ENVIRONMENT-BASED DESIGN (EBD) AND QUALITY FUNCTION DEPLOYMENT (QFD) COMPARISON

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ABSTRACT

ENVIRONMENT-BASED DESIGN (EBD) AND QUALITY FUNCTION DEPLOYMENT (QFD) COMPARISON

Ronaldo Gutierrez

Design is an important area to study because there is a continuous need to develop new, cost-effective, and high-quality products. Customers and management always want that the product to be designed is cheaper, better, and launched faster than previous ones. As a result, product cost, quality, and time to market are three measures to determine the effectiveness of the design process, and decisions made during the design process have a great effect on them.

The previous facts besides the fact that many engineering students lack of the vast experience required in the competitive labor market lead to the need of learning an appropriate design methodology since the beginning of their studies in order to assist them during the design process and to control design quality. The focus and scope of this thesis is to compare two design methodologies, EBD (Environment-Based Design) and QFD (Quality Function Deployment), covering from identifying customers' requirements until generating engineering requirements that satisfy the customer's requirements of a design problems. QFD is one of the most common used methodologies to support the design process, and it is applied in a wide variety of services, consumer products, military needs, emerging technology products, and for identifying and documenting competitive marketing strategies and tactics. The motivation of the present thesis is to prove that EBD, which is emerging and promising, can also be used to support the product definition process in addition to helping inexperience designers to cope with the difficulties encountered in it, and to providing more complete results than by using QFD.

In order to evaluate and validate the previous hypothesis, a set of criteria are developed to compare EBD and QFD, considering some of the parameters that show success in a designed product such as quality, product life cycle and viability. A case study that includes three different design problems is solved by using EBD and QFD, and the obtained results are analyzed by three different evaluators in order to achieve reliable results. Finally, after analyzing the experimental results of the case study, it is preliminarily concluded that the thesis hypothesis cannot be rejected. EBD performs better than QFD in overcoming the design difficulties, and achieving complete results defining a new product.

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Chapter 1: Introduction

1.1 Background

Design is an important area to study because there is a continuous need to develop new, cost-effective, and high-quality products (Ullman, 2003). Furthermore, design of new products has become more complex, and the need to develop them at a very rapid and accelerating pace has been fostered by the global marketplace (Ullman, 2003). As result, a company must be efficient in designing and developing its new products in order to succeed in the market.

Customers and managements always want that the product to be designed is cheaper, better, and launched faster than previous ones; therefore, product cost, quality and time to market are the three measures of the effectiveness of the design process (Ullman, 2003). Additionally, a product is often judged by its appearance (surface finish, coating, trim) and how well it performs its designated function (Sule, 2009).

Even though the design process may vary from product to product, the diagram in Figure 1 can be used as a general process in design projects, and the description of each stage is done as follows (Ullman, 2010):

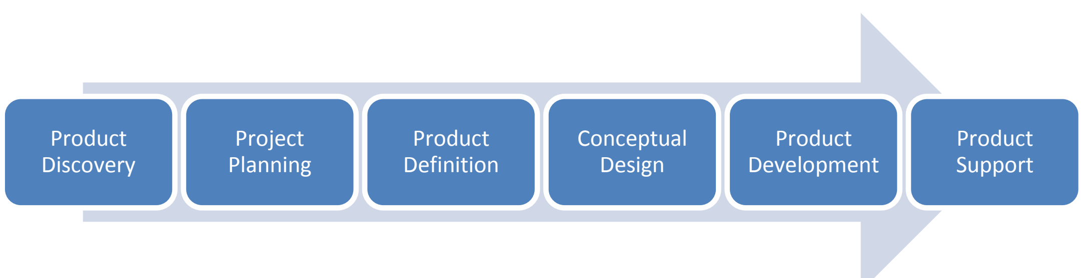


Figure 1: The Design Process (Ullman, 2010)

- *Product Discovery:* Design projects are initiated by either a market requirement, the development of a new technology, or the desire to improve an existing product (Forbes, 2009; Info entrepreneurs, 2009; Ullman, 2003). About 80 percent of new product development is market driven (Ullman, 2003). New products must contain the latest technology if they want to be perceived as high quality ones even though they are market driven (Ullman, 2003). On the other hand, companies usually want to develop a new product without market demand based on new technologies; however, these products are useless unless they can be matched to a market need or a new market can be developed for them (Beard & Easingwood, 1996; Ullman, 2003). Finally, the third way to discover a new product is by the desire to redesign existing ones. Usually the redesign of a product is market driven, and it is initiated to fix a problem with an existing product, include a new technology in an existing product, reduce the product cost, simplify manufacturing, respond to a required change of materials, or for many other reasons (Khodadadeh & Mohammadpur, 2009; Ullman, 2003).
- *Project Planning:* a set of tasks to perform the design project is developed, and they are also sequenced. After that, resources (time, money, labour force, and equipment) are allocated and accounted for. The last step is to develop a schedule and estimate the cost of the project.
- *Product Definition:* the goal of this step is to understand the design problem and to generate customers's requirements in order to lay the foundation for the remainder of the design process.

- *Conceptual Design:* the goal of this step is to generate and evaluate concepts for the product or product changes. After that, the generated concepts are compared to the developed requirements in the previous step, and a decision is made about which concept is the best one.
- *Product Development:* in this step, the product is released for production. At this point, the technical documentation defining manufacturing, assembly, and quality control instructions must be completed and ready for the purchase, manufacture, and assembly of components.
- *Product Support:* in this step we encounter manufacturing and assembly support, support for vendors, and help in introducing the product to the customer is completed. Besides that, this is the process where changes made to the product are managed and documented.

The actual cost of design is usually a small part of the manufacturing cost of a product; however, the decisions made during the design process have a great effect on the cost of a product but cost very little (Ullman, 2003). Design decisions directly determine the product' components such as material, manufacturing process, machines, labor force and so forth that affects the cost of a product. Besides that, the design process also affects the quality of the product and the time it takes to produce a new product.

It is a fact that early design changes require more engineering time and effort; however, it does not require changes in hardware or documentation.

> *"A change that would cost $1 thousand in engineering time if made early in the design process may cost $10 thousand later during product refinement*

and $1 million or more in tooling, sales, and goodwill expenses if made after production has begun (Ullman, 2003)".

1.2 Motivation

As can be seen from the previous background section, the design process has a great impact in the cost, quality, and time to launch a new product to the market. Moreover, to find the right problem to solve is not an easy task. As result, the previous reasons and the following statement by Ullman influenced me to focus my thesis in the design area:

> *"A lot of time and money can be wasted designing the wrong product. Surveys show that poor product definition is a factor in 80 percent of all time-to-market delays. Further, getting a product to market late is more costly to a company than being over cost or having less than optimal performance. Finding the "right" problem to be solved may seem a simple task; unfortunately, often it is not"(Ullman, 2003).*

In addition to finding the right problem to solve, creeping specifications are a difficult and expensive problem for most companies because they change during the design process. There are three factors occasioning creeping specifications, and they are described as follows (Ullman, 2003):

- More is learned about the product as the design progresses, so more features can be added.
- New technologies and competitive products become available during the design process because the design takes time.

- Since decision making is involved during the design process, any specification change causes a readdressing of all the decisions dependent on that specification. Sometimes, the whole product can be redesign for a simple specification change.

Taking into consideration the importance of the previous difficulties plus the fact that many engineering students lack of the vast experience required in the labor market, I would like to assess which design methodology is more appropriate to assist in the design process and to control design quality. Therefore, the focus and scope of this thesis will be the comparison of two design methodologies EBD (Environment-Based Design) and QFD (Quality Function Deployment), covering from identifying customers' requirements until generating engineering requirements that satisfy the customer's requirements of the design problems. QFD is applied in a wide variety of services, consumer products, military needs, emerging technology products, and it is also used to identify and document competitive marketing strategies and tactics. The motivation of the present thesis is to prove that EBD can also be used to support the product definition process in addition to helping inexperience designers to cope with the difficulties encountered in it, and to providing more complete results than by using QFD.

1.3 Contribution

First of all, complete information and a detailed example about EBD and QFD were recollected in order to explain and state how both methodologies can be applied. Then, a general comparison and analysis of EBD and QFD was done with the purpose of relating both methodologies to the product definition step within the scope of this thesis and understanding how they meet its different requirements. After that, a case study that includes 3 design experiments was solved by using EBD and QFD for comparison purposes. When the designers were solving the problems, the design process was recorded and that information will be also useful to other research purposes. Besides that, the detail design results of the problems can also be found in the present thesis.

The main contribution was to create a set of criteria to compare the two design methodologies and to develop preliminary conclusions that EBD helps inexperience designers such as students to cope the difficulties encountered in the product definition process in addition to providing more complete results than by using QFD. The created set of criteria can be used in the future in order to associate other design methodologies.

1.4 Thesis Organization

The rest of the present thesis is organized as follows:

- Chapter 2: Literature review, a complete review about EBD and QFD design methodologies is presented in this chapter.
- Chapter 3: EBD and QFD comparison, a general and an experimental comparison of EBD and QFD is illustrated in this chapter. Furthermore, the criteria of evaluation are developed and the design problems are solved and analyzed. At the end of the chapter, a summary and evaluation of the analyzed results is displayed.
- Chapter 4: Conclusions and Future Work. This chapter summarizes the work done in the current thesis and brings out important remarks from the results analyzed in Chapter 3. Moreover, this chapter provides thoughts on the future work.

Chapter 2: Literature review

2.1 Environment-Based Design (EBD)

Environment-Based Design (EBD) is a step-by-step design methodology to solve poorly defined design problems by finally delivering creative and innovative design solutions (Wang & Zeng, 2009) . EBD was introduced by (Zeng & Cheng, 1991), and it is derived from the Axiomatic Theory of Design Modeling (Zeng, 2002) based on the recursive logic of design.

Axiomatic theory of design modelling is a logical tool for representing and reasoning about object structures, and it provides a formal approach that allows the development of design theories following logical steps based on mathematical concepts and axioms (Zeng, 2008). Universe, object, and relation are used as primitive concepts in two axioms that conform the axiomatic theory of design modelling (Zeng, 2008). The two axioms are defined as:

1. Everything in the universe is an object, and
2. There are relations between objects.

Complex object structures are modeled by structure operations ($\oplus$) developed in the axiomatic theory of design modelling. Structure operations are defined by the union ($\cup$) of an object and intersection ($\otimes$) of the object with itself. The structure operation of an object is represented by equation 1:

$$\oplus O = O \cup (O \otimes O) \qquad \mathbf{1}$$

where $(\oplus O)$ is the structure of an object (O) (Zhang, 2011). The union and the interaction are specific relations between objects.

An object (O) can be composed of other objects. Therefore, equation 1 indeed is a recursive representation of an object (Zeng, 2008). Assuming that the object (O) includes m sub-objects $O_i (i = 1,2, \ldots, m)$**,** equation 2 shows the object recursion:

$$O = \bigcup_{i=1}^{m} O_i \qquad \mathbf{2}$$

where m is a finite natural number. As result, the structure $(\oplus O)$ of the object (O), can be expanded as equation 3 which provides the structure of a recursive and hierarchical object (Zeng, 2008).

$$\oplus O = O \cup (O \otimes O) = \left(\bigcup_{i=1}^{m} \oplus O_i \right) \cup \left(\bigcup_{i=1}^{m} \bigcup_{\substack{j=1 \\ j \neq 1}}^{m} (O_i \otimes O_j \right) \qquad \mathbf{3}$$

Additionally, Figure 2 graphically displays a hierarchical objects representation.

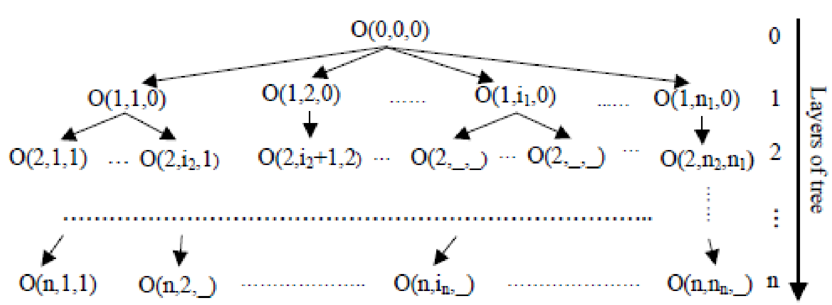


Figure 2: Hierarchical object representation (Zeng, 2002)

In the hierarchical structure, according to (Zeng, 2008), the node at the i_kth position in the kth layer with a parent node at the $j_{(k-1)}$th position in the $(k-1)$th layer is represented by $O(k, i_k, j_{k-1})$, where each node can be an object or a relation between objects.

A primitive object (O_i^a) is defined by an object that cannot be or does not need to be further decomposed, refer to equation 4:

$$\oplus O_i^a = O_i^a \quad (4)$$

Due to the human cognition capacity and the scope of an application, a group of primitive objects is defined as equation 5, and the condition of a primitive object has to be hold.

$$M = \bigcup_{i=1}^{n} O_i^a \quad (5)$$

The core of the EBD methodology is that a product system implies a design problem, and that the product system is composed of three parts: the environment, the requirements on product structure, and the requirement on performances of the designed product (Tan, Zeng, & Montazami, 2011; Zeng, 2004). The environment which can be natural, built, and human; is where the product is expected to work and it is related to the requirements on product structure and performance (Zeng, 2004). Refer to Figure 3.

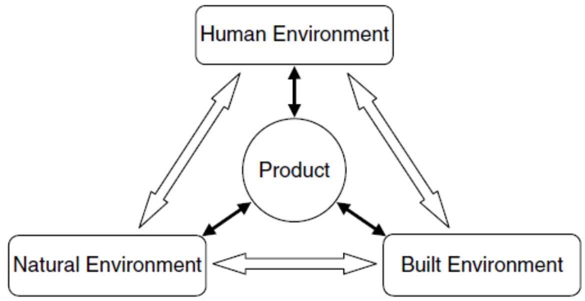


Figure 3: Product and its environment (Tan, et al., 2011)

Moreover, according to the EBD methodology, *environment analysis, conflict identification, and solution generation* in Figure 4 are the three main activities always present in a design process. These activities are interdependent and they work together to generate and refine the design specifications and the design solutions. A detailed demonstration of the logical steps based on mathematical concepts and axioms about the theory of EBD can be found in (Zeng, 2004).

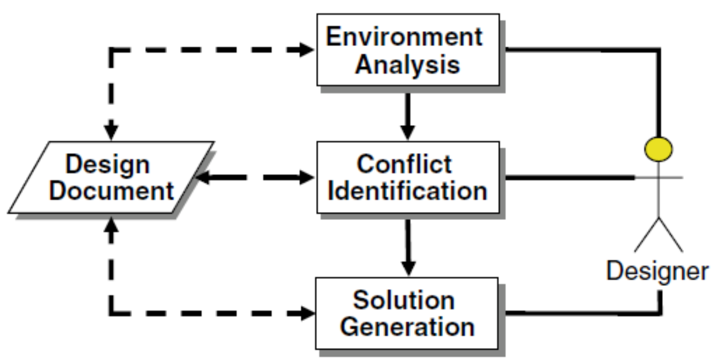


Figure 4: EBD process flow (Tan, et al., 2011)

EBD's main activities (environment analysis, conflict identification, and solution generation) are further discussed in the next subsections. Additionally, a detailed example using EBD design methodology can be found in Appendix A, which refers to "Developing a Quality Manual for Environment Monitoring System in a City" by (Sun, Zeng, & Zhou, 2011). However, before starting discussing the main activities of EBD, a subsection about the recursive object model (ROM) will be first introduced.

2.1.1 Recursive object model (ROM)

The purpose of discussing ROM at this point is because it is the foundation for environment analysis. Therefore, the objective of this subsection is to introduce what ROM is, and how to use it. The why of using ROM will be discussed in the environment analysis subsection.

ROM is a graphical representation of a linguistic structure used as an intermediate medium between natural language and structured modeling language (Zeng, 2004, 2008).

Recalling the axiomatic theory of design modelling, there are two axioms. The first axiom refers to "everything in the universe is an object". Hence, a solid box as in Figure 5 is an object that denotes the ROM's basic unit.

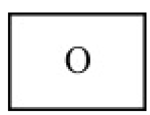


Figure 5: Graphic symbol for object (Zeng, 2008)

At least two objects form a compound object (Figure 6), and it used to represent more complex object such as ⊕O.

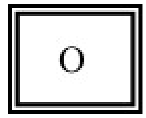


Figure 6: Graphic symbol for a compound object (Zeng, 2008)

The second axiom in the axiomatic theory of design modelling is that “there are relations between objects”. Therefore, ROM uses the relations of constraints, connection and predicate.

A constrain (ξ) is shown by an arrow with a dotted head (Figure 7) that always points to the object to be constrained.

Figure 7: Constraint relation (Zeng, 2008)

Additionally, a constraint describes, limits, or particularizes a relation of one object to another; and it can be mathematically expressed as in equation 6 by an interaction from the constraining object O_i to the constrained object O_j.

$$\xi \subset O_i \otimes O_j \qquad \textbf{6}$$

Figure 8 displays some examples of constraint relations.

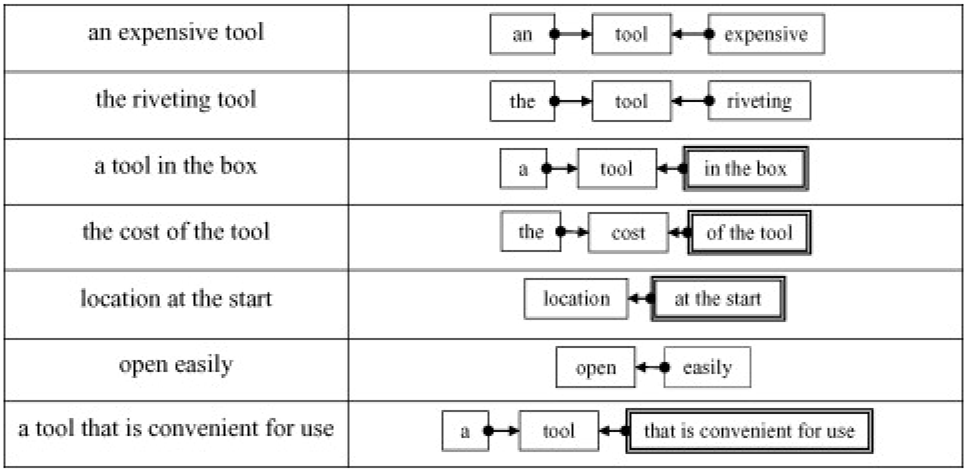


Figure 8: Examples of constraint relation (Zeng, 2008)

The second type of relations in a ROM diagram is connection(ι) which is represented by a dashed arrow. Refer to Figure 9. Depending on the semantic of the relation, the arrow is optional.

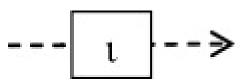


Figure 9: Connection relation (Zeng, 2008)

The purpose of the connection relation is to link two objects that do not constraint each other, and it can be mathematically represented as the equation 7 by an interaction from the constraining object O_i to the constrained object O_j.

$$\iota \subset O_i \otimes O_j \qquad \textbf{7}$$

Figure 10 displays some examples of connection relations.

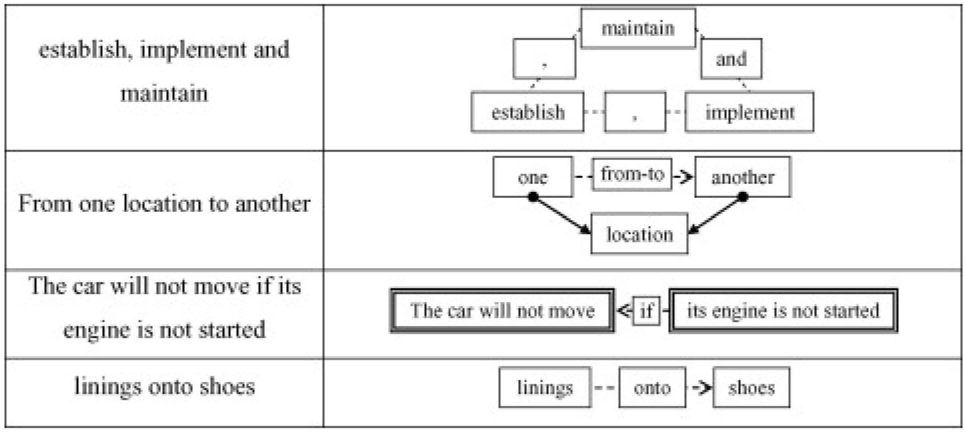


Figure 10: Examples of connection relation (Zeng, 2008)

Predicate (ρ) is the final type of relation in a ROM diagram, and it is represented by a solid arrow. Refer to Figure 11.

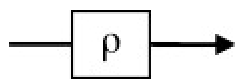


Figure 11: Predicate relation (Zeng, 2008)

Predicate relations describe an act of an object on another or they describe the state of an object. Many specific forms, for instance action and statement, are included in predicate relations that can be mathematically expressed as equation 8 by an interaction of one object O_i with another O_j.

$$\rho \subset O_i \otimes O_j \quad \mathbf{8}$$

Figure 12 displays some examples of connection relations.

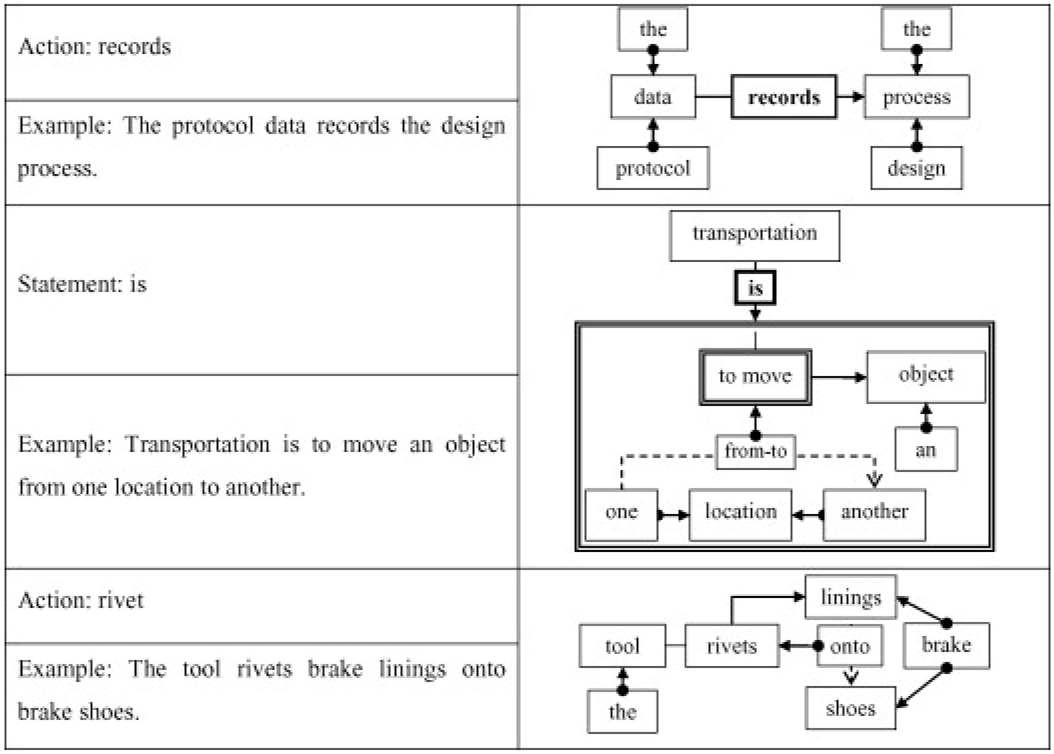


Figure 12: Examples of predicate relation (Zeng, 2008)

Figure 13 summarizes the types of objects and relations in a ROM diagram. In addition, it is important to mention that a software (ROMA) has been developed to transform technical English text into ROM diagrams (Zeng, 2008).

Type		Graphic Representation	Definition
Object	Object	O	Everything in the universe is an object.
	Compound Object	O	It is an object that includes at least two other objects in it.
Relations	Constraint		It is a descriptive, limiting, or particularizing relation of one object to another.
	Connection	ι	It is to connect two objects that do not constrain each other.
	Predicate	ρ	It describes an act of an object on another or that describes the states of an object.

Figure 13: Elements of recursive object model (ROM) (Zeng, 2008)

The ROM has been tested in and applied to different problems. Some examples of ROM's applications are as follows:

- Embedded product design (Zhang, 2011).
- Iterative and automatic generation of questions to elicit product requirements (Wang & Zeng, 2009).
- Quantification of designers' mental stress during the conceptual design process (Zhu, Yao, & Zeng, 2007).
- Agile software design (Moroz, 2011).

Now that the ROM has been introduced, the following subsections will describe *environment analysis, conflict identification, and solution generation;* the three main activities in a design process according to EBD.

2.1.2 *Environment analysis*

Most of the time, designers face the difficulty that design problems are described in an informal plain language whereas any scientific method usually is based on certain formal structure (Tan, et al., 2011). As consequence, there is a gap between the plain language and formal structures used in scientific methods that have to be bridged. Having the previous limitation, Zeng found the need and tries to overcome it by using ROM and transforming a design problem into a ROM representation that can be further analyzed (Tan, et al., 2011; Wang & Zeng, 2009).

The approach proposed by Zeng aims to identify the customer's real intent and to collect the complete product requirements. Therefore, Zeng claims that how to ask proper questions is critical for collecting right product requirements (Wang & Zeng, 2009), and he and Wang propose the generic inquiry process for obtaining product requirements (Wang & Zeng, 2007). Figure 14 shows the generic inquiry process and it can be divided in the following 8 steps (Wang & Zeng, 2009):

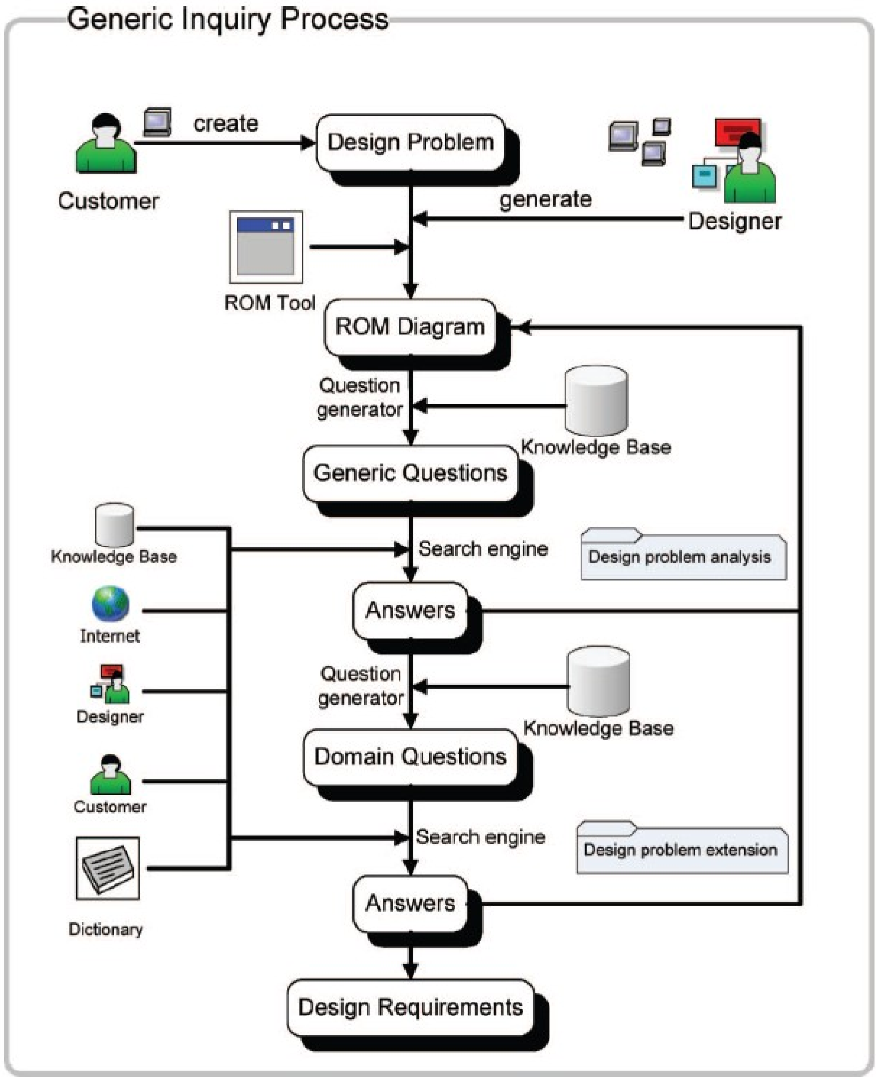


Figure 14: Generic inquiry process for requirements elicitation (Wang & Zeng, 2009)

1. *Create a ROM diagram:* in this step, the design problem is translated into a ROM diagram, and it is achieved by following the rules in the ROM subsection. The objective of creating a ROM is to enable the designer to understand more clearly the design problem.
2. *Generate generic questions:* in this step, the objects that need to be further clarified or analyzed are discovered. After that, based on a set of predefined rules

(Table 1) and the questions template in Table 2, some questions are generated in order to help the customers to understand and clarify their real intent. The rules in Table 1 help to determine which objects should be extended first, whereas the template questions in Table 2 are used to select the candidate questions based on the designer knowledge.

Table 1: Rules for object analysis (Wang & Zeng, 2009)

Rules	Analysis
1	Before an object can be further defined, the objects constraining them should be refined.
2	An object with the most undefined constraints should be considered first.

Table 2: Question template for object analysis (Wang & Zeng, 2009)

	Case	Template question
1	For a concrete, proper or abstract noun ***N***	What is ***N***?
2	For a noun naming a quantity ***Q*** of an object ***N***, such as height, width, length, capacity, and level	How many / much / long / big / … is the ***Q*** of ***N***?
3	For a verb ***V***	How to ***V***? Or why ***V***?
4	For a modifier ***M*** of a verb ***V***	How to ***V M***?
5	For an adjective or an adverb ***A***	What do you mean by ***A***?
6	For a relation ***R*** that misses related objects	What (who) ***R*** (the given object)? Or (the given object) ***R*** what (whom)?

3. *Collect answer:* by consulting a dictionary or knowledge base, by searching on the internet, or by collecting information from the customer; the designer answers the questions generated in step 2.
4. *Repeat steps 1 to 4 until no more generic questions can be asked:* in this step, the ROM that was created in step 1 is updated with the answers collected in step 3. Then, if there are unclear objects in the updated ROM, the previous steps are followed iteratively until the customer's real intent is understood, and all the objects in the ROM diagram are clear.
5. *Generate domain specific questions:* the objective of this step is to analyze the relationships between the objects in the updated ROM diagram. Firstly, a question about the product life cycle is asked to determine the stages in which the product is involved, and secondly, questions are generated in terms of environment components on their requirement levels for the identified stages (Chen & Zeng, 2006). Figure 15 displays the 7 events involved in a product life cycle, while Figure 16 shows the eight levels of product requirements and their relation to the product environments.

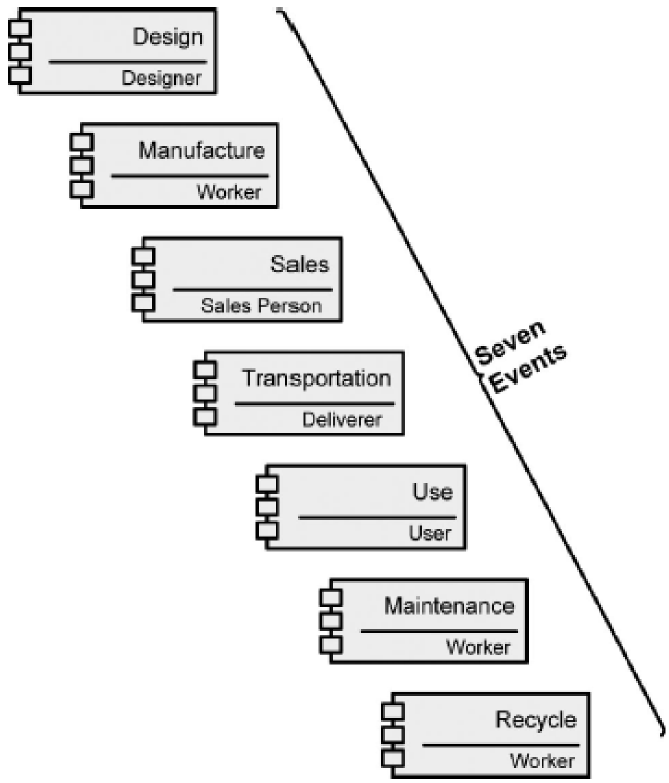


Figure 15: Seven events in a product life cycle (Chen & Zeng, 2006)

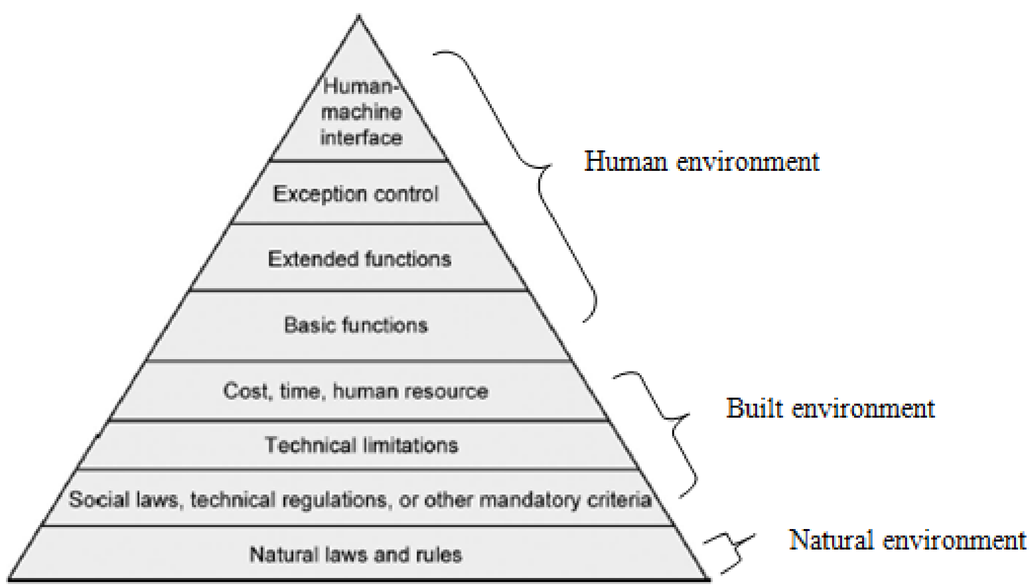


Figure 16: Eight level of requirements (Chen & Zeng, 2006)

The pyramid shape in Figure 16 means that the product requirements at the lowest level have higher priority in developing a design solution than those at the highest level. Additionally, the lower four level requirements are considered non-functional requirements while the four ones on top are considered functional requirements.

The relation of the eight levels of product requirements to the product environments is also shown in Figure 16. The highest four levels come from the human environment, while the lowest one comes from the natural environment and the rest belongs to the built environment. Those products meeting the requirements at the highest level are called high usability products. For further information and details about the product life cycle events and the level of requirements refer to (Chen & Zeng, 2006).

The sequence to ask the domain specific question is based on the rules in Table 3:

Table 3: Domain specific question rules (Chen & Zeng, 2006)

Rules	Analysis
3	What is the life cycle of the product to be designed?
4	Ask questions about the natural, built, and human environments for the identified stages of the product life cycle.
5	The sequence for asking questions is determined by the levels of requirements in Figure 16 so that those requirements at the lower levels have higher priority and can be asked earlier.
6	Ask questions about the answers from rule 1 and rule 2 by applying the rules related to step 2.

6. *Collect answer to the questions generated in step 5:* the actions taken in this step are similar to the ones in step 3.
7. *Repeat steps 1 to 7 until no more domain questions can be asked:* the objective of this step is to follow iteratively from step 1 to 7 until the domain-dependent product requirements are elicited accurately.
8. *Output the updated design problem description:* in this step a final ROM diagram is updated with the information collected in step 7.

2.1.3 Conflict identification

The objective of the conflict identification phase is to identify undesired conflicts between environment components, and they arise from three elements: two competing objects and one resource object which the former two objects contend for (Yan & Zeng, 2009). In the EBD process, conflicts are viewed as the driving force (Moroz, 2011).

Zeng claims that based on a ROM diagram is much easier for identifying conflicts than finding them from the natural language description (Tan, et al., 2011). According to Zeng, three kinds of conflicts can be found in a ROM diagram:

1. Conflict between two objects
2. Conflict between two constraint relations, and
3. Conflict between two predicate relation

Figure 17 displays the three kinds of conflicts in a ROM diagram, and they are represented from left to right respectively.

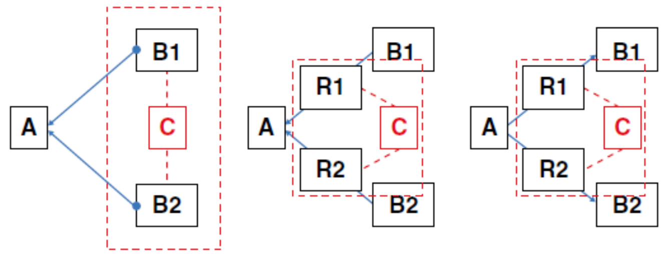


Figure 17: Three forms of existing conflicts in a ROM diagram (Tan, et al., 2011)

Potential conflicts can be identified from a ROM diagram by following the rules in Table 4. The rules are not inclusive and are complete (Zhang, 2011).

Table 4: Rules for identifying potential conflicts (Zhang, 2011)

Rules	Analysis
1	If an object has multiple constraints, then potential conflict exists between any pair of constraining objects.
2	If an object has multiple predicate relations from other objects, then potential conflict exists between a pair of those predicate relations.
3	If an object has multiple predicate relations to other objects, then a potential conflict exists between a pair of those predicate relations.

2.1.4 Solution generation

Before generating solutions to the identified conflicts, first they should be analyzed. According to Zeng, the principle is to discover the dependences among the conflicts because one conflict may be arisen from another (Tan, et al., 2011). Hence, the rules in Table 5 can be used for generating solutions.

Table 5: Rules for solution generation (Zeng, 2012)

Rules	Analysis
1	Root conflict should be resolved first.
2	Conflict from natural environment should be resolved first, then built, and human lastly.
3	If a conflict is too general or too complex, decompose it.
4	Give a solution that introduces as few potential extra conflicts as possible.

Conflict dependencies can be represented by using directed graph or adjacency matrix. Directed graph are one-way connection from one conflict to another, see Figure 18.

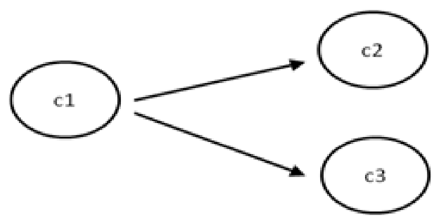


Figure 18: Directed graph (Zeng, 2012)

Adjacency matrix represents the dependency with *n* vertices using *n*n* matrix, where the entry value at *(i,j)* is ‘1’ if there is an edge from vertex *i* to vertex *j*; otherwise the entry is ‘0’(Zeng, 2012). Every entry value (i,n_j) at column n_j shows whether conflict n_j can be resulted from conflict $c_{i(Zeng,\ 2012)}$. Figure 19 is an adjacency matrix that shows the same dependency as Figure 18. Additionally, *c1* is the root conflict for both *c2* and *c3*.

conflict	c1	c2	c3
c1	0	1	1
c2	0	0	0
c3	0	0	0

Figure 19: Adjacency matrix (Zeng, 2012)

The purpose of handling root causes firsts is that by solving them other subsequent conflicts depending on the root conflicts will be eliminated. Therefore, effective solutions can be generated in this way.

After solutions have been generated for the identified conflicts, the ROM diagram is updated with them. The solution generation process is followed until no more undesired conflicts exist (Tan, et al., 2011).

2.2 Quality Function Deployment (QFD)

Quality function deployment (QFD) is one of the best and currently most popular techniques used to generate engineering specifications. QFD is an organized method, and it helps to develop necessary information to understand a problem such as (Ullman, 2003):

- The specifications or goals for the product
- How the competition meets the goals
- What is important from customer's viewpoints
- Numerical targets to work toward

In the mid-1970s, QFD was developed in Japan, and in the late 1980s, it was introduced in the US (Creative Industries Research Institute, 2007; Evans & Lindsay, 2005; Ullman, 2003). Toyota was able to reduce 60 percent of the costs of bringing a new car to market and to decrease one-third of the time required for its development by using QFD (Ullman, 2003). An important fact about QFD is that this methodology is used with cross-functional teams.

Engineering specifications that are needed in the product development phase of the design process are generated by using QFD. Figure 20 shows the main steps of the QFD methodology.

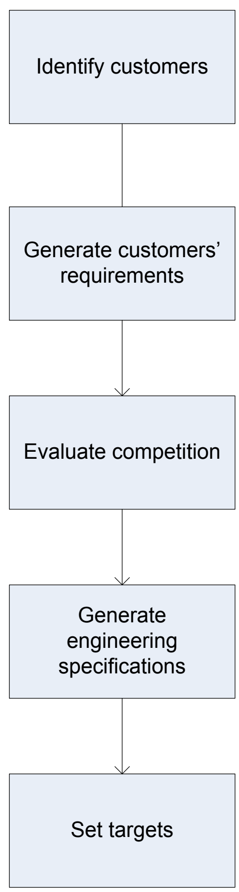


Figure 20: QFD Steps (Ullman, 2003)

The house of quality (HOQ) in Figure 21 is built by applying the QFD steps. The HOQ has many rooms and each one contains important information. The numbers in the HOQ represent the steps to follow for filling it. Before starting a detailed description of how to fill the HOQ, the following brief explanation of the steps in Figure 21 is helpful (Ullman, 2003):

- Step 1: identify *who* the customers are in order to start developing information.
- Step 2: discover *what* the customers want the product to do.
- Step 3: determine to whom the what is important (*who vs. what*).
- Step 4: identify how the problem is solved *now* by the competition, and compare this information to the customer desires (*now vs. what*). It will provide opportunities for product improvements.
- Step 5: determine *how* (engineering specifications) to measure the product's ability to satisfy the customer's requirements.
- Step 6: correlate the customer's requirements to the engineering specifications (*what vs. how*).
- Step 7: develop target information (*how much*).
- Step 8: interrelate the engineering specifications (*how vs. how*).

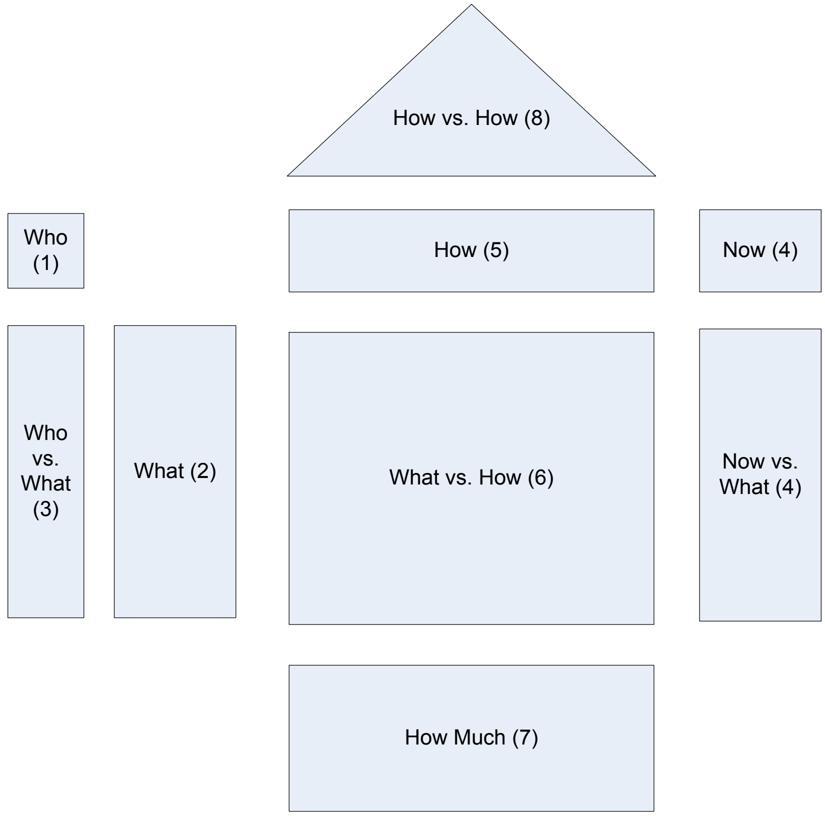


Figure 21: The house of quality (HOQ) (Ullman, 2003)

In order to explain the HOQ, a detailed example of a bicycle suspension system by (Ullman, 2003) is shown in Appendix B. The numbers in the parenthesis in Figure 21 will refer to a sub-heading in the subsequent subsections.

2.2.1 Identify the customers (who)

In a design problem, the first to do is to identify the customers. For many products the most important customers are the consumers (final user of the product); nonetheless, it is also important to consider the customers such as the designer's management, manufacturing and assembling personnel, sales staff, distribution employees, and service and support staff (Ullman, 2003). Standard organizations, environmental entities, and other associations may also set requirements for the products; therefore, they also should be considered as customers (Ullman, 2003). (Terninko, 1997) thinks that considering the stakeholders, anyone who can influence the decision to buy or use the product and anyone who is impacted by the product, is important to collect a complete list of requirements.

2.2.2 Determine the customer's requirements (What)

Since the customers were identified in the previous step, to determine what the customers want to be designed is the goal of QFD in this step. According to (Ullman, 2003), some common requirements depending on the type of customers are as follows:

- *Consumer:* a product should work as expected, last a long time, be easy to maintain, look attractive, incorporate the latest technology, and have many features. The previous requirements can be comparable to the dimensions of quality in a product (performance, features, reliability, conformance, durability, serviceability, and aesthetics) or a service (reliability, assurance, tangibles, empathy, and responsiveness) used in (Evans & Lindsay, 2005).
- *Production customer:* a product should be easy to produce (both manufacture and assemble), use available resources (human skills, equipment, and raw materials), use standard parts and methods, use existing facilities, and produce a minimum of scraps and rejected parts.
- *Marketing/sales customer:* a product should meet consumer's requirements; be easy to package, store and transport; be attractive; and be suitable for display.

The Kano model (iF Design, 2010; Mazur, 1996, 1997; Ullman, 2003; Verschuren & Hartog, 2005) of customer satisfaction also gives some important background to collect other customer's requirements. The Kano model goal is to excite the customers not only satisfy them in order they want to buy the product and recommend it to others. According to (Mazur, 1996), the Kano model considers three types of customer's requirements (refer to Figure 22):

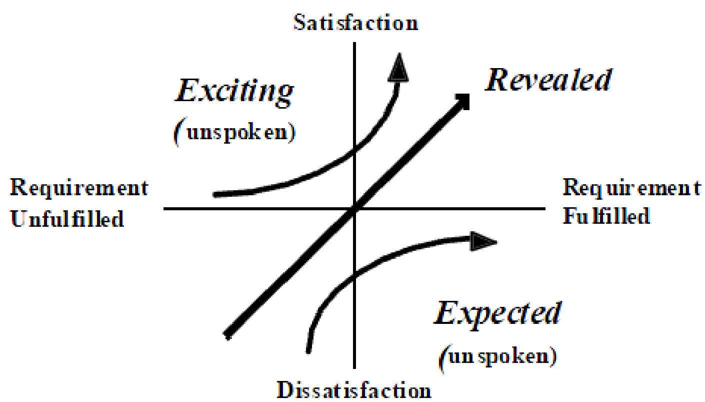


Figure 22: The Kano Model (Mazur, 1996)

- Revealed requirements: they are typically gotten by just asking customers what they want. The revealed requirements presence or absence in the product or service satisfy or dissatisfy the customers. An example of this requirement is fast delivery. The faster or slower the delivery, the more the customers like or dislike it.
- Expected requirements: these requirements are so basic that customers may fail to mention them until they are not performed. The absence of these requirements causes great dissatisfaction. For instance, if coffee is served hot, customers barely

notice it; however, if it is served cold or too hot, dissatisfaction occurs. These requirements must be fulfilled.

- Exciting requirements: they are difficult to discover because they are beyond the customer's expectations. Exciting requirements absence does not dissatisfy while their presence excites. An example of exciting requirements cited by (Mazur, 1996) is that if caviar and champagne are served on a flight from Montreal to Toronto, it would be exciting; nonetheless, if they are not, customers would hardly complaint. Exciting requirements "wow" the customers and bring them back. It is responsibility of the organizations to explore customers and opportunities to uncover such unspoken requirements because customers are usually not apt to voice them.

In the literature, the previous requirements may be found with different terminologies. For instance, (Ullman, 2003) refers to the revealed, expected and exciting requirements as performance, basic, and excitement features respectively. (Evans & Lindsay, 2005) refer to the revealed, expected and exciting requirements as satisfiers, dissatisfiers, and exciters/delighters respectively.

(Mazur, 1997) also refers to Kano's model as dynamic in that what excites customers today is expected tomorrow. It means that once that the exciting features are introduced, they will be imitated by the competition and customers will come to expect them from everybody.

The Kano model has an additional dimension which is customer segments that the target market includes (Mazur, 1997). For instance, considering again the previous flight example, the caviar and champagne that is exciting in the domestic flight might be expected for a first class passenger travelling from Montreal to London. Understanding the customer requirements may be achieved by knowing the customer segments that are intended to be served.

Observations, surveys, focus groups, complaint analysis and internet monitoring are common methods used for collecting the customer's information (Evans & Lindsay, 2005; Ullman, 2003). However, (Daikin, 2011; iF Design, 2010; Japan Institute of Design Promotion, 2005; Mazur, 1996, 1997; Verschuren & Hartog, 2005; Yin, Qin, & Holland, 2008) recommend "*Going to the Gemba*", a different and powerful method for collecting customer's requirements. For (Mazur, 1997),

> *"The gemba is where the product or service becomes of value to the customers, that is, where the product actually gets used. It is in the gemba that we actually see who our customers are, what their problems are, how the product will be used by them, etc. We go the gemba in QFD to see our customer's problems and opportunities as they happen".*

According to Ullman, the following steps help the design team to develop useful data (Ullman, 2003):

- Specify the information needed: a problem can be reduced in a single statement describing the information needed. If it is not possible to represent the problem in a single statement, it warrants more than one data collection effort.
- Determine the type of data collection method to be used based on the type of information being collected.

- Determine the content of individual questions: each question should have a clear and single goal of the expected result.
- Design the questions: unbiased, unambiguous, clear, and brief information should be sought. For this step, (Ullman, 2003) provides the following useful guidelines to follow:
    - Do not assume the customers have more than common knowledge.
    - Do not use jargon.
    - Do not lead the customers toward the answer is wanted.
    - Do not tangle two questions together.
    - Do use complete sentences.
- Order the questions to give context.
- Take data: usually the data collection process is done in several applications of the questions until usable information is obtained. The first application of the questions is used as a test or verification experiment.
- Reduce data: after the information is collected, a list of customer's requirements should be made using the customers' words such as easy, fast, natural, and other abstract terms and using positive terms; for instance, what the customers want, not what they do not want.

Ullman thinks that the major types of customer's requirements are given in Table 6. The list of requirements provides a roadmap to follow when the customer's requirements are being collected. The table is composed for the major requirement categories on the left and they have more specific requirements on the right side. The major requirement categories are detailed next.

Table 6: Types of customer requirements (Ullman, 2003)

Functional performance	Flow of energy, information, and materials
	Operational steps
	Operation sequence
Human factors	Appearance
	Force and motion control
	Ease of controlling and sensing state
Physical requirements	Available spatial envelope
	Physical properties
Reliability	Mean time between failures
	Safety (hazard assessment)
Life-cycle concerns	Distribution (shipping)
	Maintainability
	Diagnosability
	Testability
	Repairability
	Cleanability
	Installability
	Retirement
Resources concerns	Time
	Cost
	Capital
	Unit
	Equipment
	Standards

	Environment
Manufacturing requirements	Materials
	Quantity
	Company capabilities

- *Functional performance* requirements describe the product's desired behavior. The flow of energy, information, and materials or the information about the operational steps and their sequence usually express the function of a product; however, customers may not use such technical language. QDF will be use at this point with the purpose of translating the customer's requirements to the technical language needed to describe the product's function.
- *Human factors* requirements are present in any product that is seen, touched, heard, tasted, smelled, or controlled by a person; therefore, almost every product has these requirements. Some examples of human factors requirements are that a product looks good, has a certain function. Other human factors requirements are based on the flow of energy and information between the product and an individual usually expressed in terms of force and motion for easy controlling and sensing the state of the product.
- *Physical requirements* refer to physical properties such as weight, density and conductivity of light, heat or electricity; and to spatial restrictions such as how the product fits with other existing object.
- *Reliability* requirements are really important for the customers because they usually expect that a product lasts a long time. One measure of reliability is the

mean time between failures. The following questions help also to understand what acceptable reliability means to the customers: What happens when the product does fail? What are the safety implications? Is it a disposable product?

- *Life-cycle* requirements come from Figure 23. For instance, for the example in Appendix B, the sales/marketing department set the requirement that the bicycle had to be shipped by a commercial parcel service; therefore, it limited the weight and size of the product. In order to collect the requirements concerning to the life cycle of the product, the design team has to involve in the design process personnel from the different areas of the life cycle of the product.

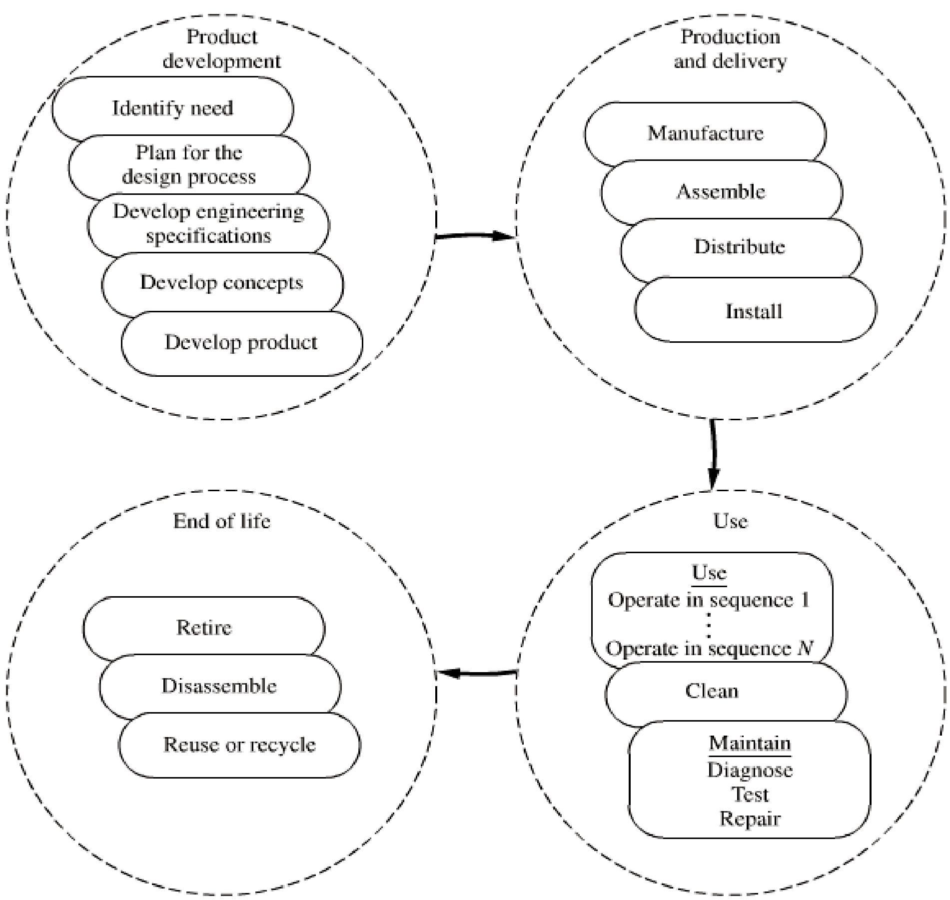


Figure 23: Product life-cycle (Ullman, 2003)

- *Resources* requirements refer to time, cost, capital, unit, equipment, standards, and environment.
    - Usually time is a limited resource in design, and it can be originated from the consumers, the market, and contracts.
    - Cost requirements concern both the capital costs and the costs per unit of production.
    - Standards (codes) are good sources of information; hence, knowledge of which standards apply to the current situation is important to requirements and must be noted since the beginning of the project. Generally standards fall within three categories: performance, test methods, and codes of practice (Ullman, 2003).
    - Environmental requirements are important and it is responsibility of the designer to consider the damage that the product can cause on the environment during production, operation and retirement.
- *Manufacturing* requirements depend on the quantity and type of the design to be produced.

Since the previous list of requirements is more focused to develop a product, the dimensions of quality in a service can be used to obtained requirements for services. (Evans & Lindsay, 2005) refer to service quality dimensions to reliability, assurance, tangibles, empathy, and responsiveness; and as follows is the description for each of them:

- Reliability: it is the ability to provide what was promised, dependably and accurately.
- Assurance: it is the knowledge and courtesy of the employees, and their ability to convey trust and confidence.
- Tangibles: it refers to the physical facilities and equipment, and the appearance of personnel.
- Empathy: it means the degree of caring and individual attention provided to the customers.
- Responsiveness: it is the willingness to help customers and provide quick service.

2.2.3 Determine relative importance of the requirements (who vs. what)

In QFD, this step refers to evaluate the importance of the customer's requirements. A weighting factor is generated for each requirement, and it will give an idea of the effort, time, and money to be invested to achieve each requirement. In addition, customer importance ratings represent the areas of greatest interest and highest expectations for the customers (Evans & Lindsay, 2005). (Ullman, 2003) suggests that at this point is important to address the questions: to whom is the requirement important? How is a measure of importance developed for this diverse group of requirements? Sometimes there are discrepancies between the customer's desires and they have to be resolved at the beginning of the design process. The analytic hierarchy process (AHP) (Terninko, 1997) can be used in this part to prioritize whom to please.

There are different methods to weight different factors. A traditional method is to rate the requirements on scale of 1 to 10 where 10 represents the most important and 1 the least important; unfortunately, often this method results in everything important for the customers (Ullman, 2003). For that reason, the fixed sum method is better (Ullman, 2003). In the fixed sum method, each customer has 100 points to distribute among the requirements. Since the customers have limited points, they are forced to rank some requirements low if they want others high. Refer to Figure 46 in Appendix B to see how the customer's requirements were ranked for the BikeE suspension system.

2.2.4 Identify and evaluate the competition (Now)

In this step, the main objective is to identify how the customers see that the competition is meeting the requirements. The purpose of the previous task is to benchmark the market and to create awareness of what already exists and what are the opportunities for improvements (Ullman, 2003). Even though a product is new, there is always competition. This step is really important to understand the competitors and to highlight their strengths and weaknesses in competing products (Evans & Lindsay, 2005) which leads to a tremendous competitive advantage (Creative Industries Research Institute, 2007).

Once the competing products are identified, they are compared to the customer's requirements usually using a scale from 1 to 5 where 1 represents that the product does not meet the requirement at all, and 5 means that the product completely fulfills the requirement. For instance, if a customer ranked a requirement as high importance and the competitors are slightly meeting the requirements, it represents an opportunity for improvement. On the other hand, if the competitors are completely fulfilling a high ranked requirement, their products should be studied and good ideas can extracted from it. However, it is always important to pay attention to patents and copy right implications.

2.2.5 Generate engineering specifications (how)

As it is stated in the sub-heading, the goal of this step is to develop engineering specifications for the customer's requirements. The engineering specifications are basically translations of the customer's requirements to terms of measurable parameters of *how* the customer's requirements can be met (Evans & Lindsay, 2005). It is important to state that the parameters have to be measurable because the objective is to set target values in the future for each specification. The focus for this step is to set the parameters whereas the targets will be set in the subsection 2.2.7. For the requirements that are directly measurable, for instance the cost and weight in Figure 45 in Appendix B, this step does not apply. Effort must be done in this step in order to find many possible ways to measure the customer's requirements that are not measurable in the customer words. It is also important to develop for each engineering specification a unit of measure (percentage, minutes, inches, lbs, kg, etc.) and the direction of improvements: more is better (↑), less is better (↓), or nominal is best which means that a specific target is known(Ullman, 2003).

2.2.6 Relate customers' requirements to engineering specifications (what vs. how)

In this step the center portion (what vs. how) in the Figure 21 is filled. Each cell will contain the relationship between the engineering specification and the customer's requirements. A customer's requirement can be related to one or more engineering specification; however, the strength of the relationships can vary. An engineering specification can provide a strong relationship to a customer requirement while it is not related at all to other customer requirements. Usually the symbols in Figure 24 are used to express the relationships:

◉ = strong relationship
○ = medium relationship
△ = weak relationship
Blank = no relationship at all

Figure 24: Engineering specifications and customer's requirements type of relationships (Ullman, 2003)

In the literature, some design teams give a weight of 1, 3 or 9 to the type of relationships depending on if it is weak, medium, or strong respectively (Creative Industries Research Institute, 2007). If there is no relationship at all the given weight is 0.

2.2.7 Set engineering targets (how much)

In this step the goal is to set targets (how much) for the engineering specifications (Creative Industries Research Institute, 2007). The targets are used to evaluate how the product to be designed meets the customer's requirements. In order to set the targets, the competition is evaluated on how they meet the engineering specifications, and then, the design team establishes the targets for the product (Evans & Lindsay, 2005). It is important to set the targets early in the design process.

Most QFD literature suggests a single value as a target (Creative Industries Research Institute, 2007; Evans & Lindsay, 2005; Terninko, 1997); however, when the design is in process, it is often not possible to meet the exact targets. As result, a more robust method for setting the targets consists in establishing the levels at which the customers will be delighted and disgusted (Ullman, 2003).

2.2.8 Identify relationships between engineering requirements (how vs. how)

The goal of this step is to identify the dependencies between the engineering specifications. It is important to know the dependencies since early stages of the design process because when the design team wants to meet one engineering specification, they can affect negatively or positively other specification (Ullman, 2003). The roof of the HOQ is used to display the relationships between the engineering specifications. If there is a negative or strongly negative relationship, the design must be compromised unless the negative impact is designed out (Terninko, 1997). The theory of Inventive Problem Solving (TRIZ) is an approach used to solve technical contradictions of negative relationships.

The symbols in Figure 25 are the most common used to represent the dependencies between the engineering specifications. If there is relationship between two engineering specification, the cell crossing the two specifications in the roof of the HOQ is marked with the symbol in Figure 25 that better represents the type of relationship.

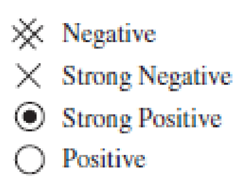


Figure 25: Engineering specifications type of relationships (Ullman, 2003)

2.2.9 Absolute importance

The goal of this step is to identify which engineering specifications of the product matters the most to the customers. The most important engineering specifications are identified by using the relative importance of each of them, and the relative importance is obtained based on the absolute importance. The greater the relative importance of the engineering specification, the more important it is.

The absolute importance for each engineering specification is calculated by multiplying the weight of the type of relationship set in step 6 for each engineering specification to the respective customer rating for the related customer requirement. If for an engineering specification there is more than one relationship, all the results of the previous multiplications are added up. The sum results are the absolute importance for each engineering specification. After that, the relative importance is calculated by finding first the total of the addition of all the absolute importance of each engineering specifications, and then each absolute importance is divided by the total of the absolute importance addition.

This step is not covered in the example in Appendix B. Nonetheless, detail examples of this step can be found on the references (Creative Industries Research Institute, 2007; Terninko, 1997).

2.2.10 Further comments about QFD

The QFD can be applied during later phases in the design process. In that case, QFD can be used to develop better measures for functions, assemblies, or components in terms of costs, failure modes, or other characteristics (Ullman, 2003). For the previous purpose, the customer's requirements should be replaced with what is to be measured and the engineering specifications with any other measuring criteria. Other literatures (Creative Industries Research Institute, 2007; Evans & Lindsay, 2005) refer to 4 different HOQs to relate the customer's requirements to technical requirements, component requirements, process control plans, and manufacturing operations.

Chapter 3: EBD and QFD comparison

In the previous chapter, EBD and QFD were introduced. In this chapter, a general and an experimental comparison are presented.

3.1 EBD and QFD general comparison

In this section, a general analysis of the methodologies is done by following the design process step involved within the scope of the thesis. Recalling the design process introduced in the background section in Chapter 1, the main steps in a design process are Product discovery, Project planning, Product definition, Conceptual design, Product development and Product support. Hence, the step involved within the scope is product definition, and EBD and QFD will be analyzed on how they achieved its requirements.

- ✓ *Product definition:* this phase is the main contribution of this thesis. The goal here is to understand the design problem and to generate customer's requirements in order to lay the foundation for the remainder of the design process. A lot of time and money is wasted designing wrong products due to the difficulty of finding the right problems. Moreover, after finding the right problem, understanding what is really needed to be designed is not an easy task either.

  From my experience, finding the right problem and understanding it is a big leap in the design process; hence, EBD becomes powerful in this phase because with the help of ROM diagrams and the rules to ask generic and domain specific questions, the real intention of the customers is found and the product definition process becomes natural. Furthermore, ROM diagrams and the rules to ask generic and domain specific questions help to clarify unclear requirements and to uncover hidden requirements.

On the other hand, QFD is vaguer than EBD in this step. In the literature review about QFD, (Ullman, 2003, 2010) is the only one who extends more about how to collect the customers' requirements; however, the roadmap to follow is based more on experience and it is not ensured that the designers understand the real problem and that all the customers (stakeholders) and their requirements are identified.

The next step of this stage is to transform the immeasurable customers' requirements into measurable engineering specifications. Some requirements are already measurable since they are in the voice of the customers, for instance cost or time to develop a product. EBD and QFD achieve similarly the task of transforming the immeasurable customers' requirements into measurable ones.

Other step in this stage is to analyze the competitors. It is important to know that even though the designed product meets all the expected and revealed customers' requirements, other products in the market may have higher customers' satisfaction due to the fact that they may be achieving exciting requirements in addition to the expected and revealed requirements in the Kano's model. Furthermore, analyzing the market helps to know how competitors are achieving certain requirements that may be causing problems to the company for which the product is being designed; therefore, some knowledge can be gained by analyzing similar products. Both methodologies are aware of analyzing competitors; however, I think QFD is more precise in this step than EBD because the latter has this task too implicit human environment.

The last but not the least step of this stage is to prioritize the customers' requirements. EBD does not consider directly this task while QFD does; however, the final output of both methodologies provides solution to all the customers' requirements. The prioritization becomes important when there are contradictions that cannot be met at the same time in a design solution, and a decision has to be made about which requirement is more important to the customers in order to satisfy and delight them.

✓ **Further comments about EBD and QFD**

EBD and QFD methodologies automatically document the product definition process and facilitate the communication and teamwork between the different areas in the organization (Evans & Lindsay, 2005; Ullman, 2003). For instance, the final updated ROM obtained after the conflict identification process for EBD and the HOQ for QFD are already design records of the product definition process and it makes it easier to explain to others what is needed in the product to be designed.

EBD and QFD can be applied during later phases in the design process to develop component requirements, process control plans, and manufacturing, assembly, and distribution operations.

Finally, since the design process is dynamic and more knowledge is gotten during the process, EBD and QFD are flexible to be reviewed and updated as needed. However, when a change is done, it is important to consider how it affects the relationships between the components in the ROM diagrams or HOQs.

3.2 EBD and QDF experimental comparison

In order to compare experimentally EBD and QFD in this thesis, a case study that includes three different design problems was solved with each methodology. The three design problems that were solved with EBD were the same solved with QFD. The design problems were categorized in accordance with the grade of complexity, and after studying them; 1, 2 and 3 hours were assigned respectively to solve them.

Two inexperience designers were volunteers to solve the design problems. The designer that solved the problems using EBD only needed to know about EBD, and the designer who worked with QFD only needed to know about QFD. The purpose of the previous constraint was to avoid that there was a mixed of both methodologies while solving the problems affecting the results. The designers were used to the design methodologies; however, training was provided for the designers and they have time to prepare themselves as well.

The designers did not know and did not have any clue about the design experiments until the time to solve them. Additionally, it was ensured that the designers had similar background to work on the design problems, which ranged from different fields and topics.

The designers signed a consent form before solving every design problem where they agreed to participate in this research. The reason of the concern forms was to let the participants know five main points. The first point was to let them know the purpose of the experiments. Then, the second point was to introduce the procedure to follow during the tests, and the third one was to describe them the devices that will be used during the experiments. For instance, devices such as video cameras and screen recorders were used during the experiments in order to record the design process. The fourth point was to state the volunteer participation of the designers and that the collected data would be stored, analyzed and possibly published; and the fifth one was to declare that their personal information will be kept confidential. A sample of the concern form can be found in Appendix C.

In the following section the three design problems will be presented and also the information related to them.

3.2.1 Design problem descriptions

As it was mentioned previously, three design problems were solved with EBD and QFD. The experiments were carried out at Concordia University, in the Design Lab, EV-9.235. The designers were able to use a computer with internet to look for any kind of information related to the design experiments, and after each experiment they were asked for feedback. As follows each design problem will be described:

(1) Design a spray nozzle for a perfume bottle that helps blind people to control the flow of the liquid.

For solving the first design problem, one hour was assigned to the designers, and the first experiment's feedback can be found in Table 7. The difficulty and knowledge related to the problem categories in Table 7 where measured in a scale from 1 to 10. For the *difficulty* category, 1 represents not to too difficult and 10 very difficult while for the *knowledge related to the problem,* 1 shows not too much knowledge and 10 lots knowledge.

Table 7: Designers feedback from design problem 1

	EBD	**QFD**
Time	Ok	Short
Difficulty	7	7
Knowledge related to the problem	4	4

(2) Design a system for video recording surgical procedures.

For the second design problem, in addition to the main statement of the problem, further description was available, and it is shown as follows:

> *"You have been hired to improve a system for video recording surgical procedures. The desire is to capture the use of various surgical instruments during operations with an aim to identify shortcomings of current tools and to develop new surgical devices. The current video system uses a camera*

mounted to a moveable light fixture and records images to a networked computer, but the quality of the images is too low and may not capture the relevant area. The proposed system should be unobtrusive and be able to record the images with a minimum of user input during the operation; i.e., the doctors and nurses should not have to stop what they are doing to position the camera".

For solving this problem, two hours were assigned to the designers, and its respective feedback can be found in Table 8. The difficulty and knowledge related to the problem categories in Table 8 were measured in the same scale as in the design problem 1.

Table 8: Designers feedback from design problem 2

	EBD	**QFD**
Time	Ok	Ok
Difficulty	3	3
Knowledge related to the problem	5	6

(3) Design a ventilation system for a thin flooring system.

The third design problem was the most complex and it has more information that the previous two problems. For the third problem 3 hours were assigned to the designers. As the second design problem, additional information besides to the main statement was provided, and it is shown as follows:

a. Detailed description of the current systems

Description of a regular overhead ventilation system

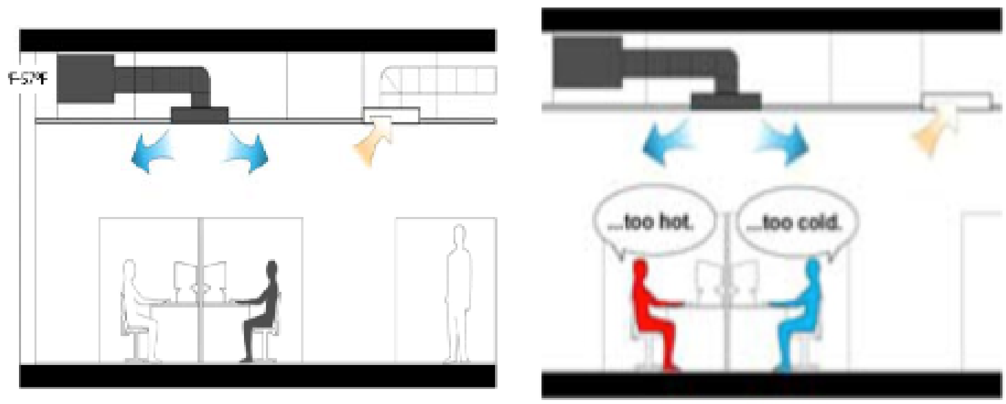


Figure 26: Overhead ventilation system

The overhead ventilation system in Figure 26 includes:

- A mechanical ventilation (motor to move the air)
- A heating or cooling system of the air (depending on the season)
- A plenum that contains air ducts and various electrical wires network

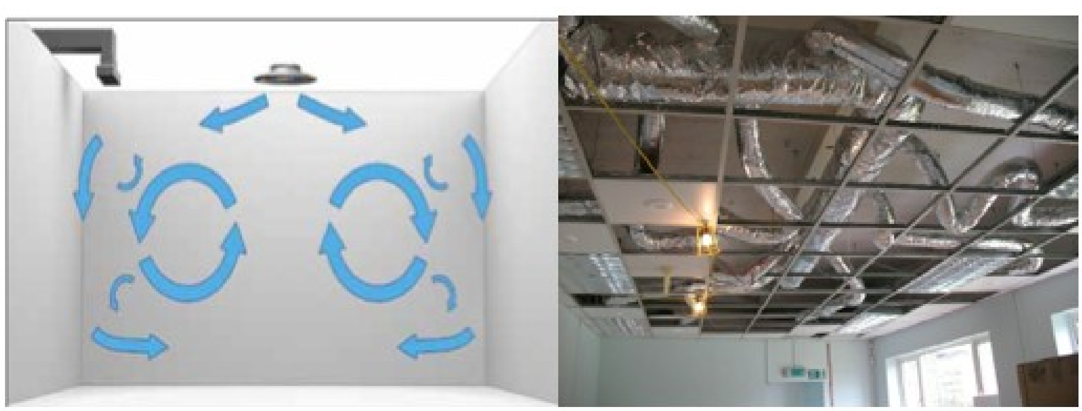


Figure 27: Mixing dilution ventilation (left), and traditional ventilation duct systems (right)

Mixing ventilation systems in Figure 27 generally supply air in such a manner that the entire room volume is fully mixed. The cool supply air exits the outlet at a high velocity, inducing room air to provide mixing and temperature equalization. Since the entire room is fully mixed, temperature variations throughout the space are small while the contaminant concentration is uniform throughout the zone.

A variant exists in which the new (sane) air is mixed with recycled air coming from the room inside the plenum, so as to reduce discomfort linked with high temperature gap between entering air and required average temperature of the room.

Description of the mechanical structure of flooring system:

The structural part of the flooring system in Figure 28 is constituted of:

- Hollow-core slabs. Compared to regular concrete slabs, those slabs enable to reduce the weight of the building, hence the cost. Those elements should be prefabricated in a factory and then transported on site by heavy trucks.
- Beams that support the hollow-core slabs

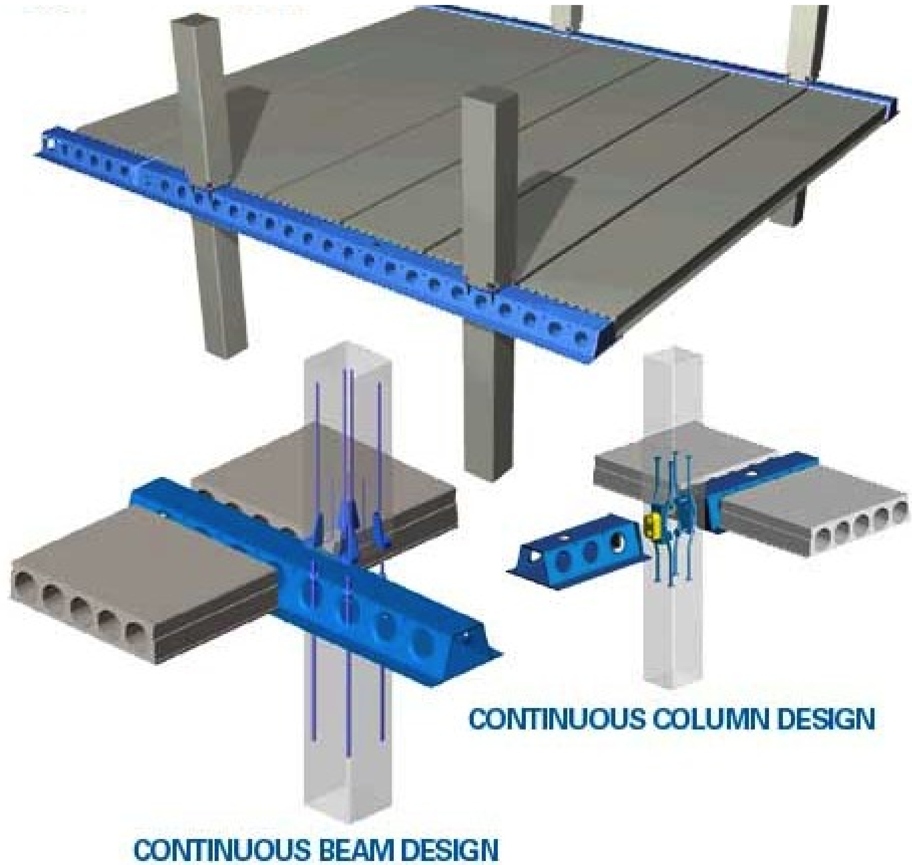


Figure 28: Mechanical structure of flooring system

b. *Description of the problem:*

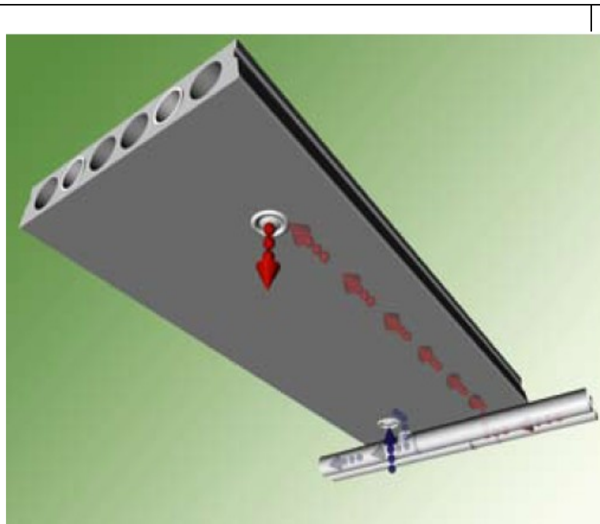
In order to benefit from thermal inertia provided by the hollow-core slab (additional comfort and energy savings) and to reduce the thickness of flooring systems (so as to reduce cost of the building), it is proposed to suppress the plenum. The electrical wires are then introduced in the hollows of hollow-core slab.

Two unsatisfying solutions to deal with the ventilation system (Figure 29) are proposed:

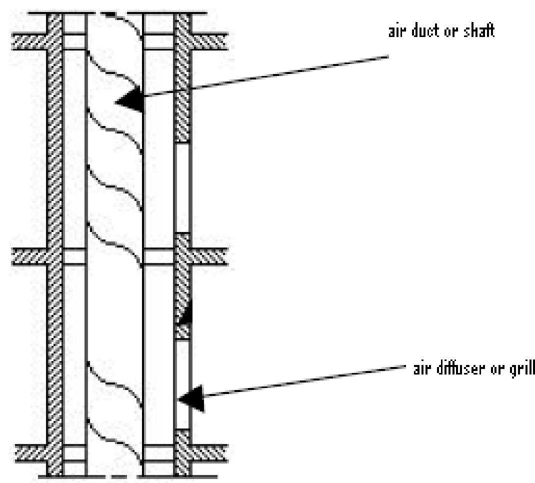
- Circulation of air in the adjacent walls
- Circulation or air in hollows of hollow-core slab

This is unsatisfying because:

- A high flow is required if we want the air to enter the room at a comfortable temperature, which leads
    - either to too big ducts compared to the size of hollows or walls
    - or to too high pressure loss in ducts
- Otherwise, uncomfortable temperature, too hot or too cold (depending on the need of heating or cooling) may enter the room in order to keep the homogenized temperature of the room at the required value.



Air circulation in hollow-core



Air circulation in wall

Figure 29: Air circulation in hollow-cores and in walls.

Additional requirements concerning the expected solution:

- Product manufacturing and in situ implementation should require only tools that already exist.
- Implementation should not require a multitude of small steps.
- There should be a restricted number of workers to implement the solution (not various skills in various domains).
- The solution should be implemented without much attention on details and finish (idiot proof…).

Annex: Some technical data about air circulating in a duct:

- **Required flow rate**

Flow rate required for heating and cooling may depends on the energy demand of the building. A reference climate needs to be fixed for calculating the maximal instantaneous energy demand.

Flow rate required for sanitary reasons depends on the type of building (dwelling, office, school, etc…). It is most of the time inferior to the flow rate required for heating or cooling the building.

- **Pressure loss**

The basic pressure loss of airflow is in function:

➔ Of the leakage rate of air estimated in the ductworks

➔ The temperature of the air conveyed

- ➔ The level of altitude where is located the installation
- ➔ The nature of the various types of materials used (steel ductwork, copper, PVC, built walls, etc)
    - o Indices of surface roughness.
- ➔ The geometrical shapes of ductworks (circular, quadrangular, oblong)
- ➔ The various types of pressure loss coefficients depending on
    - o The air density.
    - o The dynamic viscosity of the air.
    - o The Reynolds number.

It should be added a coefficient of safety margin:

- ➔ The assemblies are often badly carried out, blocking partially the passage of the fluid.
- ➔ An estimated dusty ductwork can be considered.
- ➔ With the ageing of the ductwork, a possible corrosion can increase the pressure losses by friction.

The real speed of the airflow in the ductwork is carried out from the corrected airflow.

- **Air speeds recommended**

The air velocity in the ducts cannot exceed a certain value. It results a minimal section of ducts below from which it is misadvised going down for following reasons:

- ➔ Increase the noise of rustle of the air in the strait ducts and especially on the level of the deviations.

- ➔ Increase the pressure losses and the energy consumed by the ventilator.

Example: a reduction in half of the section doubles the air velocity increases the pressure losses and the absorptive power by the ventilator by a factor 4.

After the designers solved this design problem, the feedback can be found in Table 9. The difficulty and knowledge related to the problem categories in Table 9 were measured in the same scale as in the design problem 1.

Table 9: Designers feedback from design problem 3

	EBD	**QFD**
Time	Ok	Ok
Difficulty	10	10
Knowledge related to the problem	2	2

At this point, from the designer feedbacks can be concluded that they had the same perception about the design problems respect to the time to solve them, the degree of difficulty, and the knowledge they had related to the problem. The purpose of this information is to show that the designers had similar abilities and capacities; therefore, the final results will not be biased for the knowledge of the designers.

3.2.2 Criteria of evaluation

In order to compare EBD and QFD methodologies, and to test the thesis hypothesis, evaluation criterions are needed. In the literature review, papers about software comparisons (Osterweil & Song, 1996; Song & Osterweil, 1991; Song & Osterweil, 1994) have been found; however the association is based on the software architecture and its components which are different from this thesis area. Daniel Frey from MIT has been also working on comparing design methodologies based on analogies, and quantitative methods such as robust parameters design, design of experiments (DOE) and hierarchical probability model (Frey & Dym, 2006; Frey & Li, 2004, 2005; Frey & Wang, 2006; Milani, Wang, Frey, & Abeyaratne, 2008). Nevertheless, for this thesis in order to associate EBD and QFD, from our knowledge and research, it would be better and more effective to do the evaluation by using qualitative (Verschuren & Hartog, 2005) and quantitative methods instead of only the quantitative ones used by Daniel Frey. Some helpful qualitative criteria were found and used in some design competitions (Daikin, 2011; iF Design, 2010; Japan Institute of Design Promotion, 2005; Yin, Qin, & Holland, 2008). So, the set of criteria that will be employed will have qualitative characteristics that will be quantified by using a scoring model. In the subsequent section more information about the evaluation process will be provided.

After reviewing the design literature, the following criterions were identified to compare objectively and impartially EBD and QFD methodologies:

(1) Viability: Is it possible to implement the design solution? Can the functional requirements be achieved?

(2) Product life cycle consideration: Do the designers consider and identify the life cycle involved in the product development when generating the engineering specifications?

(3) Customers' identification: Do the designers consider and identify all the stakeholders when working on the design problems?

(4) Customers' requirements identification: Do the designers identify all the customers' requirements related to the design problem?

(5) Customer requirements prioritization: Do the designers consider if there are some requirements that are more important for the customers?

(6) Conflict identification / functional requirements relationship: Do the designers identify if there are functional/technical contradictions?

(7) Conformance / completeness of the generated results: Do the generated results satisfy the customer's requirements? Do the designers understand the real customer's intentions?

(8) Ease to understand the results: are the designed results clear and easy to understand?

(9) Performance / measurability of functional requirements: Can the developed engineering specification be clearly measured?

It is important to recall that in this thesis the scope of comparison of EBD and QFD is done covering from identifying customers' requirements until generating engineering requirements that satisfy the customer's requirements of the design problems. In the following section, the design problem 2 that was introduced previously will be completely analyzed.

3.2.3 Experiment analysis

Before starting analyzing the results of the second design problem, some comments about the experiment analysis are clarified:

- Each design problem will be analyzed following the process that will be introduced promptly.
- Additionally, each design problem will be assessed by three different evaluators in order to provide a more objective analysis.
- A summary of the analyzed results will be shown in the next section.

Recalling the second design problem, a system for recording surgical procedures had to be designed. Besides that, the following problem description was provided:

> *"You have been hired to improve a system for video recording surgical procedures. The desire is to capture the use of various surgical instruments during operations with an aim to identify shortcomings of current tools and to develop new surgical devices. The current video system uses a camera mounted to a moveable light fixture and records images to a networked computer, but the quality of the images is too low and may not capture the relevant area. The proposed system should be unobtrusive and be able to record the images with a minimum of user input during the operation; i.e., the doctors and nurses should not have to stop what they are doing to position the camera".*

The designers had two hours for solving this problem, and the results for both EBD and QFD are shown as follows:

- *EBD results:* the designer applied the EBD methodology to solve the design problem. First, the designer tried to understand the problem by building and using the ROM diagram in Figure 30. After that, the environment components were analyzed, and the conflicts were identified also in Figure 30.

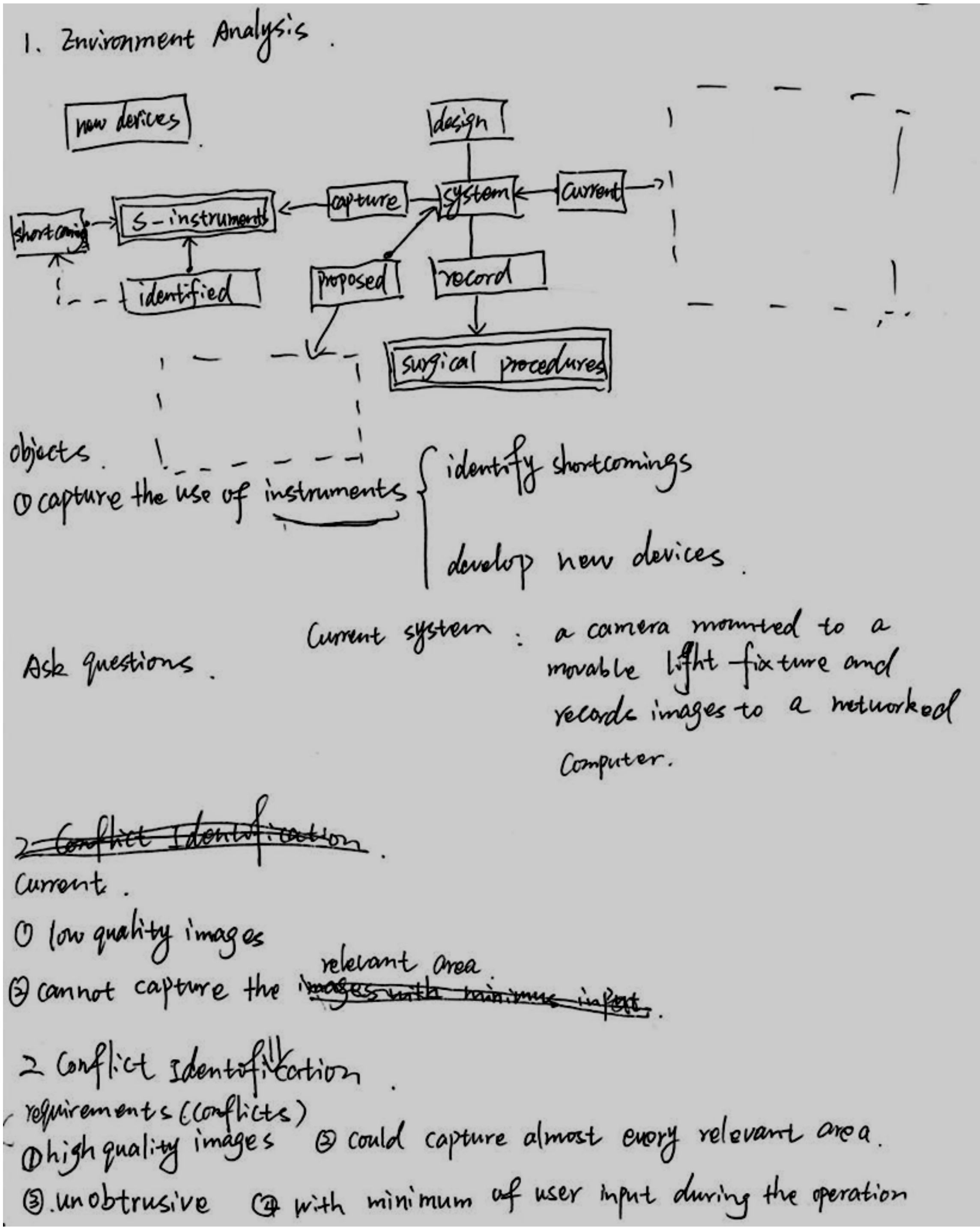


Figure 30: EBD solution for design problem 2

- *QFD results:* the designer applied the QFD methodology to solve the design problem. First, the designer collected the customer requirements in Figure 31. After, the house of quality (HOQ) was built, refer to Figure 32 and Figure 33. From the HOQ can be seen that the customers' requirements were translated to functional requirements. Additionally, the relationships between the customers' requirements and functional requirements, and the relationships between the functional requirements were identified and analyzed. Other QFD components as customers' requirements prioritization was also carried out.

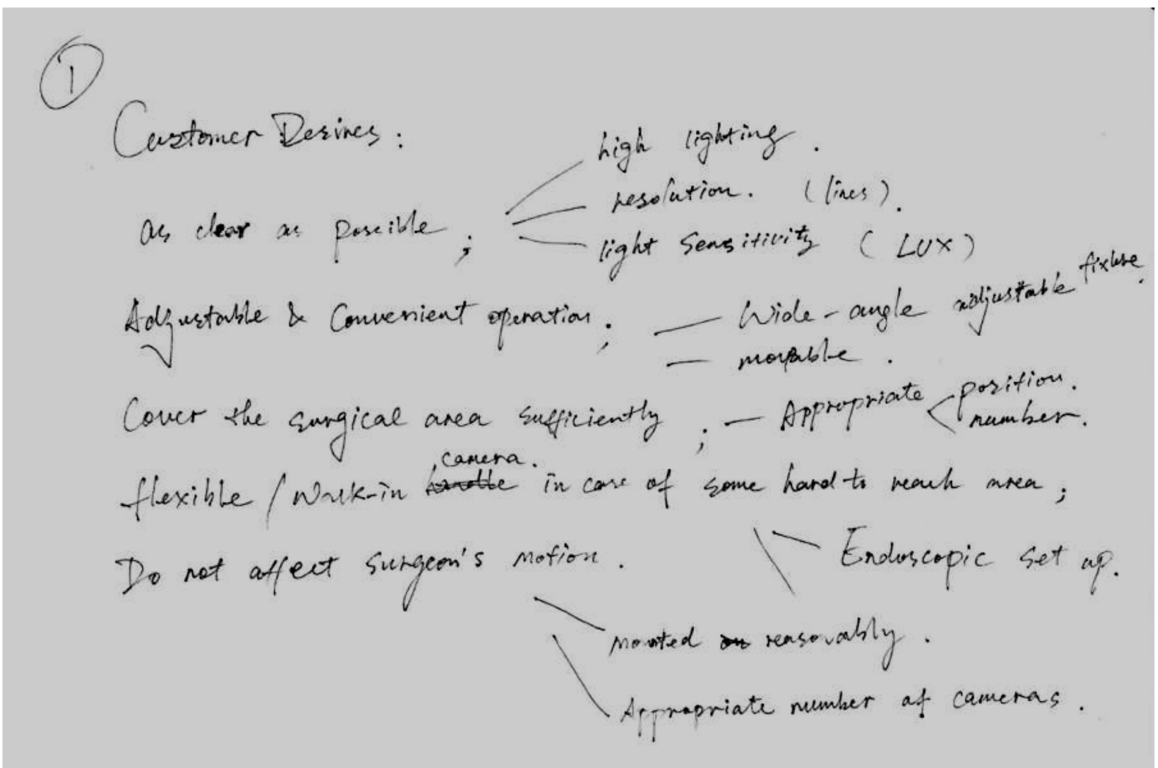


Figure 31: QFD solution for design problem 2 (page 1)

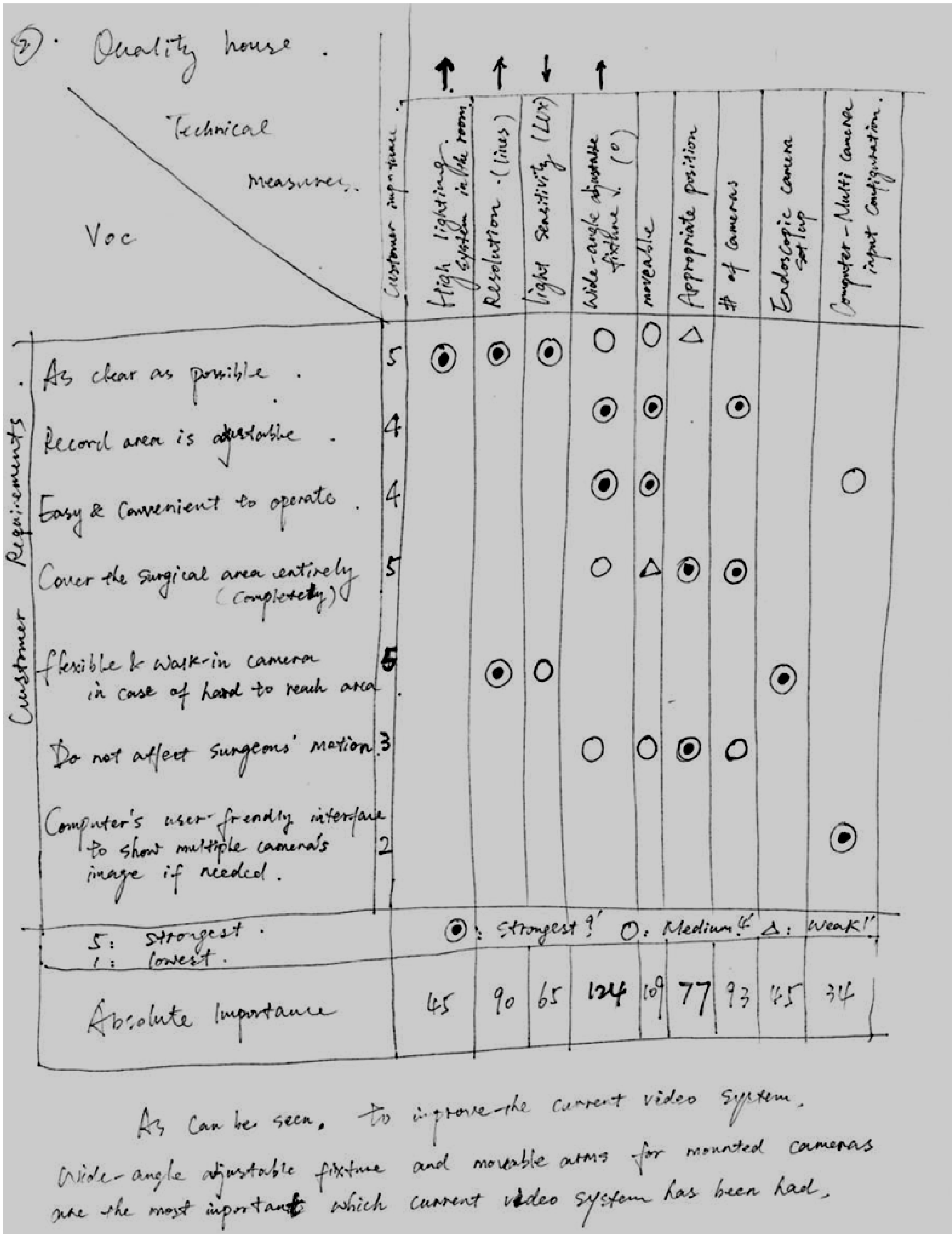


Figure 32: QFD solution for design problem 2 (page 2)

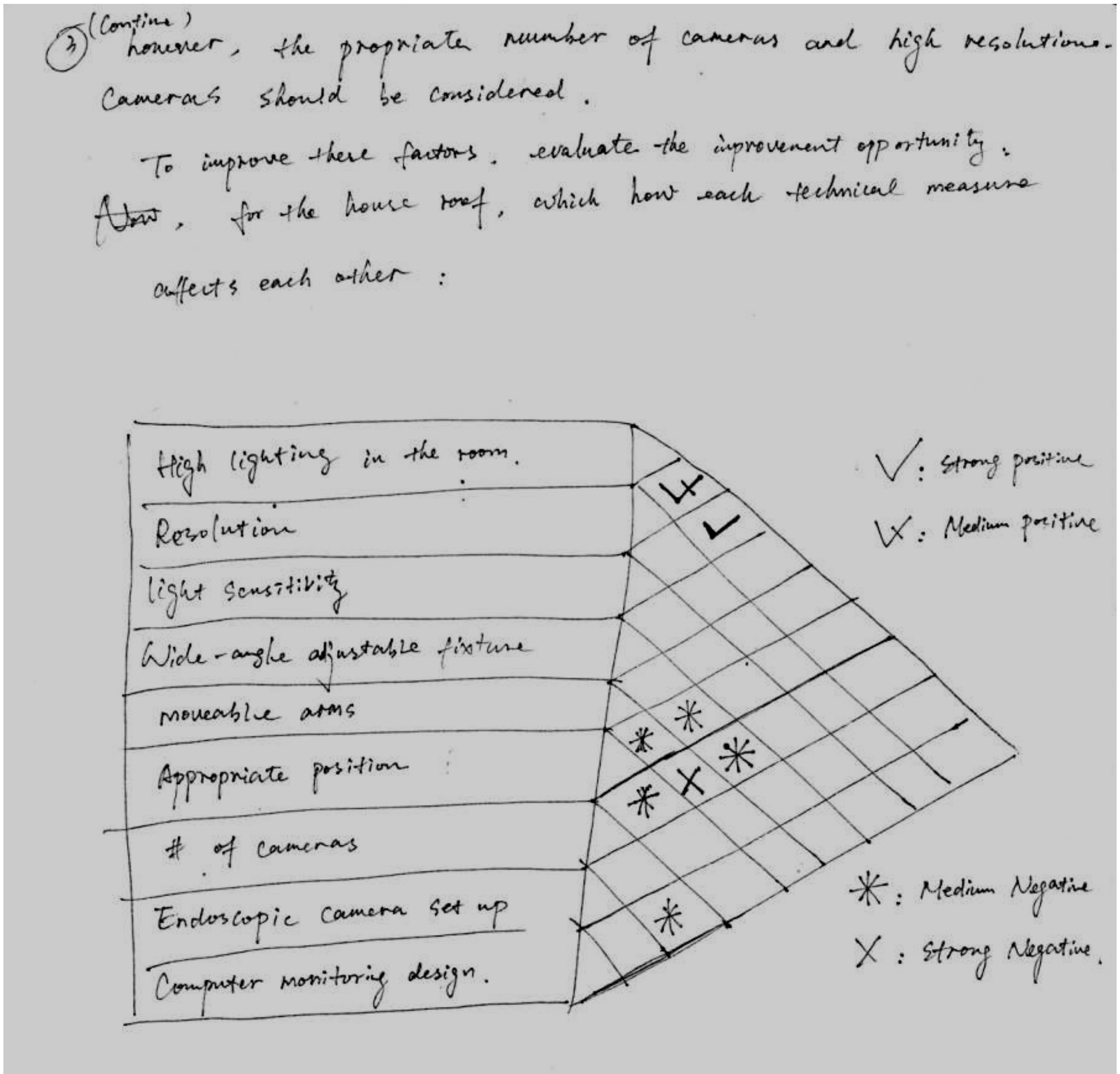


Figure 33: QFD solution for design problem 2 (page 3)

In order to analyze the generated results, the criterions introduced in the previous section will be used. Table 10 contains the criteria to compare EBD and QFD results that will be applied to evaluate them. Moreover, a scale of 1 to 10 will be used to fill out the table where 1 means that the criterion is poorly met and 10 is that the criterion was successfully achieved. Furthermore, if the criterions are not applicable for the design results, N/A (equal to 0) will be used. At the end, the results will be added up, and the design methodology that has the greatest score will be considered the best one.

The following comments are also important and they should be taken into consideration:

- As it was mentioned before, each criterion will be assessed by three different evaluators. For the purpose of demonstrating how the evaluators will assess each design solution, Table 10 and Table 11 show how one evaluator gave points to the criterions. In order to give the points, the evaluator asked the questions that belong to each criterion. If mark deductions exist, they are explained after Table 10 and Table 11. The same work was exercised by every evaluator, and in the next section all the results will be shown and summarized.

- The criterions will be considered to have the same importance for this thesis; however, they can be weighted for future use depending on how important they are in the developed design.

Table 10: EBD criteria evaluation for design problem 2

Criteria		EBD
1	Viability	7
2	Product life cycle consideration	8
3	Customers' identification	8
4	Customers' requirements identification	7
5	Customers' requirements prioritization	10
6	Conflict identification / functional requirements relationships	7

Criteria		EBD
7	Conformance / completeness of the concept generated	8
8	Ease to understand the results	10
9	Performance / measurability of functional requirements	N/A

- *EBD results evaluation:*

(1) Viability: 3 marks were deducted because it is not mentioned how to connect the cameras to some surgery devices such as the camera in the doctor's glasses to the network computer. Additionally, the camera in the doctor's glasses can be blocked with the patient blood or doctors' sweat, and it is not mentioned how to do in these cases.

(2) Product life cycle consideration: 2 marks were deducted because the designer only took into account from collecting the images until analyzing the results. The designer did not consider the cleaning procedure post surgery.

(3) Customers' identification: 2 marks were deducted because the designer identified the stakeholders (patients, doctors, nurses, technical staff, and video analysts), but the cleaning/maintainability staff was not considered.

(4) Customers' requirements identification: 3 marks were deducted because in the design solution there is not enough information about the network computer or server capacity in order to store the video records. Additionally, cleaning/maintainability staff may have some requirements such as disposable or washable cameras adapted to some surgery instruments.

(5) Customer requirements prioritization: full mark because the designer provided solutions to all the identified customer's requirements.

(6) Conflict identification / functional requirements relationship: 3 marked were subtracted because the designer did not identified the conflict about higher video resolution, higher storage capacity. Additionally, if they are using wireless cameras, the higher the video resolution, the higher wireless/internet speeds to transfer the data to the network computer.

(7) Conformance / completeness of the concept generated: 2 marks were deducted because the designer did not provide solution to the important conflicts that were not identified; therefore, the current solution has some functional issues.

(8) Ease to understand the results: full mark because the design solution is clear and the problem was worked following the methodology steps.

(9) Performance / measurability of functional requirements: N/A, at this point was unclear to specify what high resolution means, for instance, 5, 10 or 15 megapixels. Additional, the storage capacity, camera sizes, or internet/wireless speed were not specific.

Table 11: QFD criteria evaluation for design problem 2

Criteria		QFD
1	Viability	6
2	Product life cycle consideration	6
3	Customers' identification	6
4	Customers' requirements identification	6
5	Customers' requirements prioritization	10

Criteria		QFD
6	Conflict identification / functional requirements relationships	6
7	Conformance / completeness of the concept generated	6
8	Ease to understand the results	10
9	Performance / measurability of functional requirements	4

- *QFD results evaluation:*

(1) Viability: 4 points were deducted because it is not mentioned how collect the information from the cameras in order to analyze it. Additionally, the video records storage is not considered by the designer.

(2) Product life cycle consideration: 4 marks were deducted because the designer did not consider the cleaning post surgery and the video storage.

(3) Customers' identification: 4 marks were deducted because the designer did not identify the cleaning/maintenance staff of the surgery rooms and devices involved in the solution, and technical staff that will store and analyze the videos information.

(4) Customers' requirements identification: 4 marks were deducted because in the design solution there is not enough information about how to transfer the information from the cameras to a server. Additionally, the technical staff may have some requirements about video storage capacity.

(5) Customer requirements prioritization: full mark was assigned because the designer prioritized the requirements according to how important they are to the customers.

(6) Conflict identification / functional requirements relationship: 4 marked were deducted because the designer did not identify the conflict about higher video resolution, higher storage capacity. Furthermore, the designer did not consider the possible technical conflict to transfer the data from the cameras to a server.

(7) Conformance / completeness of the concept generated: 4 marks were deducted because neither the transmission of the videos from the cameras to a server nor the server storage capacity was considered.

(8) Ease to understand the results: full mark because the designer follows QFD methodologies procedures and the results are clear.

(9) Performance / measurability of functional requirements: 6 marks were deducted because the technical requirements do not have established performance; however, the designer gained 4 marks because for some technical requirements the unit of measure is given as well as the direction of improvement.

Other two evaluators analyzed the results of the design problem 2 in order that the comparison is more objective. The results can be found in the next section. Besides that, the other two design problems were assessed in the same way as the second design problem, and the evaluation and summary of the analyzed results are also shown in the next section. Refer to Appendix D for the design results of the problems 1 and 3.

3.2.4 Evaluation and summary of the analyzed results

3.2.4.1 Evaluation of the analyzed results

The design results were analyzed by each evaluator one by one, and the evaluation results are displayed in Table 12, Table 13, and Table 14 for the design problems 1, 2 and 3 respectively. Each one of the previous tables contains the punctuation given by the evaluators to each criterion for EBD and QFD design methodologies. Then, the evaluator punctuations were subtracted (EBD – QFD) for each evaluator respectively in order to quantify the evaluators' perception compared to the criterions' requirements.

Since EBD – QFD was used:

1. If the result is positive, EBD was better for the perception of the evaluator.
2. If the result is negative, QFD was better for the perception of the evaluator.
3. If the result is 0, EBD and QFD were tied for the perception of the evaluator.

A total score for each criterion was calculated by adding up the three evaluator's perceptions. Besides that, a total score for each evaluator was obtained by adding up their respective punctuations for each criterion. Finally, a total score for the design problems was calculated by summing the total scores per criterion or the total scores per evaluator. The score results can be analyzed following the three previous considerations.

It is important to recall the thesis hypothesis in order to assess and validate it:

> *EBD helps inexperience designers such as students to cope the difficulties encountered in the product definition process in addition to providing more complete results than by using QFD.*

In order to verify if the designers overcame the difficulties of the design problems, and to evaluate if the generated results are complete; each criterion will be evaluated and a conclusion will be driven based on the total score of each design problem.

As follows, each problem is analyzed and at the end a summary for the three problems is presented. For each problem the hypothesis will be evaluated.

- *Evaluation results design problem 1:*

Table 12: Evaluation results design problem 1

Criteria	Design problem 1									
	EBD			QFD			EBD-QFD			Total score
	E1	E2	E3	E1	E2	E3	E1-E1	E2-E2	E3-E3	
Viability	10	10	9	8	8	7	2	2	2	**6**
Product life cycle consideration	10	1	0	8	1	0	2	0	0	**2**
Customers' identification	10	2	5	8	3	4	2	-1	1	**2**
Customers' requirements identification	10	1	8	8	5	6	2	-4	2	**0**
Customers' requirements prioritization	10	1	6	10	7	8	0	-6	-2	**-8**
Conflict identification / functional requirements relationships	10	1	7	0	7	7	10	-6	0	**4**
Conformance / completeness of the generated results	10	5	8	5	8	7	5	-3	1	**3**
Ease to understand the results	10	10	9	7	1	8	3	9	1	**13**
Performance / measurability of functional requirements	10	9	7	4	1	8	6	8	-1	**13**
Total score							**32**	**-1**	**4**	**35**

E1, E2, and E3 refer to evaluator 1, 2 and 3 respectively.

From the results in Table 12, it can be observed that:

(1) Viability: the three evaluators think that EBD generated more viable results than QFD, having a total score of 6.

(2) Product life cycle consideration: evaluator 1 thinks that the EBD generated results have a greater consideration of the product life cycle while the other two evaluators think that both methodologies were tied and had a poor consideration of the product life cycle. The final score of the criterion is 2, being EBD better than QFD.

(3) Customers' identification: evaluators 1 and 3 think that the EBD generated results identify more customers than the QFD one. Evaluator 2 thinks that both methodologies were poor identifying the customers, and that QFD slightly identified more customers with -1. The final score of the criterion is 2, being EBD better than QFD.

(4) Customers' requirements identification: two evaluators think that EBD identified more customers' requirements than QFD while one evaluator considers the opposite. The final score of the criterion is 0, being a draw for EBD and QFD.

(5) Customer requirements prioritization: two evaluators think that QFD customer's requirements prioritization was better than EBD. The other evaluator thinks that EBD and QFD were tied. The final score of the criterion is -8, being QFD better than EBD.

(6) Conflict identification / functional requirements relationship: evaluator 1 thinks that EBD identified more conflicts than QFD while evaluator 2 considers the opposite. Evaluator 3 believes that there was a draw between

EBD and QFD. The final score of the criterion is 4, being EBD better than QFD.

(7) Conformance / completeness of the generated results: two evaluators think that EBD was better than QFD while the other one considers the opposite. The final score of the criterion is 3, being EBD better than QFD.

(8) Ease to understand the results: the three evaluators believe that results generated by EBD were clearer and easier to understand than the ones generated by QFD. The final score of the criterion is 13, being EBD better than QFD.

(9) Performance / measurability of functional requirements: two evaluators think that the engineering requirements developed by EBD are more measurable than the ones generated by QFD; the other evaluator believes the opposite. The final score of the criterion is 13, being EBD better than QFD.

Overall EBD performed better in all the comparison parameters than QFD except for customer's requirements prioritization. The final score for the design problem was 35; therefore, the hypothesis cannot be rejected.

- *Evaluation results design problem 2:*

The second design problem will be analyzed using the same direction as for the evaluation of the design problem 1.

Table 13: Evaluation results design problem 2

Criteria	Design problem 2									
	EBD			QFD			EBD-QFD			Total score
	E1	E2	E3	E1	E2	E3	E1-E1	E2-E2	E3-E3	
Viability	7	9	8	6	10	6	1	-1	2	**2**
Product life cycle consideration	8	1	0	6	1	0	2	0	0	**2**
Customers' identification	8	2	7	6	2	3	2	0	4	**6**
Customers' requirements identification	7	5	8	6	9	6	1	-4	2	**-1**
Customers' requirements prioritization	10	1	0	10	5	7	0	-4	-7	**-11**
Conflict identification / functional requirements relationships	7	9	6	6	10	6	1	-1	0	**0**
Conformance / completeness of the generated results	8	2	8	6	3	6	2	-1	2	**3**
Ease to understand the results	10	9	9	10	4	7	0	5	2	**7**
Performance / measurability of functional requirements	0	5	5	4	4	6	-4	1	-1	**-4**
Total score							**5**	**-5**	**4**	**4**

E1, E2, and E3 refer to evaluator 1, 2 and 3 respectively.

From the results in Table 13, it can be observed that:

(1) Viability: two evaluators think that EBD generated more viable results than QFD, while the other evaluator considers the opposite. The final score of the criterion is 2, being EBD better than QFD.

(2) Product life cycle consideration: evaluator 1 thinks that the EBD generated results have a greater consideration of the product life cycle while the other two evaluators think that both methodologies were tied and had a poor

consideration of the product life cycle. The final score of the criterion is 2, being EBD better than QFD.

(3) Customers' identification: evaluators 1 and 3 think that the EBD generated results identify more customers than the QFD one. Evaluator 2 believes that both methodologies were tied and poor identifying the customers. The final score of the criterion is 6, being EBD better than QFD.

(4) Customers' requirements identification: two evaluators think that EBD identified more customers' requirements than QFD while one evaluator considers the opposite. The final score of the criterion is -1, being QFD better that EBD because evaluator 2 ranked higher score for QFD than the one assigned for the other 2 evaluators for EBD.

(5) Customer requirements prioritization: two evaluators think that QFD customer's requirements prioritization was better than EBD. The other evaluator thinks that EBD and QFD were tied. The final score of the criterion is -11, being QFD better than EBD.

(6) Conflict identification / functional requirements relationship: evaluator 1 thinks that EBD identified more conflicts than QFD while evaluator 2 considers the opposite. Evaluator 3 believes that there was a draw between EBD and QFD. The final score of the criterion is 0; hence, EBD and QFD are tied.

(7) Conformance / completeness of the generated results: two evaluators think that EBD was better than QFD while the other one considers the opposite. The final score of the criterion is 3, being EBD better than QFD.

(8) Ease to understand the results: two evaluators believe that results generated by EBD were clearer and easier to understand than the ones generated by QFD. The other evaluator thinks that both methodologies generated similar outputs. The final score of the criterion is 7, being EBD better than QFD.

(9) Performance / measurability of functional requirements: two evaluators think that the engineering requirements developed by QFD are more measurable than the ones generated by EBD; the other evaluator believes the opposite. The final score of the criterion is -4, being QFD better than EBD.

Overall EBD performed better in 5 criterions which are viability, product life cycle consideration, customer's identification, conformance/completeness of the generated results, and ease to understand the results than QFD while they tied in the conflict identification/functional requirements relationships one. QFD performed better than EBD in the remaining criterions. The final score for the design problem was 4; therefore, the hypothesis cannot be rejected.

- *Evaluation results design problem 3:*

The third design problem will be analyzed using the same direction as the previous ones.

Table 14: Evaluation results design problem 3

Criteria	Design problem 3									
	EBD			QFD			EBD-QFD			Total score
	E1	E2	E3	E1	E2	E3	E1-E1	E2-E2	E3-E3	
Viability	8	6	7	8	4	5	0	2	2	**4**
Product life cycle consideration	7	1	0	7	1	0	0	0	0	**0**
Customers' identification	7	1	6	7	1	3	0	0	3	**3**
Customers' requirements identification	7	8	8	7	9	7	0	-1	1	**0**
Customers' requirements prioritization	7	9	6	10	1	7	-3	8	-1	**4**
Conflict identification / functional requirements relationships	7	9	7	10	8	5	-3	1	2	**0**
Conformance / completeness of the generated results	7	9	8	8	2	6	-1	7	2	**8**
Ease to understand the results	8	8	9	8	5	5	0	3	4	**7**
Performance / measurability of functional requirements	0	1	8	5	5	4	-5	-4	4	**-5**
Total score							**-12**	**16**	**17**	**21**

E1, E2, and E3 refer to evaluator 1, 2 and 3 respectively.

From the results in Table 14, it can be observed that:

(1) Viability: two evaluators think that EBD generated more viable results than QFD, while the other evaluator considers a draw. The final score of the criterion is 4, being EBD better than QFD.

(2) Product life cycle consideration: the three evaluators think that there is a draw for this criterion. Two evaluators think that both methodologies had a poor consideration of the product life cycle. The final score of the criterion is 0; hence, EBD and QFD are tied.

(3) Customers' identification: evaluator 3 thinks that the EBD generated results identify more customers than the QFD one. Evaluators 1 and 2 believe that both methodologies were tied identifying the customers. The final score of the criterion is 3, being EBD better than QFD.

(4) Customers' requirements identification: evaluator 3 thinks that EBD identified more customers' requirements than QFD while evaluator 2 considers the opposite. Evaluator 1 believes that EBD and QFD were tied. The final score of the criterion is 0; hence, EBD and QFD are tied.

(5) Customer requirements prioritization: two evaluators think that QFD customer's requirements prioritization was better than EBD while the other evaluator thinks the opposite. The final score of the criterion is 4, being EBD better than QFD because evaluator 2 ranked higher score for EBD than the one assigned for the other 2 evaluators for QFD.

(6) Conflict identification / functional requirements relationship: evaluators 2 and 3 think that EBD identified more conflicts than QFD while evaluator 1 considers the opposite. The final score of the criterion is 0; hence, EBD and QFD are tied.

(7) Conformance / completeness of the generated results: two evaluators think that EBD was better than QFD while the other one considers the opposite. The final score of the criterion is 8, being EBD better than QFD.

(8) Ease to understand the results: two evaluators believe that results generated by EBD were clearer and easier to understand than the ones generated by QFD.

The other evaluator thinks that both methodologies generated similar outputs. The final score of the criterion is 7, being EBD better than QFD.

(9) Performance / measurability of functional requirements: two evaluators think that the engineering requirements developed by QFD are more measurable than the ones generated by EBD; the other evaluator believes the opposite. The final score of the criterion is -5, being QFD better than EBD.

Overall EBD performed better in 5 criterions which are viability, customer's identification, customer's requirements prioritization, conformance/completeness of the generated results, and ease to understand the results than QFD while they tied in the product life cycle consideration, customer's requirements identification, and conflict identification/functional requirements relationships ones. QFD achieved better results than EBD in the performance/measurability of functional requirements criterion. The final score for the design problem was 21; therefore, the hypothesis cannot be rejected.

3.2.4.2 <u>Analyzed results summary</u>

In this summary, the total score for each design problem were summed up per criteria in order to obtain a final total score for the case study. After that, the following three possible scenarios were able to happened, and based on each of them, also the following could be concluded:

1. If the result is positive, EBD was better for the perception of the evaluator.
2. If the result is negative, QFD was better for the perception of the evaluator.
3. If the result is 0, EBD and QFD were tied for the perception of the evaluator.

In order to verify if the designers overcame the difficulties of the design problems, and to evaluate if the generated results are complete; each criterion will be evaluated and a conclusion will be driven based on the total final score of the design problems.

Table 15: Summary of the analyzed results

Criteria	Analyzed results summary			
	Design problems scores			Total final score
	DP1	DP2	DP3	
Viability	6	2	4	**12**
Product life cycle consideration	2	2	0	**4**
Customers' identification	2	6	3	**11**
Customers' requirements identification	0	-1	0	**-1**
Customers' requirements prioritization	-8	-11	4	**-15**
Conflict identification / functional requirements relationships	4	0	0	**4**
Conformance / completeness of the generated results	3	3	8	**14**
Ease to understand the results	13	7	7	**27**
Performance / measurability of functional requirements	13	-4	-5	**4**
Total score/design problem	**35**	**4**	**21**	**60**

DP1, DP2, and DP3 refer to design problem 1, 2 and 3 respectively.

From the results in Table 15 can be concluded that:

(1) Viability: EBD generated more viable results than QFD for the three design problems. The final score of the criterion is 12, being EBD better than QFD.

(2) Product life cycle consideration: EBD had greater life cycle consideration in the design problems 1 and 2 than QFD while they tied for the design problem 3. The final score of the criterion is 4, being EBD better than QFD.

(3) Customers' identification: EBD performed better than QFD identifying the different customers in the three design problems. The final score of the criterion is 11, being EBD better than QFD.

(4) Customers' requirements identification: QFD identified more customers' requirements than EBD for the second design problem while they tied in the other two design problems. The final score of the criterion is -1, being QFD better than EBD.

(5) Customer requirements prioritization: QFD performed better than EBD prioritizing the customers' requirements for two design problems while EBD was better for the third design problem. The final score of the criterion is -15, being QFD better than EBD.

(6) Conflict identification / functional requirements relationship: EBD identified more conflicts than QFD for the design problem 1 while they tied for the other two design problems. The final score of the criterion is 4, being EBD better than QFD.

(7) Conformance / completeness of the generated results: EBD generated more complete results than QFD for the three design problems. The final score of the criterion is 14, being EBD better than QFD.

(8) Ease to understand the results: EBD results were clearer and easier to understand than the QFD ones for the three design problems. The final score of the criterion is 27, being EBD better than QFD.

(9) Performance / measurability of functional requirements: EBD generated more measurable functional requirements than QFD for the design problem 1 while QFD was better for the other two design problems. The final score of the criterion is 4, being EBD better than QFD because the results for the design problem 1 were greater than the results of the other two design problems together.

Overall EBD performed better than QFD in 7 criterions which are viability, product life cycle consideration, customer's identification, conflict identification/functional requirements relationships, conformance/completeness of the generated results, ease to understand the results, and performance/measurability of functional requirements. QFD achieved better results than EBD in the customer's requirements identification, and customer's requirements prioritization criterions. The total final score for the case study was 60; therefore, the hypothesis cannot be rejected.

Chapter 4: Conclusions and Future Work

In the present thesis, EBD and QFD design methodologies were compared in order to have preliminary conclusions for the hypothesis that EBD helps inexperience designers to cope the difficulties encountered in the product definition process in addition to providing more complete results than by using QFD. EBD and QFD were also compared to the product definition process in order to understand how both methodologies meet the requirements involved in it. After that, a case study of three design problems was solved using each methodology, and a set of criteria was created with the purpose of being able to compare the results generated by EBD and QFD. Furthermore, the results evaluation was done by three different evaluators for the comparison to be more objective.

4.1 Conclusions

The design process has a great impact in the cost, quality and time to launch a new product to the market plus the fact that many engineering students lack of the vast experience required in the labour market; with the current thesis is preliminary shown that EBD is a promising design methodology that should be learnt and taught in design courses in order to help inexperience designers (students) to overcome the design difficulties for defining a new product.

The set of criteria used in the current thesis in order to compare EBD and QFD was developed taking into consideration some of the main parameters that show success in a designed product such as quality, product life cycle, and viability.

After evaluating the results generated by using EBD and QFD, the following can be preliminarily concluded:

- The thesis hypothesis cannot be rejected. Therefore, EBD helps inexperience designers to overcome the difficulties encountered in the product definition process and provide more complete results than by using QFD.
- From Table 15, EBD has a greater total final score (60) than QFD, being unquestionably better in the three design problems.
- Since EBD did preliminarily better than QFD, I would highly recommend to learn and use EBD in order to be able to meet all the important requirements present in the product definition process.

4.2 Future work

In the future, some work can be done in different directions such as:

- Since the results that were obtained are preliminary, more research can be performed to fully validate this study.
- The developed set of criteria can be used to compare any other design methodologies; so, in the journey of helping inexperience designers, EBD can be compared to any other design methodology.
- Some research can be performed in order to study the possibility that EBD can be merged or associated with other design methodologies such as Design For Six Sigma (DFSS), Systematic Design Methodology, Axiomatic Design, Decision-Based Design Theory, or AI-Based Design Theory. Besides that, other tools such as Design of Experiments (DOE), Failure Mode and Effect Analysis (FMEA) and Optimization can be incorporated when designing a product using EBD.

Appendix

Appendix A

EBD Example: Developing a Quality Manual for Environment Monitoring System in a City" by Sun and Zeng (Sun, et al., 2011)

The background information is that:

> *"City of Edmonton, Alberta, Canada, runs a monitoring program to monitor and report the performance of the city's drainage system (City of Edmonton, Asset Management and Public Works, Drainage Services, 2004). Under the obligation of ISO 9001 and ISO 14001, the city's monitoring group (the customer, hereafter) decided to develop and implement a quality management manual to provide higher quality and more efficient services with current available resources (Sun, et al., 2011)".*

The objective of the design problem in example is summarized as follows: "Develop a quality manual for current monitoring system to meet quality requirements and to provide efficient services" (Sun, et al., 2011).

Hence, since the design problem is already described, the first step is to create a ROM diagram, and it can be found in Figure 34.

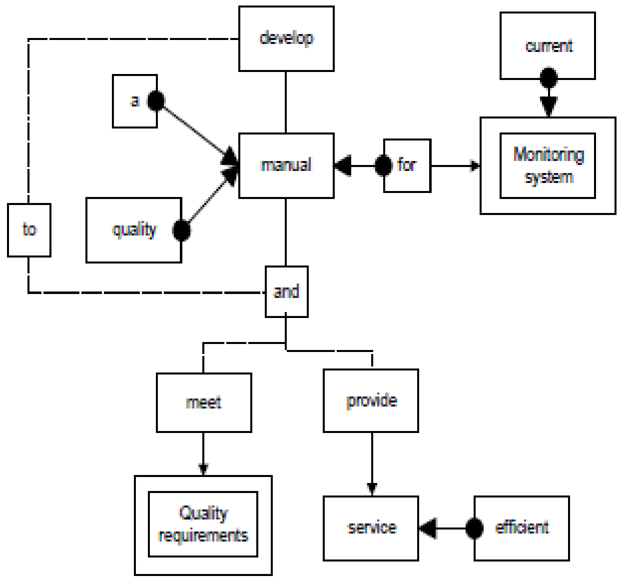


Figure 34: EBD example, ROM of requirements description (Sun, et al., 2011)

After the ROM diagram is drawn, the second, third and fourth steps are done iteratively. From the ROM diagram, the component manual is the most important because it has the most undefined constraint relations. Therefore, generic questions should be asked firsts about objects constraining it such as “monitoring system”, “quality requirements”, “efficient service”, and “quality manual”. For instance, a generic question is “what kinds of quality requirements should be met?”, and its respective answer is ISO 9001 and ISO 24511. After, more questions can be asked about ISO 9001 and ISO 24511 such as “what is the related information in ISO 24511?” and so on. Based on the answers, the ROM diagram can be updated.

Questions about the relation objects “meet” and “provide” should be asked when the questions about the environment components are finished. Using “meet” as example, “how to meet?” can be asked. The quality requirements content should be analyzed to answer the previous question. Steps 2, 3, and 4 continue until there are no more unclear objects and relationships between them in the updated ROM and the customer's real intent is understood.

The fifth, sixth and seventh steps start when the conditions in the fourth step are met. Domain specific questions are asked concerning to the life cycle of the product to be designed. For instance, the first domain specific question to ask is: "what is the life cycle of the manual?" and its respective answer is design, communication, use and maintenance because the quality manual is specialized for the monitoring group.

Generic Question	Answer
What kinds of quality standards should be met?	ISO 24511, ISO 9001 …
What is the related information in ISO24511?	"The wastewater utility should define the sequence of all essential operations required for the proper performance of its tasks, processes and activities… More detailed working instructions (such as standard operating procedures and operation and maintenance manuals) should be prepared whenever required, in order to ensure the proper and expert handling of individual activities, adhering to applicable national or generally accepted requirements or practices" (ISO24511, 2008).
What are the requirements based on ISO 9001?	According ISO 9001, a quality manual should include the scope of the quality management system, including details of and justification for any exclusions; the documented procedures established for the quality management system, or reference to them; and a description of the interaction between the processes of the quality management system (ISO9001, 2000).
What does efficient mean?	Performing or functioning in the best possible manner with the least waste of time and effort; satisfactory and economical to use.
What are the characteristics of efficient service?	Less time consuming, low cost, low error rate, high data quality…
What is the environmental monitoring program?	The city of XYZ has a drainage monitoring program under the Environmental Monitoring group which consists of performing several processes for the maintenance and monitoring of different parameters of the drainage systems. People install equipments to different sites for meeting customers' monitoring requirements.
What kinds of objects are included in the monitoring system?	People, device, information system, software.
What is the current situation of monitoring system?	There is no quality manual in current monitoring system. The document management is not good. Technologists just follow their own procedure based on experience, some operations are not proper. The software popularization is not good, so most operations depend on human being. It is hard to avoid human error, time consuming and high cost.
How to meet these quality requirements?	According to the quality standards, it is better to define the proper operation sequences of monitoring activities and to give clear instruction of each activity.
How to provide efficient service?	Reduce the operation time, ensure the quality of data …
Specific Question	**Answer**
What is the lifecycle of our manual?	In our case, the lifecycle of manual includes design, communication, use, and maintenance.

Figure 35: EBD example, Generic and domain specific questions (City of Edmonton, Asset Management and Public Works, Drainage Services, 2004)

Refer to Figure 35 to see the complete set of generic and domain specific questions asked in the example by Sun and Zeng.

For each stage of the life cycle identified, the related components and requirements are further classified into built, human, and natural environment. After that, the component relationships are analyzed. Refer to Figure 36.

Environment Lifecycle	Built Environment	Human Environment	Natural Environment
Design	quality requirement, cost, time, interface, basic function	designer, consultant	N/A
Transportation	Time, transportation software	N/A	N/A
Use	information system, equipment	technologist, contractor	N/A
Maintenance	warranty time, maintenance activities	designer, technologist	N/A

Figure 36: EBD example, Requirement classification (City of Edmonton, Asset Management and Public Works, Drainage Services, 2004)

After the previous steps are completed, the final step of environment analysis is done by updating the ROM (Figure 37) with the previous answers. Figure 37 also provides a clear map of the quality management manual to be designed.

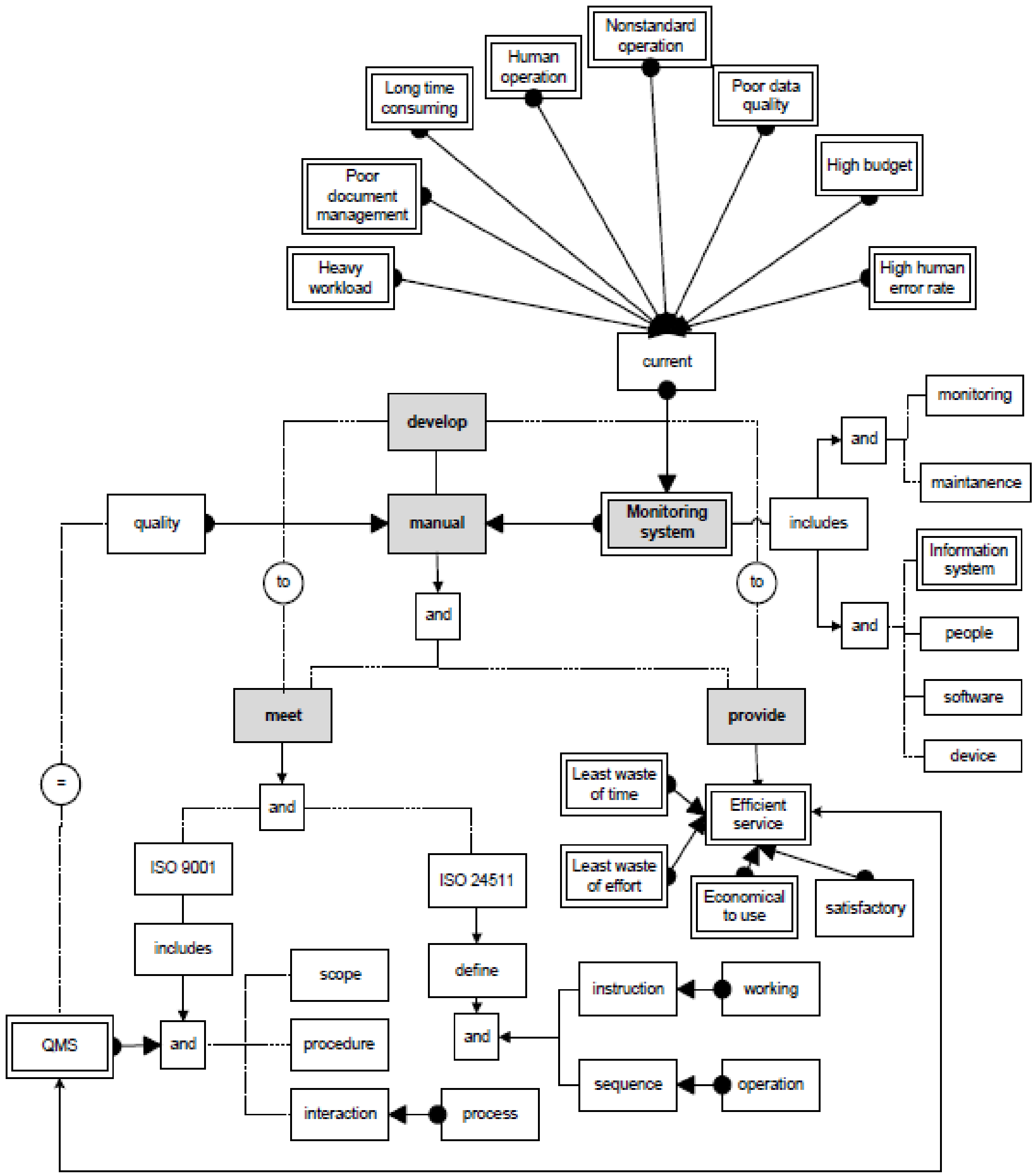


Figure 37: EBD example, Updated ROM diagram (City of Edmonton, Asset Management and Public Works, Drainage Services, 2004)

The updated ROM in Figure 37 is the basis for the conflict identification phase, and from it, it is evident that there interdependent relations between the environment components meaning that that there are conflicts. The found conflicts are listed in Figure 38.

#	Significant Conflicts	
c1	High human error rate	Least waste of time; least waste of effort.
c2	High cost	Economical to use; satisfactory.
c3	Heavy workload	Economical to use.
c4	Long time consuming	Least waste of time; least waste of effort.
c5	Poor document management	Least waste of time; least waste of effort; economical to use.
c6	Nonstandard operations	Least waste of time; least waste of effort; economical to use.
c7	Poor data quality	Least waste of time; least waste of effort; economical to use; satisfactory.
c8	Too many human operations	Least waste of time; least waste of effort.
c9	No improve or warranty activities	Economical to use; satisfactory.
c10	No defined efficient sequence of operations	Economical to use; satisfactory.

Figure 38: EBD example, Conflicts (Sun, et al., 2011)

For instance, conflict 3 (c3) in Figure 38 comes from that technologists complain that their workload is too heavy while the city of Edmonton wants that the new monitoring system is economical to use.

After the conflicts have been identified in Figure 38, the rules for solution generation are followed. Figure 39 and Figure 40 show the directed graph and adjacency matrix respectively of the conflicts identified in Figure 38.

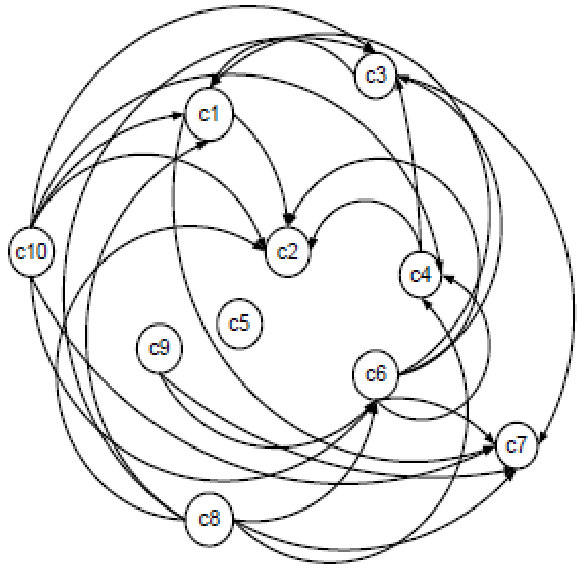


Figure 39: EBD example, Directed graph – Dependencies among conflicts (Sun, et al., 2011)

Conflicts	c1	c2	c3	c4	c5	c6	c7	c8	c9	c10
c1	0	1	0	0	0	0	1	0	0	0
c2	0	0	0	0	0	0	0	0	0	0
c3	1	0	0	0	0	0	1	0	0	0
c4	0	1	1	0	0	0	0	0	0	0
c5	0	0	0	0	0	0	0	0	0	0
c6	1	1	1	1	0	0	1	0	0	0
c7	0	0	0	0	0	0	0	0	0	0
c8	1	1	1	1	0	1	1	0	0	0
c9	0	0	0	0	0	1	1	0	0	0
c10	1	1	1	1	0	1	1	0	0	0

Figure 40: EBD example, Adjacency matrix (Sun, et al., 2011)

From Figure 40, since all the entry values for the columns c5, c8, c9, and 10 are zero; they are the root conflicts for the monitoring system. Therefore, once these conflicts are solved, the other ones will be removed or changed.

According to (Sun, et al., 2011), at this point, based on the previous analysis, it is known what should be included in the manual, and they claim that the manual should focus on "solving the problems caused by human operations, eliminating unnecessary human operations, defining the efficient sequence of monitoring operations, developing improvement activities and managing documents efficiently". The current monitoring system is analyzed again with EBD in order to get the final quality manual.

In this case, the monitoring system gives information for assessment and control of the existing drainage system performance besides the monitoring report the requirements of City Environment Department and agreements with organizations outside of the city (City of Edmonton, Asset Management and Public Works, Drainage Services, 2004). The environment components are detailed in Figure 41.

	Component	Description
Built Environment	Drainage system	The drainage system is responsible for planning, building, operating, and maintaining the pipes, tunnels, pump stations, storm water management facilities that make up the city's drainage network.
	WISIK system	The WISKI Application system is an information system used to monitor and evaluate the effectiveness of city's existing and future sewer systems using accurate and timely monitoring data.
	GIS system	The GIS System can provide site information help select candidate manholes; it also can help identify the potential data quality issues and maintenance cost.
	Equipment	The equipment includes velocity sensors, pipes, bands, probe and meter hooks.
Human Environment	Employee	The field technologists mainly focus on the field practical work and coordinate contractor resources to install, replace and maintain flow monitors; Office technologists issue site installation request, collect site information for requested locations and negotiate with requestors for alternative sites if needed. They also review graphs for problems at the site; circulate graphs for review by senior staff; notify field monitoring staff of site problems; mark incorrect data as bad; store data in database and prepare the final report for customers.
	Contractor	Contractors' work scope include: installing temporary flow monitors; providing maintenance as requested; removing temporary flow monitors; completing two flow monitor verifications; securely fastening flow monitors and sensors; securing the site as required, including the obtaining of permits and allowable times for street/lane closures from Transportation and Streets as needed; and so on.
	Customer	Different customers have different requirements. Some of them need the raw data of drainage system to analyze the performance of sewer system; some of them want to use monitoring data to generate a computer model for data checking; some of them just need the annual report that describe the performance of the drainage system for the whole year.
Natural Environment	Site	The condition of site determines the kind of equipment, the installing location of equipment, and the type of monitoring data and so on.

Figure 41: EBD example, Environment components in the monitoring system (Sun, et al., 2011)

Therefore, after analyzing all the important components, Figure 42 displays the relations between them.

Monitoring program		Built				Human			Natural
		Equipment	WISKI System	GIS System	Drainage System	Employee	Customer	Contractor	Site
Built	Equipment		Transfer information through	N/A	Measure	Selected & Used by	N/A	Installed by	Stay in
	WISKI System	Transfer & Save data of		Transfer & Save data of	Transfer & Save data of	Transfer information to	Transfer information to	Transfer information to	N/A
	GIS System	N/A	Transfer information through		N/A	Used by	N/A	N/A	Guide the selection of
	Drainage System	Measured by	Transfer information through	N/A		Monitored by/Working place	Managed by	Working place	Offers
Human	Employee	Select & Use	Transfer information through	Use	Monitor & Work in		Work for	Request	Select
	Customer	N/A	Transfer information through	N/A	Manage	Request		N/A	N/A
	Contractor	Install	Transfer information through	N/A	Work in	Obey	N/A		Work in
Natural	Site	Hold	N/A	Selected based on	Belong to	Selected by	N/A	Working place	

Figure 42: EBD example, Relations between environment components (Sun, et al., 2011)

From Figure 42 and the operation process analysis, (Sun, et al., 2011) state that in data quality assurance and control (QA/QC) process, a critical conflict was found about human operations. Hence, human operations in QA/QC are the key to solve the conflicts related to human operations.

QA/QC is carried out manually and based on experience in the current monitoring system occasioning two main human errors. The first one is related to the manual checking process that overloads the technologists leading to poor data quality. The second one is concern to data problems that cannot be identified without comprehensive data analysis. Hence, the human errors can be solved and data quality can be improved by implementing new technologies/techniques that replace human operations and eliminate unnecessary operations in the QA/QC process.

Due to the property of the conflicts, a computer program instead of human beings can be used for the QA/QC process. The program should deal with data rationality and effectiveness check, data drifting check, and data sudden change check. (Sun, et al., 2011) think that the advantages of automating the QA/QC process are to enhance quality and accuracy of data, assurance, improve the efficiency of data quality assurance and to avoid human errors by relieving technologists overload.

(Sun, et al., 2011) state that the correct sequence of all monitoring performance is shown in Figure 43, and it come from checking each monitoring activity and analyzing the relations the performances in Figure 42. Also, with the sequence in Figure 43, the monitoring technologists and contractors are informed about what to do first and after some specific tasks. As result, a standard operation is constructed ensuring the effectiveness and efficiency of the monitoring operation.

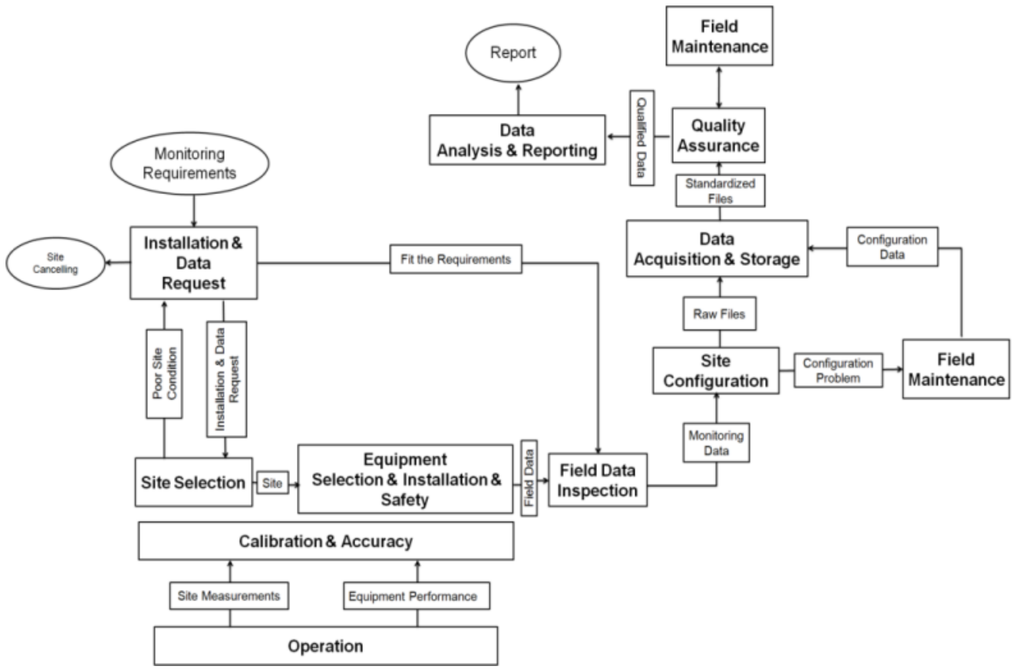


Figure 43: EBD example, Sequence of Monitoring Activities (Sun, et al., 2011)

With the correct sequence of working activities and the ideal template of quality requirements in (Sun, Feng, & Zeng, 2010), the quality manual can be improved. Therefore, on the one hand, the operation instructions can be improved by comparing the quality requirements to the current operation state. On the other hand, proper items from the quality requirement template can be chosen and followed in the quality manual ensuring it meets the quality requirements besides having enough information to support the operation instructions. An example showing the main contents of the developed quality manual is displayed in Figure 44.

<table>
<tr><td colspan="3">Activity 10: Quality Assurance</td></tr>
<tr><td colspan="2">Predecessors: Data Acquisition and Storage</td><td>Successors: Data Analysis and Reporting</td></tr>
<tr><td rowspan="8">Operational Manual</td><td colspan="2">1. Check the data</td></tr>
<tr><td colspan="2">2. Draw the graphs</td></tr>
<tr><td colspan="2">3. Review graphs for problems at sites</td></tr>
<tr><td colspan="2">4. Circulate graphs for review by sensor staff</td></tr>
<tr><td colspan="2">5. Notify field monitoring staff of site problem</td></tr>
<tr><td colspan="2">6. Mark incorrect data as bad</td></tr>
<tr><td colspan="2">7.Store data in database</td></tr>
<tr><td colspan="2">8. Data repairing and finalization</td></tr>
<tr><td rowspan="4">Quality Audit</td><td>Audit duration</td><td>one day to three days</td></tr>
<tr><td>Audit procedure</td><td>check and record each procedure</td></tr>
<tr><td>Audit people</td><td>Office Work technologists</td></tr>
<tr><td>Audit report</td><td>N/A</td></tr>
<tr><td rowspan="2">Non-conformance and possible actions</td><td colspan="2">QA/QC process depend on technologists' experience</td></tr>
<tr><td colspan="2">Use computer program instead of human to operate the QA/QC process</td></tr>
<tr><td>Continuous Improvement</td><td colspan="2">Since we use computer program to replace human operation in QA/QC process, continuous program debug should be considered.</td></tr>
</table>

Figure 44: EBD example, Sample manual – manual for quality assurance (Sun, et al., 2011)

(Sun, et al., 2011) conclude that the content of the manual was not precisely defined in the beginning; however, by using EBD, they were able to clarify the goals of the project step by step and to guide the project members to follow the right path. Additionally, they found out that that two main deliverables were needed, a quality manual and data processing tool.

Appendix B

QFD Example: BikeE suspension system by (Ullman, 2003)

Based on the example used by (Ullman, 2003), the main customers for the BikeE suspension system are the bicycle riders, and they can be of two types. The first type uses the bicycles solely on streets while the second one rides on rough roads or trails. However, there are also other customers to consider such as manufacturing, assembly, shipping personnel, bicycle shops and mechanics. The last two customers are often the same people. However, for further QFD explanation, only street rider and bike shop sales-repair customers will be considered. Refer to the complete HOQ of the BikeE suspension system in Figure 46.

The design team used surveys and interviews to collect the requirements in Figure 45.

Smooth ride on streets
Eliminate shocks from bumps
Easy to adjust suspension system for different weight riders
Easy to adjust suspension system for different height riders
Easy to adjust suspension system for ride hardness
Easy to maintain
Looks like a suspension
Not noticeably affected by temperature
Not noticeably affected by dirt
Not noticeably affected by water
No pogoing[1]
Easy to assemble
Cost less than $50 to manufacture over the rigid rear fork
Weigh less than 400 grams over the rigid rear fork
Does not change bike height

[1] A bike that pogos moves up each time a pedal is pushed so it bounces up and down twice for each pedal revolution. Pogoing results from a poor design where the chain tension interacts with the suspension.

Figure 45: List of customer's requirements for the BikeE suspension system (Ullman, 2003)

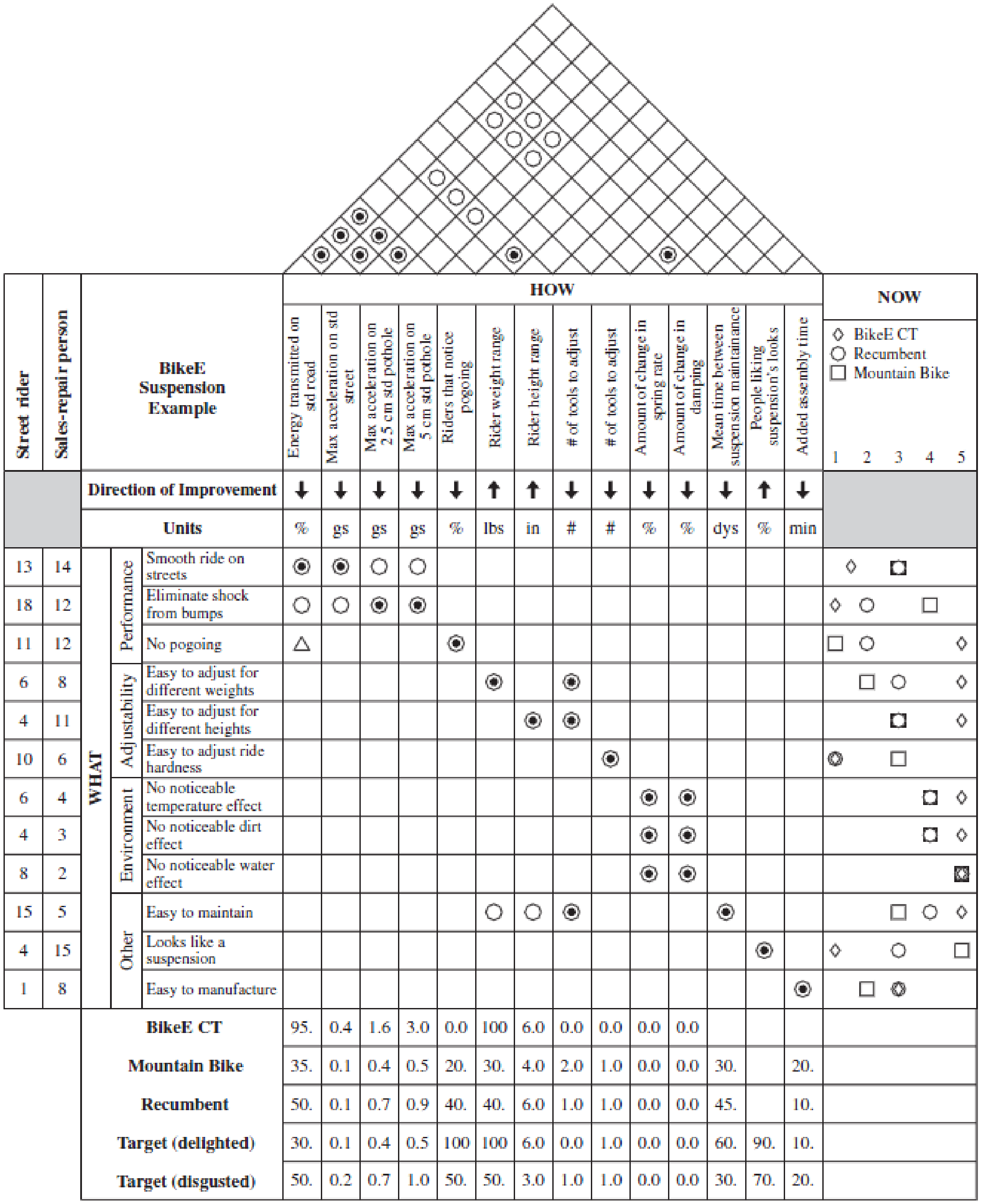


Figure 46: HOQ BikeE suspension system (Ullman, 2003)

It is important that the customer's requirement list is made of what is needed in the product not how it will look or work. After the list has been developed, the requirements are compared to the list of requirements in Table 6. The objective is to group the requirements using the major categories shown Table 6 and to revise the completeness of the list. After the revision is done, requirement additions and omissions can be done. When the customer's requirements are complete, the place of the "what" in the HOQ (Figure 21) is filled. However, only the customer's requirements that are related to function and are not directly measurable in the customer requirements list are included in the HOQ with the purpose of translating them to measurable technical requirements in the next steps. For that reason, the cost and weight requirements listed in Figure 45 are not included in Figure 46.

In the next step, the customer's requirements were ranked. Refer to Figure 46 to see how it was done.

After ranking the customers' requirements, three competitors where benchmarked (refer to Figure 46). In the place of "now vs. what" in Figure 21, the average results from street riders are shown in Figure 46.

The engineering specifications are shown in Figure 46 in the corresponding place of the "how" in Figure 21. It is important to pay attention to the units of measures and the directions of improvements provided by the arrows in Figure 46.

The next step was to relate the customer's requirements to engineering specifications, refer to Figure 46 which displays the relations.

The bottom of the HOQ in Figure 46 contains the information of the target. For instance, for the engineering specification "Rider weight range", the unit of measure is "lbs" and the improvement direction is more is better (↑). The competitors were evaluated to measure how they meet the engineering specifications and BikeE CT is the best now with 100 lbs, while Mountain Bike is the worst with 20 lbs. Therefore, since more is better and with the competitor's evaluation information, the design team decided to establish as delighting target 100 lbs and as disgusting target 50 lbs for this engineering specification.

The roof of the HOQ in Figure 46 shows the type of engineering specification relationships. The types of relationships are described in Figure 25.

Appendix C

CONSENT FORM TO PARTICIPATE IN RESEARCH

This is to state that I agree to participate voluntarily in a program of research being conducted by the student Ronaldo Gutierrez under the supervision of Dr. Yong Zeng of Concordia University. Two copies of consent form will be given to the participant – one to keep and one to sign and return to the researcher.

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A. PURPOSE

The main purpose of the research is to develop designer's cognitive model during the design process by using the following devices:

1) Video cameras
2) Screen recorders
3) EEG system
4) Eye movement tracking system

5) Heart rate variability recorder

The result of this research will be used to guide the improvements of product development through new design methodology and new computer aided design tools.

To achieve the above objective, the research is divided into sub-goals. For this particular work, the goal is to compare two design methods: Quality Function Deployment (QFD) and Environment-Based Design (EBD). The following devices will be used:

1. Video cameras
2. Screen recorders

B. PROCEDURES

The experiments will take place in the lab at EV.9.235 at Concordia University. The participator will work on 3 different design problems that will be distributed one at a time. The time to solve the design problems will be 1, 2 and 3 hours respectively.

C. RISKS AND BENEFITS

- *Risks:* There will be no risks in this experiment.
- *Benefits:* Participant helps contribute to the development of design research field.

D. CONDITIONS FOR PARTICIPATION

Your participation in this research is voluntary. If you decide not to take part in the project you are free to discontinue at any time. Your personal information will be kept confidential. If we publish article on this research project, your identity will be protected.

- I consent that my data will be collected, stored and analyzed. ☐ Yes ☐ No

- I understand that the data from this study may be published. ☐ Yes ☐ No

I HAVE CAREFULLY STUDIED THE ABOVE AND UNDERSTAND THIS AGREEMENT. I FREELY CONSENT AND VOLUNTARILY AGREE TO PARTICIPATE IN THIS STUDY.

NAME (please print) ______________________________

SIGNATURE ______________________________

WITNESS SIGNATURE ______________________________

DATE ______________________________

If at any time you have questions about your rights as a research participant, please contact Adela Reid, Research Ethics and Compliance Officer, Concordia University, at (514) 848-7481 or by email at areid@alcor.concordia.ca

Appendix D

The results of the design problems 1 and 3 can be found in Appendix D. The QFD results for the design problems 1 and 3 are displayed first, and the EBD results after.

- QFD results design problem 1:

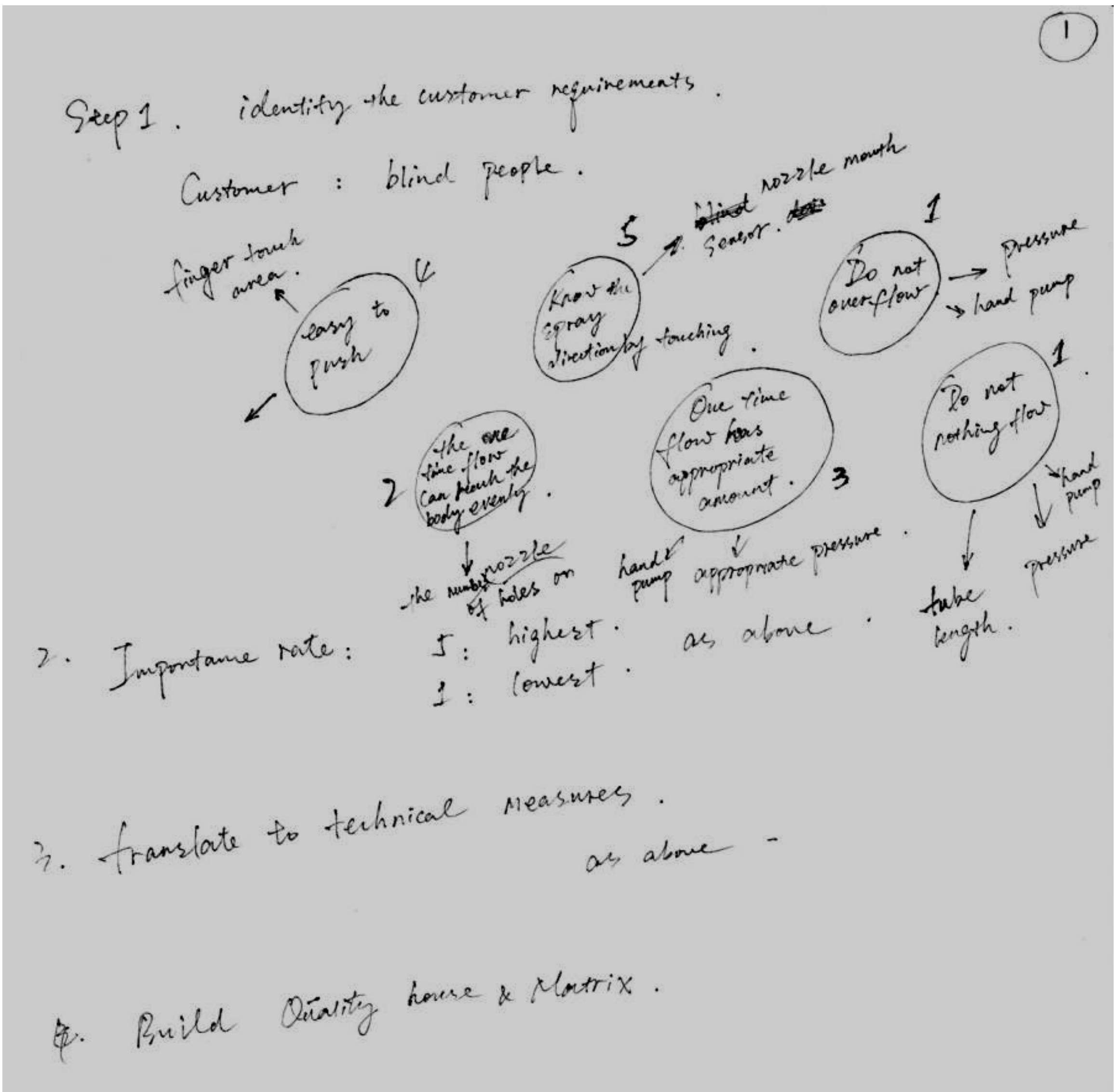


Figure 47: QFD solution for design problem 1 (page 1)

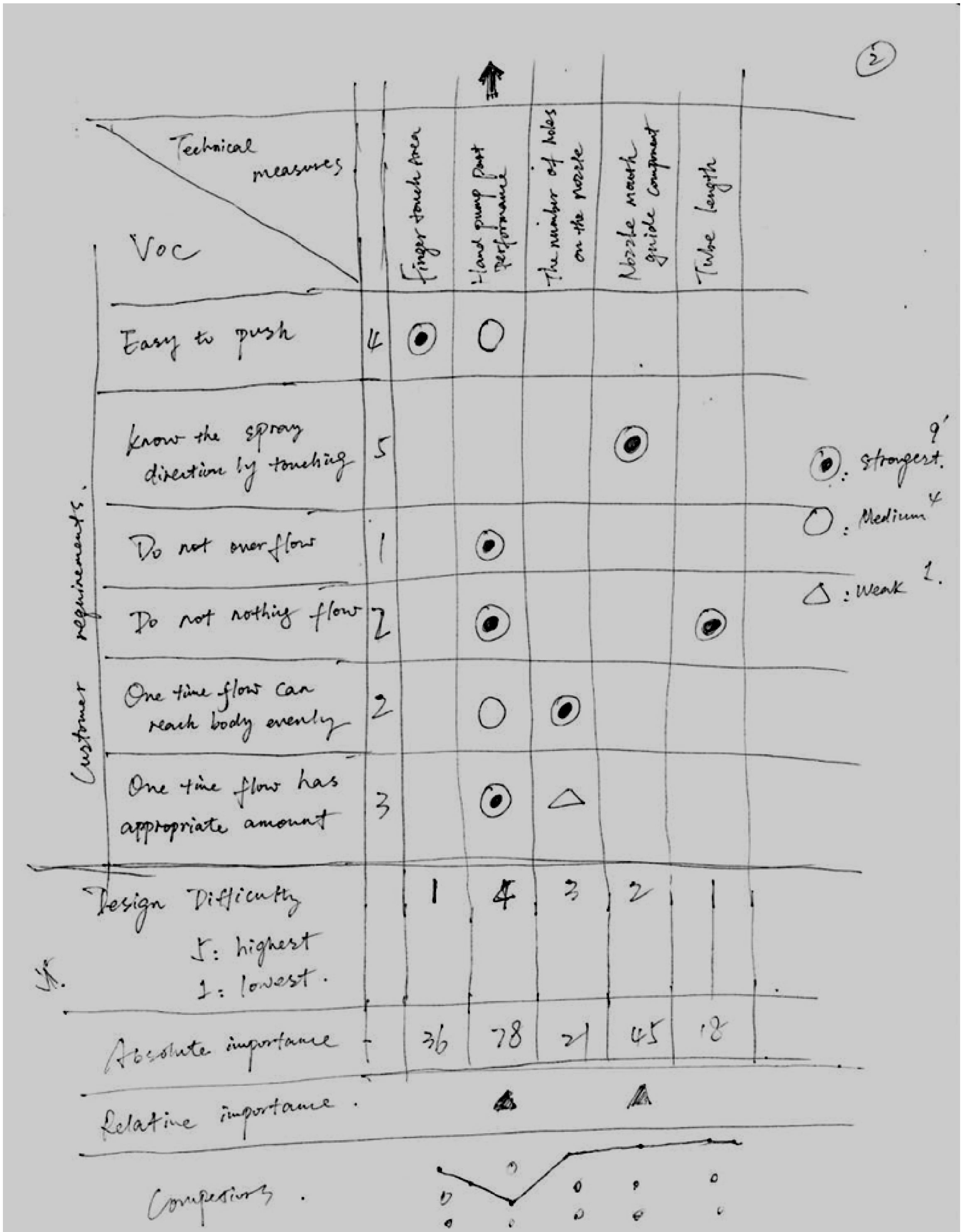
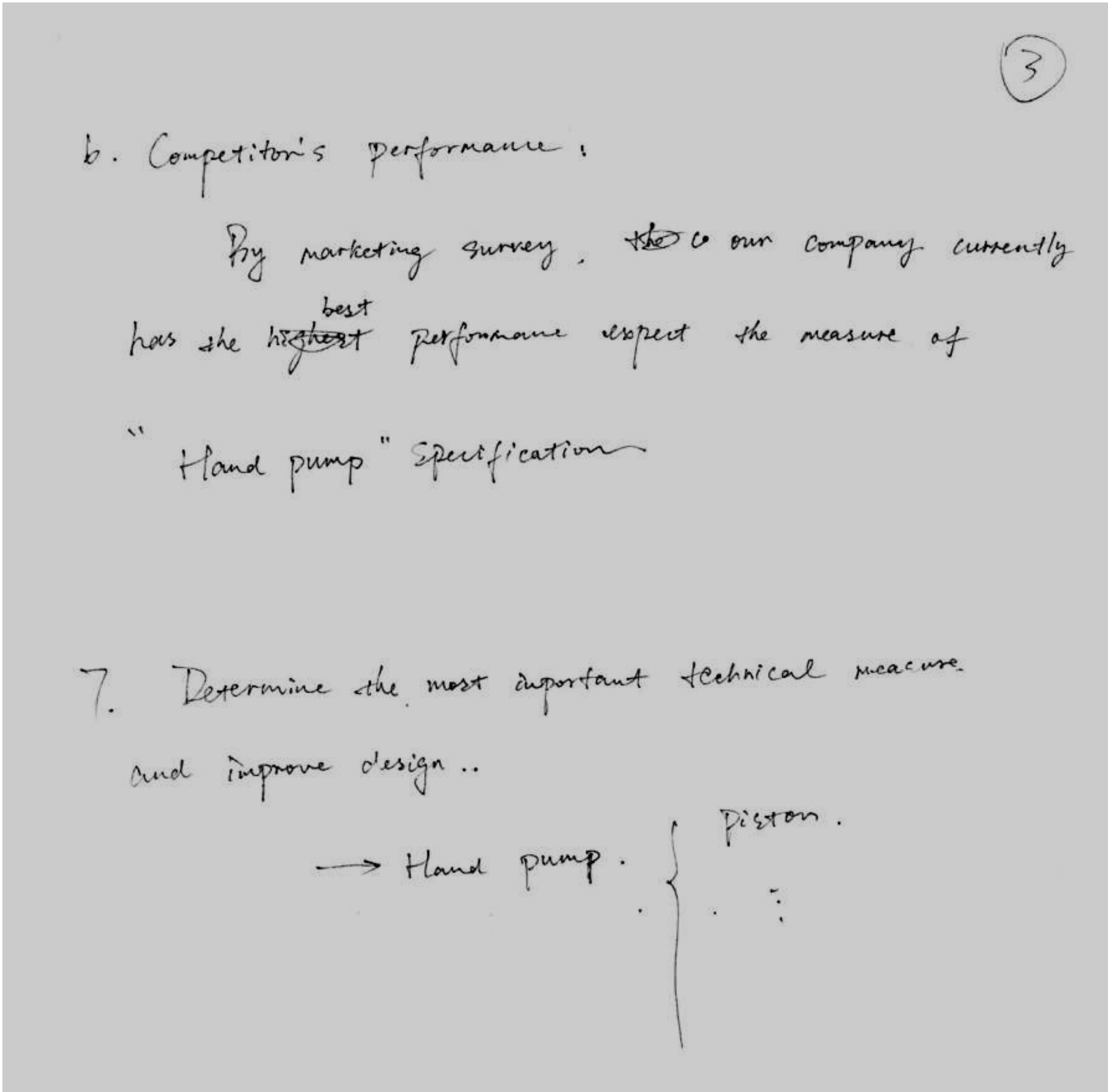


Figure 48: QFD solution for design problem 1 (page 2)



(3)

b. Competitor's performance:

By marketing survey, ~~the~~ our company currently has the ~~highest~~ best performance expect the measure of "Hand pump" Specification

7. Determine the most important technical measure and improve design ..

→ Hand pump. { piston.
⋮

Figure 49: QFD solution for design problem 1 (page 2)

- QFD results design problem 3:

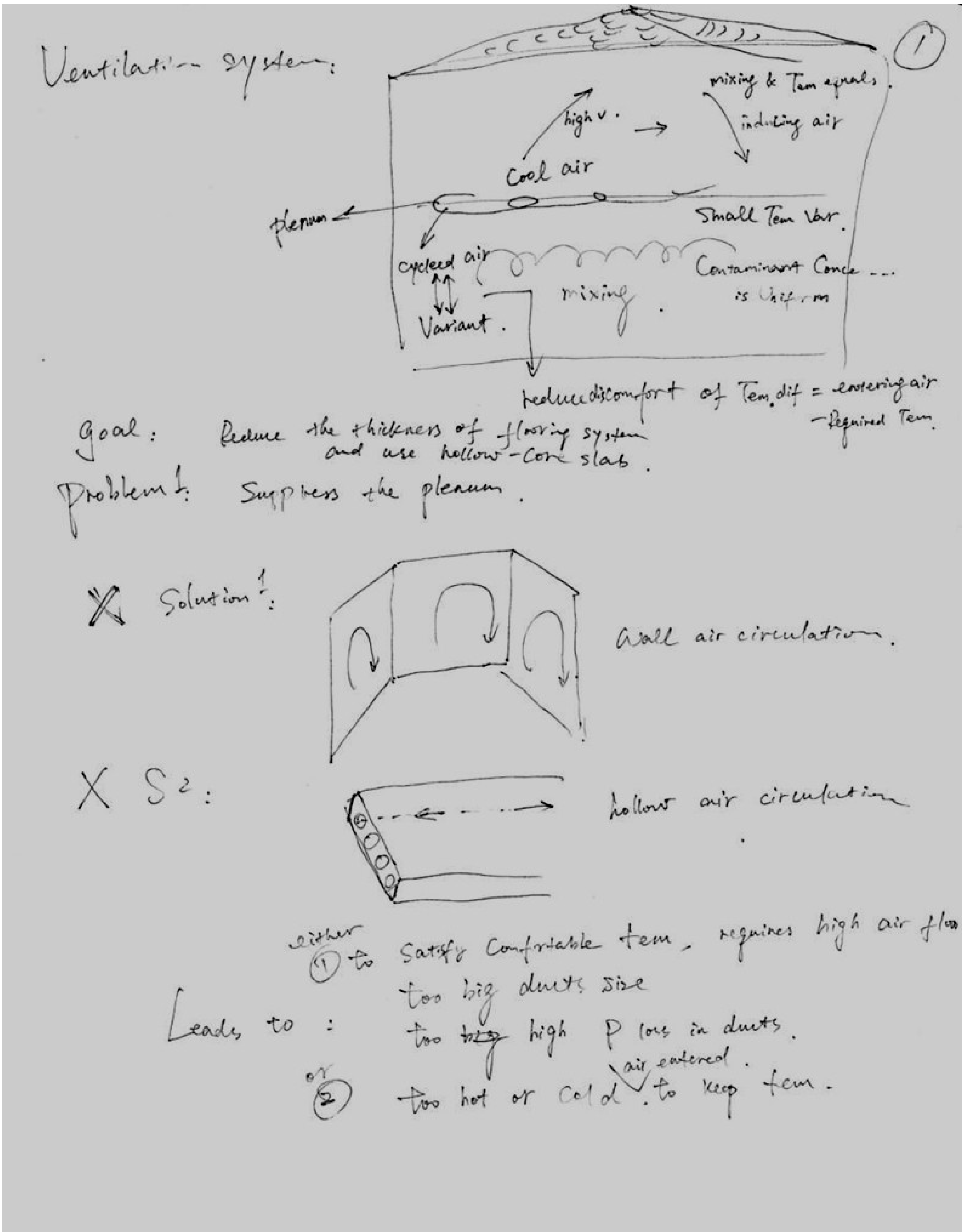
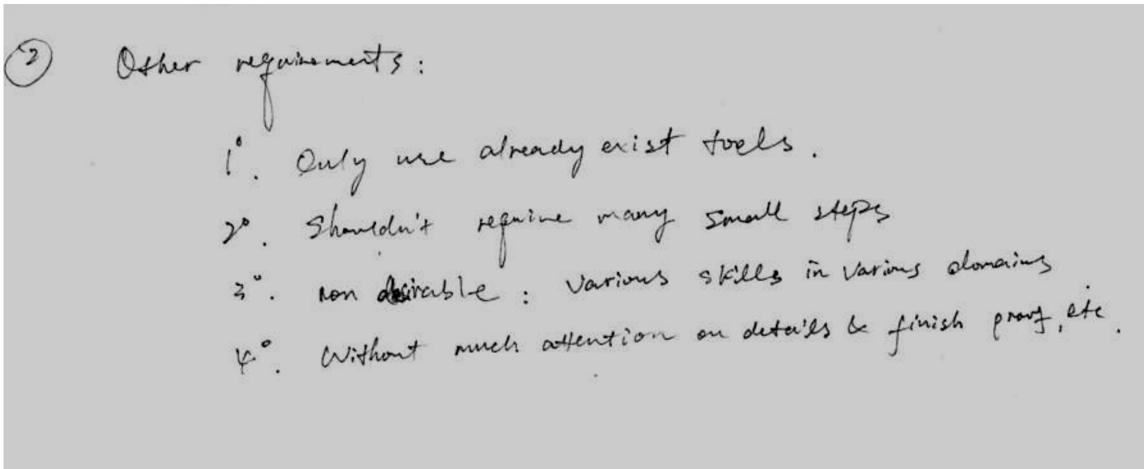


Figure 50: QFD solution for design problem 3 (page 1)



② Other requirements:

1°. Only use already exist tools.

2°. Shouldn't require many small steps

3°. non desirable: various skills in various domains

4°. Without much attention on details & finish proof, etc.

Figure 51: QFD solution for design problem 3 (page 2)

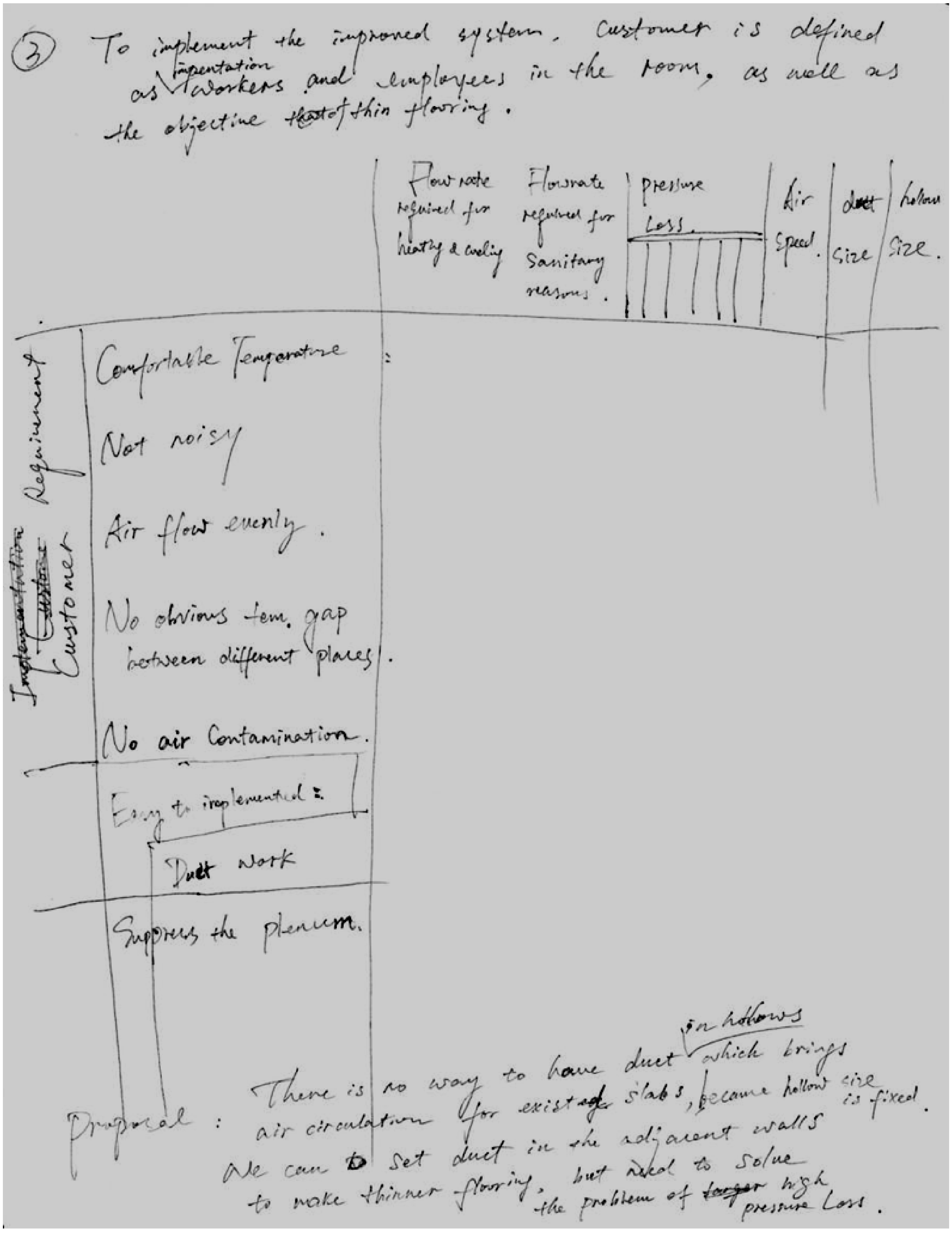


Figure 52: QFD solution for design problem 3 (page 3)

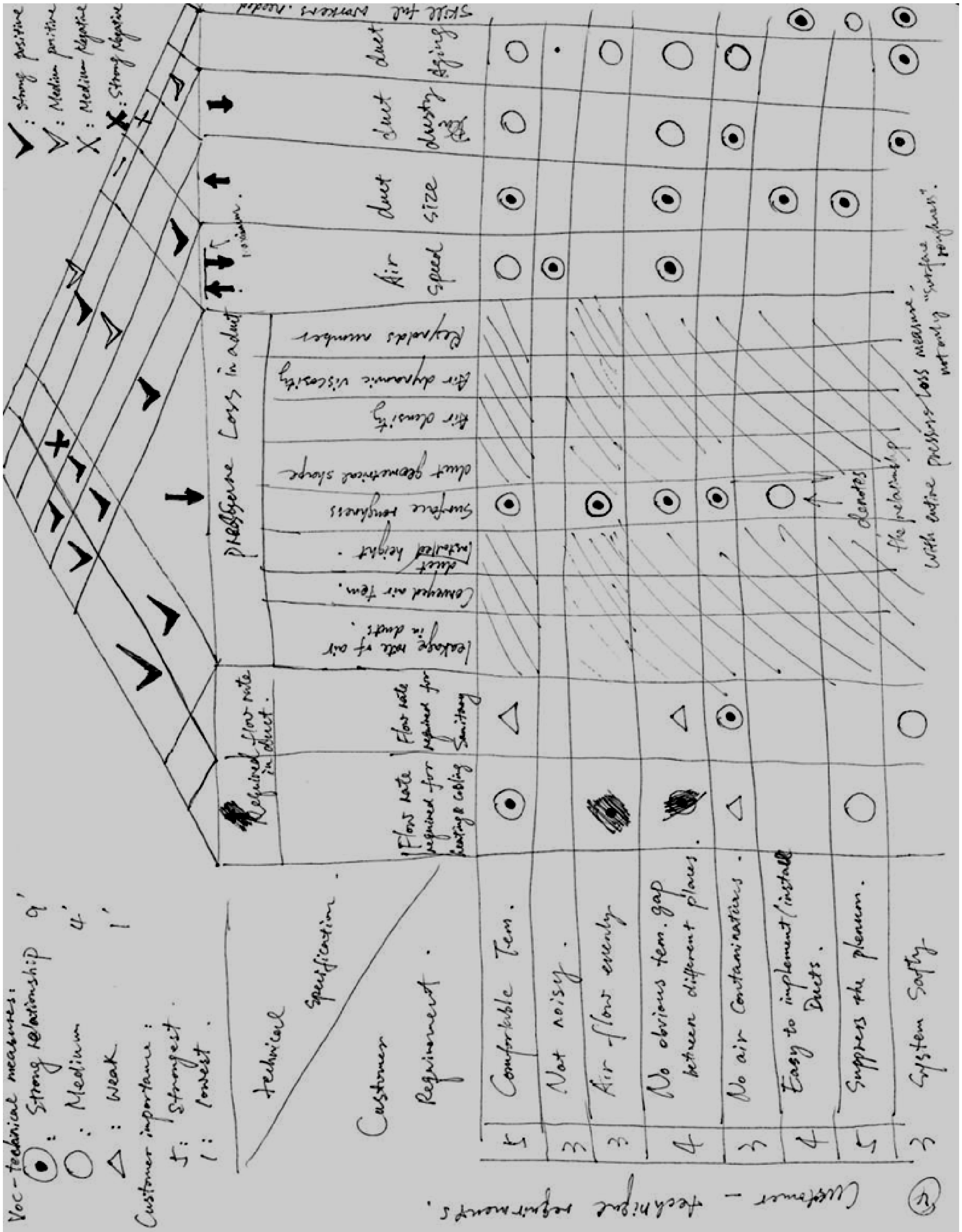
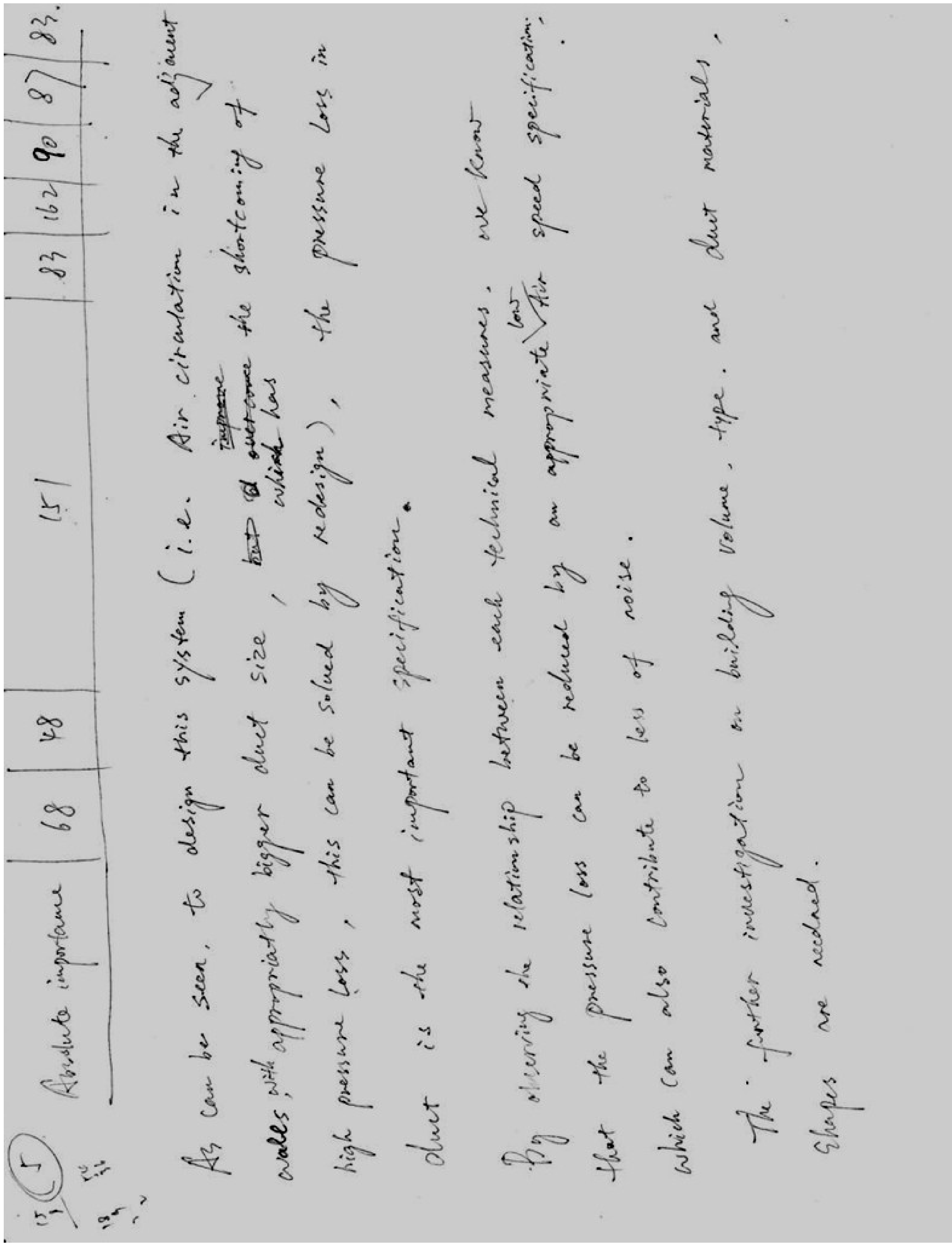


Figure 53: QFD solution for design problem 3 (page 4)



Absolute importance	68	48	151	83	162	90	87	83.

As can be seen, to design this system (i.e. Air circulation in the adjacent walls, with appropriatly bigger duct size, ~~but~~ ~~to~~ ~~overcome~~ improve the shortcoming of ~~which~~ has high pressure loss, this can be solved by redesign), the pressure loss in duct is the most important specification.

By observing the relationship between each technical measures, we know that the pressure loss can be reduced by an appropriate low Air speed specification, which can also contribute to less of noise.

The further investigation on building volume, type, and duct materials, shapes are needed.

Figure 54: QFD solution for design problem 3 (page 5)

- EBD results design problem 1:

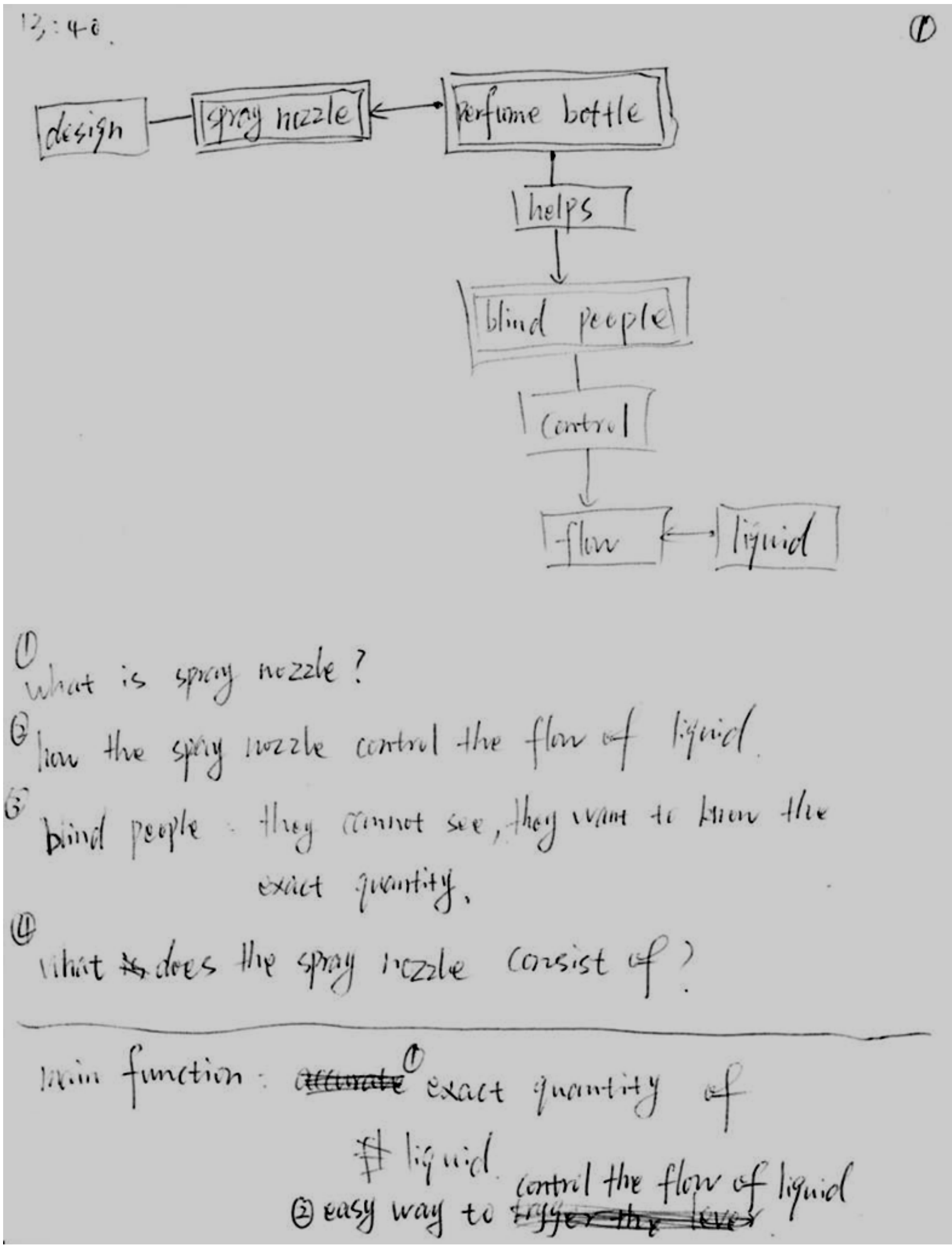
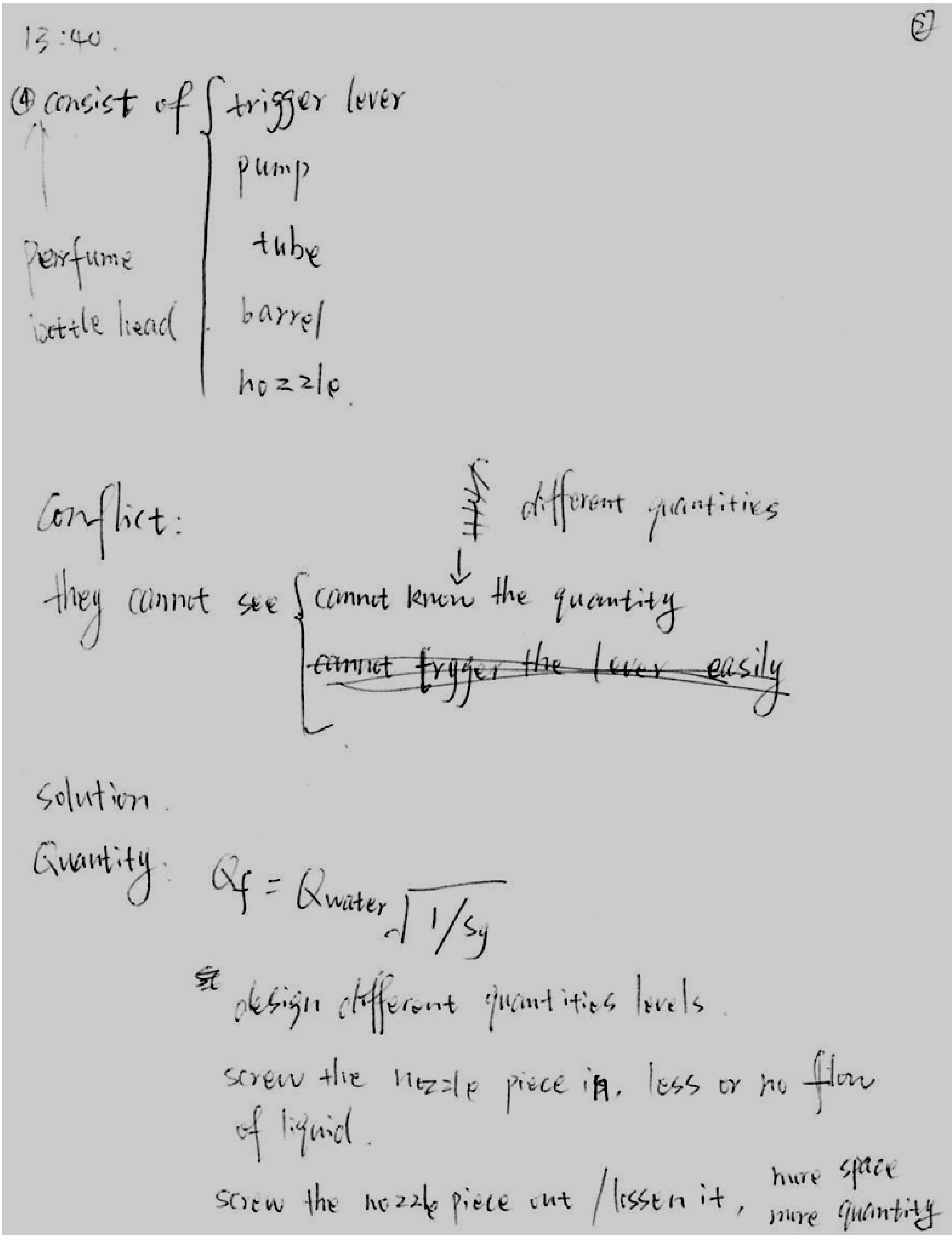


Figure 55: EBD solution for design problem 1 (page 1)



13:40.

④ consist of { trigger lever
pump
tube
barrel
nozzle.

perfume bottle head

Conflict:

different quantities

they cannot see { cannot know the quantity
~~cannot trigger the lever easily~~

solution.

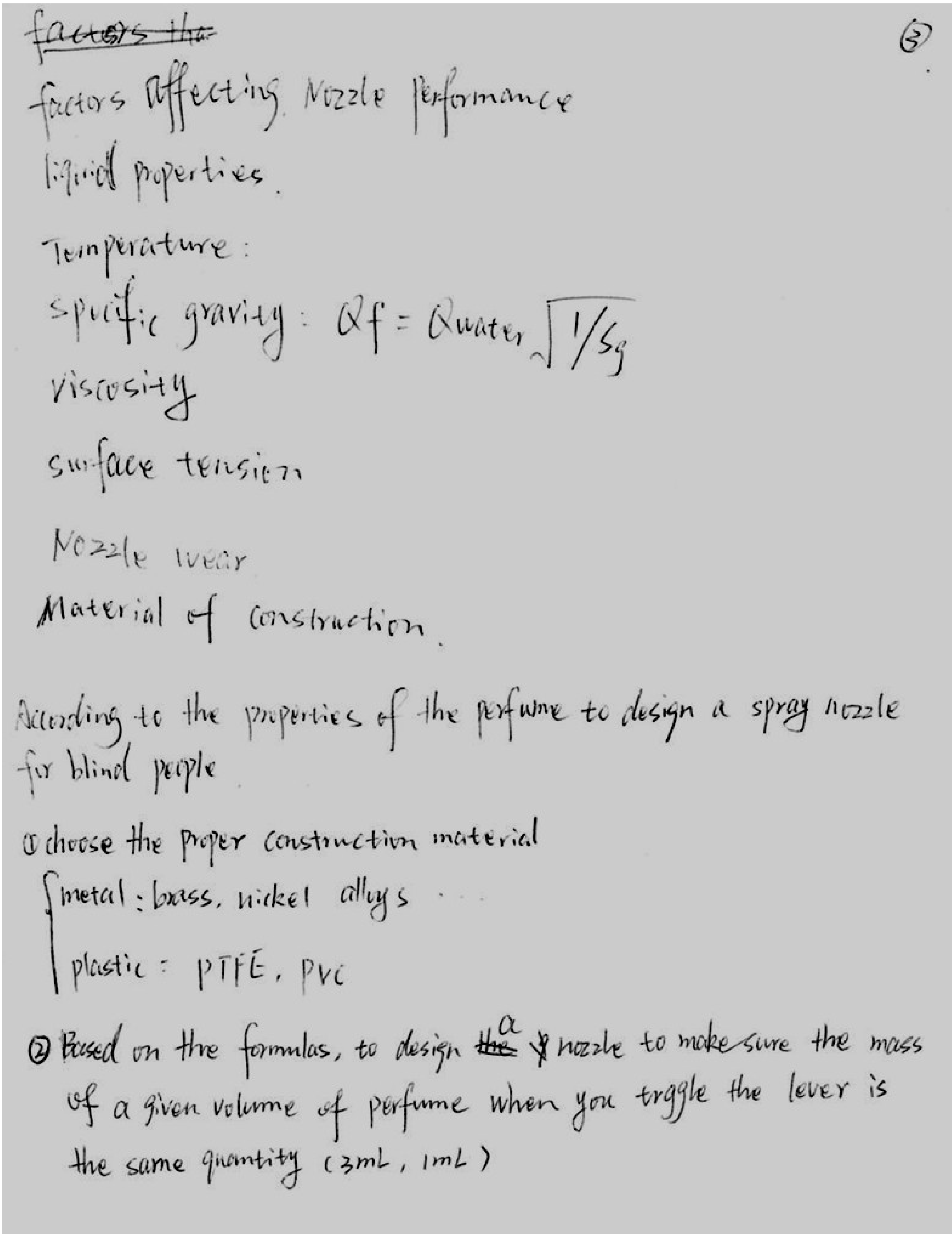
Quantity: $Q_f = Q_{water}\sqrt{1/S_g}$

design different quantities levels.

screw the nozzle piece in, less or no flow of liquid.

screw the nozzle piece out / lessen it, more space more quantity

Figure 56: EBD solution for design problem 1 (page 2)



factors Affecting Nozzle Performance

liquid properties.

Temperature:

specific gravity: $Qf = Qwater\sqrt{1/Sg}$

viscosity

surface tension

Nozzle wear

Material of construction.

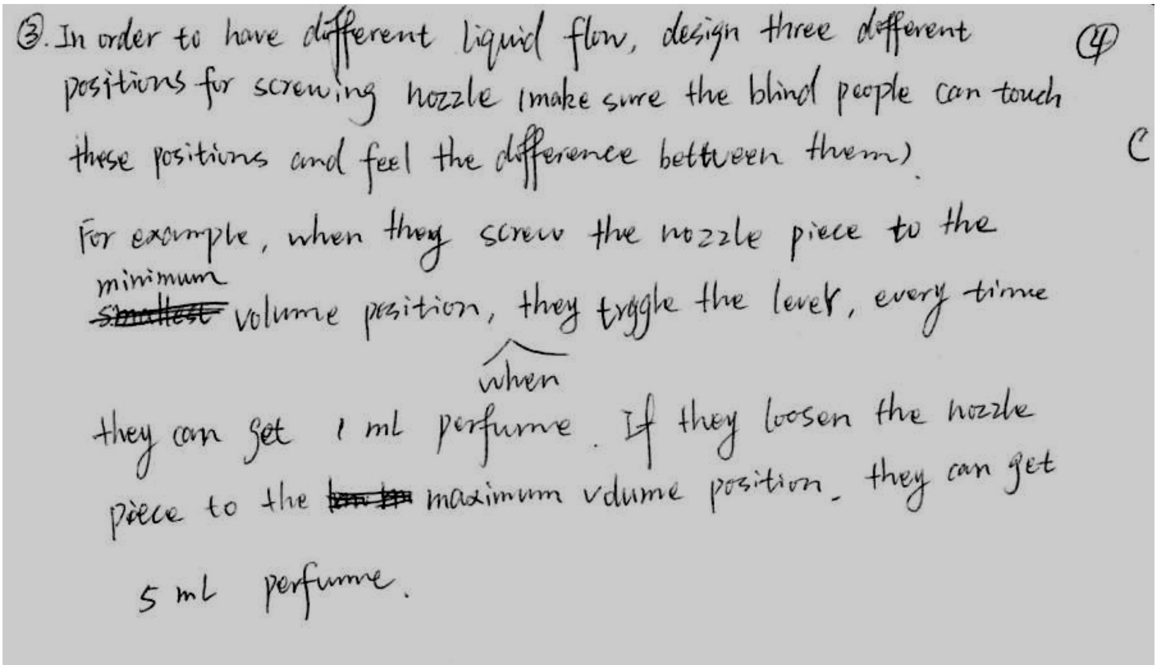
According to the properties of the perfume to design a spray nozzle for blind people

① choose the proper construction material

- metal: brass, nickel alloys ...
- plastic: PTFE, PVC

② Based on the formulas, to design a nozzle to make sure the mass of a given volume of perfume when you triggle the lever is the same quantity (3mL, 1mL)

Figure 57: EBD solution for design problem 1 (page 3)



③. In order to have different liquid flow, design three different positions for screwing nozzle (make sure the blind people can touch these positions and feel the difference between them). ④ C

For example, when they screw the nozzle piece to the ~~smallest~~ minimum volume position, they tryggle the lever, every time when they can get 1 mL perfume. If they loosen the nozzle piece to the ~~[illegible]~~ maximum volume position, they can get 5 mL perfume.

Figure 58: EBD solution for design problem 1 (page 4)

- EBD results design problem 3:

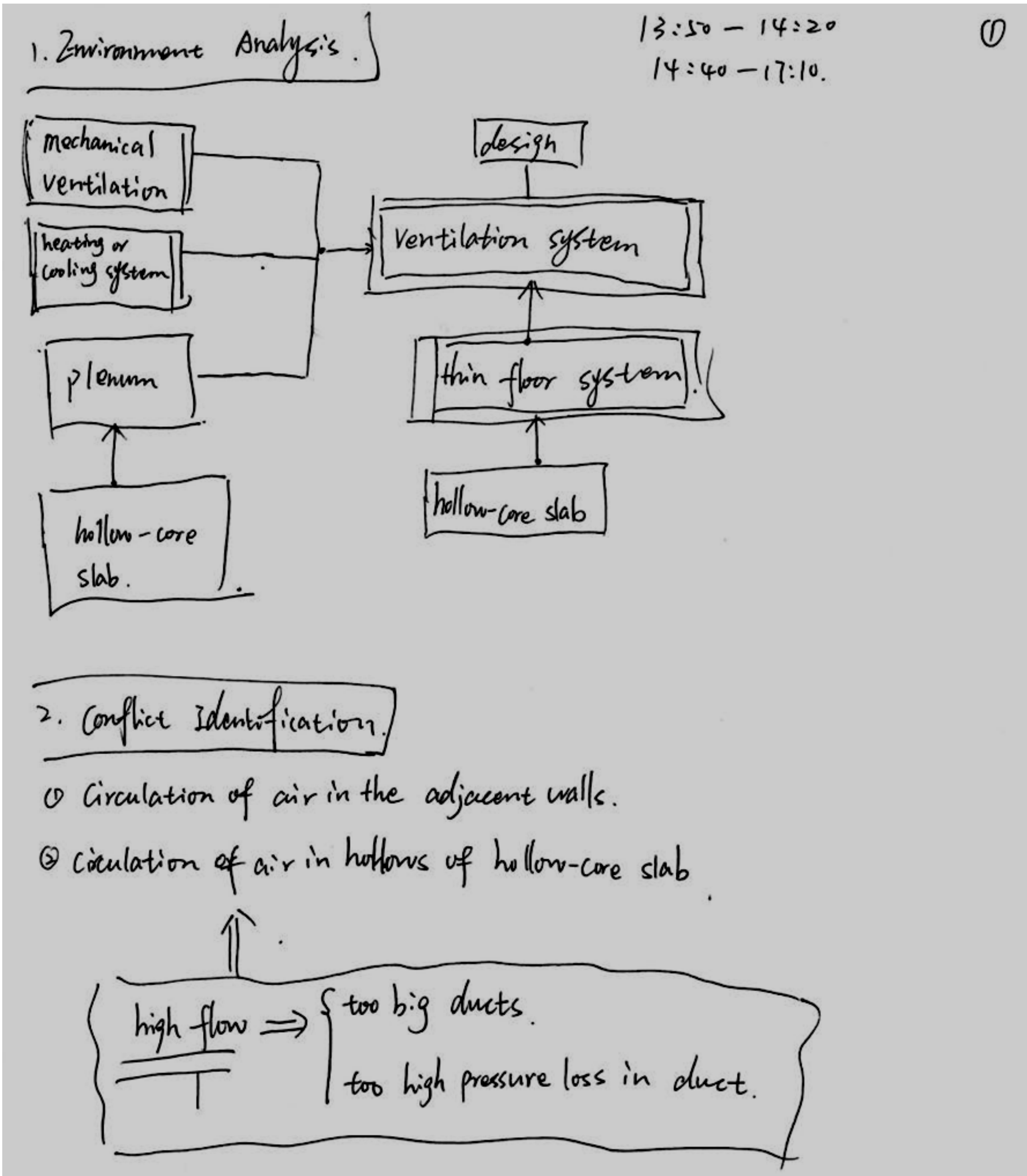


Figure 59: EBD solution for design problem 3 (page 1)

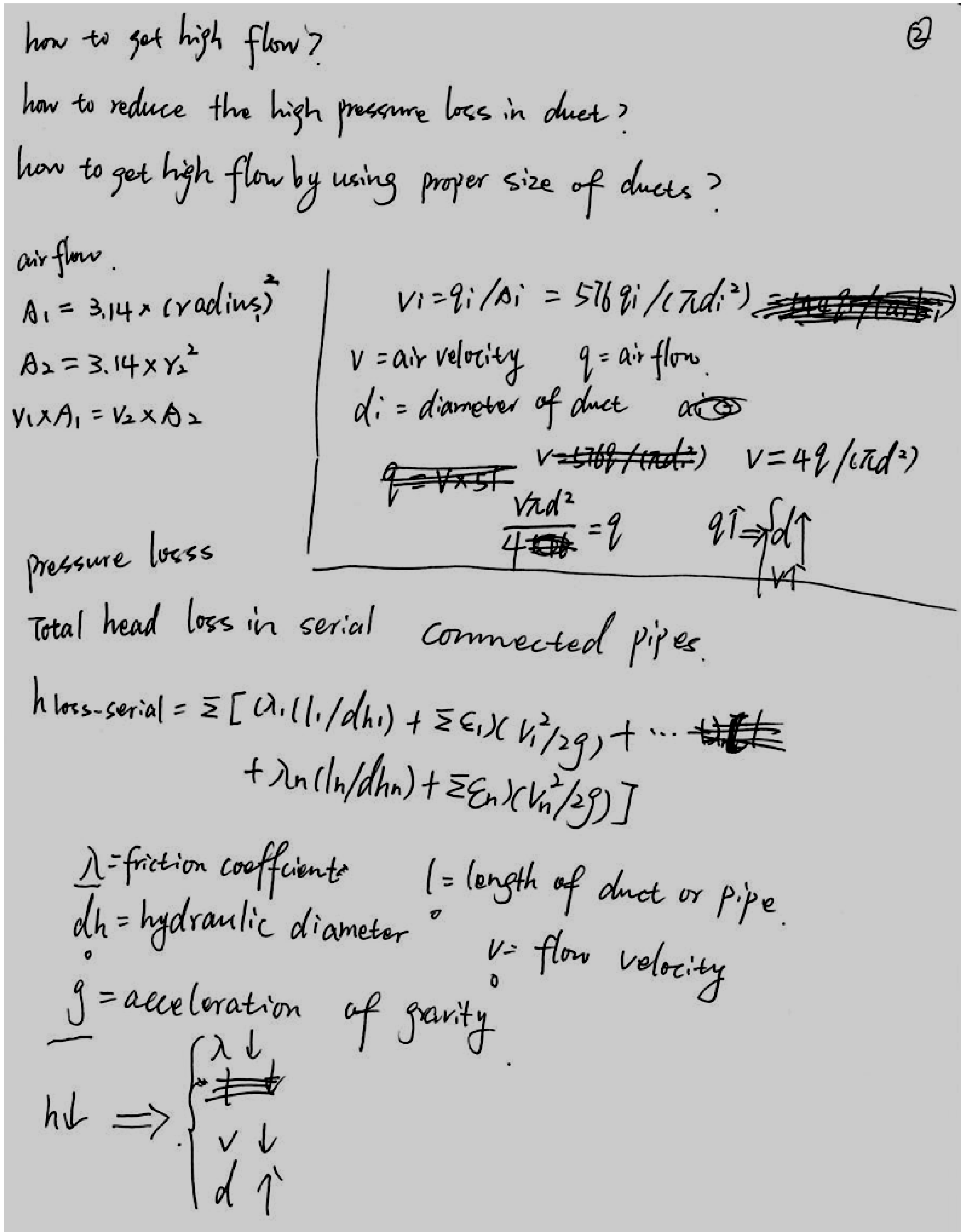
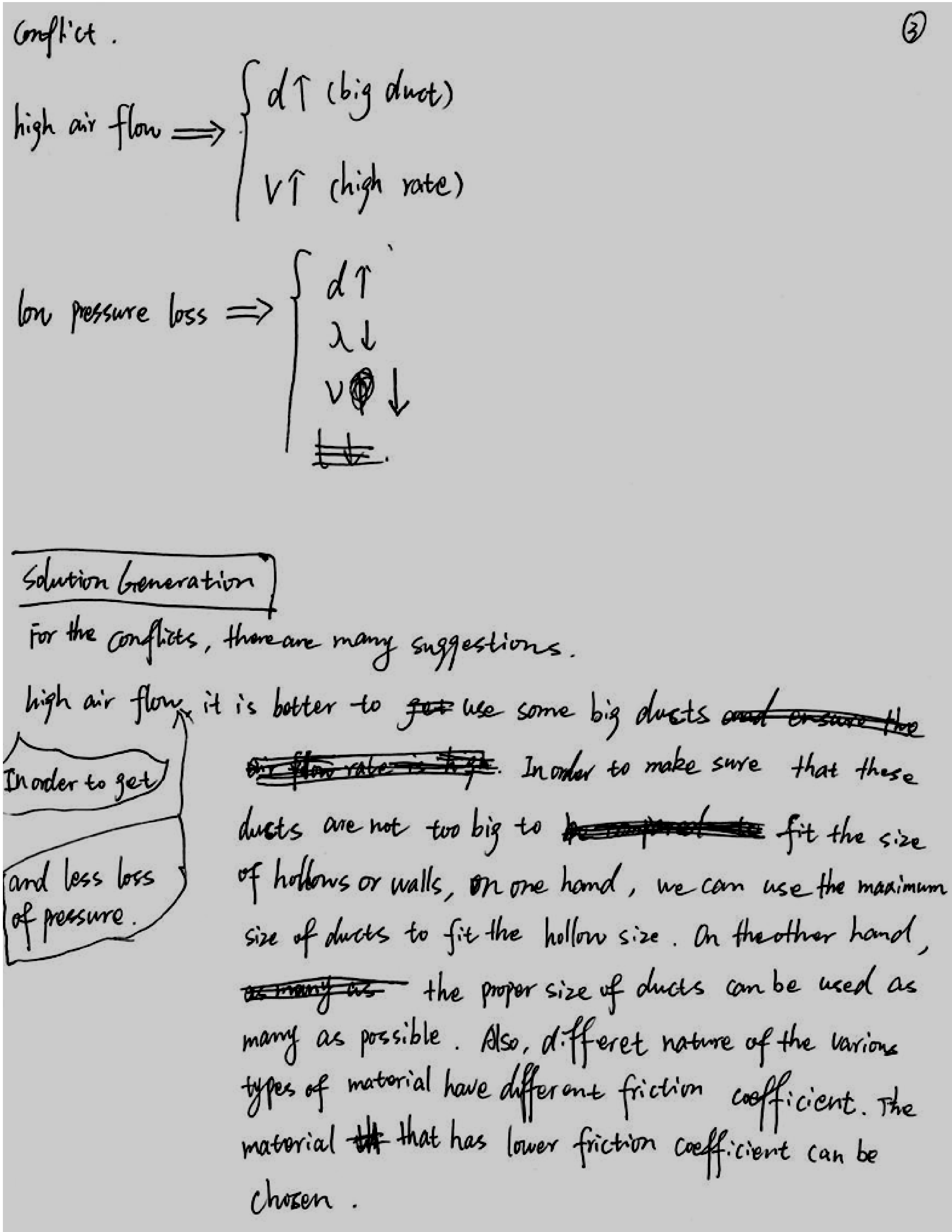


Figure 60: EBD solution for design problem 3 (page 2)



Conflict.

high air flow ⟹ { $d\uparrow$ (big duct) ; $V\uparrow$ (high rate) }

low pressure loss ⟹ { $d\uparrow$; $\lambda\downarrow$; $V\downarrow$ }

Solution Generation

For the conflicts, there are many suggestions.

high air flow, it is better to ~~get~~ use some big ducts ~~and ensure the air flow rate is high~~. In order to make sure that these ducts are not too big to ~~[illegible]~~ fit the size of hollows or walls, on one hand, we can use the maximum size of ducts to fit the hollow size. On the other hand, ~~as many as~~ the proper size of ducts can be used as many as possible. Also, differet nature of the various types of material have different friction coefficient. The material ~~th~~ that has lower friction coefficient can be chosen.

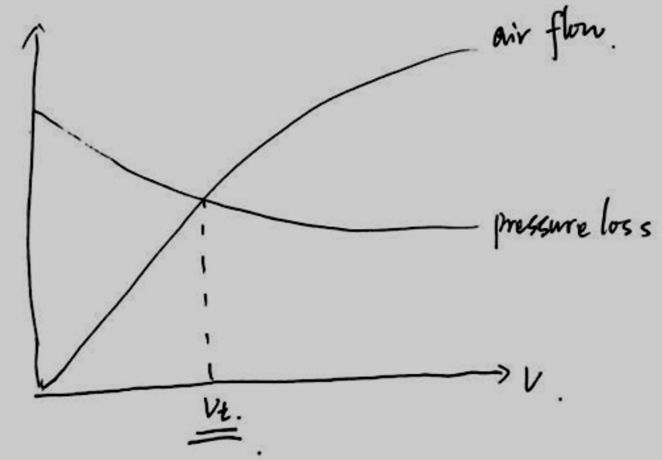
(In order to get / and less loss of pressure.)

Figure 61: EBD solution for design problem 3 (page 3)

since high flow requires high air velocity.

less high pressure loss requires lower air velocity, we can get a ④

banlance velocity which can get the ~~highest~~ best efficiency for the whole ventilation system based on calculations.



Also, to design a ventilation system, other factors also should be considered.

- heat and cooling loads
- air supply temperature
- air quantity
- temperature loss in ducts

According these data, the appriproate heaters, washers, humidifiers and coolers ~~etc~~ can be selected.

Figure 62: EBD solution for design problem 3 (page 4)

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