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Rochester Institute of Technology

PRODUCT DEVELOPMENT KNOWLEDGE-PROCESSING SYSTEM

A Thesis

**Submitted in partial fulfillment of the
requirements for the degree of
Master of Science in Industrial Engineering**

in the

**Department of Industrial & Systems Engineering
Kate Gleason College of Engineering**

by

Jiefei Qiu

B.E., Industrial Design, Hefei University of Technology, 2003

August, 2005

DEPARTMENT OF INDUSTRIAL AND SYSTEMS ENGINEERING
KATE GLEASON COLLEGE OF ENGINEERING
ROCHESTER INSTITUTE OF TECHNOLOGY
ROCHESTER, NEW YORK

CERTIFICATE OF APPROVAL

M.S. DEGREE THESIS

The M.S. Degree Thesis of Jiefei Qiu
has been examined and approved by the
thesis committee as satisfactory for the
thesis requirement for the
Master of Science degree

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ABSTRACT

This thesis develops a methodology that integrates Quality Function Deployment (QFD), Theory of Inventive Problem Solving (TRIZ) and Design Structure Matrix (DSM) to address the problem of analyzing, interpreting, and transforming the knowledge data flow during the product development process.

A product development process is the sequence of steps an enterprise takes to conceive, design, and commercialize a product. The general process includes: Planning, Concept Development, System-Level Design, Detail Design, Testing and Refinement, and Production Ramp-Up. One way to think about the development process is as a knowledge-processing system.

Prior to this study, there are few articles integrating TRIZ and QFD. QFD is a tool for “identifying the needs of the customer and translating the language of the customer into the language of the engineer”. The QFD process also identifies engineering contradictions within the existing system. TRIZ can provide solutions for these contradictions. It offers one of the most efficient means to generate creative solutions for the desired improvements prioritized in QFD. Once a creative solution is developed using TRIZ, the corresponding part characteristics can be further decomposed using QFD.

If we think of knowledge-processing as a work process, then both rework and iterative design requires additional project resources and time. Iteration is the repetition of activities due to the input of new information. DSM is an effective tool to plan and manage product development processes through information flow analysis by helping managers understand and mitigate unintentional rework or iteration.

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NOMENCLATURE

ICOM:

1. “The term ICOM refers collectively to the group of information flows between activities which have one of four roles in the activity” (Department of Defense par. 5). I, C, O and M represent Input, Control, Output and Mechanism respectively.
2. I represents a matrix as *the input of data* “used to produce the output of an activity” (Department of Defense par. 5). O represents a matrix as *the output of data* “produced by or resulting from the activity” (Department of Defense par. 5). Both I and O are usually expressed by two or three capital characters such as CR, EC and so on.
3. The rectangle represents the function process, including the Mechanism that is under constraint of Control. Control is defined as “Information that constrains or controls an activity” (Department of Defense par. 5). Mechanism is defined as “Usually people, machines, or systems that perform the activity” (Department of Defense par. 5).
4. The subscript on the right of I/O represents the sequence of the inputs/outputs through that function.
5. This thesis focuses on the data exchange during the product development process, so the content for M and O will not be discussed here.
6. Arrows represents the data movements.

Ordered Set:

$A = (a_1, a_2, a_3, \dots, a_j)$ is an “ordered set” with j elements, and also a $1 \times j$ matrix in cases

when $a_j \in \mathbb{R}$ (Jech par. 2). The definition for “ordered set” is introduced on

<http://plato.stanford.edu/entries/set-theory/primer.html#1>.

$B = (b_1, b_2, b_3, \dots, b_j)$ is just an ordered set with j elements in cases when $b_j \notin \mathbb{R}$

$$C = \begin{bmatrix} c_{11} & c_{12} & \cdot & \cdot & \cdot & c_{1N} \\ c_{21} & c_{22} & \cdot & \cdot & \cdot & c_{2N} \\ \cdot & & & & & \\ \cdot & & & & & \\ \cdot & & & & & \\ c_{M1} & c_{M2} & \cdot & \cdot & \cdot & c_{MN} \end{bmatrix} \text{ is a matrix such that } c_{mn} \in \mathbb{R}$$

$CR_m, m=1, 2, \dots, M$ ($M=7$ in this case): Customer Requirements for our product.

$IP_m, m=1, 2, \dots, M$ ($M=7$ in this case): Importance Priorities for CRs.

F1 represents the assignment of relative importance IP_m to the customer requirement CR_m , using the pair-wise comparison method.

$(EC_j \mid CR_i \text{ depends on } EC_j), i = 1, 2, \dots, M \text{ and } j = 1, 2, \dots, N$: An ordered set of Engineering

Characteristics upon which a given Customer Requirement depends, $EC = \bigcup_{i=1}^M (EC_j \mid$

$CR_i \text{ depends on } EC_j)$.

F2 is the mapping of CR to EC.

MT: A $M \times N$ matrix, showing the extent to which each CR_m is dependent upon each EC_n .

F3: Define $MT_{mn} = 0$ if CR_m is independent of EC_n ;

$MT_{mn} = 1$ if CR_m depends weakly on EC_n ;

$MT_{mn} = 3$ if CR_m depends moderately on EC_n ; and

$MT_{mn} = 9$ if CR_m depends strongly on EC_n .

$\forall m, n \quad m=1,2,\dots,M \text{ and } n=1,2,\dots,N.$

FR: The Final Importance ratings for each element of EC.

F4: The transform to get the FR values.

$$FR = IP^T \times MT.$$

$CT = (CT_{1,2} \ CT_{1,3} \ CT_{1,4} \ \dots \ CT_{1,N} \ CT_{2,3} \ CT_{2,4} \ \dots \ CT_{2,N} \ \dots \ CT_{N-1,N})$, showing “1” or “0” for the contradiction relationship between every two elements of the Engineering Characteristics.

Where $CT_{x,y} = 0$ if there is no contradiction between EC_x and EC_y ;

$CT_{x,y} = 1$ if there is a contradiction between EC_x and EC_y .

$\forall x, y \quad x=1,2,\dots,N-1 \text{ and } y=2,\dots,N.$

F5: It represents the contradiction selection from the Engineering Characteristics, using the knowledge from engineering, physics, design and other fields.

$SL^{x,y} = (SL^{x,y}_1 \ SL^{x,y}_2 \ \dots \ SL^{x,y}_z)$: An ordered set of solutions, only if $CT_{x,y} = 1$.

F6 represents the TRIZ process, using the contradiction to provide creative solutions (SL).

SS: An ordered set of solutions, selected from $SL^{x1,y1} \cup SL^{x2,y2} \cup \dots \cup SL^{xw,yw}$.

F7 represents the selected solutions (SS) from $SL^{x1,y1} \cup SL^{x2,y2} \cup \dots \cup SL^{xw,yw}$, based on our analysis and knowledge.

$NPC = (NPC_1 \ NPC_2 \ \dots \ NPC_{P1+P2+\dots+PW}) = (NPC_1 \ NPC_2 \ \dots \ NPC_E)$, E is the total number of part characteristics: An ordered set shows corresponding part characteristics for SS.

F8: To identify the part characteristics (NPC) related with SS.

NEC: The new engineering characteristics in House 2.

F9 transforms the engineering characteristics in House 1 into the new engineering characteristics in House 2.

F10: Once this creative solution is developed using TRIZ, the corresponding engineering characteristics can be further decomposed into House 2.

DM: It shows the DSM relationship matrix with 18 variables.

F11 represents the DSM process.

DP: The DSM relationship matrix after being partitioned.

F12 represents the partitioning process.

TR: The Technical Risk values for corresponding engineering characteristics.

F13: To access the Technical Risk values for each of the engineering characteristics.

RI: The Relative Importance values for corresponding engineering characteristics.

F14: To access the Relative Importance values for each of the engineering characteristics.

TS: The more effective time sequence for the product development plan.

F15: To use tearing, another approach to analyze and improve the DSM.

1 PROBLEM STATEMENT

As Fig. 1 shows, this thesis develops a methodology, which integrates Quality Function Deployment (QFD), Theory of Inventive Problem Solving (TRIZ) and Design Structure Matrix (DSM) to transform the knowledge data flow during the product development process.

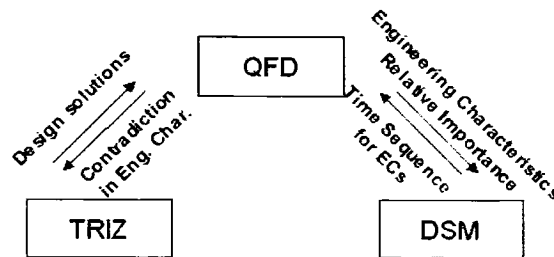


Figure 1

The process to apply this methodology is described as follow. First of all, QFD identifies the language of the customers and translates them into the language of the engineers, which is referred to as “engineering characteristics” (Terninko par. 1). The QFD process also identifies engineering contradictions within the existing product. TRIZ then provides creative solutions using these contradictions for the desired improvements prioritized in QFD. Once a creative solution is developed using TRIZ, the corresponding part characteristics of this solution can be further decomposed into House 2 using QFD. This is the process to integrate QFD and TRIZ, which is shown in Fig. 2 below.

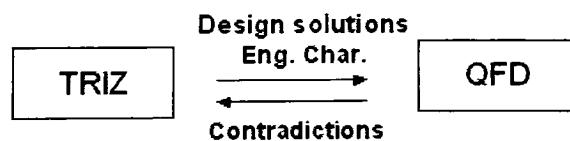


Figure 2 Data flow between TRIZ and QFD

Secondly, these engineering characteristics become variables in DSM. By reordering the variables, DSM provides a more effective product development plan for the complex process system through information flow analysis, with the input parameters such as Relative Importance and Technical Risk. This process is shown in Fig. 3 below.

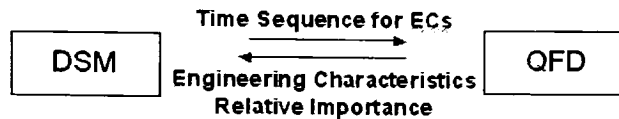


Figure 3 Data flow between DSM and QFD

Fig. 4 shows the data flow in QFD, TRIZ and DSM using time sequence.

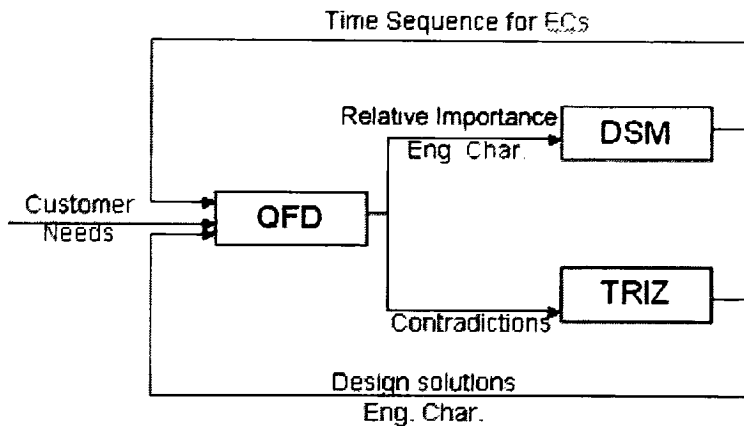


Figure 4 Data flow in TRIZ, QFD, DSM (Time sequence)

We use a tool called ICOM as shown in Fig 5 and 6 during this process. I, C, O and M represent Input, Control, Output and Mechanism respectively. Input is transformed into Output by using the Mechanism that is under constraint of Control. This function can be expressed as F_i . i is the sequence of the function. Function is defined as: “A rule of correspondence between two sets such that there is a unique element in the second set assigned to each element in the first set” (Dictionary par. 2). For example, in Fig. 5 and 6, I represents our product and the competitor’s product; O represents our future product; C

represents the control such as our manufacturing capability and so on; M represents the mechanism such as QFD and so on. Based on our manufacturing capability, F1 means that we can use QFD as a tool to analyze our product and our competitor's product, to establish the details for our future product.

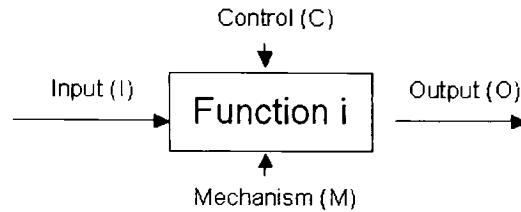


Figure 5 ICOM

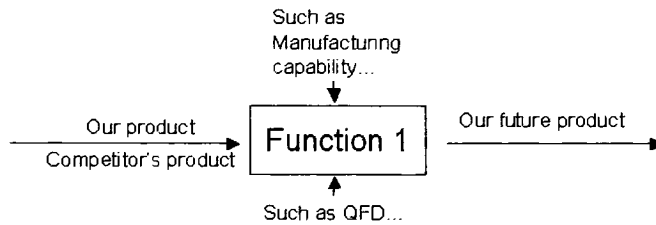


Figure 6 ICOM example

Prior to this study, there are few articles integrating TRIZ, QFD, and DSM. It is an innovative trial, but is it reasonable? In particular, the following research questions will be answer:

1. What new knowledge is gained by combing QFD, TRIZ and DSM during the design phase of a product?
2. What process should be followed to obtain the new knowledge?
3. What data structure represents the knowledge?

In an effort to answer these questions, this paper uses the product development process from a knowledge processing perspective. The knowledge processing system is then applied to a HP printer case study.

2 INTRODUCTION

2.1 Introduction to QFD

Quality Function Deployment (QFD) is a structured method to translate the voice of customers into the voice of the engineers to meet the needs (Terninko par. 1). The House of Quality is a basic design tool of QFD. It is composed of several tables, including the Customer Requirement (CR), Engineering Characteristics (EC), the Relationship Matrix between CR&EC, the Tradeoff Table, Benchmarking, and Overall Importance Table. All of these parts are shown below in Fig. 7.

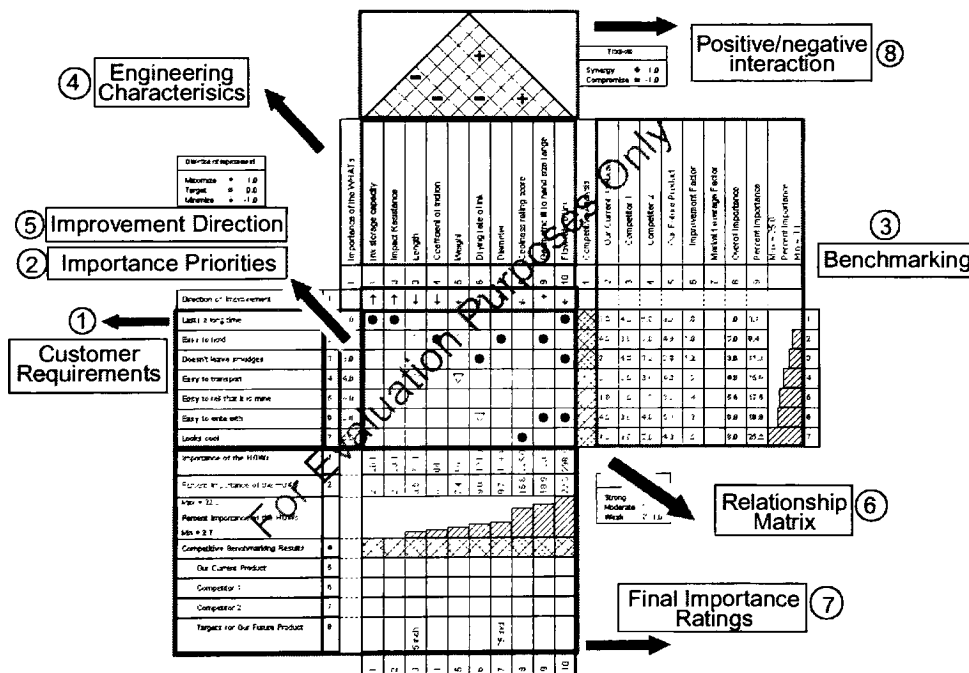


Figure 7 House of Quality

The process for using House of Quality is explained as below:

- 1. List the Customer Requirements (CR) on the left side of the matrix. The Customer Requirements are usually acquired through customer surveys.**

First of all, the customers for a product are identified. In the consumer market, there might be different kinds of customers. For example, if the product is a cellphone, the customers include both the young students and old people. The driven desire to purchase the cellphone for these two kinds of people is usually different. “There are even multiple customer voices within a single organization: the voice of the procuring organization, the voice of the user, and the voice of the supporting or maintenance organization” (Crow par. 1).

Secondly, the voice of the customers, which is also called Customer Requirements (CR), should be collected. These Customer Requirements are usually acquired from observations, surveys, feedbacks, interviews and group meetings. “Interviews are useful because they allow you to effectively probe for detail. Focus groups are productive because they allow you to develop a lot of creative ideas by having the participants build upon one another’s comments. In-context customer visits allow team members to actually observe how customers use existing products or perform existing functions and can lead to a dramatically improved understanding of what the customer really needs” (QFD Capture par. 2).

This list of CR is then entered into the left side of the matrix as shown above.

2. Evaluate the Importance Priorities for the Customer Requirements.

In this process, compare all of the Customer Requirements to each other to determine the customer Importance Priority using a 1 to 5 rating for each Customer Requirement. “Use ranking techniques and paired comparisons to develop priorities” (Crow par. 2).

3. Develop the benchmarking evaluation between our product and competitive products.

The development team compares our product with competitive products, in order to better understand what the factors are leading to the purchase. Therefore, the development team knows what the customer likes and dislikes. Based on this Customer Competitive Analysis, the development team should determine the Customer Competitive Priority Ratings, Customer Performance Goals for the Customer Requirements, and Customer Improvement Ratio.

4. Establish the Engineering Matrix (EM), which is composed of Engineering Characteristics (EC), to respond to customer requirements.

Establish the technical requirements, which are called Engineering Characteristics here, to respond to each Customer Requirement. All Engineering Characteristics are then formulated the Engineering Matrix as the Fig. 7. The Engineering Characteristics should be measurable and practical. That is to say, “The measurement should be determined without extensive data collection or testing” (Crow par. 3).

5. Decide the improvement direction for each of the Engineering Characteristics.

The development team should decide whether each Engineering Characteristic should be increased or decreased.

6. Develop the Relationship Matrix between CR and EC.

The relationship between CR and EC represents how these two lists are related with each other. This relationship might be defined by asking, “To what degree does this Engineering Characteristic predict the customer’s satisfaction with this requirement?” (Crow par. 4). The development team can determine the scale used to define the relationship. For example, it can be used with values of 1 through 10. “Standard QFD practice usually supports the values 1, 3, and 9” (Crow par. 4). Ask this question for each CR and EC combination, and then the answers can be used to develop the relationship matrix, which is shown above.

7. Develop the Target Values and Final Importance Ratings for the Engineering Characteristics.

Setting Target Values should be based on the data followed:

“The team has benchmarked the existing products to gain a good understanding of what level of actual performance is required in order to produce the desired level of perceived performance.

By evaluating the Tradeoffs between every two Engineering Characteristics in order to determine what compromises may be required and how those compromises would be made” (QFD Capture par. 26).

After considering so many data, the team sets the Target Values for each element of the EC. These values are acquired by answering the question “What

are we really going to do with respect to this product or service?” (QFD Capture par. 26).

Based on this Technical Competitive Analysis, the development team should determine the Initial Technical Ratings, the Technical Competitive Priority Ratings, Technical Target Values for the Engineering Characteristics, Technical Improvement Ratio and Final Importance ratings.

8. Use symbols to determine potential positive and negative interactions between every two Engineering Characteristics

This can be determined by asking “If we improve our performance for one element of the Engineering Characteristics, what is the impact on every other EC?” (QFD Capture par. 27). The development team will determine whether improvement of this Engineering Characteristics helps or weaken the effect of every other Engineering Characteristics and mark them using positive or negative symbols.

9. Analyze the matrix and finalize the product development strategy and product plans. Determine required actions and areas of focus.

“Finalize target values. Are target values properly set to reflect appropriate tradeoffs? Do target values need to be adjusted considering the difficulty rating? Are they realistic with respect to the price points, available technology, and the difficulty rating? Are they reasonable with respect to the importance ratings? Determine items for further QFD deployment” (QFD Capture par. 27).

2.2 Introduction to TRIZ

TRIZ is the acronym for “Theory of Inventive Problem Solving” in Russian. ARIZ is the acronym for “Algorithm for Inventive Problem Solving” in Russian. It is the main TRIZ method for solving contradiction.

ARIZ has been developed for many years, so there are several versions for it. The main parts of different versions are the same, though every version has its own features. For example, the ARIZ presented in the book *And Suddenly the Inventor Appeared* has seven steps, compared to another Americanized version of ARIZ, which has nine steps.

The Americanized version of ARIZ is used as example to introduce ARIZ as below.

1.0 “Analyze the System” (Marconi par. 15)

The purpose of this step is to build a model for the problem. The 9-screen method is one of the methods used to define the problem.

2.0 “Analyze the Resources” (Marconi par. 15)

The resources include space, time, substances and fields. By analyzing the resources of the system, subsystem, supersystem and the environment, it provides us information to deal with the upcoming Contradictions.

3.0 “Define the Ideal Final Result and Formulate the Contradiction” (Marconi par. 15)

Improving one part of a system may impair other parts of the system. This is called a Contradiction. The Contradictions are stated here, which we need to remove later. The Ideal Final Result gives us the target of the problem.

Ideal Final Result (IFR) cannot be reached sometimes, but it allows us to build a path to the solution.

4.0 “Separate the Contradiction” (Marconi par. 16)

By using resources which have been analyzed in step 2, we separate the Contradiction in order to eliminate it in the later steps.

5.0 “Apply the Knowledge Base: Effects, Standards, and Principles” (Marconi par. 16)

Apply the 40 principles to provide the solutions for the Contradiction.

6.0 “Change the ‘Mini-Problem’” (Marconi par. 16)

Sometimes, the definition and contradictions of the problem contain the limitations of psychological inertia, and then this step offers ways to revisit both of them.

7.0 “Review the Solution and Analyze the Removal of the Contradiction” (Marconi par. 17)

The solutions will be evaluated to see how well it fits the requirements of the problem.

8.0 “Develop Maximum Usage of the Solution” (Marconi par. 17)

We generalize the solution into a method, and then we would like to maximize the usage of this solution. Can this solution be applied to other cases? Seeking this answer is the purpose of the step. This step cannot give us much information for our product, but will give us useful resources in the future.

9.0 “Review All the Stages in ARIZ in ‘Real Time’ Application.” (Marconi par. 17)

Review what our actual steps were in using ARIZ. Compare the steps with the standard process, and then specify the difference, add the solutions to our knowledge database.

2.3 Introduction to DSM

The definition of a system is as follow: “A system is a collection of parts and relations between the parts such that the behavior of the whole is a function not only the behavior of the parts, but also of the relations among them” (Steward “Systems Analysis” 1). Generally speaking, we can consider the product development process as a system. As the system gets larger, it becomes more complex. Therefore, one way to understand the system is to take it apart to study the relations. As we break a system into smaller and smaller parts, the parts usually become easier and easier to understand.

There are two ways to represent the structure of the system: graph and matrix.

A graph is a combination of points (called vertices) and directed lines (called arcs) between certain pairs of points. The vertices represent the parts of a system. “An arc

which is drawn from one vertex to another vertex shows that the behavior of the one part affects the behavior of the other part” (Steward “Systems Analysis” 12). In Fig. 8, the arrow from vertex 1 to vertex 2 implies that part 1 affects part 2.

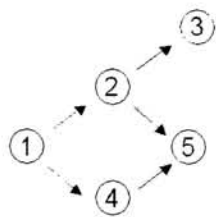


Figure 8 Graph for a system

Another way of representing the structure of a system is using a matrix called Design Structure Matrix (DSM). It is a matrix representation of a project. The purpose of DSM is to find the best way to sequence activities. For example, the graph in Fig. 8 can be represented using the matrix in Fig. 9. The cells on the diagonal are filled. The rows and the columns correspond to the parts of a system. Each cell with value “1” in the matrix corresponds to an arc in the graph. That is to say, a cell with value “1” in column i row j represents an arc from vertex i to vertex j. For example, the cell in row 2 column 1 represents an arc from vertex 1 to vertex 2.

| | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| 1 | | | | | |
| 2 | 1 | | | | |
| 3 | | 1 | | | |
| 4 | 1 | | | | |
| 5 | | 1 | | 1 | |

Figure 9 Matrix for the system

“Reading along a single row reveals all of the tasks whose output is required to perform the task corresponding to that row” (Reading the DSM par. 3). For example, activity 2 relies on information from activities 1.

“Reading down a specific column reveals which task receives information from the task corresponding to that column” (Reading the DSM par. 3). For example, activity 1 delivers information to activities 2 and 4.

The process to build a DSM is as below:

- 1) Interview the engineers to identify the appropriate system elements. List them in the DSM as labels for the rows and columns. Both of the elements in the row and column should be in the same order.
- 2) Determine the relationship between the elements, including the inputs and outputs of the system interaction.
- 3) Fill the cells on the diagonal.
- 4) Fill the value of “1” into a cell in column i row j if there is an arc from vertex i to vertex j .
- 5) Double-check the matrix with engineers and managers to verify the DSM.

Just as what was mentioned before, a system is usually broken into smaller and smaller parts to become easier to understand. There are two approaches to do this: partitioning and tearing. These two processes will be introduced when they are applied in this thesis.

3 LITERATURE REVIEW

3.1 An Introduction to QFD, TRIZ and DSM

TRIZ is the acronym for "Theory of Inventive Problem Solving" in Russian.

DSM is a tool to represent the task interactions of a project. It is a matrix with m rows and columns. "If there is an information dependency from task i to task j , then the cell of element ij is marked with an X. Otherwise, the cell of element ij is left empty" (Yassine and Falkenburg 224).

There are two main categories of DSMs: static and time-based. Terninko gave us the definition as below:

1) "Component-Based or Architecture DSM: Used for modeling system architectures based on components and/or subsystems and their relationships.

2) Team-Based or Organization DSM: Used for modeling organization structures based on people and/or groups and their interactions.

3) Activity-Based or Schedule DSM: Used for modeling processes and activity networks based on activities and their information flow and other dependencies.

4) Parameter-Based (or Low-Level Schedule) DSM: Used for modeling low-level relationships between design decisions and parameters, systems of equations, subroutine parameter exchanges etc" (292-293).

All of the examples for this definition are shown in Fig. 10.

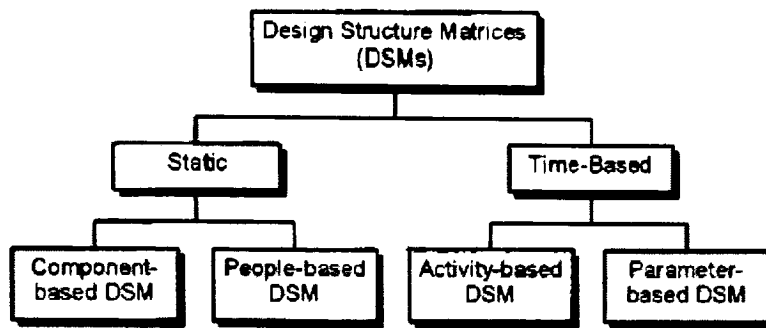


Figure 10 DSM taxonomy

Sabbaghian, Eppinger and Murman introduced three types of task interactions of DSM. “In Figure 11, Tasks 1 and 2 are ‘independent’ since no information is exchanged between them. These tasks can be executed simultaneously (in parallel). Tasks 3, 4, and 5 are engaged in a sequential information transfer and considered ‘dependent’. These tasks would typically be performed in series. Tasks 7 and 8, however, are mutually dependent on information. These are ‘interdependent’ or ‘coupled’ tasks often requiring multiple iterations for completion” (par. 12).

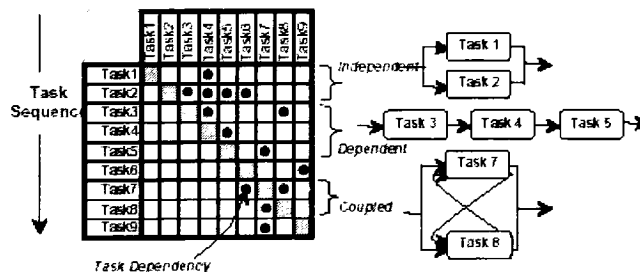


Figure 11 Sample Task-based Design Structure Matrix

Sabbaghian, Eppinger and Murman also introduced Data-Driven Approach as follow. “A dependency (marked cell) is created once a task’s output is defined as input to another task in the process. Figure 12 presents a sample DSM constructed using explicit

information flow. As seen, the dependency between tasks 5 and 7 in the DSM results from task 7” (par. 15).

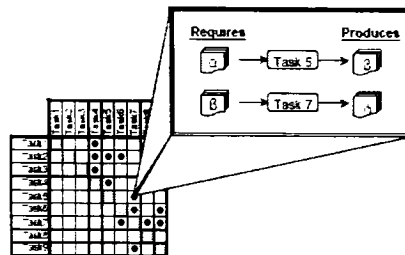


Figure 12 Sample DSM with explicit information flow

DSM can be decomposed into a hierarchy of smaller DSMs as Figure 13. “The modeling effort begins from the highest level activities and deliverables in a project (called Level 1). Next, each high-level task is further decomposed into a set of sub-tasks forming a series of level 2 DSMs” (Sabbaghian, Eppinger and Murman par. 19).

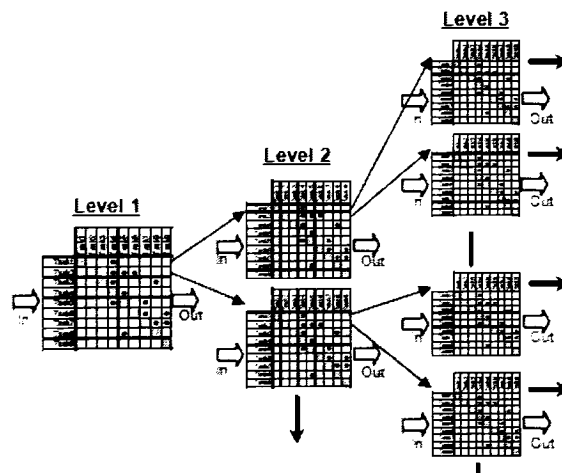


Figure 13 Multi-tiered DSM configuration sample

3.2 The QFD, TRIZ and Taguchi Connection: Customer-Driven

Robust Innovation (Terninko)

This paper combines Quality Function Deployment (QFD), TRIZ, and Taguchi in the design process. In my thesis, I also combine QFD and TRIZ, but the approaches of these two papers are different. This paper just gave me some thoughts about how to combine them.

After gathering the customer requirements (the voice of the customer), QFD translates them into design requirements (the voice of the engineer) (par. 1). The TRIZ methodology provides creative solutions for the design improvements.

The process combining QFD and TRIZ is as follow.

- “The first step is to identify the customer requirements, and then rank the priority of the requirements. TRIZ allows a more aggressive attitude because of the possibilities offered by the technical lines of evolution.
- The second step is to understand the customer's needs. The voice of the customer context table should add the system and environment resources to the "who," "what," "where," "when" and "how" information needed in TRIZ.
- The third step maps the subjective demanded quality information of the customer into the objective measures of performance used by the engineer. The matrix used is called the House of Quality. If a product is a model upgrade, it is important to identify contradictions between different performance measures. TRIZ can provide solutions for these contradictions.

- The fourth step is concept generation. This is one of the most powerful aspects of TRIZ. TRIZ would generate many alternatives for the improvement in the reliability, manufacturability, cost, and environmental impact.
- The last step is about the manufacturing process. TRIZ provides for a search for technologies which can improve process, the equipment and the capability of their current technology” (par. 31-66).

3.3 A Framework for Design Process Specifications Management (Yassine, and Falkenburg)

This paper mainly focuses on Design Process Specification Management, but there are still some useful approaches to DSM, which are related with my thesis.

Firstly, the paper introduced DSM in section 2. Then it introduced axiomatic design in section 3. Section 4 combined them through a sensitivity design structure matrix (SDSM) representation. Section 5 was about the new concept of specification management. Section 6 presented an application example of the new method. Section 7 proposed a generalized graphical solution. Finally, Section 8 presented a summary and some concluding remarks.

SDSM can be considered as the improved DSM. It gives us a new method to improve the design process, by combining DSM and axiomatic. “In the SDSM matrix, the off-diagonal entries in row i and column j represent the partial derivative for the output of task i to the output of task j : $\partial O_i / \partial O_j$. Extending the classical DSM representation by the inclusion of the sensitivity coefficients allows us to understand and capture the design process task interactions more accurately than the binary DSM.” (226).

From this paper, I can learn three methods.

- Sometimes, we can use mathematical knowledge to improve existing models.
- We can also combine two methods (models) in our research.
- It is a good choice to use graphical tools in some research. From the graphical perspective, the relationship between the parameters will become more obvious.

3.4 Product Development Process Capture and Display Using Web-Based Technologies (Sabbaghian, Eppinger and Murman)

“Today’s large product development programs can be divided into hundreds of cross-functional teams, characterized by the participation of thousands of designers, working on hundreds of thousands of tasks over a period of several years” (par. 5). Automobiles, rockets, or satellites are typical examples of such products.

Now, the information needed in the development process is usually obtained by tremendous interviews and cross-function group meetings. However, there are some problems during this process. Just as what Sabbaghian, Eppinger and Murman said, “Significant effort is spent facilitating interactions among users in order to resolve data integration issues”. “This synchronous data acquisition approach is logistically difficult to carry out and is therefore time consuming” (par. 27-28). Internet technology was chosen as the most suitable infrastructure for the proposed system due its ease of deployment, cross platform capabilities and flexibility in data capture (par. 33).

“The system has been developed on the Windows NT platform using Java, Active Server Pages (ASP), MS SQL-Server RDBMS and JDBC middleware” (par. 24).

3.5 Apply the Design Structure Matrix to System Decomposition and Integration Problems: A Review and New Directions (Browning)

This paper reviews four DSM applications: Component-Based or Architecture, Team-Based or Organization DSM, Activity-Based or Schedule DSM, and Parameter-Based DSM. It also discusses research directions and new DSM applications.

The fourth part of the paper focuses on Information Flow-Based Process Modeling Using the Activity-Based DSM. The knowledge here is much related with my thesis, so I would like to focus on this part. It is helpful to think of product development from an information processing perspective. First, we use the DSM to describe the input/output activities based on the information flow, to show the dependency structure of a process. Then, the DSM is rearranged to show the improved process architecture, which will minimize the unintentional iteration.

- 1) Decompose the process into activities;
- 2) Document the information flow among the activities (their integration);
- 3) Analyze the sequencing of the activities into a (generally) maximally feed forward process flow.

The widely practiced initial step in analysis is called partitioning. Besides these methods, there are several other methods to resolve the coupled blocks of activities into a feasible execution sequence. The following two methods are the ones related with my thesis.

- “Aggregation: While aggregating two or more activities into a single activity to reduce subdiagonal marks and simplify the DSM may seem attractive, doing so makes the model less useful by ‘sweeping under the rug’ the very issues it should expose.

- Decomposition: Decomposing coupled activities can reveal ways to intermingle the lower-level activities that eliminate feedback” (299).

3.6 Design of Objective Functions for Optimization of Multi-Domain Systems (Andersson, Jochen and Petter)

Multi-domain systems can be characterized as complex systems, which combine different fields of engineering (1). The aircraft landing gear in the paper is a true example of a multi-domain simulation problem, because it is combined of mechanical, electrical and hydraulic sub systems.

“The landing gear system consists of the actual landing gear, the hydraulic actuator that creates the retardation movement and the hydraulic supply system” (1).

First of all, the paper used DSM to analyze the system. As we can see from Fig. 14, the DSM method can visualize the coupling between different design tasks for the gear design process. We also find that the parameters for the system that creates the movement are totally dependent on the landing gear parameters but not the other way around. This indicates that these two design processes can be done in sequence (3).

| Landing gear leg | | | | | Movement control | | | | | | | | | |
|------------------|---|---|---|---|------------------|---|---|---|--------|---|---|---|---|------------------|
| | | | | | Actuation | | | | Supply | | | | | |
| | A | B | C | D | E | F | G | H | I | J | K | L | M | |
| A | ● | X | | | | | | | | | | | | Wheel diameter |
| B | X | ● | | | | | | | | | | | | Number of wheels |
| C | X | | | | | | | | | | | | | Leg length |
| D | | | ● | X | | | | | | | | | | Leg diameter |
| E | | | X | ● | | | | | | | | | | Supporting beam |
| F | | | X | X | ● | | | | | | | | | Length of lever |
| G | X | X | X | X | | ● | X | X | X | X | | X | | Angle of lever |
| H | X | X | X | X | | X | ● | X | X | X | | X | | Piston Area |
| I | X | | X | | | X | X | | ● | | | | | Piston stroke |
| J | | | | | | | | X | | ● | | | | System pressure |
| K | | | | | | | | X | X | X | ● | | | Valve size |
| L | | | | | | | | X | X | | | ● | X | Pump size |
| M | | | | | | | | X | X | X | | X | ● | Accumulator size |

Figure 14 Design Structure Matrix for the landing gear design process

Secondly, it used QFD to analyze the system.

- “Establish the characteristics of the landing gear system on the vertical axis on the left in Figure 14. Some characteristics come from aircraft regulations (FAR) that have to be fulfilled, i.e. these are demands that the system has to meet, for instance minimum descending velocity or maximum brake distance” (3). Other characteristics come from the customer requirements.
- List the system parameters (engineering characteristic) on the horizontal axis.
- As being shown in Fig. 15, fill the matrix to express the relationship between the system characteristics and the system parameters.

| | | Weighting | System Parameters | | | | | | | | | | | | | |
|------------------------|--------------------------|-----------|-------------------|------------------|------------------|--------|------------------|--------------|--------------|-------------|-------------|---------------|------------|-----------|------------------|----------------|
| | | | Wheel | | | | Landing gear leg | | | Actuator | | Hyd. Supply | | | | |
| | | | Supporting beam | Wheel dimensions | Number of wheels | Brakes | Leg length | Leg diameter | Lever length | Lever angle | Piston area | Piston stroke | Valve size | Pump size | Accumulator size | Pressure level |
| System Characteristics | Descending velocity | D | | | | | 5 | 5 | | | | | | | | |
| | Retraction time | D | | | | | | | 5 | 5 | 5 | 5 | | | | |
| | Weight | 3 | | 5 | 5 | 5 | 5 | 5 | | | 1 | 1 | 1 | 3 | 3 | |
| | Energy consumption | 3 | | 5 | 5 | 5 | 5 | 5 | 1 | 1 | 3 | 3 | 3 | 3 | 3 | 3 |
| | Price | 1 | 3 | 3 | 3 | 5 | 5 | 5 | | | 1 | 1 | 1 | 3 | 1 | |
| | Ground carrying capacity | D | | 5 | 5 | | | | | | | | | | | |
| | Locking landing gear | D | 5 | | | | | | | | | | | | | |
| | Brake distance | D | | | | 5 | | | | | | | | | | |

Figure 15 Relationship matrix for the landing gear system

Then the paper used the simulation package Pro Mechanica Motion, which is a Multi-Body-Simulation (MBS) environment and HOPSAN package to analyze the system.

3.7 The Design Structure System: A Method for Managing the Design of Complex Systems (Steward “The Design Structure System”)

This paper applied the techniques of the Design Structure System to develop an effective engineering plan in the process of the design of a system.

System design involves the determination of interdependent variables. “Before some variables can be determined, other variables must first be known or assumed. For example, A cannot be determined unless B is first known or assumed, but B cannot be determined unless A is first known or assumed. This implies a precedence order of the variables, and consequently of the tasks of determining these variables” (71).

This paper introduced two approaches to rearrange the DSM to generate a faster development process: Partitioning and Tearing.

“Partitioning is the process of manipulating (i.e. reordering) the DSM rows and columns such that the new DSM arrangement does not contain any feedback marks.” It is an ideal way to transform the DSM into a lower triangular form. However, it is hard to do so for complex engineering systems. Therefore, “the variables can be reordered so as to confine the marks in the matrix to appear either below the diagonal or within square blocks on the diagonal.” “The variables with the block each depend on all the other variables in the same block and, therefore, cannot be determined one at a time without making estimates.” Then, the next step is to break the circuits to find a place to begin the iteration. (72)

“Tearing is to choose a set of marks representing where we might make estimates.” We want to remove these marks so that no marks then would appear above the diagonal. That means no additional estimates need to be made. The marks we removed are called tears. “The first choice of marks to tear is those that the engineer feels would make good estimates. These are the predecessors that he already has a good estimate for, or, can make a poor estimate for without significantly affecting the variables they precede. We assign these a high-level number, e.g., 9. High numbers may be used to indicate the better places to tear, lower numbers may be used to indicate where estimates are harder to make. We usually use level numbers in the range from 6 to 9 to indicate these sensitivities. If this tearing leaves a reduced matrix with blocks containing more than one variable, then we still have circuits that have not been torn yet. We have to make further tears to break these circuits. We usually use level numbers in the range from 1 to 5 to show these tears.” (72-73)

3.8 Planning and Managing the Design of Systems (Steward “Planning and Managing”)

This paper presents a method for planning the design process by applying partitioning, tearing and using shunt diagrams into DSM.

The paper by the same author The Design Structure System: A Method for Managing the Design of Complex Systems has introduced partitioning and tearing well, so I will focus on how to use shunt diagrams here. The purpose of tearing is to choose a set of marks where we might make estimates, and then we can break the iteration.

First, there are some concepts we shall know. A principal circuit is the longest circuit we can find in the block. Now there are four paths between nodes in this principal circuit which have no arc or other node in common with the principal circuit. These are called shunts. Two paths between the same nodes in the same directions are said to be parallel. Otherwise, they are called ant parallel. In Fig. 16, B represents the shunt begins at the node; E represents the end of the shunt; P shows the number of shunts that pass this node neither beginning nor ending here; S shows the number of parallel shunts; I shows the largest index of any of the parallel shunts.

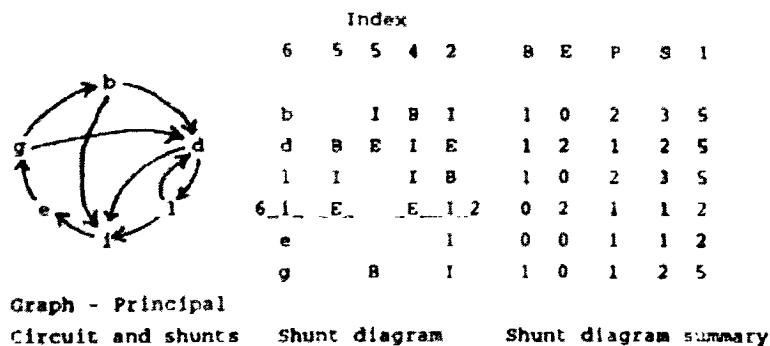


Figure 16

There is no unique or optimal answer for tearing. The paper here gives us three methods that can be used. The first is to tear the principal circuit where P is low. We can tear either the arcs entering the node (just above the node) or the arcs exiting the node (just below the node). The second is to tear where S is small, giving a big drop in the size of the remaining block, as in Fig. 17. We can choose multiple tears in the principal circuit so no single shunt crosses all the lines, as in Fig. 18.

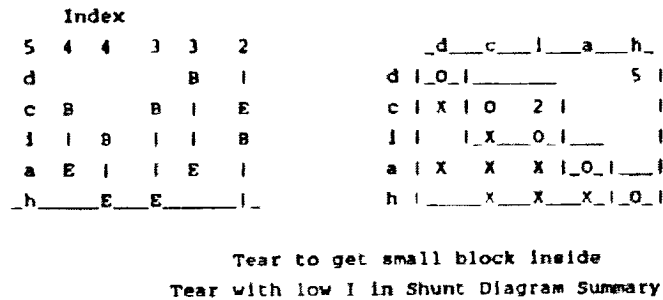


Figure 17

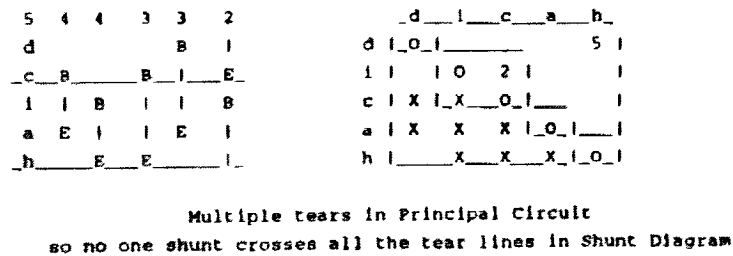


Figure 18

4 PRODUCT DEVELOPMENT KNOWLEDGE- PROCESSING SYSTEM

4.1 Architecture of HP DeskJet 1200C

In order to explain the new methodology in this thesis clearly, the methodology is applied into the HP DeskJet 1200C Printer case.

“The DeskJet 1200C made a quantum leap in the already impressive DeskJet capabilities” (Printer Works par. 1).

First of all, the printing mechanism is explained in this part.

As the Fig. 19 below shows, the printing system components consist of the paper advance mechanism (stepper motor, drive shafts, and gearing system), the print cartridges, the carriage and its axis, the carriage drive (dc motor, belt, pulleys, etc.), the main heater, and the vapor removal system.

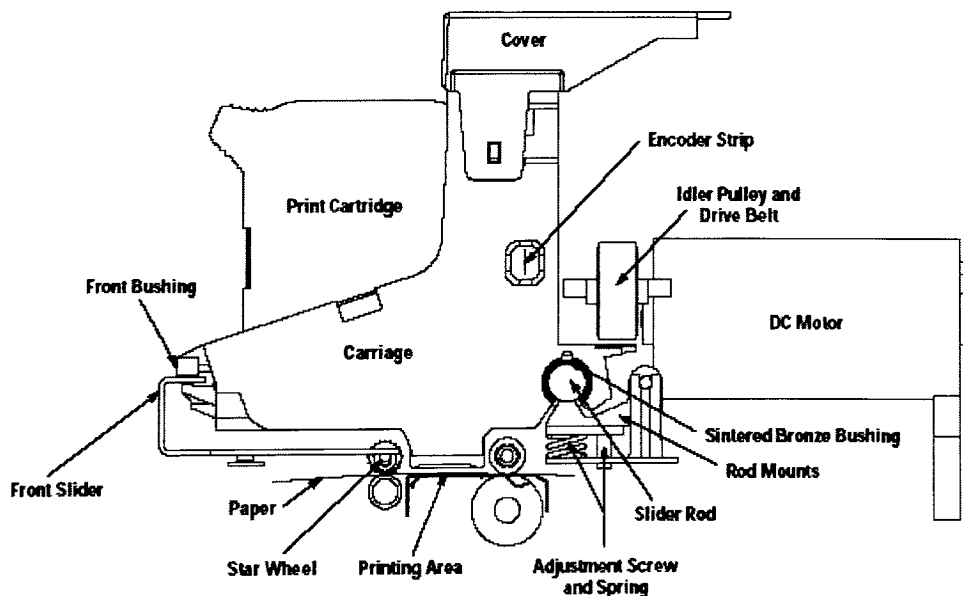


Figure 19 DeskJet 1200C architecture (Dangelo 69)

The printing process is explained as followed. “Media stacked in the input tray (1) is individually picked by a media pick roller (not shown) and driven around the curved preheat zone (2) where it is preconditioned (moisture is driven off and the temperature is raised). When the page reaches the pinch/drive rollers (3), the main drive system (4) takes over from the pick roller drive (not shown). Once in the print zone (5) the media is heated further and ink is sprayed onto the page. The heating, soaking, and drying causes the media to move out of its plane, but the media control shims (6) help hold it flat for better print quality. The page is then incrementally advanced and printed upon until the entire page has been printed. Finally, the page is fed out into the output tray (7) and the process is ready to repeat” (Broder 74). This whole process could be understood with the help of Fig. 20.

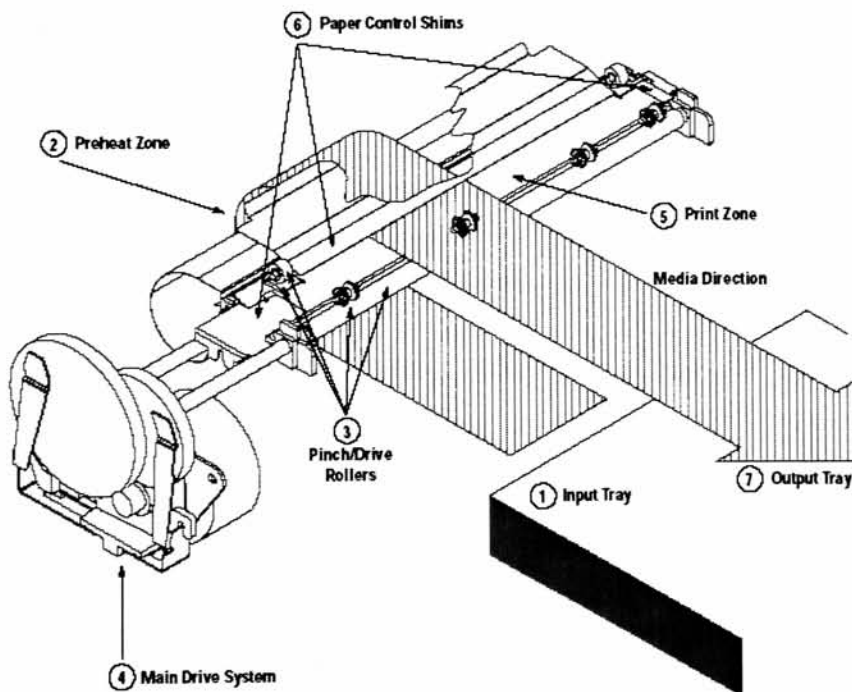


Figure 20 Overview of the media path of the HP DeskJet 1200C printer (Broder 72)

4.2 The Network of ICOMs overview

We use a tool called ICOM as shown in Fig 21 and 22 during this process. I, C, O and M represent Input, Control, Output and Mechanism respectively. Input is transformed into Output by using the Mechanism that is under constraint of Control. This function can be expressed as F_i . i is the sequence of the function. Function is defined as: “A rule of correspondence between two sets such that there is a unique element in the second set assigned to each element in the first set” (Dictionary par. 2). For example, in Fig. 21 and 22, I represents our product and the competitor’s product; O represents our future product; C represents the control such as our manufacturing capability and so on; M represents the mechanism such as QFD and so on. Based on our manufacturing capability, F1 means that we can use QFD as a tool to analyze our product and our competitor’s product, to establish the details for our future product.

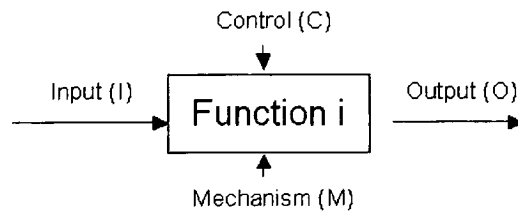


Figure 21 ICOM

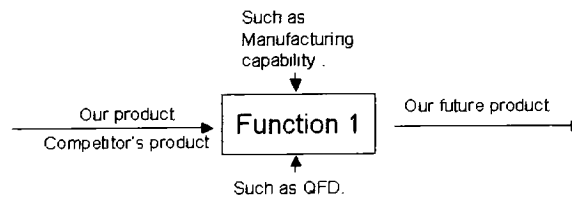


Figure 22 ICOM example

For the purpose of representing the data movement in the whole product development knowledge processing system, we use a graphic network of ICOMs showing data flows, data processes, and data sources/destinations.

Throughout the follow discussion, the definitions for the symbols used in Figures 23 – 67 are as follow:

1. “The term ICOM refers collectively to the group of information flows between activities which have one of four roles in the activity” (Department of Defense par. 5). I, C, O and M represent Input, Control, Output and Mechanism respectively.
2. I represents a matrix as *the input of data* “used to produce the output of an activity” (Department of Defense par. 5). O represents a matrix as *the output of data* “produced by or resulting from the activity” (Department of Defense par. 5). Both I and O are usually expressed by two or three capital characters such as CR, EC and so on.
3. The rectangle represents the function process, which transforms input data to unique output data. This process includes the Mechanism that is under constraint of Control. Control is defined as “Information that constrains or controls an activity” (Department of Defense par. 5). Mechanism is defined as “Usually people, machines, or systems that perform the activity” (Department of Defense par. 5).
4. The subscript on the right of I/O represents the sequence of the inputs/outputs through that function.
5. This thesis focuses on the data exchange during the product development process, so the content for M and O will not be discussed here.
6. Arrows represents the data movements.

4.3 Network of ICOMs for QFD

Figure 23 is a description for the House of Quality model. It is based on Fig. 2 of Lai-Kow's paper.

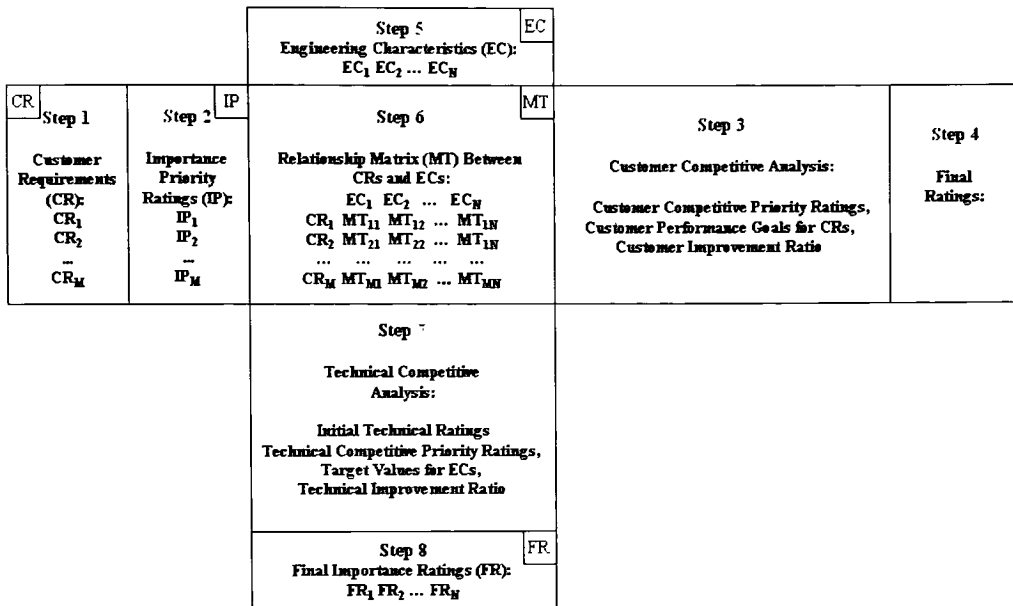


Figure 23 HOQ Model (Adapted from Fig. 2 of Lai-Kow's paper)

This network of ICOMs shows how the data moves from one process to another during QFD. There are four transforms during this process, which are shown in Fig 24.

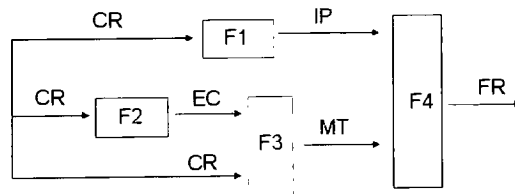


Figure 24 A graphic network of ICOMs for QFD

All of these transforms can be represented using ICOMs as Fig. 25.

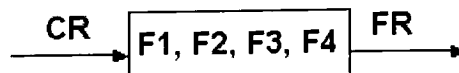


Figure 25 Using ICOMs to represent these transforms

F1 Transform

Fig. 26, 27, Table 1 and 2 represent the 1st transform of the network. Fig. 26 is derived from Fig. 24. Table 1 and 2 are the contents for this transform.

According to what Clausing says “The language of the customer tends to be subjective, qualitative, and nontechnical”, seven Customer Requirements are acquired through surveys and interviews with the customers (Clausing 65). They are denoted as CR_m , $m=1,2, \dots, M$. In this case, M equals 7, so CR is an ordered set with 7 elements. The elements of CR are shown in Table 1.

IP stands for the Importance Priorities for each element of the CR . In this case it is an ordered set as well as a 7×1 matrix, the values of which are shown in Table 2.

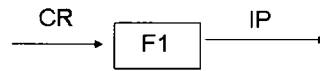


Figure 26 F1 transform from the network

F1 represents the assignment of relative importance IP_m to the customer requirement CR_m . “Relative” here means this is an example of “ordinal and rational” scale. That is to say, in Fig. 27, Color quality is five times as important as Archivability, because of $IP_1=5$ and $IP_7=1$. The value of IP_m can be determined using a number of attribute weighting methods. In this example, the pair-wise comparison method was used (based on Ulrich 135), as illustrated in Figure 27.

| i | CR_i | Design reference (eg. one type of Canon printer) | Rating |
|---|-----------------------|--|--------|
| 1 | Color quality | 3 | 5 |
| 2 | Air fill quality | 3 | 4 |
| 3 | Line and edge quality | 3 | 4 |
| 4 | Archivability | 3 | 1 |
| 5 | Cockle | 3 | 3 |
| 6 | Curl | 3 | 3 |
| 7 | Whiteness | 3 | 2 |

Figure 27 The pair-wise comparison method

First of all, the elements of CR are listed in the second column of the matrix, as shown in Fig. 27. Secondly, given the existence of a design reference, a weighting of 5 is assigned if the design attribute is much better than the reference; a weighting of 4 is assigned if the design attribute is better than the reference; 3 if the design attribute is the same as the reference; 2 if it is worse than the reference; and 1 if it is much worse than the reference. A competitive product or alternate design of known performance may be used as a reference, for example, one type of Canon printer. The result is shown in Table 2. In our example, the purpose is to explain how to use this method, so the elements of IP might be different from the real values, because this determination of these values requires a lot of resources, such as real data, enough time and experience. However, what will be discussed in this thesis is sure to be correct using these values.

| Seven Customer Requirements for our product | | Importance Priorities |
|---|----|-----------------------|
| CR ₁ : Color quality | | IP ₁ : 5 |
| CR ₂ : Air fill quality | | IP ₂ : 4 |
| CR ₃ : Line and edge quality | F1 | IP ₃ : 4 |
| CR ₄ : Cockle | → | IP ₄ : 3 |
| CR ₅ : Curl | | IP ₅ : 3 |
| CR ₆ : Whiteness | | IP ₆ : 2 |
| CR ₇ : Archivability | | IP ₇ : 1 |
| Table 1 | | Table 2 |

F2 Transform

Fig. 28 and Table 3 represent the 2nd transform of the network.

Define $(EC_j | CR_i \text{ depends on } EC_j)$, $i = 1, 2, \dots, M$ and $j = 1, 2, \dots, N$ as an ordered set of Engineering Characteristics upon which a given Customer Requirement depends, then

$EC = \bigcup_{i=1}^M (EC_j | CR_i \text{ depends on } EC_j)$. There are $N=18$ Engineering Characteristics in

this case, all of which are given on Hunt's paper (Hunt 18-20). The elements of EC are shown in Table 3 below and the definitions for these Engineering Characteristics are given on Appendix 3.

F2 is the mapping of CR to EC (see Fig. 28).

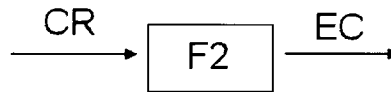


Figure 28 F2 transform from the network

EC₁: [↔] Color Gamut

EC₂: [↓] Drop placement accuracy

EC₃: [↓] Banding

EC₄: [↓] Wait time banding

EC₅: [↓] Mottling

EC₆: [↓] Bleed

EC₇: [↔] Coalescence

EC₈: [↔] Registration

EC₉: [↓] Resolution enhancement technology

EC₁₀: [↓] Spray, leathering, and jaggy lines

EC₁₁: [↓] Visual measurement of paper flatness

EC₁₂: [↓] Visual measurement of the height of the corners on a flat surface

EC₁₃: [↔] The amount of ink placed on the media

EC₁₄: [↑] Dot density

EC₁₅: [↔] The consistency of the drop volume

EC₁₆: [↔] The consistency of the drop size

EC₁₇: [↔] Ink penetration rate

EC₁₈: [↔] Orifice diameter

Note: “↓” represents to decrease the amount; “↑” represents to increase; “↔” represents it is not necessary or hard to decide the direction.

Table 3 Eighteen Engineering Characteristics

F3 Transform

Fig. 29 and Table 4 represent the 3rd transform of the network

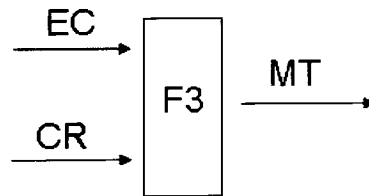


Figure 29 F3 transform from the network

MT is the matrix that represents the extent to which each CR_m is dependent upon each EC_n. This relationship matrix might be defined by asking, “To what degree does this Engineering Characteristic predict the customer’s satisfaction with this requirement?”

(Crow par. 4). In this case, the rational scale 1, 3, 9 (corresponding to weak, moderate, and strong dependence respectively) is used. The transform F3 is defined as followed:

Define $MT_{mn} = 0$ if CR_m is independent of EC_n ;

$MT_{mn} = 1$ if CR_m depends weakly on EC_n ;

$MT_{mn} = 3$ if CR_m depends moderately on EC_n ; and

$MT_{mn} = 9$ if CR_m depends strongly on EC_n .

$\forall m, n \quad m=1,2,\dots,M \text{ and } n=1,2,\dots,N.$

The full matrix of these relationships is shown in Table 3 below. For example, the relationship between CR_1 and EC_1 is considered as “strong” that corresponds to the value $MT_{11} = 9$. The process to get these values is shown in Appendix 4.

| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
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| Relationship between | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|----------------------|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|

Table 4 Content for F3 transform

F4 Transform

Fig. 30, 31 and Table 5 represents the 4th transform of the network.

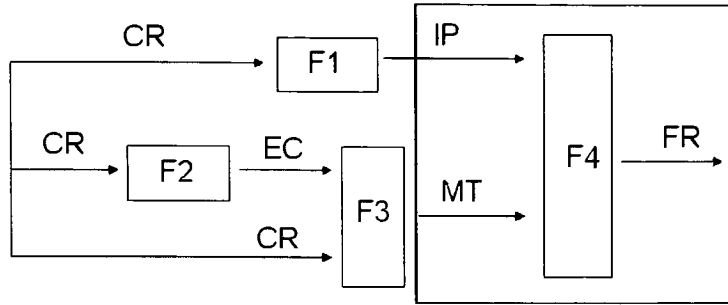


Figure 30 F4 transform from the network

F4 integrates the Importance Priorities (IP) and relationship matrix (MT) to calculate the Final Importance ratings for each of the EC, which is denoted as FR.

Based on the values of IP and MT, the values of $FR = IP^T \times MT$. In our case, these Final Importance values are acquired through the software called QFD Capture. The values are shown in Table 5 and Fig. 31.

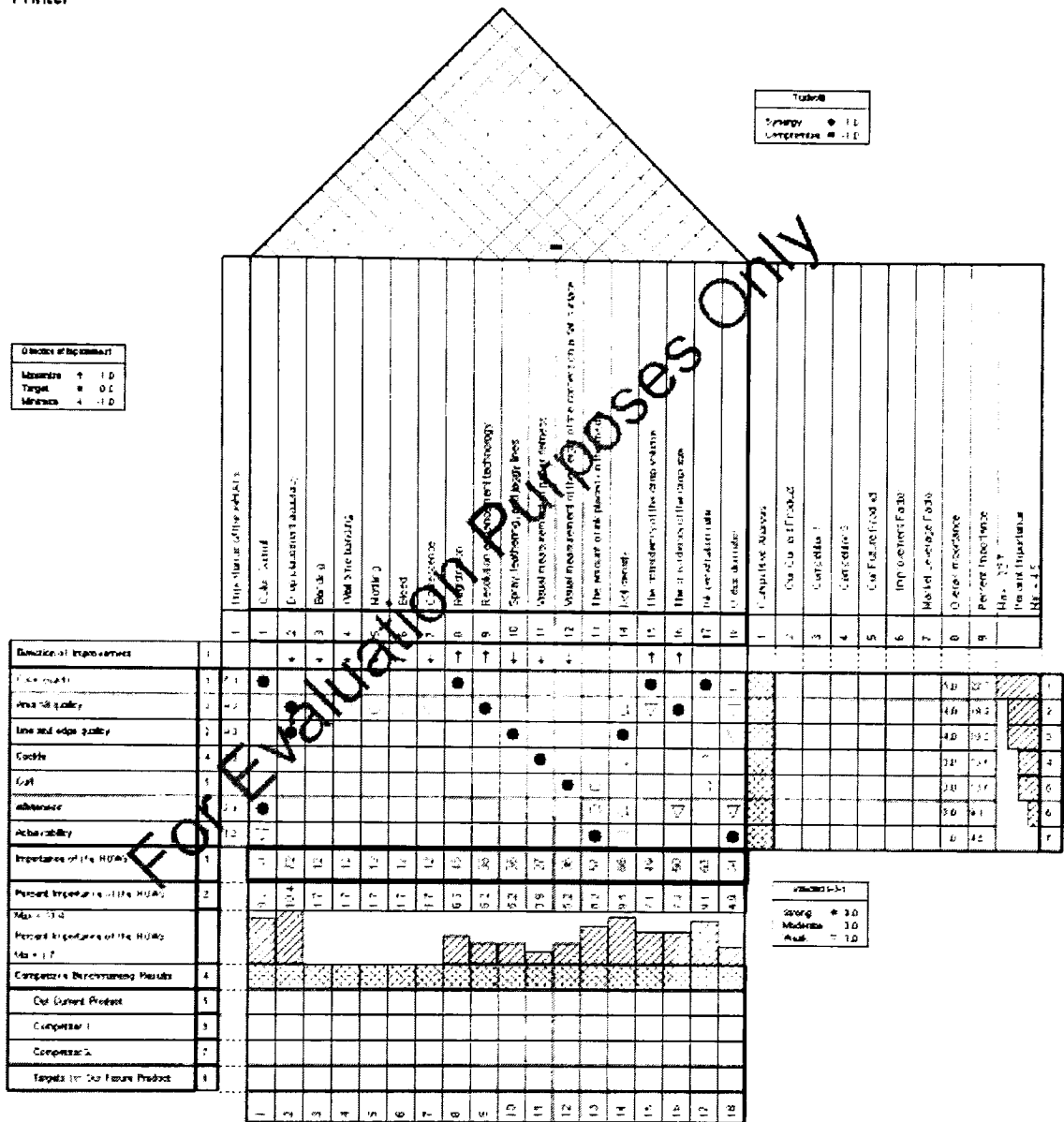


Figure 31 House of Quality (Adapted from QFD Capture)

| | | | | | | | | | |
|---------------------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|
| Importance of the EC (FR) | FR ₁ = 64 | FR ₂ = 72 | FR ₃ = 12 | FR ₄ = 12 | FR ₅ = 12 | FR ₆ = 12 | FR ₇ = 12 | FR ₈ = 45 | FR ₉ = 36 |
| Importance of the EC (FR) | FR ₁₀ = 36 | FR ₁₁ = 27 | FR ₁₂ = 36 | FR ₁₃ = 57 | FR ₁₄ = 66 | FR ₁₅ = 49 | FR ₁₆ = 50 | FR ₁₇ = 63 | FR ₁₈ = 34 |

Table 5 Final Importance Ratings

That is to say, FR = [64 72 12 12 12 12 12 12 45 36 36 27 36 57 66 49 50 63 34].

The process to get these values is also shown in Appendix 5.

4.4 Network of ICOMs between QFD and TRIZ

As Fig. 32 and 33 show, this network of ICOMs shows the data exchange between QFD and TRIZ.

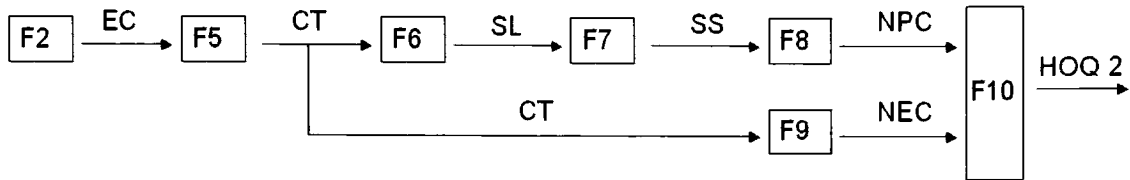


Figure 32 The Network of ICOMs between QFD and TRIZ

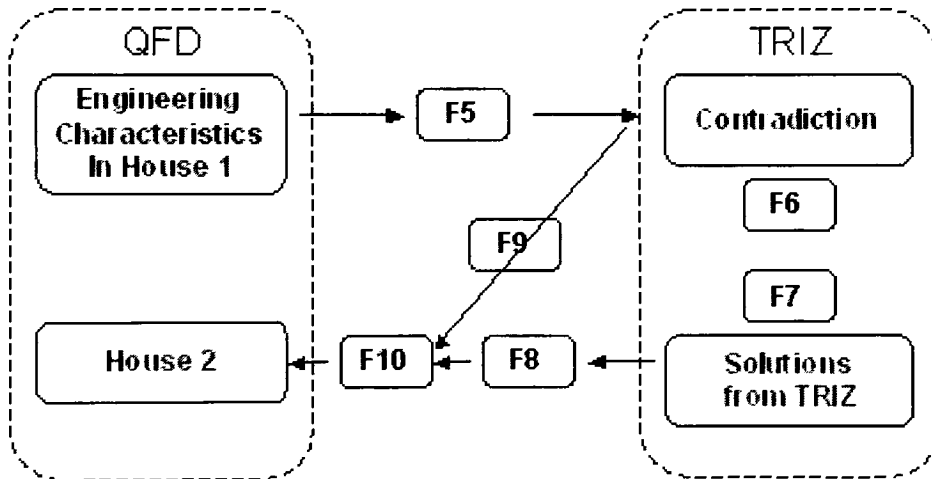


Figure 33 The Network of ICOMs between QFD and TRIZ

All of these transforms can be represented using ICOMs as Fig. 34.

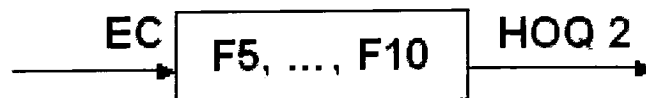


Figure 34 Using ICOMs to represent these transforms

The phases representing different transforms in this network are explained below.

F5 Transform

Fig. 35 and 36 represent the 5th transform of the network.

The purpose of F5 is to represent the contradiction selection from the Engineering Characteristics, using the knowledge from engineering, physics, design and other fields. That is to say, to identify the engineering contradictions from the EC in House of Quality 1 (Fig. 23). This process should identify every contradiction between every two Engineering Characteristics. However, in this case, one contradiction is just used as the example to explain this transform.



Figure 35 F5 transform from the network

In this example, CT is an ordered set with $\binom{N}{2} = \binom{N}{2} = \frac{18!}{2! 16!} = 153$ elements,

showing “1” or “0” for the contradiction relationship between every two elements of the Engineering Characteristics.

$$CT = (CT_{1,2} \ CT_{1,3} \ CT_{1,4} \ \dots \ CT_{1,18} \ CT_{2,3} \ CT_{2,4} \ \dots \ CT_{2,18} \ \dots \ CT_{17,18})$$

Where $CT_{x,y} = 0$ if there is no contradiction between EC_x and EC_y ;

$CT_{x,y} = 1$ if there is a contradiction between EC_x and EC_y .

$\forall x, y \ x=1,2,\dots,N-1 \ (N = 18 \text{ in this case}) \text{ and } y=2,\dots,N \ (N= 18 \text{ in this case}).$

In our example, $CT = (0 \ 0 \ 0 \ \dots \ 0 \ 0 \ 0 \ 1 \ 0 \ 0 \ 0 \ \dots \ 0 \ 0 \ 0)$ where $CT_{11,12} = 1$, others = 0. This means that there is a contradiction between EC_{11} and EC_{12} . These two elements are used as the increasing parameter/worsening parameter set for the TRIZ process. EC_{11} = “Visual measurement of paper flatness”. EC_{12} = “Visual measurement of the height of

the corners on a flat surface”. EC_{11} is measurement of paper cockle. EC_{12} is measurement of paper curl.

If the process identifies all of the contradictions, then CT should be $CT = (CT_{1,2} CT_{1,3} CT_{1,4} \dots CT_{1,N} CT_{2,3} CT_{2,4} \dots CT_{2,N} \dots CT_{N-1,N})$.

$$\begin{aligned} \text{In this example, } EC &= (EC_1 EC_2 \dots EC_{18}) \xrightarrow{\text{F5}} \\ CT &= (CT_{1,2} CT_{1,3} CT_{1,4} \dots CT_{1,18} CT_{2,3} CT_{2,4} \dots CT_{2,18} \dots CT_{17,18}) \\ &= (0 \ 0 \ 0 \ \dots \ 0 \ 0 \ 0 \ 1 \ 0 \ 0 \ 0 \ \dots \ 0 \ 0 \ 0) \text{ Where } CT_{11,12} = 1 \end{aligned}$$

$$\begin{aligned} \text{In general, } EC &= (EC_1 EC_2 \dots EC_N) \xrightarrow{\text{F5}} \\ CT &= (CT_{1,2} CT_{1,3} CT_{1,4} \dots CT_{1,N} CT_{2,3} CT_{2,4} \dots CT_{2,N} \dots CT_{N-1,N}) \\ \text{Where } CT_{x,y} &= 0 \text{ if there is no contradiction between } EC_x \text{ and } EC_y; \\ CT_{x,y} &= 1 \text{ if there is a contradiction between } EC_x \text{ and } EC_y. \\ \forall x, y \quad x &= 1, 2, \dots, N-1 \text{ and } y = 2, \dots, N. \end{aligned}$$

Figure 36 Content for F5 transform

“Paper cockle is a distortion in which bumps or ridges are randomly produced on the printed paper”. “Curl is a phenomenon in which the edges of the paper migrate towards the center of the paper” (Hunt 19). Obviously, we need to reduce both of the cockle and the curl. The reason why this contradiction is selected will be explained in the next transform.

F6 Transform

Fig. 37 to 39 represents the 6th transform of the network.

F6 represents the TRIZ process, using the contradiction to provide creative solutions (SL). In this example, there is a contradiction between these two values: EC_{11} and EC_{12} . They are used as the increasing parameter/worsening parameter for the TRIZ process.

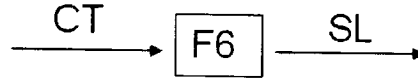


Figure 37 F6 transform from the network

In the 6th transform, only if $CT_{x,y} = 1$, then $SL^{x,y} = (SL^{x,y}_1 SL^{x,y}_2 \dots SL^{x,y}_z)$, an ordered set of solutions.

$CT_{x,y} = 1$ means that there is a contradiction between EC_x and EC_y . Using this contradiction, TRIZ provides solutions as $SL^{x,y} = (SL^{x,y}_1 SL^{x,y}_2 \dots SL^{x,y}_z)$ (see Table 6). $SL^{x,y}_1$ is the first solution, $SL^{x,y}_2$ is the second solution... $SL^{x,y}_z$ is the z^{th} solution. This process can be also expressed as:

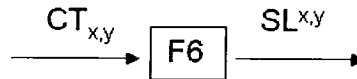


Figure 38 TRIZ process

In our example, $CT_{11,12} = 1$, $SL^{11,12} = (SL^{11,12}_1 SL^{11,12}_2 \dots SL^{11,12}_{14})$. The process to get these 14 solutions is explained as below.

The improving factors are engineering parameters that can help to improve the system's functionality. The worsening parameters are parameters that cause a system's deterioration. We would like to reduce the cockle, which means we need to increase the Loss of Substance (liquid component of the ink here).

If we increase the temperature of the solid area of the paper, it leads to increasing the curl. Therefore, we use Loss of Substance as the increasing factor, and use Temperature as the worsening factor.

With the help of CREAX Innovation, we use TRIZ to solve this contradiction. The report using CREAX for the HP DeskJet 1200C is shown in Appendix 6. When there is a contradiction between Loss of Substance (23) and Temperature (17), the principles to solve this problem are: 21, 31, 36, and 39.

The principles are listed as below.

Principle 21. Skipping

Conduct a process, or certain stages (e.g. destructible, harmful or hazardous operations) at high speed.

Principle 31. Porous materials

1. Make an object porous or add porous elements (inserts, coatings, etc.).
2. If an object is already porous, use the pores to introduce a useful substance or function.

Principle 36. Phase transitions

Use phenomena occurring during phase transitions (e.g. volume changes, loss or absorption of heat, etc.).

Principle 39. Inert atmosphere

1. Replace a normal environment with an inert one.

2. Add neutral parts, or inert additives to an object.

TRIZ can provide solutions for these contradictions. There are 14 solutions, which are shown in the CREAX report. SL is a 1×14 matrix, showing these 14 solutions.

$SL^{11,12}_1$ = After the heat propagates in the bottom of the paper, move it away quickly.

$SL^{11,12}_2$ = Use Infrared Heating process. The infrared radiation is often supplied by high-intensity, quartz, heat lamps, producing radiation with wavelengths around 1 micron.

$SL^{11,12}_3$ = Use Laser device, which is one of the several devices that emit highly amplified and coherent radiation of one or more discrete frequencies.

$SL^{11,12}_4$ = Use Light wave heating, which is process of heating materials through the application of light wave (combination of infrared and visible light).

$SL^{11,12}_5$ = Use radiation, which is the emission and propagation, and emission of energy in the form of rays or waves.

$SL^{11,12}_6$ = Use Solar energy for heating.

$SL^{11,12}_7$ = Use Thermoacoustic Effect which states that, a sound wave heats and cools small parcels of gas along the length of its propagation.

$SL^{11,12}_8$ = Add a heat pump to use the heat of vaporization and heat of condensation of a closed thermodynamic cycle to do useful work

$SL^{11,12}_9$ = Use multi-layer paper.

$SL^{11,12}_{10}$ = Carry out the process in vacuum.

$SL^{11,12}_{11}$ = Use a temperature gradient instead of constant temperature around the environment of the paper.

$SL^{11,12}_{12}$ = Heat both the top and the bottom of the paper.

$SL^{11,12}_{13}$ = Drill holes in the bottom side of the paper.

$SL^{11,12}_{14}$ = Use Microwaves, which are a form of "electromagnetic" radiation.

That is, they are waves of electrical and magnetic energy moving together through space.

Table 6 14 solutions from TRIZ

If F5 identifies all contradictions as $CT = (CT_{1,2} CT_{1,3} CT_{1,4} \dots CT_{1,N} CT_{2,3} CT_{2,4} \dots CT_{2,N} \dots CT_{N-1,N})$, then only if $CT_{x,y} = 1$, we should use F6 transform as below:

$CT_{x1,y1} = 1$, $SL^{x1,y1} = (SL^{x1,y1}_1 SL^{x1,y1}_2 \dots SL^{x1,y1}_{z1})$, there are $z1$ solutions;

$CT_{x2,y2} = 1$, $SL^{x2,y2} = (SL^{x3,y3}_1 SL^{x4,y4}_2 \dots SL^{x5,y5}_{z2})$, there are $z2$ solutions;

...

$CT_{xw,yw} = 1$, $SL^{xw,yw} = (SL^{xw,yw}_1 SL^{xw,yw}_2 \dots SL^{xw,yw}_{zw})$, there are zw solutions,

where w is the total number of contradictions.

As the process below, use every contradiction in $CT = (CT_{1,2} CT_{1,3} CT_{1,4} \dots CT_{1,N} CT_{2,3} CT_{2,4} \dots CT_{2,N} \dots CT_{N-1,N})$ to provide TRIZ solutions.

In our example,

$$CT_{11,12} = 1 \xrightarrow{F6} SL^{11,12} = (SL^{11,12}_1 SL^{11,12}_2 \dots SL^{11,12}_{14})$$

In general,

if $CT_{x,y} = 1$ ($x=1,2,\dots, N-1$; $y= 2,3,\dots, N$), then

$$CT = (CT_{1,2} CT_{1,3} CT_{1,4} \dots CT_{1,N} CT_{2,3} CT_{2,4} \dots CT_{2,N} \dots CT_{N-1,N}) \xrightarrow{F6}$$

$$CT_{x1,y1} = 1 \quad SL^{x1,y1} = (SL^{x1,y1}_1 SL^{x1,y1}_2 \dots SL^{x1,y1}_{z1}), \text{ there are } z1 \text{ solutions;}$$

$$CT_{x2,y2} = 1 \quad SL^{x2,y2} = (SL^{x3,y3}_1 SL^{x4,y4}_2 \dots SL^{x5,y5}_{z2}), \text{ there are } z2 \text{ solutions;}$$

...

$$CT_{xw,yw} = 1 \quad SL^{xw,yw} = (SL^{xw,yw}_1 SL^{xw,yw}_2 \dots SL^{xw,yw}_{zw}), \text{ there are } zw \text{ solutions,}$$

where w is total number of contradictions.

Figure 39 Content for F6 transform

F7 Transform

Fig. 40 and 41 represent the 7th transform of the network.

Two solutions that are consistent with Principle 18 are:

1. Use a heater to heat the paper when the ink is landed on the paper. This action increases the temperature, so it reduces the cockle. Then, stop using the heater, which leads to reducing the temperature, so it can reduce the curl. In fact, this method is what we use in most current printers.

2. Use “the Microwave solution”. “Microwaves are a form of ‘electromagnetic’ radiation; that is, they are waves of electrical and magnetic energy moving together through space” (CDRH par. 3).

The second one is a creative solution for the contradiction. The reason to choose this solution is explained here. First of all, “Microwaves work by shooting tiny waves

called microwaves through food. When the microwaves go through the food, they make the water molecules vibrate (This is because water molecules happen to have positive and negative ends and respond to the electric fields generated by the waves. The explanation for this is a bit tricky, but that's the general idea.)” (Tamara par. 3). Secondly, “Molecules other than water won't be affected by this much. Microwaves can go straight through most (but not all) kinds of paper, plastic or glass with no effect” (Tamara par. 5).

According to the reasons above, this solution can increase the temperature of the solid area of the paper without increasing the curl, so it is a creative solution. This solution is so new that there might be some technical problems on the real application, but the purpose of this process is to provide creative solutions for the contradiction, so it is definitely a good solution.

In this case, F7 represents the selected solutions (SS) from $SL^{x1,y1} \cup SL^{x2,y2} \cup \dots SL^{xw,yw}$, based on our analysis and knowledge. In this example, SS_1 is an ordered set with one element, showing “the Microwave” solution. The corresponding engineering characteristics for SS_1 can be further decomposed in the next transform.

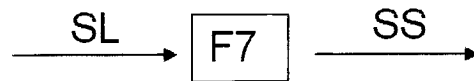


Figure 40 F7 transform from the network

As the process above, select every best solution from $SL^{x1,y1}$, $SL^{x2,y2}$, ... $SL^{xw,yw}$ as SS_1 , SS_2 , ... SS_w . (see Fig. 41).

| | | |
|--|--------------------|--------|
| In our example, $SL^{11,12}$ | $\xrightarrow{F7}$ | SS_1 |
| In general, | | |
| $SL^{x1,y1} = (SL^{x1,y1}_1 SL^{x1,y1}_2 \dots SL^{x1,y1}_{z1})$ | | SS_1 |
| $SL^{x2,y2} = (SL^{x3,y3}_1 SL^{x4,y4}_2 \dots SL^{x5,y5}_{z2})$ | $\xrightarrow{F7}$ | SS_2 |
| ... | | |
| $SL^{xw,yw} = (SL^{xw,yw}_1 SL^{xw,yw}_2 \dots SL^{xw,yw}_{zw})$ | | SS_w |

Figure 41 Content for F7 transform

F8 Transform

Fig. 42 and 43 represents the 8th transform of the network.

The purpose of F8 is to identify the part characteristics (NPC) related with SS (see Fig. 42).

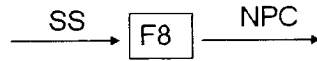


Figure 42 F8 transform from the network

In this case, NPC is an ordered set with 3 elements, showing three corresponding part characteristics for SS_1 .

$NPC_1 = f$: A design parameter of the microwave transmitter;

$NPC_2 = Lf$: Dielectric lost factor; and

$NPC_3 = E^2$: Gradient of potential field.

If the selected solutions are SS_1, SS_2, \dots, SS_w . SS_1 is the first selected solution, SS_2 is the second selected solution... SL_w is the w^{th} selected solution. The F8 transform can be also expressed as:

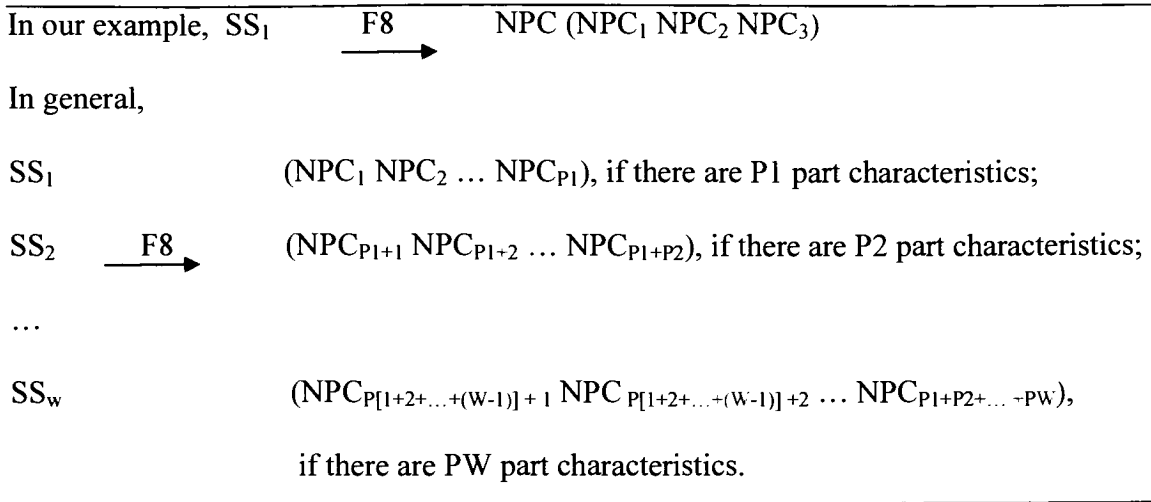


Figure 43 F8 transform from the network

As the process above, other corresponding part characteristics are composed as $NPC = (NPC_1 NPC_2 \dots NPC_{P1+P2+\dots+PW}) = (NPC_1 NPC_2 \dots NPC_E)$, E is the total number of part characteristics.

NPC can be used as the part characteristic matrix in House of Quality 2.

F9 Transform

Fig. 44 and 45 represents the 9th transform of the network. F9 transforms the engineering characteristics in House 1 into the new engineering characteristics (NEC) in House 2.

QFD involves four linked houses used for product specification, component specification, manufacturing process capability specification, and production rules specification. Each new house takes information from the preceding house as its starting point. The Engineering Characteristics in HOQ 1 are listed down the left side of HOQ 2, the component specification house. In this case, $(NEC_1 NEC_2) = (EC_{11} EC_{12})$ are transformed into the new engineering characteristics (NEC) in House 2.

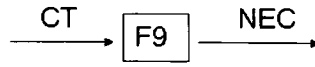


Figure 44 F9 transform from the network

In our example,

$$CT_{11,12} = 1 \xrightarrow{\text{F9}} NEC = (EC_{11} \ EC_{12}) = (NEC_1 \ NEC_2)$$

In general,

$$CT = [CT_{1,2} \ CT_{1,3} \ CT_{1,4} \ \dots \ CT_{1,N} \ CT_{2,3} \ CT_{2,4} \ \dots \ CT_{2,N} \ \dots \ CT_{N-1,N}]$$

$$\text{if } CT_{x,y} = 1 (x=1,2,\dots, N-1; y= 2,3,\dots, N), \text{ then } \xrightarrow{\text{F9}}$$

$$\begin{aligned} NEC &= (EC_i \mid CT_{x,y} = 1, x = 1,2,\dots,N-1 \text{ and } y = 2,3,\dots,N) \\ &= (NEC_1 \ NEC_2 \ \dots \ NEC_F), F \text{ is total number of unique } EC_i \text{ across all} \\ &\text{contradictions} \end{aligned}$$

Figure 45 Content for F9 transform

As what has been explained before, the two values in EC_{11} and EC_{12} are two elements of a contradiction. In this case, one contradiction is just used as the example to explain this process. If the process identifies all of the contradictions, then the elements of NEC should be listed down the left side of HOQ 2.

F10 Transform

Once this creative solution is developed using TRIZ, the corresponding engineering characteristics can be further decomposed using QFD. The result is shown in Fig. 46 to 51.

The Engineering Characteristics in HOQ 1 are listed down the left side of HOQ 2, the parts deployment house. Thus, the Engineering Characteristics are transformed into

the Part Characteristics. This process continues to a third and fourth phase as Fig. 46 below. These four linked houses transform the Customer Requirements to the Production Requirements step by step. Fig 49 and 50 are derived from Fig. 51. Fig 51 is also shown in Appendix 6.

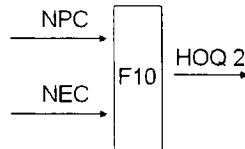


Figure 46 F10 transform from the network

Fig. 47 shows the F8 to F10 transforms, which explain how to develop from house 1 to house 2 clearly.

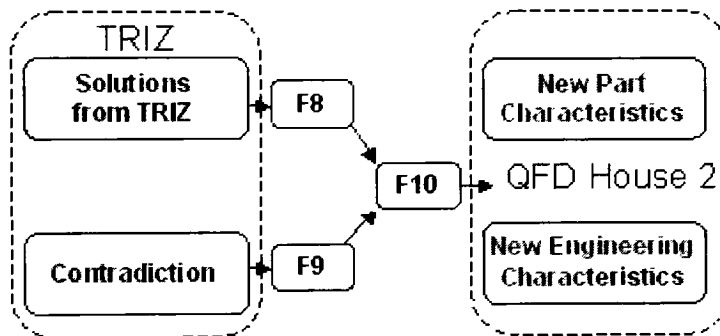


Figure 47 F8 to F10 transform

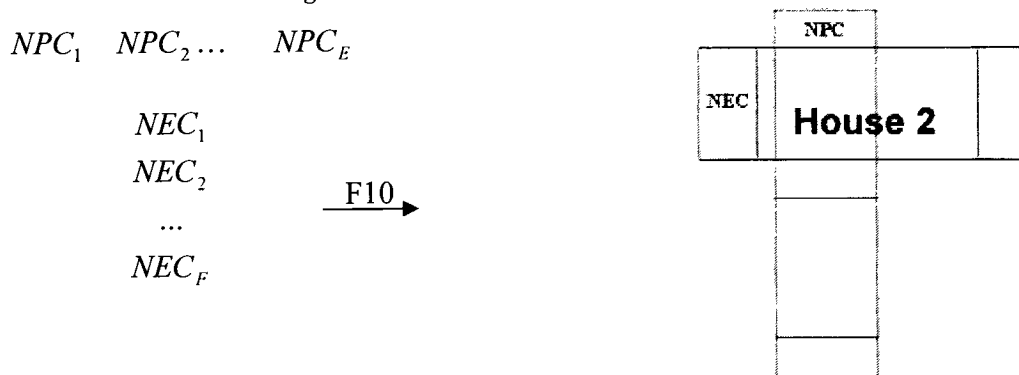


Figure 48 Content for F10 transform

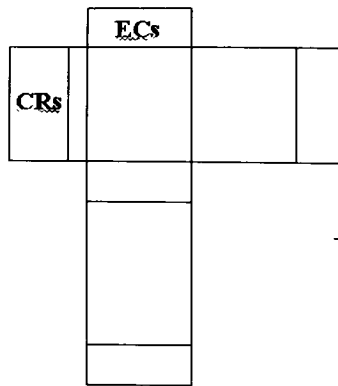


Figure 49 HOQ 1

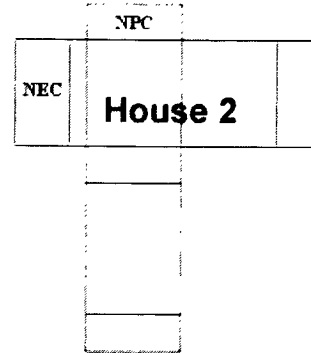
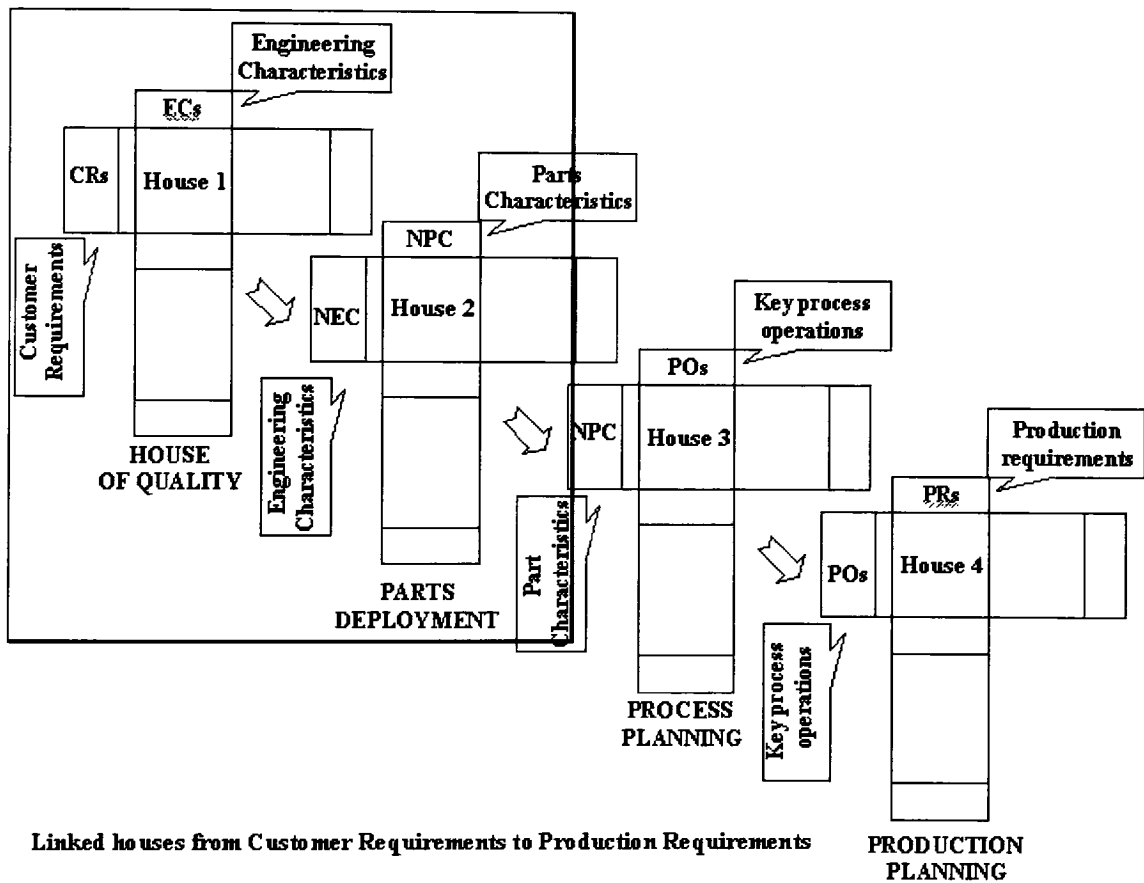


Figure 50 HOQ 2



Source: Modified from a figure supplied by the American Supplier Institute, Inc., Dearborn, Michigan

Figure 51 Linked houses from Customer Requirements to Production Requirements

4.5 Network of ICOMs between QFD and DSM

This network of ICOMs (see Fig. 52) shows the data exchange between QFD and DSM, and how the data moves from one process to another during the system. The engineering characteristics become variables in DSM. By reordering the variables, DSM provides a more effective product development plan for the complex process system through information flow analysis.

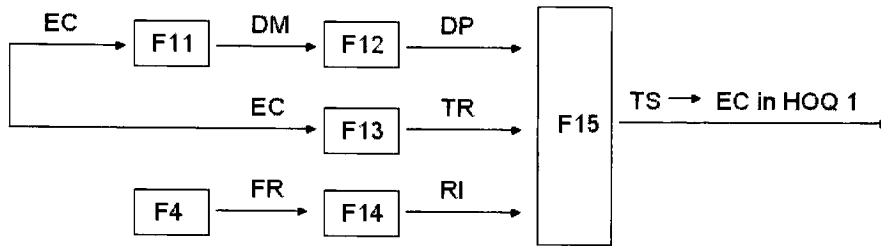


Figure 52 The Network of ICOMs between QFD and DSM

All of these transforms can be represented using ICOMs as Fig. 53.

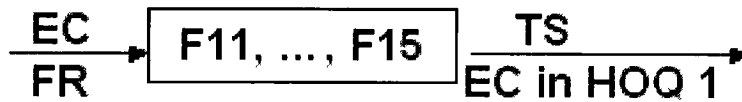


Figure 53

The phases representing different transforms in this network are explained below.

F11 Transform

Table 7, Fig. 54 and 55 represent the 11th transform of the network. F11 represents the DSM process. In this case, EC shows the corresponding engineering characteristics in House of Quality 1.

First of all, list the EC in the DSM as row and column labels. Both of the elements in the row and column should be in the same order. Fill the cells on the diagonal. Secondly, determine the relationship between the elements, including the inputs and outputs of the system interaction. Fill the value of “1” into a cell in column i row j if there is an arc from vertex i to vertex j. Double check the matrix with engineers and managers to verify the DSM. Finally, DM, which includes a 18×18 relationship matrix and the variables, is acquired as in Fig. 54.



Figure 54 F11 transform from the network

Variables in DSM

EC₁: Color Gamut

EC₂: Drop placement accuracy

EC₃: Banding

EC₄: Wait time banding

EC₅: Mottling

EC₆: Bleed

EC₇: Coalescence

EC₈: Registration

EC₉: Resolution enhancement technology

EC₁₀: Spray, leathering, and jaggy lines

EC₁₁: Visual measurement of paper flatness

EC₁₂: Visual measurement of the height of the corners on a flat surface

EC₁₃: The amount of ink placed on the media

EC₁₅: The consistency of the drop volume

EC₁₆: The consistency of the drop size

EC₁₇: Ink penetration rate

EC₁₈: Orifice diameter

Table 7 Variables in DSM

| Name | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 |
|--|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|----|----|----|
| Color Gamut | 1 | | | | | | | | | | | | | | | | | |
| Drop placement accuracy | | 2 | | | | | | | 1 | | | | 1 | | 1 | 1 | | 1 |
| Banding | | | 3 | | | 1 | | 1 | | 1 | | | | | | | | 1 |
| Wait time banding | | | | 4 | | | | | | | | | | | | | | |
| Motting | | | | | 5 | | | | | | | | | | | | | |
| Bleed | | | | | | 6 | | | | | | | 1 | | 1 | | | 1 |
| Coalescence | | | | | | | 7 | | | | | | | | | | | |
| Registration | | | 8 | | | | | 8 | 1 | | | | 1 | | | | | 1 |
| Resolution enhancement technology | | | | | | | | | 9 | | | | 1 | | 1 | 1 | | 1 |
| Spray, leathering and jaggy lines | | | | | | | 1 | 1 | 1 | 10 | | | 1 | | | | | |
| Visual measurement of paper flatness | | 1 | | | | | | 1 | 1 | | 11 | | 1 | | 1 | 1 | | |
| Visual measurement of height of the coat | | | 1 | | | | | 1 | 1 | | | 12 | 1 | | 1 | 1 | | |
| The amount of ink placed on the media | | | | | | | | | | | | | 13 | | 1 | 1 | | 1 |
| Dot density | | | 1 | | | 1 | 1 | 1 | | | | | 1 | 14 | 1 | 1 | | |
| The consistency of the drop volume | | | | | | | | | | | | | | | 15 | | | 1 |
| The consistency of the drop size | | | | | | | | | | | | | | | | 15 | | 1 |
| Ink penetration rate | | | | | | 1 | 1 | | | | | | 1 | | 1 | 1 | 17 | |
| Orifice diameter | | | | | | | 1 | | | | | | | | | | | 18 |

Figure 55 Content for the original DSM

F12 Transform

Fig. 56 and Fig. 57 represent the 12th transform of the network.

F12 represents the partitioning process, one of the two approaches to analyze and improve the DSM. “Partitioning is the process of manipulating (i.e. reordering) the DSM rows and columns such that the new DSM arrangement does not contain any feedback marks. Thus, transforming the DSM into a lower triangular form” (DSM Partitioning 1).

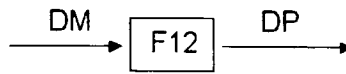


Figure 56 F12 transform from the network

However, if the system is complex, it is usually impossible to acquire a lower triangular form. For example, from the above DSM of Fig. 57, EC₃ depends on the information from EC₂, EC₆, EC₈, and EC₁₀. The value for EC₂ is acquired before EC₃, but the values for EC₆, EC₈, and EC₁₀ have not been decided. Therefore, only after the values for EC₆, EC₈, and EC₁₀ have been decided, the value of EC₃ can be acquired. This is called iteration, which is the repetition of activities due to the input of new information. In such situations, the object becomes to move the feedback as close as possible to the diagonal

There are several approaches for the partitioning process. In this case, a DSM Excel macro is used to perform the partitioning process. This DSM tool was downloaded from <http://www.dsmweb.org/macros.htm>, the DSM website provided by MIT & UIUC.

The result for the DSM after partitioning is shown as Fig. 57. From Fig. 57, the feedbacks have been formed a block, which is as close as possible to the diagonal, so the object has been realized. In doing so, fewer system elements will be involved in the iteration cycle, resulting to a faster development process.

| Name | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 |
|---|----|---|---|---|---|---|---|---|---|----|----|----|----|----|----|----|----|----|
| Color Gamut | 1 | 1 | | | | | | | | | | | | | | | | |
| Drop placement accuracy | 2 | 2 | | | | | | | 1 | | | | 1 | | 1 | 1 | | 1 |
| Banding | 3 | 1 | 1 | | | | 1 | | 1 | | 1 | | | | | | | 1 |
| Wait time banding | 4 | | 4 | | | | | | | | | | | | | | | |
| Mottling | 5 | | | 5 | | | | | | | | | | | | | | |
| Bleed | 6 | | | | 6 | | | | | | | | 1 | | 1 | | | 1 |
| Coalescence | 7 | | | | | 7 | | | | | | | | | | | | |
| Registration | 8 | 1 | | | | | 8 | 1 | | | | | 1 | | | | | 1 |
| Resolution enhancement technology | 9 | | | | | | | 9 | 1 | | | | 1 | | 1 | 1 | | 1 |
| Spray, leathering and jaggy lines | 10 | | | | | | | | 1 | 1 | 1 | 10 | | 1 | | | | |
| Visual measurement of paper flatness | 11 | 1 | | | | | | 1 | 1 | | | 11 | | 1 | | 1 | | |
| Visual measurement of height of the cor | 12 | 1 | | | | | | 1 | 1 | | | | 12 | 1 | | 1 | 1 | |
| The amount of ink placed on the media | 13 | | | | | | | | | | | | | 13 | | 1 | 1 | |
| Dot density | 14 | 1 | | | | | 1 | 1 | 1 | | | | 1 | 14 | 1 | 1 | | |
| The consistency of the drop volume | 15 | | | | | | | | | | | | | | 15 | | | 1 |
| The consistency of the drop size | 16 | | | | | | | | | | | | | | | 16 | | 1 |
| Ink penetration rate | 17 | | | | | 1 | 1 | | | | | | 1 | | 1 | 1 | 17 | |
| Orifice diameter | 18 | | | | | | 1 | | | | | | | | | | | 18 |

F12

| | Color Gamut | Drop placement accuracy | Bleed | Coalescence | Registration | Resolution enhancement technology | The amount of ink placed on the media | The consistency of the drop volume | The consistency of the drop size | Ink penetration rate | Orifice diameter | Wait time banding | Mottling | Spray, leathering and jaggy lines | Visual measurement of paper flatness | Visual measurement of height of the cor | Dot density | Banding |
|---|-------------|-------------------------|-------|-------------|--------------|-----------------------------------|---------------------------------------|------------------------------------|----------------------------------|----------------------|------------------|-------------------|----------|-----------------------------------|--------------------------------------|---|-------------|---------|
| | 1 | 2 | 6 | 7 | 8 | 9 | 13 | 15 | 16 | 17 | 18 | 4 | 5 | 10 | 11 | 12 | 14 | 3 |
| Color Gamut | 1 | 1 | | | | | | | | | | | | | | | | |
| Drop placement accuracy | 2 | 2 | | | | 1 | 1 | | | | 1 | | | | | | | |
| Bleed | 6 | 1 | 6 | | | 1 | 1 | | | 1 | 1 | | | | | | | |
| Coalescence | 7 | 1 | | 7 | 1 | | 1 | 1 | 1 | | 1 | | | | | | | |
| Registration | 8 | 1 | | | 8 | 1 | 1 | | | | | | | | | | | |
| Resolution enhancement technology | 9 | 1 | 1 | | 1 | 9 | 1 | 1 | 1 | | 1 | | | | | | | |
| The amount of ink placed on the media | 13 | | | 1 | 1 | | 13 | 1 | 1 | | 1 | | | | | | | |
| The consistency of the drop volume | 15 | | | | | 1 | 1 | 15 | | | 1 | | | | | | | |
| The consistency of the drop size | 16 | | | | 1 | | 1 | 1 | 16 | | 1 | | | | | | | |
| Ink penetration rate | 17 | | | 1 | 1 | | 1 | 1 | | 17 | | | | | | | | |
| Orifice diameter | 18 | | | | 1 | | 1 | 1 | 1 | 1 | 18 | | | | | | | |
| Wait time banding | 4 | | | | | | | | | | | 4 | | | | | | |
| Mottling | 5 | | | | | | | | | | | | 5 | | | | | |
| Spray, leathering and jaggy lines | 10 | | | | 1 | 1 | 1 | 1 | | | 1 | | | 10 | | | | |
| Visual measurement of paper flatness | 11 | 1 | | | 1 | 1 | 1 | 1 | 1 | | | | | | 11 | | | |
| Visual measurement of height of the cor | 12 | 1 | | | 1 | 1 | 1 | 1 | 1 | | | | | | | 12 | | |
| Dot density | 14 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | | | | | | | | 14 | |
| Banding | 3 | | 1 | 1 | | 1 | | 1 | 1 | | 1 | | | 1 | | | | 3 |

Figure 57 Content for F12 transform

F13 Transform

Fig. 58 and Table 8 represent the 13th transform of the network. The purpose of F13 is to access the Technical Risk values for each of the engineering characteristics.

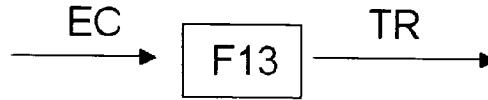


Figure 58 F13 transform from the network

The definition for Technical Risk is as followed:

1. “High Technical Risk: The element has large impact on the performance of the instrument. This includes single-point failures and key requirements for which the margin is just” (LOFAR ... 6).
2. “Low Technical Risk: The impact is restrained within the expected performance of the system. This includes elements with sufficient margin with respect to the requirements, redundant elements, etc” (LOFAR ... 6).

According to this definition, the Technical Risk values for each of the engineering characteristics are shown in Table 8.

| Engineering Characteristics | Technical Risk |
|---|------------------------|
| EC ₁ : Color Gamut | TR ₁ = Low |
| EC ₂ : Drop placement accuracy | TR ₂ = High |
| EC ₃ : Banding | TR ₃ = Low |
| EC ₄ : Wait time banding | TR ₄ = Low |
| EC ₅ : Mottling | TR ₅ = Low |
| EC ₆ : Bleed | TR ₆ = High |
| EC ₇ : Coalescence | TR ₇ = High |

| | |
|---|-------------------------|
| EC ₈ : Registration | TR ₈ = High |
| EC ₉ : Resolution enhancement technology | TR ₉ = High |
| EC ₁₀ : Spray, leathering, and jaggy lines | TR ₁₀ = Low |
| EC ₁₁ : Visual measurement of paper flatness | TR ₁₁ = Low |
| EC ₁₂ : Visual measurement of the height of the corners on a flat surface | TR ₁₂ = Low |
| EC ₁₃ : The amount of ink placed on the media | TR ₁₃ = High |
| EC ₁₄ : Dot density | TR ₁₄ = Low |
| EC ₁₅ : The consistency of the drop volume | TR ₁₅ = High |
| EC ₁₆ : The consistency of the drop size | TR ₁₆ = High |
| EC ₁₇ : Ink penetration rate | TR ₁₇ = Low |
| EC ₁₈ : Orifice diameter | TR ₁₈ = High |

Table 8 Technical Risks for the Engineering Characteristics

F14 Transform

Fig. 59 and 60 represent the 14th transform of the network. The purpose of F14 is to access the Relative Importance values for each of the engineering characteristics.

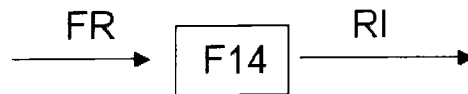


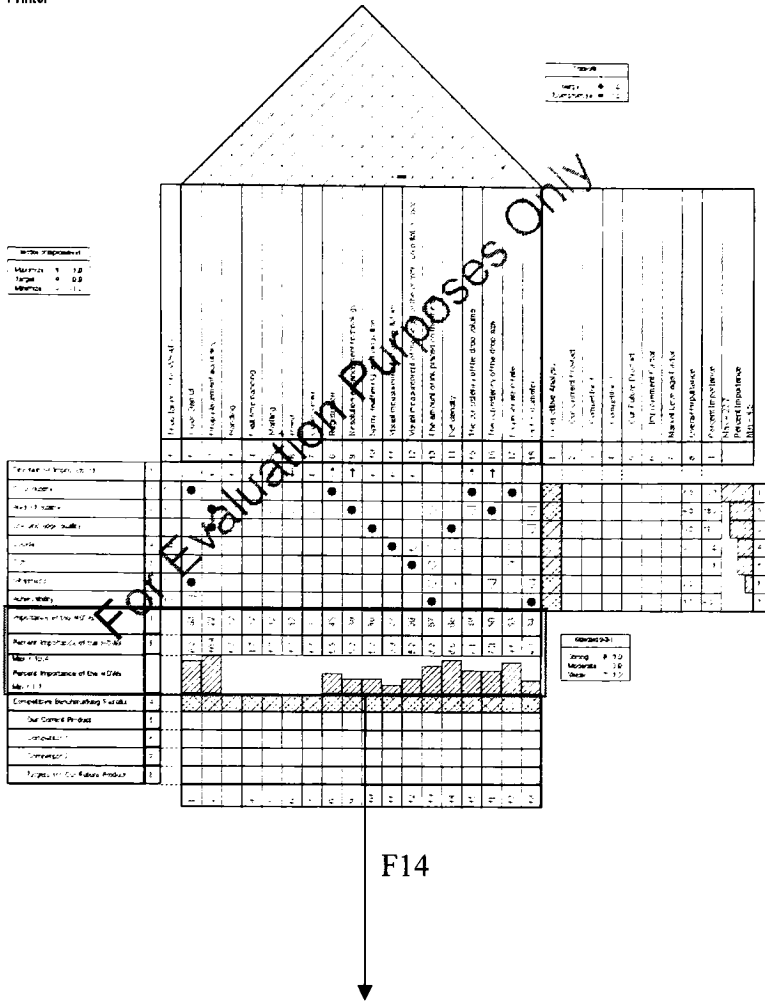
Figure 59 F14 transform from the network

The final importance ratings for each of the Engineering Characteristics are acquired through F4 transform on HOQ 1. The above part of Fig. 60 shows these ratings named as Importance of the Engineering Characteristics. The bottom part of Fig. 60 also

shows these values. The Relative Importance values are transformed from the Importance of the Engineering Characteristics. The rule is as below:

1. Order the values of Importance of the Engineering Characteristics from low to high. In the case here, the order is: 12, 12, 12, 12, 12, 27, 34, 36, 36, 36, 45, 49, 50, 57, 63, 64, 66, and 72.
2. There are eighteen values in this case. First half of the values on the ordered list should be denoted as “Low” (Lo) for the Relative Importance. The other half values on the ordered list are denoted as “High (Hi) for the Relative Importance.
3. According to this rule, in this case, the first nine values are denoted as “Low”. However, all of the values from the 8th to 10th are 36. The 8th and the 9th values are denoted as “Low”, so the 10th one should also be denoted as “Low”.

The result using this rule is shown as the bottom part of Fig. 60.



| | | | | | | | | | |
|---------------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| Importance of the EC (FR) | FR ₁ = 64 | FR ₂ = 72 | FR ₃ = 12 | FR ₄ = 12 | FR ₅ = 12 | FR ₆ = 12 | FR ₇ = 12 | FR ₈ = 45 | FR ₉ = 36 |
| Relative Importance (RI) | RI ₁ = Hi | RI ₂ = Hi | RI ₃ = Lo | RI ₄ = Lo | RI ₅ = Lo | RI ₆ = Lo | RI ₇ = Lo | RI ₈ = Hi | RI ₉ = Hi |
| Importance of the EC (FR) | FR ₁₀ = 36 | FR ₁₁ = 27 | FR ₁₂ = 36 | FR ₁₃ = 57 | FR ₁₄ = 66 | FR ₁₅ = 49 | FR ₁₆ = 50 | FR ₁₇ = 63 | FR ₁₈ = 34 |
| Relative Importance (RI) | RI ₁₀ = Lo | RI ₁₁ = Lo | RI ₁₂ = Lo | RI ₁₃ = Lo | RI ₁₄ = Hi | RI ₁₅ = Hi | RI ₁₆ = Hi | RI ₁₇ = Hi | RI ₁₈ = Lo |

Figure 60 Relative Importance from HOQ 1

F15 Transform

Fig. 61 to 67 represent the 15th transform of the network. The purpose of F15 is to use tearing, another approach to analyze and improve the DSM.

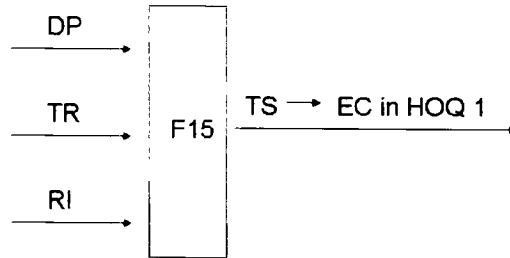


Figure 61 F15 transform from the network

“Tearing is the process of choosing the set of feedback marks that if removed from the matrix (and then the matrix is re-partitioned) will render the matrix lower triangular” (DSM Tearing 1).

There is no optimal method for tearing. Here, a new method was recommended to make the tearing decisions as followed:

- (1) In order to break the circuit, we need to remove the arcs in the block on the partitioned DSM one by one. Use $|A \ B|$ to represent a pair of variables inside the block on the partitioned DSM. A or B represents the sequence of the variable. They can be found on the second column as in Fig. 62. For example, $|17 \ 18|$ represents the pair of variables which is combined with Ink penetration rate and Orifice diameter. Each pair of variables contains two variables, named variable i and variable j.

| | Color Gamut | Drop placement accuracy | Bleed | Coalescence | Registration | Resolution enhancement technology | The amount of ink placed on the media | The consistency of the drop volume | The consistency of the drop size | Ink penetration rate | Orifice diameter | Wait time banding | Mottling | Spray, leathering and jaggy lines | Visual measurement of paper flatness | Visual measurement of height of the corner | Dot density | Banding |
|--|-------------|-------------------------|-------|-------------|--------------|-----------------------------------|---------------------------------------|------------------------------------|----------------------------------|----------------------|------------------|-------------------|----------|-----------------------------------|--------------------------------------|--|-------------|---------|
| Color Gamut | 1 | 1 | | | | | | | | | | | | | | | | |
| Drop placement accuracy | 2 | | 2 | | | | 1 | 1 | | | | 1 | | | | | | |
| Bleed | 6 | 1 | 6 | | | | 1 | 1 | | 1 | 1 | | | | | | | |
| Coalescence | 7 | 1 | | 7 | 1 | | 1 | 1 | 1 | | 1 | | | | | | | |
| Registration | 8 | 1 | | | 8 | 1 | 1 | | | | | | | | | | | |
| Resolution enhancement technology | 9 | 1 | 1 | | 1 | 9 | 1 | 1 | 1 | | 1 | | | | | | | |
| The amount of ink placed on the media | 13 | | | 1 | | | 13 | 1 | 1 | | 1 | | | | | | | |
| The consistency of the drop volume | 15 | | | | | | 1 | 1 | 15 | | 1 | | | | | | | |
| The consistency of the drop size | 16 | | | 1 | | | 1 | 1 | 16 | | 1 | | | | | | | |
| Ink penetration rate | 17 | | | 1 | 1 | | 1 | 1 | 1 | 17 | | | | | | | | |
| Orifice diameter | 18 | | | | 1 | | 1 | 1 | 1 | 1 | 18 | | | | | | | |
| Wait time banding | 4 | | | | | | | | | | | 4 | | | | | | |
| Mottling | 5 | | | | | | | | | | | | 5 | | | | | |
| Spray, leathering and jaggy lines | 10 | | | | 1 | 1 | 1 | 1 | | | 1 | | | 10 | | | | |
| Visual measurement of paper flatness | 11 | | 1 | | | 1 | 1 | 1 | 1 | 1 | | | | | 11 | | | |
| Visual measurement of height of the corner | 12 | | 1 | | | 1 | 1 | 1 | 1 | 1 | | | | | | 12 | | |
| Dot density | 14 | | 1 | 1 | 1 | 1 | | 1 | 1 | 1 | | | | | | | 14 | |
| Banding | 3 | | 1 | 1 | | 1 | | | 1 | 1 | | 1 | | 1 | | | | 3 |
| Technical Risk | | Lo | Hi | Hi | Hi | Hi | Hi | Hi | Hi | Lo | Lo | Lo | Lo | Lo | Lo | Lo | Lo | Lo |
| Relative Importance | | Hi | Hi | Lo | Lo | Hi | Lo | Hi | Hi | Hi | Hi | Lo | Lo | Lo | Lo | Lo | Lo | Hi |

Figure 62 Partitioned DSM with Technical Risk & Relative Importance

- (2) Use T_n to represent Technical Risk. T_1 represents the Technical Risk of i , and T_2 represents the Technical Risk of j . Use R_m to represent Relative Importance. R_1 represents the Relative Importance of i , and R_2 represents the Relative Importance of j . Then, as Fig. 63 shows, use $\begin{bmatrix} T_1 & T_2 \\ R_1 & R_2 \end{bmatrix}$ to represent the values of Technical Risk and Relative Importance for i and j .

| | | |
|---|--|---|
| T_1 represents the Technical Risk of element i . | $\begin{bmatrix} T_1 & T_2 \\ R_1 & R_2 \end{bmatrix}$ | T_2 represents the Technical Risk of element j . |
| R_1 represents the Relative Importance of element i . | | R_2 represents the Relative Importance of element j . |

Figure 63 Tearing heuristics

(3) There are sixteen possible combinations as in Table 9.

| Technical Risk Relative Importance | H H | H L | L H | L L |
|---------------------------------------|-----|-----|-----|-----|
| H H | | | | |
| H L | | | | |
| L H | | | | |
| L L | | | | |

Table 9 Tearing heuristics

(4) Suppose both of the Technical Risks for i and j are High, and both of the

$$\text{Relative Importance for i and j are low, then } \begin{bmatrix} T_1 & T_2 \\ R_1 & R_2 \end{bmatrix} = \begin{bmatrix} H & H \\ L & L \end{bmatrix}.$$

(5) The tearing rule is defined as: denote values from 0 to 4 to the values as in Table 10. The lesser the value is, the higher the possibility to tear it might be.

| Technical Risk Relative Importance | H H | H L | L H | L L |
|---------------------------------------|-----|-----|-----|-----|
| H H | 4 | 3 | 3 | 2 |
| H L | 3 | 2 | 2 | 1 |
| L H | 3 | 2 | 2 | 1 |
| L L | 2 | 1 | 1 | 0 |

Table 10 Tearing heuristics

(6) That is to say, if there exists value 0, tear it first. Otherwise tear value 1 if there exists. After tear the value 0, tear 1 if there exists.

(7) Therefore, the tearing process is shown as below:

$$\begin{bmatrix} L & L \\ L & L \end{bmatrix} = 0$$

$$\begin{bmatrix} L & L \\ H & L \end{bmatrix} = \begin{bmatrix} L & L \\ L & H \end{bmatrix} = \begin{bmatrix} H & L \\ L & L \end{bmatrix} = \begin{bmatrix} L & H \\ L & L \end{bmatrix} = 1$$

$$\begin{bmatrix} L & L \\ H & H \end{bmatrix} = \begin{bmatrix} H & L \\ H & L \end{bmatrix} = \begin{bmatrix} L & H \\ H & L \end{bmatrix} = \begin{bmatrix} H & L \\ L & H \end{bmatrix} = \begin{bmatrix} L & H \\ L & H \end{bmatrix} = \begin{bmatrix} H & H \\ L & L \end{bmatrix} = 2$$

$$\begin{bmatrix} H & L \\ H & H \end{bmatrix} = \begin{bmatrix} L & H \\ H & H \end{bmatrix} = \begin{bmatrix} H & H \\ H & L \end{bmatrix} = \begin{bmatrix} H & H \\ L & H \end{bmatrix} = 3$$

$$\begin{bmatrix} H & H \\ H & H \end{bmatrix} = 4$$

(8) According to this method, the tearing process is shown through Fig. 64 to 67.

A. There is no pairs of variables for $\begin{bmatrix} L & L \\ L & L \end{bmatrix} = 0$.

B. The pairs of variables for $\begin{bmatrix} L & L \\ H & L \end{bmatrix} = \begin{bmatrix} L & L \\ L & H \end{bmatrix} = \begin{bmatrix} H & L \\ L & L \end{bmatrix} = \begin{bmatrix} L & H \\ L & L \end{bmatrix} = 1$ are

$|18 \ 17|$, $|6 \ 18|$, $|7 \ 18|$, $|18 \ 7|$, $|9 \ 18|$. Remove all of these pairs from

the block. The result after removing is shown as Fig. 64.

| | Color Gamut | Drop placement accuracy | Bleed | Coalescence | Registration | Resolution enhancement technology | The amount of ink placed on the media | The consistency of the drop volume | The consistency of the drop size | Ink penetration rate | Orifice diameter | Wait time banding | Mottling | Spray, leathering and jaggy lines | Visual measurement of paper flatness | Visual measurement of height of the corr | Dot density | Banding |
|--|-------------|-------------------------|-------|-------------|--------------|-----------------------------------|---------------------------------------|------------------------------------|----------------------------------|----------------------|------------------|-------------------|----------|-----------------------------------|--------------------------------------|--|-------------|---------|
| | 1 | 2 | 6 | 7 | 8 | 9 | 13 | 15 | 16 | 17 | 18 | 4 | 5 | 10 | 11 | 12 | 14 | 3 |
| Color Gamut | 1 | | | | | | | | | | | | | | | | | |
| Drop placement accuracy | | 2 | | | | | 1 | 1 | | | | 1 | | | | | | |
| Bleed | | | 6 | | | | 1 | 1 | | 1 | | | | | | | | |
| Coalescence | | | | 7 | | 1 | 1 | 1 | 1 | | | | | | | | | |
| Registration | | | | | 8 | | 1 | 1 | | | | | | | | | | |
| Resolution enhancement technology | | | | | | 9 | 1 | 1 | 1 | | | | | | | | | |
| The amount of ink placed on the media | | | | | | | 13 | 1 | 1 | | | 1 | | | | | | |
| The consistency of the drop volume | | | | | | | | 15 | | | | | | | | | | |
| The consistency of the drop size | | | | | | | | | 16 | | | | | | | | | |
| Ink penetration rate | | | | | | | | | | 17 | | | | | | | | |
| Orifice diameter | | | | | | | | | | | 18 | | | | | | | |
| Wait time banding | | | | | | | | | | | | 4 | | | | | | |
| Mottling | | | | | | | | | | | | | 5 | | | | | |
| Spray, leathering and jaggy lines | | | | | | | | | | | | | | 10 | | | | |
| Visual measurement of paper flatness | | | | | | | | | | | | | | | 11 | | | |
| Visual measurement of height of the corr | | | | | | | | | | | | | | | | 12 | | |
| Dot density | | | | | | | | | | | | | | | | | 14 | |
| Banding | | | | | | | | | | | | | | | | | | 3 |

Figure 64 DSM after process A, B

C. Now, the pairs of variables

$$\begin{bmatrix} L & L \\ H & H \end{bmatrix} = \begin{bmatrix} H & L \\ H & L \end{bmatrix} = \begin{bmatrix} L & H \\ H & L \end{bmatrix} = \begin{bmatrix} H & L \\ L & H \end{bmatrix} = \begin{bmatrix} L & H \\ L & H \end{bmatrix} = \begin{bmatrix} H & H \\ L & L \end{bmatrix} = 2 \text{ are}$$

$$\begin{bmatrix} 2 & 18 \\ 17 & 6 \\ 6 & 17 \end{bmatrix}$$

$$\begin{bmatrix} 13 & 18 \end{bmatrix}$$

$$\begin{bmatrix} 15 & 18 \end{bmatrix}$$

$$\begin{bmatrix} 16 & 18 \end{bmatrix}$$

Remove all of these pairs from the block. The result after removing is shown as Fig. 65.

| | Color Gamut | Drop placement accuracy | Bleed | Coalescence | Registration | Resolution enhancement technology | The amount of ink placed on the media | The consistency of the drop volume | The consistency of the drop size | Wait time banding | Mottling | Visual measurement of paper flatness | Visual measurement of height of the corr | Dot density | Ink penetration rate | Orifice diameter | Spray, leathering and jaggy lines | Banding |
|--|-------------|-------------------------|-------|-------------|--------------|-----------------------------------|---------------------------------------|------------------------------------|----------------------------------|-------------------|----------|--------------------------------------|--|-------------|----------------------|------------------|-----------------------------------|---------|
| Color Gamut | 1 | | | | | | | | | | | | | | | | | |
| Drop placement accuracy | | 2 | | | | | | | | | | | | | | | | |
| Bleed | | | 6 | | | | | | | | | | | | | | | |
| Coalescence | | | | 7 | | | | | | | | | | | | | | |
| Registration | | | | | 8 | | | | | | | | | | | | | |
| Resolution enhancement technology | | | | | | 9 | | | | | | | | | | | | |
| The amount of ink placed on the media | | | | | | | 13 | | | | | | | | | | | |
| The consistency of the drop volume | | | | | | | | 15 | | | | | | | | | | |
| The consistency of the drop size | | | | | | | | | 16 | | | | | | | | | |
| Wait time banding | | | | | | | | | | 4 | | | | | | | | |
| Mottling | | | | | | | | | | | 5 | | | | | | | |
| Visual measurement of paper flatness | | | | | | | | | | | | 11 | | | | | | |
| Visual measurement of height of the corr | | | | | | | | | | | | | 12 | | | | | |
| Dot density | | | | | | | | | | | | | | 14 | | | | |
| Ink penetration rate | | | | | | | | | | | | | | | 17 | | | |
| Orifice diameter | | | | | | | | | | | | | | | | 18 | | |
| Spray, leathering and jaggy lines | | | | | | | | | | | | | | | | | 10 | |
| Banding | | | | | | | | | | | | | | | | | | 3 |

Figure 65 DSM after process C

D. After the processes above, the pairs of variables

$$\begin{bmatrix} H & L \\ H & H \end{bmatrix} = \begin{bmatrix} L & H \\ H & H \end{bmatrix} = \begin{bmatrix} H & H \\ H & L \end{bmatrix} = \begin{bmatrix} H & H \\ L & H \end{bmatrix} = 3 \text{ are}$$

|13 6|

|13 7|

|7 15|

|16 7|

|2 9|

|8 9|

|15 9|

Remove all of these pairs from the block. The result after removing is shown as Fig. 66.

| | Color Gamut | Wait time banding | Mottling | The amount of ink placed on the media | The consistency of the drop volume | The consistency of the drop size | Drop placement accuracy | Orifice diameter | Bleed | Registration | Coalescence | Resolution enhancement technology | Spray, leathering and jaggy lines | Visual measurement of paper flatness | Visual measurement of height of the corr | Dot density | Ink penetration rate | Banding |
|--|-------------|-------------------|----------|---------------------------------------|------------------------------------|----------------------------------|-------------------------|------------------|-------|--------------|-------------|-----------------------------------|-----------------------------------|--------------------------------------|--|-------------|----------------------|---------|
| | 1 | 4 | 5 | 13 | 15 | 16 | 2 | 18 | 6 | 8 | 7 | 9 | 10 | 11 | 12 | 14 | 17 | 3 |
| Color Gamut | 1 | | | | | | | | | | | | | | | | | |
| Wait time banding | | 4 | | | | | | | | | | | | | | | | |
| Mottling | | | 5 | | | | | | | | | | | | | | | |
| The amount of ink placed on the media | | | | 13 | 1 | 1 | | | | | | | | | | | | |
| The consistency of the drop volume | | | | | 15 | | | | | | | | | | | | | |
| The consistency of the drop size | | | | | | 16 | | | | | | | | | | | | |
| Drop placement accuracy | | | | | | | 2 | | | | | | | | | | | |
| Orifice diameter | | | | | | | | 18 | | | | | | | | | | |
| Bleed | | | | | | | | | 6 | | | | | | | | | |
| Registration | | | | | | | | | | 8 | | | | | | | | |
| Coalescence | | | | | | | | | | | 7 | | | | | | | |
| Resolution enhancement technology | | | | | | | | | | | | 9 | | | | | | |
| Spray, leathering and jaggy lines | | | | | | | | | | | | | 10 | | | | | |
| Visual measurement of paper flatness | | | | | | | | | | | | | | 11 | | | | |
| Visual measurement of height of the corr | | | | | | | | | | | | | | | 12 | | | |
| Dot density | | | | | | | | | | | | | | | | 14 | | |
| Ink penetration rate | | | | | | | | | | | | | | | | | 17 | |
| Banding | | | | | | | | | | | | | | | | | | 3 |

Figure 66 DSM after process D

E. Now, the pairs of variables $\begin{bmatrix} H & H \\ H & H \end{bmatrix} = 4$ are $|13 \ 15|$, $|13 \ 16|$. Remove

all of these pairs from the block. The result after removing is shown as

Fig. 67.

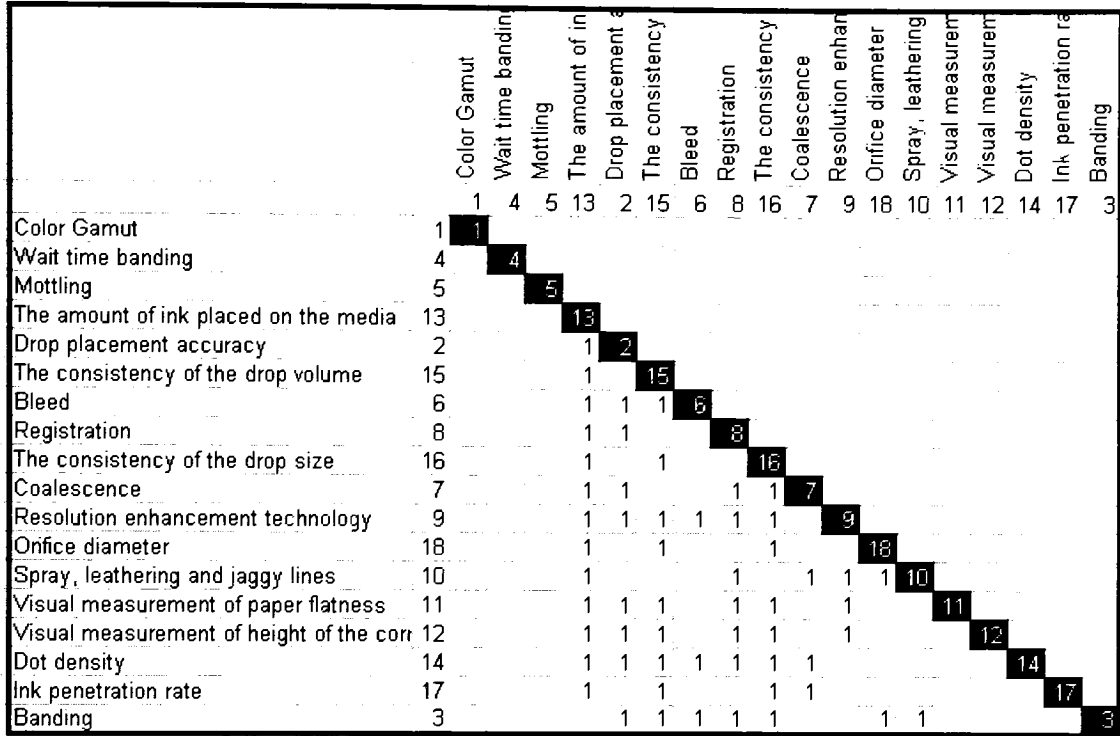


Figure 67 DSM after process E

Therefore, after this process, DSM provides a more effective time sequence for the product development plan. It is: $1 \rightarrow 4 \rightarrow 5 \rightarrow 13 \rightarrow 2 \rightarrow 15 \rightarrow 6 \rightarrow 8 \rightarrow 16 \rightarrow 7 \rightarrow 9 \rightarrow 18 \rightarrow 10 \rightarrow 11 \rightarrow 12 \rightarrow 14 \rightarrow 17 \rightarrow 3$.

5 RECOMMENDATIONS AND CONCLUSION

We asked three questions at Chapter one (Problem Statement) as below.

1. What new knowledge is gained by combining QFD, TRIZ and DSM during the design phase of a product?
2. What process should be followed to obtain the new knowledge?
3. What data structure represents the knowledge?

Now, these questions can be answered.

5.1 Conclusions from this research

The objective of this research is to provide an effective strategy for product development process modeling, by exploiting the relationships between QFD, TRIZ and DSM.

In order to represent the data movement during the whole product development knowledge processing system, this paper presented a graphical tool called the Network of ICOMs to show the data flows, data processes, and data sources/destinations.

This thesis tries to combine the three design methods QFD, TRIZ and DSM from a broad perspective. Firstly, prior to this study, there is no formal method to solve the contradictions between engineering characteristics. In this case, a new knowledge is gained here by the application of combining QFD and TRIZ. Secondly, by rearranging the DSM, the system was given a better activities sequence with the input parameters such as Relative Importance and Technical Risk. This is the answer for the first question.

The answer for the second question is:

First of all, this paper integrated QFD and TRIZ to perform simulation-based development for the HP DeskJet 1200C printer. It also built a comprehensive mathematical model for this integration method. After identifying the key customer requirements, a series of calculations were performed for the data transform during QFD process. There usually exist contradictions between the Engineering Characteristics. Prior to this study, there is no method to solve these contradictions. In this case, a new knowledge is gained here by the application of combining QFD and TRIZ. As an inventive problem solving method, TRIZ was applied here to generate creative solutions for the desired improvements of the printer. Therefore, the outcome of this optimization process, the design solutions, was transformed into the second house: Parts Deployment.

Then, another model combining DSM and QFD was built to facilitate system integration analysis. By rearranging the DSM, the system was decomposed with the input parameters such as Relative Importance and Technical Risk. This approach improved the system configuration understanding and gave a better time sequence solution for the tasks in the system.

Finally, TRIZ enables me to solve contradictions from a new direction. I will continue to use this method whenever possible.

In all, it is revolutionary to unite the data exchange between QFD, TRIZ and DSM.

5.2 Future research

By successfully combining QFD and TRIZ, QFD and DSM, this research provided an innovative perspective for the data transform in the knowledge-processing system. However, there is no approach to combine DSM and TRIZ right now, so one area of future research is looking for the relationship between DSM and TRIZ.

In this thesis, the innovative data structure, called matrix-based technique was presented. It facilitated the complex data transform and movement during the knowledge processing system. This technique united the whole knowledge data flow in the product development process, using same parameters. This is also the answer for question 3rd.

According to this method, another way to expand on this topic is that these parameters can be even freely exchanged from one to another during the whole process including: customer requirements, engineering characteristics, parts characteristics, process operations and production.

This matrix-based model can also be further easily developed using computer program such as Visual C++.

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APPENDIX 1 House of Quality Model description

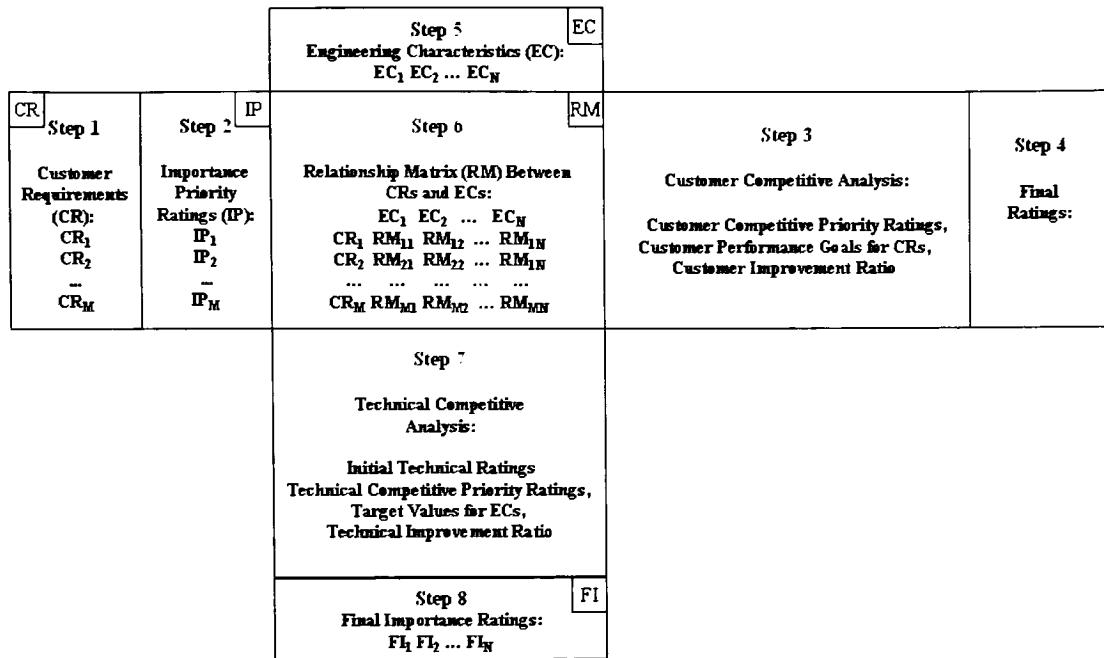


Figure 68 House of Quality Model

APPENDIX 2 Customer Requirements Definitions

Paper cockle

“It is a distortion in which bumps or ridges are randomly produced on the printed paper” (Hunt 19).

Curl

“It is a phenomenon in which the edges of the paper migrate towards the center of the paper (see Fig. 69). Visual measurement, which is done on paper cockle, involves measuring the height of all four corners of a sample resting on a flat surface” (Hunt 19).



Figure 69 Curl

Whiteness

It is the quality or state of the achromatic color of greatest lightness (bearing the least resemblance to black).

APPENDIX 3 Engineering Characteristics Definitions

Color Gamut:

“Color Gamut = Value x Chroma² x Hue

Color quality of a printed output is determined using the Munsell color measurement system. Chroma is a measure of the vividness or brightness of the color. Hue refers to the shade or tone of the color. Value is a measure of the darkness or lightness of the color. The color gamut describes this three-dimensional color space” (Hunt 18).

Drop placement errors:

“Drop placement errors caused by swath advance (see Fig. 70) and theta-Z (printhead rotational misalignment) errors” (Hunt 18).

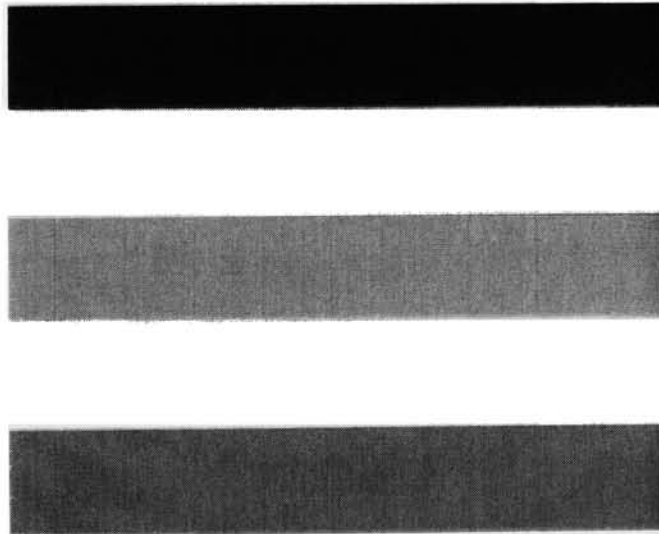


Figure 70 Drop placement errors caused by swath advance

Banding

“Banding is caused by pen defects such as misdirection (see Fig. 71) and variations in drop volume or dot size” (Hunt 18-19),

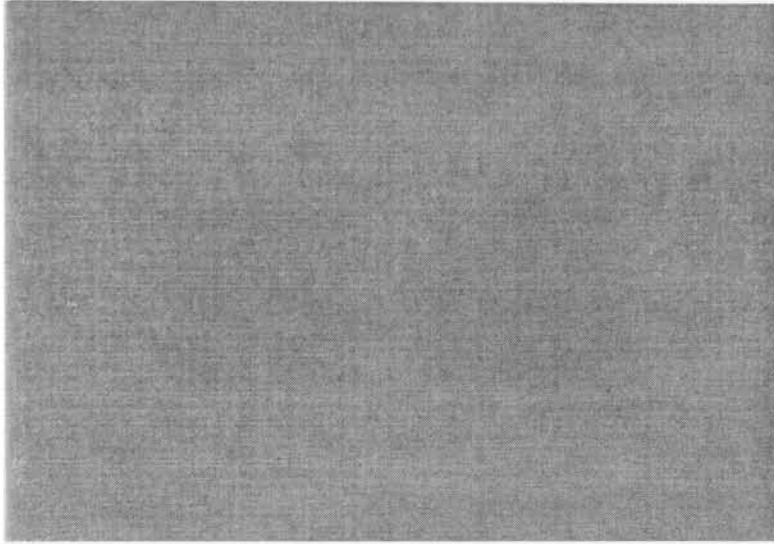


Figure 71 Banding caused by misdirection

Wait time banding (see Fig. 72) (Hunt 19)

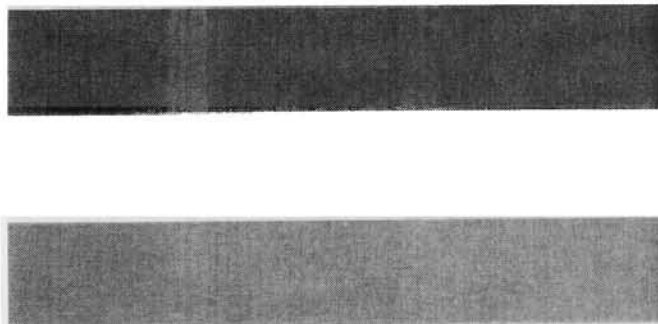


Figure 72 Wait time banding

Mottling (see Fig. 73) (Hunt 19)

“A term used to describe the unwanted effect of two ink drops pooling together. Mottling has a negative effect on image quality and can lead to "muddy" colors. It often occurs when there is excessive ink strain applied to the media surface and the media can not handle the absorption of the ink” (Glossary par. 12).

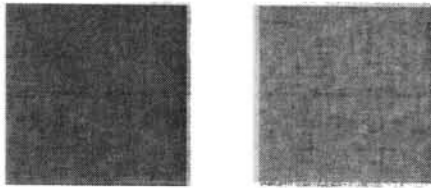


Figure 73 Mottling

Bleed

“A term used to describe the action of ink spreading. It is also called dot gain. A matched printing system would design the ink, media, and dot gain to produce a perfect balance of bleed. Too much bleed, and mottling occurs (see mottling). Not enough bleed (or dot gain) and large white spaces occur between the dots (which produces light or non-vivid colors). (Glossary par. 2)

It is caused by different penetration rates of the ink into the media (see Fig. 74)” (Hunt 19).

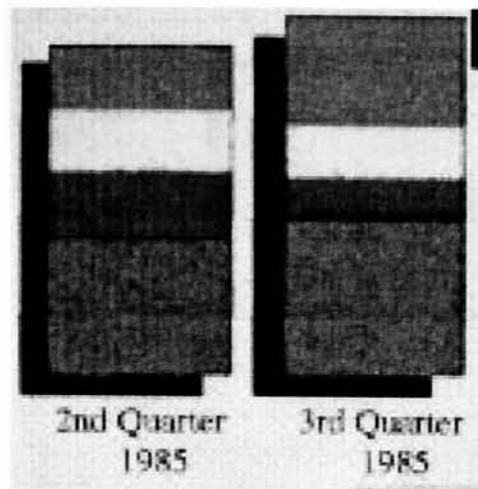


Figure 74 Bleed

Coalescence

“It is caused by drops pulling together before the printing surface is wetted” (Hunt 19).

The print mode

“To achieve this aggressive goal, the amount of ink placed on the media per dot location, the speed with which the ink is placed, and the number of passes required to complete the image became very critical factors. The print mode is the mechanism used to control these factors” (Hunt 19).

Spray, leathering, and jaggy lines (see Fig. 75– 77 Hunt 19)

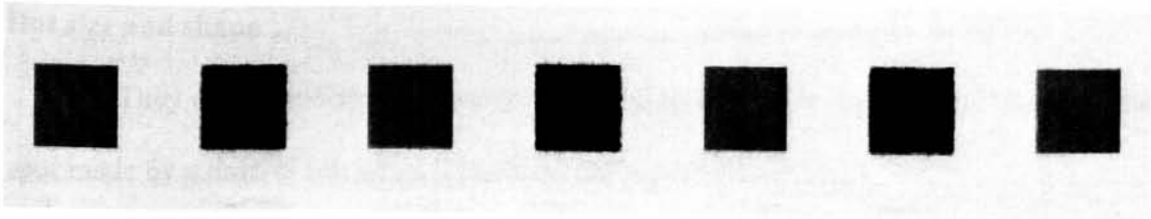


Figure 75 Spray

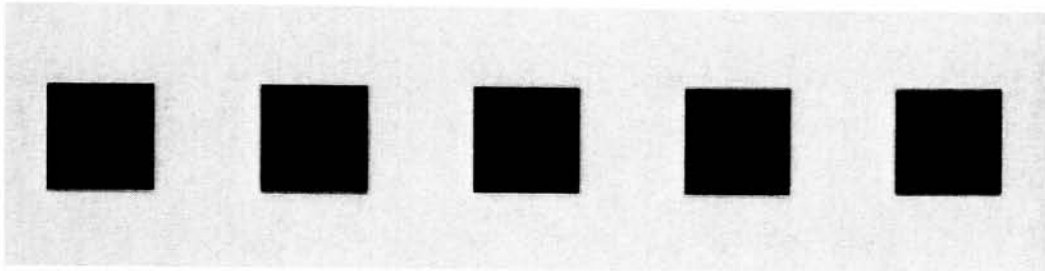


Figure 76 Shim spray

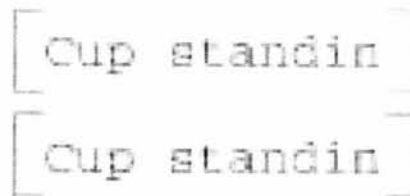


Figure 77 Jagged lines

The print cartridge architecture

“It is an important print cartridge parameter that, in conjunction with the ink, controls these attributes” (Hunt 20).

The amount of ink placed on the media

“It is a very important, parameter to control since it affects several print quality attributes such as bleed, transparency film bleed and blocking, glossy film bleed and color transfer, cockle, curl, and banding” (Hunt 20).

Dot size and shape

“They are engineering measurements used to determine the size and shape of the spot made by a drop of ink when it lands on the paper” (Hunt 20).

APPENDIX 4 Relationship between CRs and ECs

| Print Quality | | | | | | | | | | | | | | | |
|---------------|-----------------------|---|----|----|-----|----|----|-----|----|----|----|----|----|----|---------|
| | | ↑ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | | ↓ | ↓ | ↓ | | ↑ | |
| | Color quality | 5 | 9① | | | | | | | | | | | | 9 3 |
| | Area fill quality | 4 | | 9② | 3②⑤ | 3② | 3② | 3②⑤ | 3② | 9② | | | | 3⑦ | 3⑦ 9⑦ 1 |
| | Line and edge quality | 4 | | 9③ | | | | | | | 9③ | | | 3⑦ | 9⑦ 3⑦ 1 |
| | Cockle | 3 | | | | | | | | | | 9④ | 3 | 3⑤ | 3 3 3 |
| | Curl | 3 | | | | | | | | | | | 9⑤ | 3⑤ | |
| | Whiteness | 2 | 9 | | | | | | | | | | | 3 | 3 1 1 |
| | Archivability | 1 | 1 | | | | | | | 3 | | | | 9 | 3 9 |

① (Hunt 18)

② (Hunt 18-19)

③ (Hunt 19)

④ (Hunt 19)

⑤ (Hunt 19)

⑥ (Hunt 209)

⑦ (Hunt 20)

Hunt, Catherine B., Ronald A. Askeland, Leonard Slevin, and Keshava A. Prasad. "High-Quality Inkjet Color Graphics Performance on Plain Paper" Hewlett-Packard Journal Feb. (1994): 18-27

Figure 78 Relationship between CR and EC

APPENDIX 5 House 1 for QFD

House 1 for HP DeskJet 1200C Printer

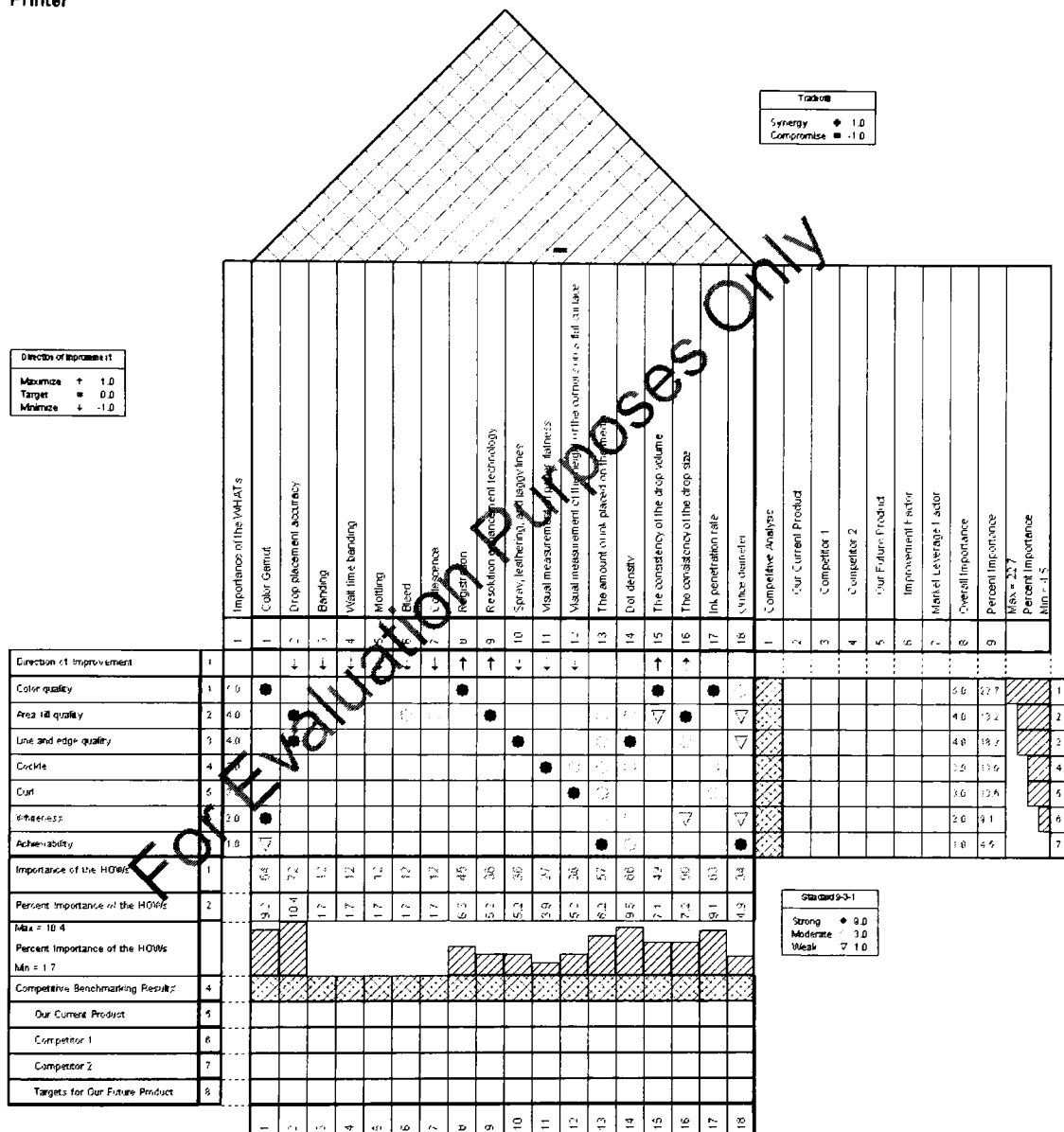


Figure 79 House 1 for QFD (Adapted from QFD Capture)

APPENDIX 6 TRIZ Report using CREAX

HP DeskJet 1200C

Problem description

Briefing

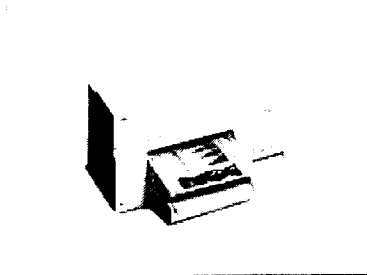
Reduce the cockle and curl on the printing paper

Question

Can we improve the printing process that makes the cockle and curl on the paper less?

| | |
|------------------|--|
| Project title | Project Title |
| Project sponsor | ISE department at RIT |
| Project customer | Customer who uses HP DeskJet 1200C |
| Project team | Jiefei Qiu, Professor Stiebitz, Dr. Hensel |

| Benefits | What are the goals? | Measures of success |
|--|--|--|
| ISE department at RIT | Improve the HP DeskJet printers that increase market-share, revenue and ultimately profitability | When sales are increased |
| Customer who uses HP DeskJet 1200C | A printer that is cheap, easy and fun to use. | Majority of a test group of customers are impressed with product |
| Jiefei Qiu, Professor Stiebitz, Dr. Hensel | Working as a team to improve the HP DeskJet 1200C. | Highly motivated team members throughout the process |



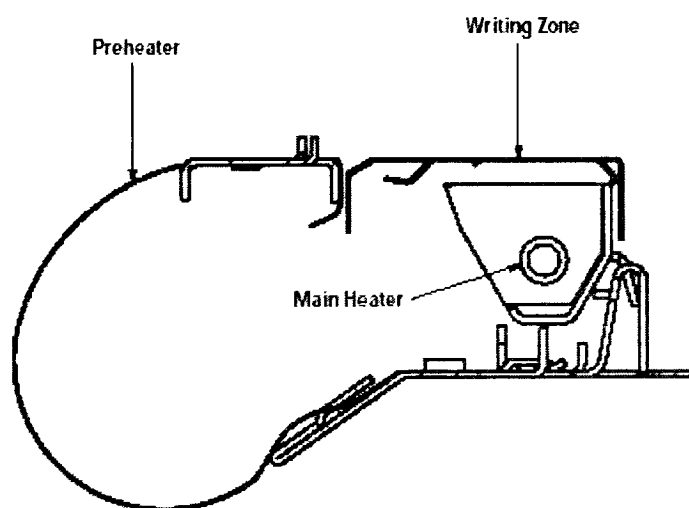
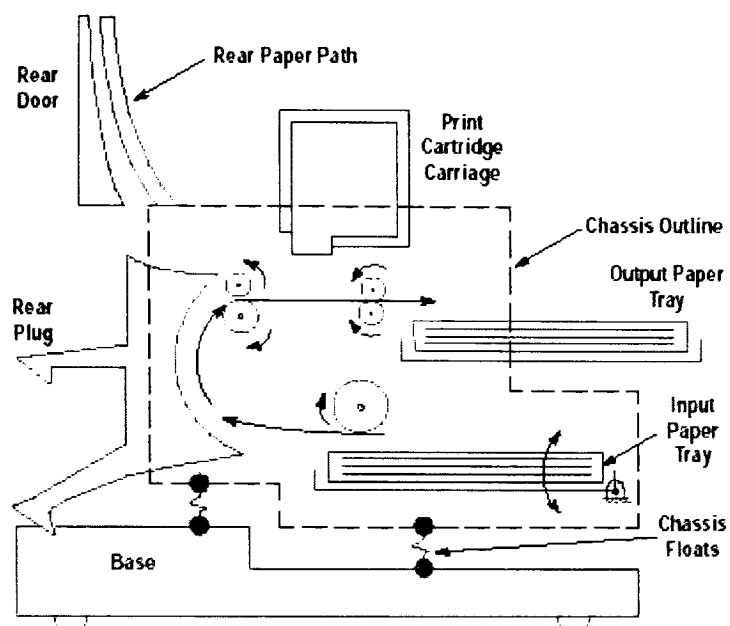


Fig. 3. Heated media path.

Redefinition

.....

People want the area fill
quality
and edge quality better
without spending too
much money.

An improved DeskJet
1200C printer which
reduces the cockle and
curl on the printing paper.

There is a distortion in
which bumps or ridges are
randomly produced on the
paper.

The edges of the paper
migrate towards the center
of the paper.

Reduce the water in the
paper when printing, but
don't let this process lead
to the distortion of the
edges of the paper.

It is required to inc
rease the temperature of
the solid area of the paper
to reduce the cockle.
However, increasing the
temperature leads to
increasing the curl.

.....

Ideality

| | |
|-----------------------------------|--|
| Function trying to achieve | Can not reduce the cockle and curl together |
| Current situation | Improve the printing process |
| Ideal final result | Reduce both of the cockle and curl |
| | |
| The IDEAL FINAL RESULT | The printer does not produce the cockle and curl. |
| OBSTACLES | |
| Reason(s) for OBSTACLES | |
| Solution for OBSTACLES | |
| | |
| The IDEAL FINAL RESULT | The process of reduction doesn't interrupt user |
| OBSTACLES | |
| Reason(s) for OBSTACLES | |
| Solution for OBSTACLES | |
| | |
| The IDEAL FINAL RESULT | Reducing both of them without effort |
| OBSTACLES | |
| Reason(s) for OBSTACLES | |
| Solution for OBSTACLES | |
| | |
| The IDEAL FINAL RESULT | Both of them have no bad effect |
| OBSTACLES | |
| Reason(s) for OBSTACLES | |
| Solution for OBSTACLES | |
| | |
| The IDEAL FINAL RESULT | Reduced while printing |
| OBSTACLES | |
| Reason(s) for OBSTACLES | |
| Solution for OBSTACLES | |
| | |
| The IDEAL FINAL RESULT | No manual action required |
| OBSTACLES | |
| Reason(s) for OBSTACLES | |
| Solution for OBSTACLES | |
| | |
| The IDEAL FINAL RESULT | Fewer negative effects |
| OBSTACLES | |
| Reason(s) for OBSTACLES | |
| Solution for OBSTACLES | |

Constraints

| | | |
|--|---|--|
| No additional purchase price No additional effort required No increase of manufacture cost | 220V Electricity | |
| Manufacture: Cannot become contaminated during packing | Printing paper: Limited space in the printer Should be compatible with many other componets of the printer | After use: Should not have much bad effect on the enviroment |
| Manufacture individual components: No increase of manufacture cost | Manufacture individual components: Should not make other componets of the printer less effective | Materials should be recyclable Materials should be disposable |

Resources

| | | |
|---|---|--|
| Printer, paper in shop Noise Vibration | Preheater Main heater Paper control shims Paper input/output tray Ink cartridge Electricity Other printer componets | Improvement in printing quality Speed Paper cost per copy Color cost per copy Media support |
| Manufacture: Assemble the printer Adjust the heater and paper's position | Printing on the paper: Ink Heat Air around the paper Heater | After use: The printing process won't produce any bad effect to the enviroment. Disposal of the ink cartridge and paper |
| Manufacture individual components: Vibrations | Water contained in the ink Water contained in the paper Upper part of the paper Bottom part of the paper | Re-usability Recyclability Disposal |

Idea(s)

Sorting option: Chronological

Idea No. : 1

Category : None

Source : Principle : Hurry

After the heat propagates in the bottom of the paper, move it away quickly.

Idea No. : 2

Category : None

Source Principle : Mechanics Substitution

Use Infrared Heating process. The infrared radiation is often supplied by high-intensity, quartz, heat lamps, producing radiation with wavelengths around 1 micron.

Idea No. : 3

Category : None

Source : Principle : Mechanics Substitution

Use Laser device, which is one of the several devices that emit highly amplified and coherent radiation of one or more discrete frequencies.

Idea No. : 4

Category : None

Source : Principle : Mechanics Substitution

Use Light wave heating, which is process of heating materials through the application of light wave (combination of infrared and visible light).

Idea No. : 5

Category : None

Source : Principle : Mechanics Substitution

Use radiation, which is the emission and propagation, and emission of energy in the form of rays or waves.

Idea No. : 6

Category : None

Source : Principle : Mechanics Substitution

Use Solar energy for heating.

Idea No. : 7

Category : None

Source : Principle : Mechanics Substitution

Use Thermoacoustic Effect which states that, a sound wave heats and cools small parcels of gas along the length of its propagation.

Idea No. : 8

Category : None

Source Principle Phase Transition

Add a heat pump to use the heat of vaporization and heat of condensation of a closed thermodynamic cycle to do useful work

Idea No. : 9

Category : None
Source : Principle Cheap Disposable

Use multi-layer paper.

Idea No. : 10

Category : None
Source Principle : Calm

Carry out the process in vacuum.

Idea No. : 11

Category : None
Source : Principle : Local Quality

Use a temperature gradient instead of constant temperature around the environment of the paper.

Idea No. : 12

Category : None
Source : Principle : Local Quality

Heat both the top and the bottom of the paper.

Idea No. : 13

Category : None
Source : Principle : Hole

Drill holes in the bottom side of the paper.

Idea No. : 14

Category : None
Source : Principle : Vibrate

Use Microwaves, which are a form of "electromagnetic" radiation. That is, they are waves of electrical and magnetic energy moving together through space.

APPENDIX 7 Linked houses from CRs to PRs

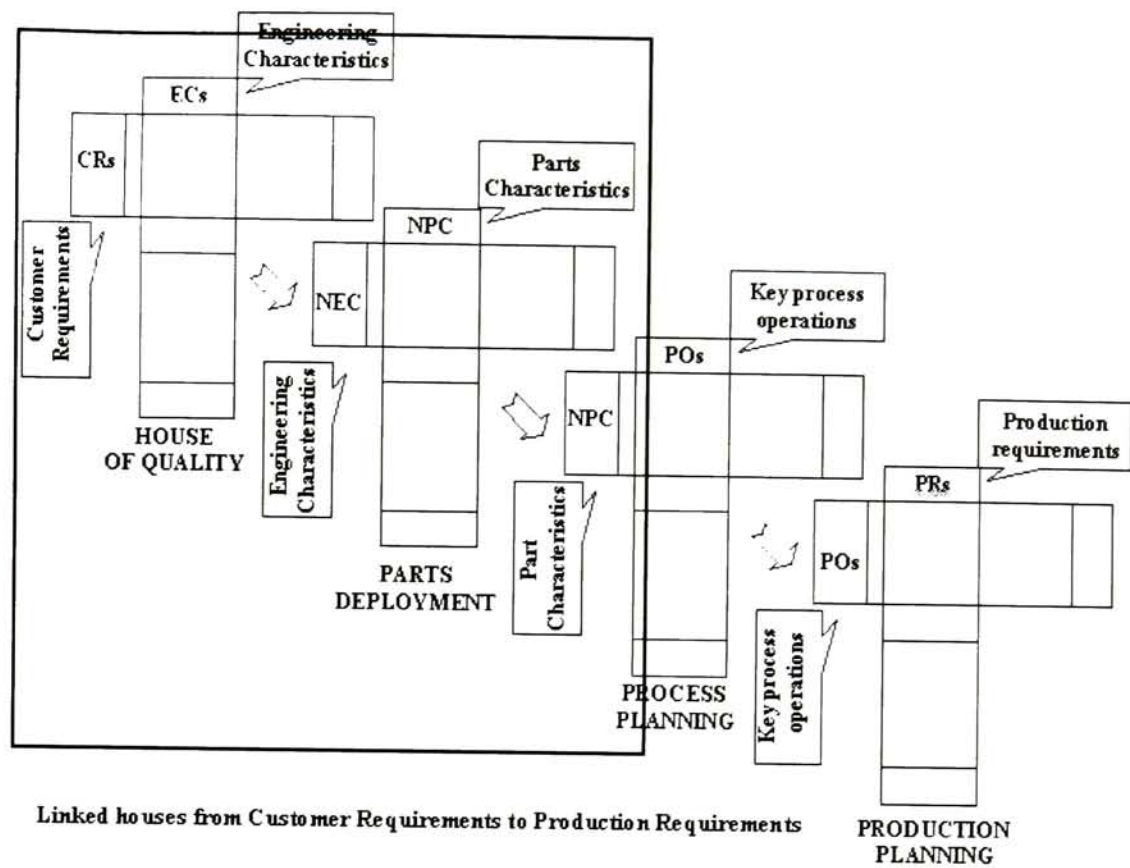


Figure 80 Linked houses from Customer Requirements to Production Requirements