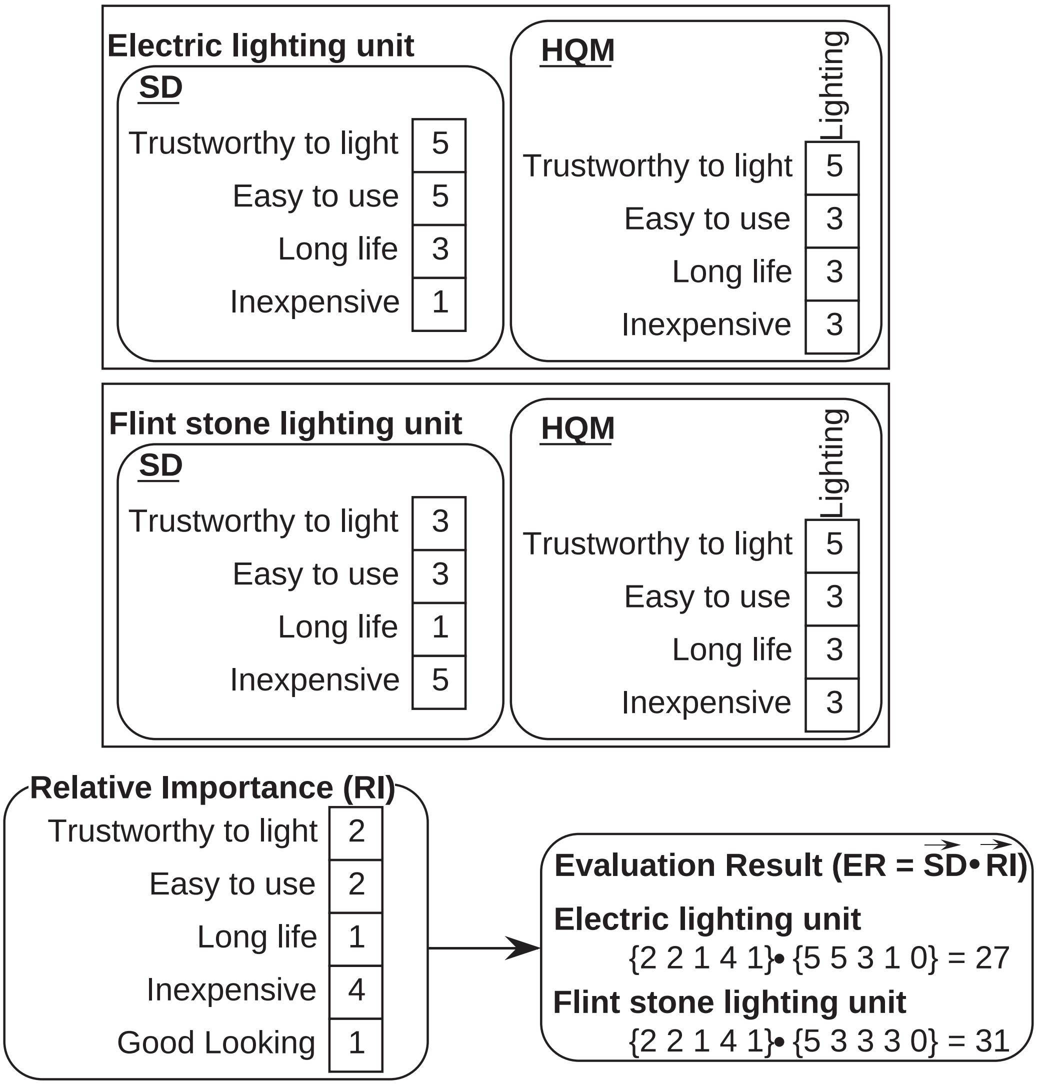


Figure 5 Evaluation of design alternatives

ure 6, "X" in QFM represents the identified relationships. The degrees of relationship for these relationships will be determined by the designer.

10. Now, we are able to obtain critical quality elements, functions, and mechanisms by looking at WQE, WF, and WM.

4 EXAMPLE

In this section, we illustrate an example of design of a photocopier that will be later redesigned to improve the quality. Because this type of activities very often takes place in practical design situations, this example demonstrates the power of the knowledge intensive engineering concepts.

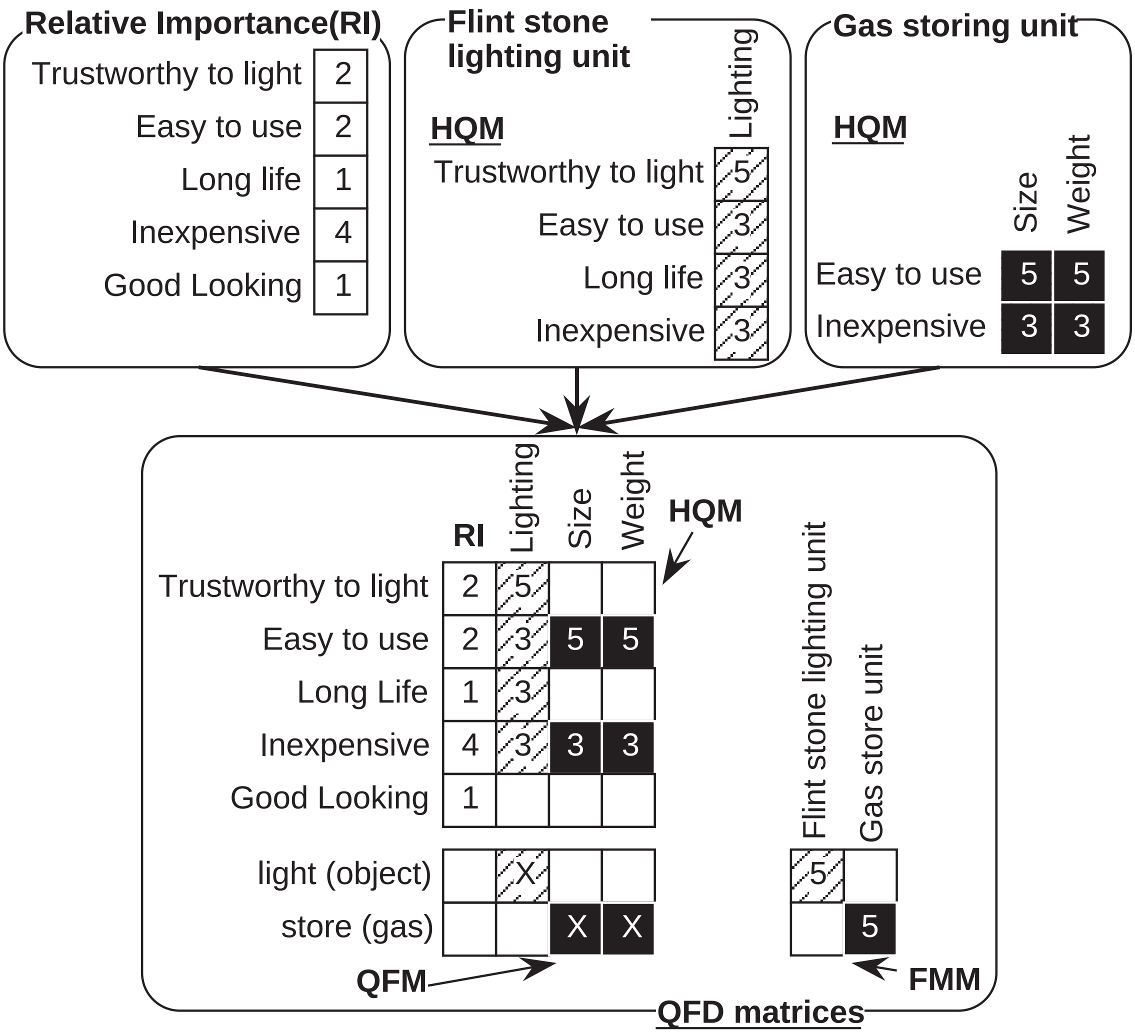


Figure 6 Composing QFD matrices

4.1 Designing a photocopier

First, a designer describes the functional specification in the FBS modeler, i.e., to copy original paper to a blank sheet and the market requirements in the QFD tool that calculate their RI in consultation with marketing officers. Figure 7 is screen hard copy of Relative Importance Calculator which results in RI in Table 3.

Then the designer decomposes the functional specification to subfunctions until the system can suggest design alternatives for each subfunction. After this, the designer evaluates the design alternatives suggested by the FBS modeler on the QFD tool. Figure 8 shows an example of comparison between two types of development mechanism. One is a cascade development method and the other is a magnet brush development method *.

*Those who are interested in technical details of these methods, please refer to the books about electro photography, e.g., (Scharfe, 1984)

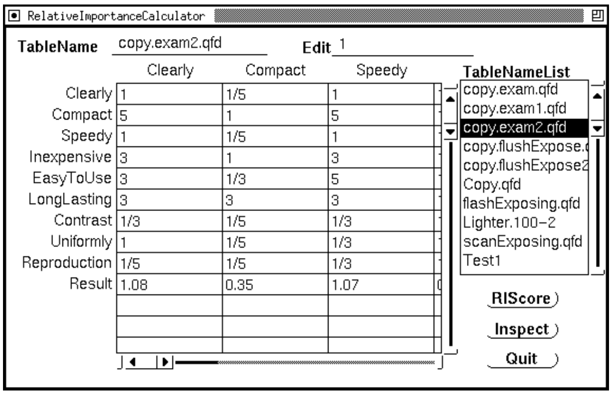


Figure 7 Calculation of RI for each customer requirement

Table 3 Relative Importance (RI) for customer requirements

Clearly	1.08
Compact	0.35
Speedy	1.07
Inexpensive	0.39
Easy to Control	0.56
Long Lasting	0.3
Contrast	1.62
Uniformly	1.84
Reproduction	2.8

Since the magnet brush development method gets a good evaluation result in this case, magnet brush development method is selected as a design solution. After embodiment for each subfunction, the QFD tool can generate HQM with the mechanism knowledge (Figure 9).

In addition, QFM and FMM are composed by using the F-B relationship in the FBS modeler and the mechanism knowledge. With these matrices the QFD tool selects critical quality elements (i.e., optical intensity and static electric power), mechanisms (i.e., optical transmission, JC lamp, main charger, and transfer charger), and functions (i.e., to transmit dielectronics to paper, to make contact distribution of electrical charge to dielectronics, to transmit distribution of optical intensity, and to light up paper). This information will be used later in detail design.

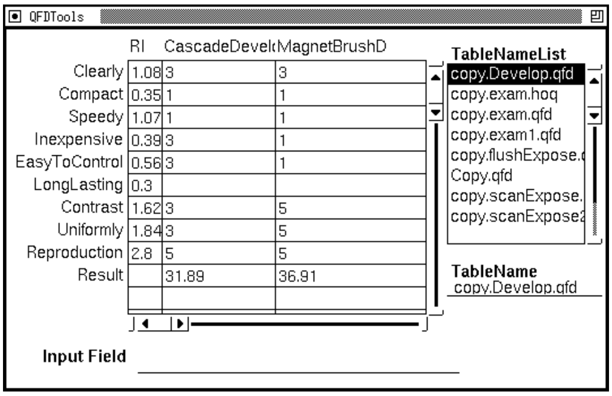


Figure 8 Comparison of the developing method

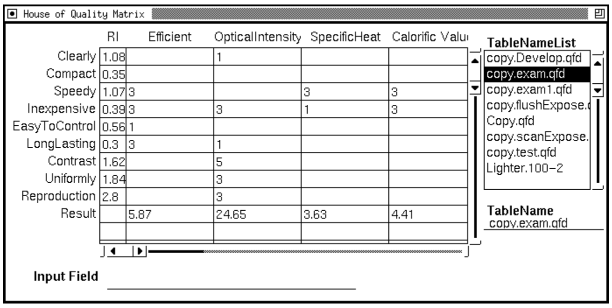


Figure 9 HQM of a photocopier

4.2 Redesigning a photocopier by using old design history

The QFD method facilitates redesigning to improve the design quality. Next we redesign the photocopier designed in the previous section, because, for instance, the market requirements changes. Suppose customers want to take a copy much faster even though they have to sacrifice the image quality.

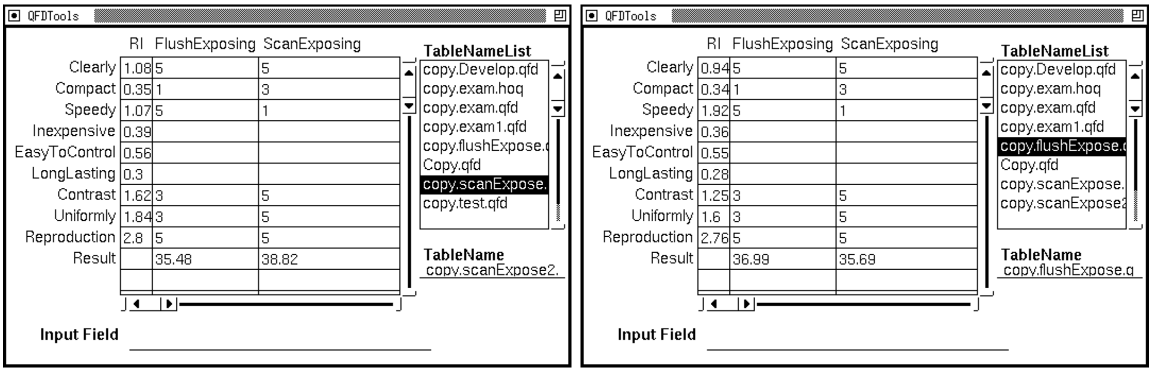
With those new market requirements listed in Table 4, the system re-evaluates all design alternatives and compares them with old design solution. In this case, the Evaluation Result of exposing units are different (Figure 10). The old design employs the scan exposing method, while the new design the flush exposing method.

4.3 Discussions

The first example shows that this framework can represent all design alternatives considered in the decision-making process during the conceptual design of a photocopier. These decision-making process can be clearly explained with WQE, WF, WM, and ER of the QFD method. By recording temporal history together with the FBS diagram and the

Table 4 Relative Importance (RI) for new customer requirements

Clearly	0.94
Compact	0.34
Speedy	1.92
Inexpensive	0.36
Easy to Control	0.55
Long Lasting	0.28
Contrast	1.25
Uniformly	1.6
Reproduction	2.76



(a) Old design solution (b) New design solution

Figure 10 Comparison of exposing method

QFD matrices, design process knowledge can be described. The example also proved that the QFD method can be used for not only quality assurance but also conceptual design.

The second example indicates that information about the decision-making process which dictates the designer's intention is useful for redesigning in a later stage to improve design quality or even for educational purposes. This system facilitates systematization of such design process knowledge to be shared and reused by other designers.

These two examples demonstrates the power of the knowledge intensive engineering concept in two ways. First, intensively stored knowledge can be applied to various engineering activities (in this examples, quality control knowledge to conceptual design and *vice versa*) to guarantee and improve quality of design. Second, design knowledge is explicitly systematized to be shared and reused by other designers or engineers in different sections. This was extremely difficult with design process knowledge and conceptual knowledge which are dealt with in this paper.

There are some reports that discussed approaches relevant to ours. Bradley (1993) developed a computational method to select an appropriate mechanism with multiple objectives. His approach is appropriate for the mathematically well-formalized design problems. Bascaran (1994) proposed an application of the QFD method to Suh's Axiomatic Design methodology (Suh, 1990). It is also an extension of the QFD method, but he only extends the design review method part.

5 CONCLUSIONS AND FUTURE WORK

In this paper, we proposed a new framework, that combines the FBS and QFD methods to describe the designer's intention with respect to the decision-making information. In addition, the QFD method is applicable to conceptual design on the system. Through an example design of a photocopier, we demonstrated that this idea of knowledge intensive engineering can guarantee and improve design quality, and that design process knowledge, in particular, decision-making information can be recorded and stored for sharing and reusing.

For future work, we should improve simulation capabilities to distinguish critical differences among design alternatives and to evaluate them from various aspects.

6 ACKNOWLEDGMENTS

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