INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED15
27-30 JULY 2015, POLITECNICO DI MILANO, ITALY

QUALITY FUNCTION DEPLOYMENT USING MULTISPACE DESIGN MODEL AND ITS APPLICATION

Kato, Takeo (1); Horiuchi, Shigehiro (2); Miwa, Toshiharu (3); Matsuoka, Yoshiyuki (4)
1: Tokai University, Japan; 2: Lenovo Japan, Ltd., Japan; 3: Hitachi, Ltd., Japan; 4: Keio University, Japan

Abstract

Due to the rapid growth of the information and communication technology, most system developments are required not only the high functionality but also the flexibility to collaborate with the other one through the network. For the successful implementation of the difficult development, the conceptual design process in which the various stakeholders' requirements and their bottlenecks are discussed, has become important.

This paper introduces the multispace quality function deployment (M-QFD) and its analytical methods and illustrates their application to a lithography system design. M-QFD is comprised of four deployment charts which includes the four types of design elements: value, meaning, state, and attribute. M-QFD enables designers to extract the design elements based on diverse requirements (requirements of the customer, company, society, etc.) and the circumstance of the design objects (user physique, ambient temperature, etc.). In addition, the analytical methods for M-QFD (correspondence analysis, interpretive structural modeling, design structure matrix, and multi domain matrix) enable them to easily understand the design element relationships.

Keywords: Design methods, Design theory, Product structuring

Contact:
Dr. Takeo Kato
Keio University
Mechanical Engineering
Japan
kato@mech.keio.ac.jp

Please cite this paper as:
Surnames, Initials: *Title of paper*. In: Proceedings of the 20th International Conference on Engineering Design (ICED15), Vol. nn: Title of Volume, Milan, Italy, 27.-30.07.2015

1 INTRODUCTION

Internet of things (i.e. the interconnection of various devices through the internet infrastructure) has been realized due to the rapid growth of the information and communication technology. Thus, most system developments are required not only the high functionality for the system but also the flexibility to collaborate with the other one through the network and become large scale and complicated (Matsuoka, 2010a). For the successful implementation of the difficult development, the conceptual design process in which the various stakeholders' requirements and their bottlenecks are discussed, has become important. In the previous study (Kato et al., 2013), the multispace quality function deployment (M-QFD), which allows designers to extract the design elements regarding diverse values (e.g. user, company, and society values) and circumstances (e.g. users and surrounding environment), was proposed. This study applies M-QFD to a lithography system design for manufacturing semiconductor LSI to confirm the effectiveness.

This paper is organized as follows. Section 2 overviews M-QFD and the design theory and analytical methods applied thereto. Section 3 illustrates an application of M-QFD to a lithography system design, while Section 4 provides conclusions and the future research direction.

2 MULTISPACE QUALITY FUNCTION DEPLOYMENT

This section overviews M-QFD by illustrating the multispace design model that suggests the design element classification structure in M-QFD and several analytical methods to clarify the relationships between the elements.

2.1 Multispace design model

The multispace design model (Matsuoka, 2010a and 2010b) is one of the design theories and was constructed based on the general design theory (Yoshikawa, 1991 and Reich, 1995). The model aims to comprehensively deal with design and defines design activities as the reasoning in the designers' thinking space (designers' brain) based on the designers' knowledge. In the thinking space, two kinds of reasoning (abduction and deduction) are repeating. The abduction extracts the design elements that meet to their superior elements (e.g. requirements and specifications), while the deduction evaluates how they meet them. After the reasoning, the relationships between design elements are constructed. The model defines four subspaces in the thinking space and design activities as the reasoning in each space and inter-spaces (Figure 1 left). These spaces are described below.

- The value space is a set of value elements, which are psychological elements related to the values generated from the functions and images of the design objects (meaning elements), including values of the users, company, and society;
- The meaning space is a set of meaning elements, which are psychological elements with regard to meaning (functions and images of the design objects) that draw the value elements, including the robustness, streamlined shape, etc.;
- The state space is a set to describe the circumstance and state elements. Circumstance is composed of the physical elements with respect to the environment where the design object is used, and includes time, external force, and users physique, etc. The state elements are physical quantities generated when products are in the circumstance, including stress, acceleration, etc.
- The attribute space is a set to describe the attribute elements: physical elements that are not related to circumstance elements, such as the geometrical and physical properties of the products, and include dimension, material, etc.

The previous study (Kato et al., 2013) applied the concept of the four spaces in the model to quality function deployment (QFD) and proposed M-QFD. QFD is an effective design method to analyze the design elements using quality charts (Akao, 1990 and Akao et al., 1994), and diverse QFDs have been proposed. Research on QFDs can be classified as follows: 1) improved methods to evaluate the design elements (Hsiao (2002), Kuo et al. (2009), Chen et al. (2011), etc.); 2) change in the items of the quality charts (Zhang et al. (1999), Ashihara et al. (2005), Barad (2008), etc.); 3) usage assistance (Yeh et al. (2011), Huang et al. (2002), Miwa et al. (2009), etc.). Quality charts enables designers to transform the design elements of customer demands (considered in the early process of design) into those of the engineering characteristics, product function, parts, etc. (considered in the latter process of design). The quality charts are composed by the deployment charts, relationship matrices, and correlation matrices. The deployment charts, including allied design elements, are used to prepare quality charts, and the relationship matrices and correlation matrices depict the relationship between design elements in the different and same deployment charts, respectively. M-QFD has the four-space deployment charts with correlation matrices, which correspond to the intra-space models, and three relationship matrices, which correspond to the inter-space models (Figure 1 right).

M-QFD has two main merits. One is the design members can properly consider the relationship between the meanings of the design objects and the diverse values generated from them using the value and meaning deployment charts. The other is the category of the circumstance included in the state deployment chart clarifies the diverse circumstance of the product based on the extracted diverse values and enables the design members to advance the design activities.

Next subsection illustrates the methods to analyze the relationships between these elements.

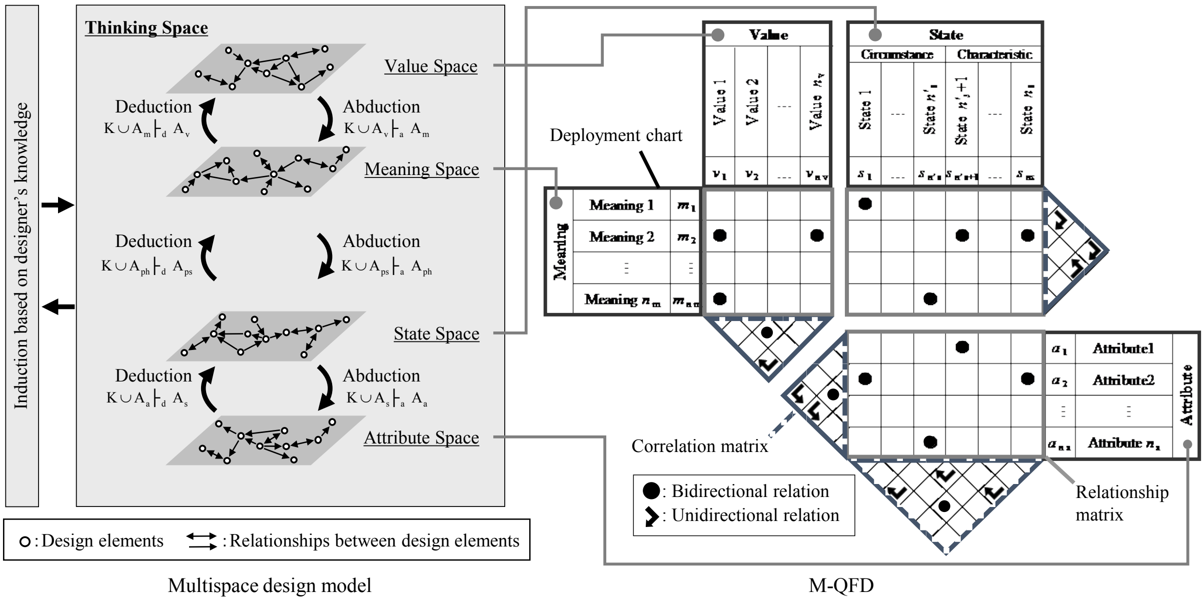


Figure 1. Conceptual drawing of Multispace design model and M-QFD

2.2 Design element relationship analyses

M-QFD has three relationship matrices and four correlation matrices, and the designers proceed their design activities with attention to the design element relationships described in these matrices. However, in the case of designing the large-scale and complicated system, the relationships are difficult to be understood, and this requires the methods to organize them. This subsection introduces the correspondence analysis for organizing the relationships described in the relationship matrices and interpretive structural modeling (ISM) and design structure matrix (DSM) for that in the correlation matrices, and multi domain matrix (MDM) for that in both matrices.

2.2.1 Correspondence analysis

Correspondence analysis (Benzécri, 1992) is a multivariate statistical technique and displays or summarizes some types of data in two-dimensional graphical form on the basis of their relatedness. This method can be applied to the relationship matrices of M-QFD and plot the two types of the design elements on the two-dimensional scatter graph based on their relatedness (Figure 2). However, this method sometimes derives an outlier in the scatter graph when there are elements that have few relationships to others. To avoid the problem, it is effective to classify the elements of one type into some groups and set the average value of each group as the data for input. Note that the element type, which is less important in the analysis, is chosen to be grouped. Additionally, the application of cluster analysis (Iwata et al., 2008) to the scatter graph is effective to organize the design elements plotted on the graph into some categories.

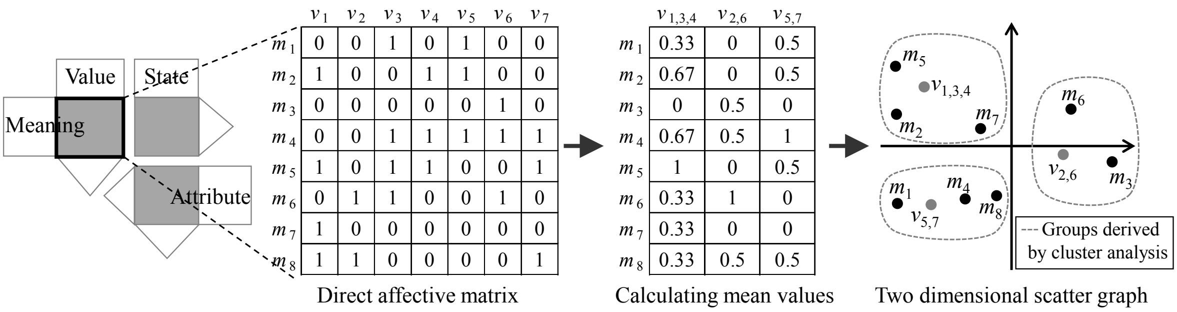


Figure 2. Correspondence analysis for M-QFD

2.2.2 Interpretive structural modeling

ISM is a design method to visually express the complex relationships between design elements (Warfield, 1976 and Olsen, 1982). Designers start by making the direct affective matrix that expresses the direct relationships between the design elements. The matrix is transformed into the skeleton matrix that simplifies the relationships using computer program. Skeleton matrix has two main features: 1) elements affecting each other are grouped; 2) the higher an element is located, the more elements it can affect. Thus, ISM can simultaneously group and stratify. On the basis of the matrix, the designers can depict the directed graph (structural model) in which the elements affecting others are located higher and are connected only to the directly affected elements by arrowed lines.

Thus, this method can be applied to the direct affective matrix made from each correlation matrix of M-QFD and construct the structural model regarding each type of the elements in order for the designers to easily understand their relationships (Figure 3 upper part) (Kato et al., 2014a). Note that the elements (values) of the direct affective matrix are one (the design element in the row relates to that in the column) or zero (no relationship between them), and the matrix calculation is based on Boolean operations.

ISM extracts indirect relationships between design elements by calculating the power of the direct affective matrix, and then automatically groups and stratifies them. Thus, ISM can analyze the general relationships of the elements and is useful in conceptual and basic designs (the early process of design) in which the number of the relationships is small. However, ISM is not applicable to detailed design (the late process of design), in which the number is large and the designer's heuristic decision is required, because it derives the indirect relationships (i.e. increases the number of the relationships) and make the analysis complicated. In the situation, DSM described in the next subsection is effective.

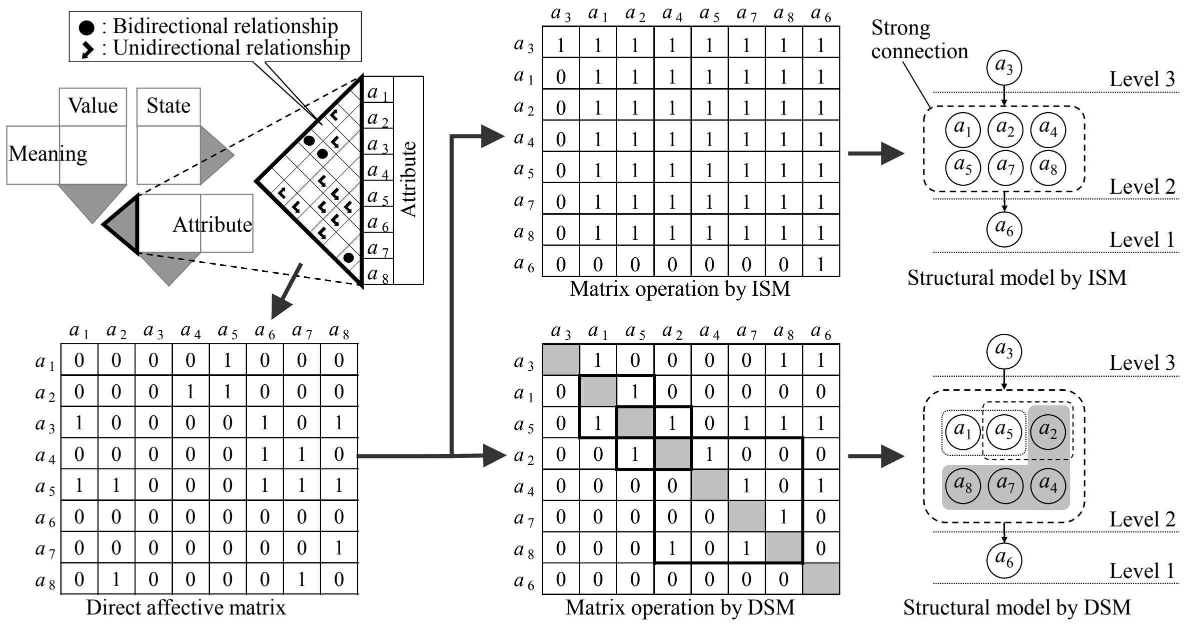


Figure 3. ISM and DSM for M-QFD

2.2.3 Design structure matrix

DSM is a matrix to express the relationships between design elements (e.g., parts, tasks, and staff assignments) considered during a product development (Lindemann et al., 2009 and Eppinger et al., 2012). The lines and columns of DSM are reordered to simplify their relationships by designers. Consequently, DSM is easy to comprehend, and improves the efficiency in the late process of design for tasks such as management of the development schedule, manufacturing, and parts. Three methods are typically used to reorder the lines and columns of DSM: clustering, partitioning, and tearing. (Details of each are described elsewhere [Eppinger et al., 2012].)

- Clustering: This method reorders design elements to construct chunks (modules) of related elements by transferring their relationships close to the diagonal position of the matrix. Because the design elements are grouped based on their relationships, designers can comprehend the complex architecture. In this method, each chunk should have a minimal number of elements or relationships with other chunks.
- Partitioning (sequencing): This method reorders design elements to decrease design feedback (relationships are located in the upper triangular matrix), improving the design process. However, if the design object is complex, it is impossible to completely delete feedback. Thus, the designers must determine whether to accept some feedback or to delete it using the tearing method.
- Tearing: This method deletes feedback to improve the design process after partitioning.

DSM differs from ISM. 1) DSM excludes indirect relationships. 2) DSM includes partitioning and clustering methods to organize the relationships and incorporate designers' opinions. This means DSM can be applied to the direct affective matrix derived from M-QFD similar to ISM and can organize the complex (numerous) design element relationships using designer's heuristic decision (Figure 3 bottom part) (Kato et al., 2014b).

2.2.4 Multi domain matrix

MDM is an extension matrix of DSM in order to express an inter-domain (inter-type) design element relationships (Lindemann et al., 2009). MDM is comprised of DSMs and Domain mapping matrices (DMMs) to express the intra- and inter-domain relationships, respectively. DSMs are located diagonally in MDM while DMMs are placed upper right corner of them (Figure 4).

This study employed MDM to construct the design process (priority order of design elements) based on both intra- and inter-domain relationships using the following two procedures: 1) DSM partitioning to reorder design elements to decrease design feedback (intra-relationships are located in the upper triangular matrix); 2) DMM clustering to reorder design elements to construct chunks (modules) of the elements by transferring the inter-relationships close to the diagonal position of the matrix. The application of MDM to the relationship and correlation matrices of the state and attribute elements in M-QFD is shown in Figure 5. This figure shows the matrices after employing the two matrix operations and a structural model (design process) constructed using them. Note that the 3D visualization is made with reference to the conventional study (Diehl et al., 2008).

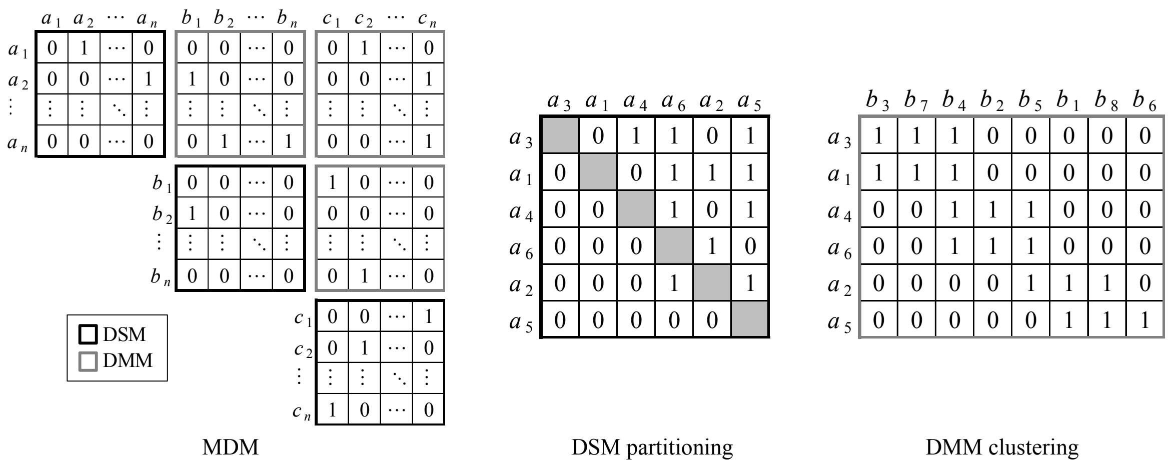


Figure 4. Conceptual drawing of MDM

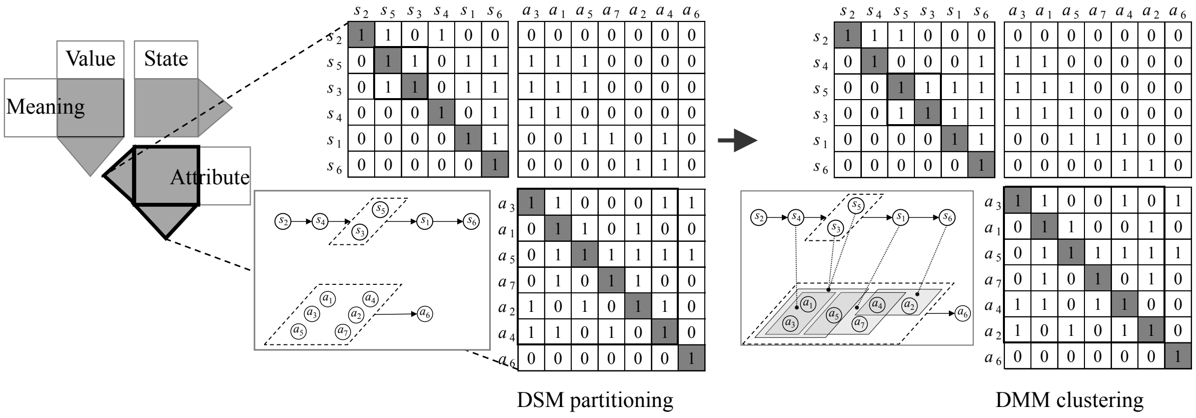


Figure 5. MDM for M-QFD

3 LITHOGRAPHY SYSTEM DESIGN

This study compared M-QFD and traditional QFD in order to confirm the effectiveness. The traditional one was made for designing lithography system to manufacture semiconductor LSI (Miwa et al., 2012). Thus this study chose the same theme and constructed M-QFD with the help of the person who is a lithography engineer and made the traditional one to ensure the fairness of user's experience and skill.

3.1 Design object

Lithography system has been developed to improve the resolution due to the requirement for the higher density integration of semiconductor devices. To improve the resolution, shortening the laser wavelength and heightening the numerical aperture of the reduction projection lens have been progressing (Miwa et al., 2012). Figure 6 shows a step-and-scan type projection aligner. This device transfers the whole pattern on a mask to a wafer by irradiating the laser beam through the mask and synchronously operating both stages to fix the mask and wafer. Additionally, to maintain the dimension accuracy of the pattern, the advanced process control system, which adjusts the process conditions automatically based on the dimension measurement result of each exposure processing, has been introduced to this system. Therefore, the lithography system has been developed based on some clarified (common) aims (e.g. high resolution, high precision processing, and high throughput) repeatedly, and the other aims have not been focused and needs to be discussed.

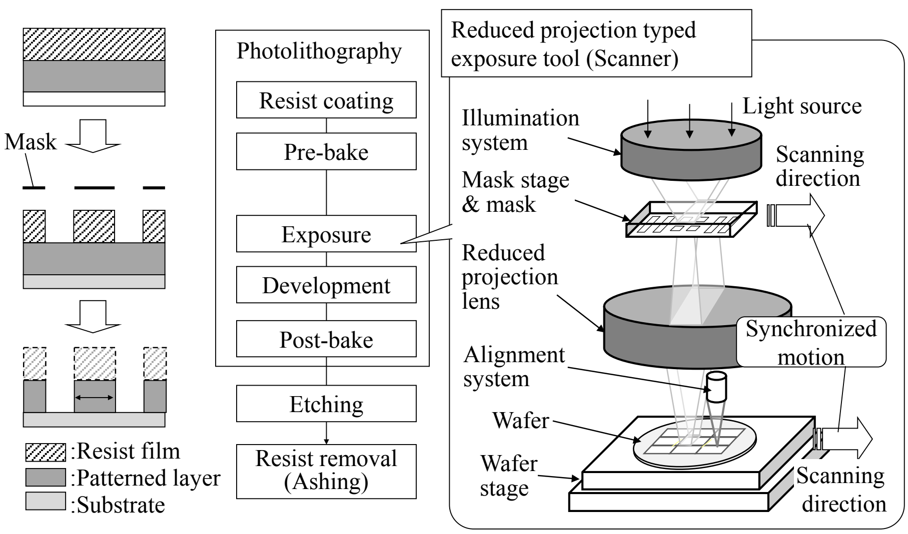


Figure 6. Pattern transformation process based on lithography technology in exposure tool

3.2 Results and discussion

Figure 7 shows the result of M-QFD. The design elements were extracted and linked by the lithography engineer. Almost all the elements of the conventional QFD are included in the M-QFD because the same design member deployed. Thus, the conventional QFD is omitted because of space limitations. Newly extracted elements are indicated in gray in this figure. The difference between the two QFDs is discussed below.

M-QFD extracted not only the primary user's (LSI manufacturer's) value elements but also those of secondary user (LSI product manufacturer), company (lithography system manufacturer), and society, such as, "just in time delivery of LSI (v_{12})", "company profit (v_{14})", and "energy saving (v_{22})". Additionally, the extracted values (e.g. "better maintainability (customer support) of lithography system (v_{16})" and "resources saving (v_{23})") were transformed into the two meaning elements ("easy to set up (m_7)" and "high energy efficiency (m_{11})"). Figure 8 describes the result of applying ISM and correspondence analysis to the correlation and relationship matrices of the value and meaning elements, respectively. The structure model (Figure 8 left) illustrates the lithography system's values are generated from the company values (e.g. "original technology (patent) (v_{15})" and "better maintainability of lithography system (v_{16})") and transformed into those of the primary and secondary user's (e.g. "better productivity per lithography system (v_6)" and "reasonable price of LSI (v_9)"). And then, through the society values (e.g. "better efficiency (shortening the time to search for information) (v_{19})" and "creation of new employment (new market exploration) (v_{20})"), they are returned to the company value ("company image (v_{13})"). The two dimensional scatter graph (Figure 8 middle) visualizes the relationships between the value and meaning elements and summarizes each type of the value elements as follows: 1) company values ($v_{13\text{-}18}$) relate to the ease of installing and maintaining the lithography system; 2) primary user's values ($v_{1\text{-}8}$) include the easy operation and reliability; 3) secondary user's values ($v_{9\text{-}12}$) focus on LSI stable supply; 4) society values ($v_{19\text{-}23}$) correlate with the energy efficiency; 5) the values of all types require the meaning element "high resolution (m_1)". The input data to the correspondence analysis (Figure 8 right) are shown for the reference.

M-QFD also extracted some environment elements (e.g. "surroundings (temperature, pressure, humidity) (s_1)" and "lot-to-lot variation (s_4)" as state elements. These elements enabled the design members to remind of some state and attribute elements related to the environment, such as "overlay accuracy of pattern transformation (s_{14})", "pattern transformation measurement accuracy (s_{20})", "manufacturing control system (a_4)", and "dimension measurement tool (a_{14})". This study employed MDM to construct the structural model (design process) and organize the state and attribute elements. Figure 9 shows the derived model to clarify both the intra- and inter-relationships of the elements. Particularly, the strongly connected attribute elements can be classified into some groups on the basis of the inter-relationships. For example, "development condition (a_3)" and "developer material (a_6)", which relate to the state elements placed in the upper part of the state element model, such as "developer material's spraying uniformity (s_8)" and "developer reaction uniformity (s_9)", are located same as in the attribute model. This enables designers to design each attribute element group concurrently with the evaluation of the corresponding state elements and streamlines the development.

If the designers focus on the newly extracted value elements regarding environment-friendliness (e.g. "energy saving (v_{22})" and "resources saving (v_{23})"), they confirm their corresponding state elements ("consumption energy (s_{21})") and their relationships using the structure model (Figure 9). In this case, the element strongly connects to "resist optical property (s_5)", "modulation transfer function (s_{17})", and "light intensity distribution (s_{18})" and they relate to some attribute elements, such as "resist material" (a_5) and "Laser" (a_9). Thus, these elements can be assigned as the design valuables and objective characteristics and optimized to develop new environment-friendly lithography system.

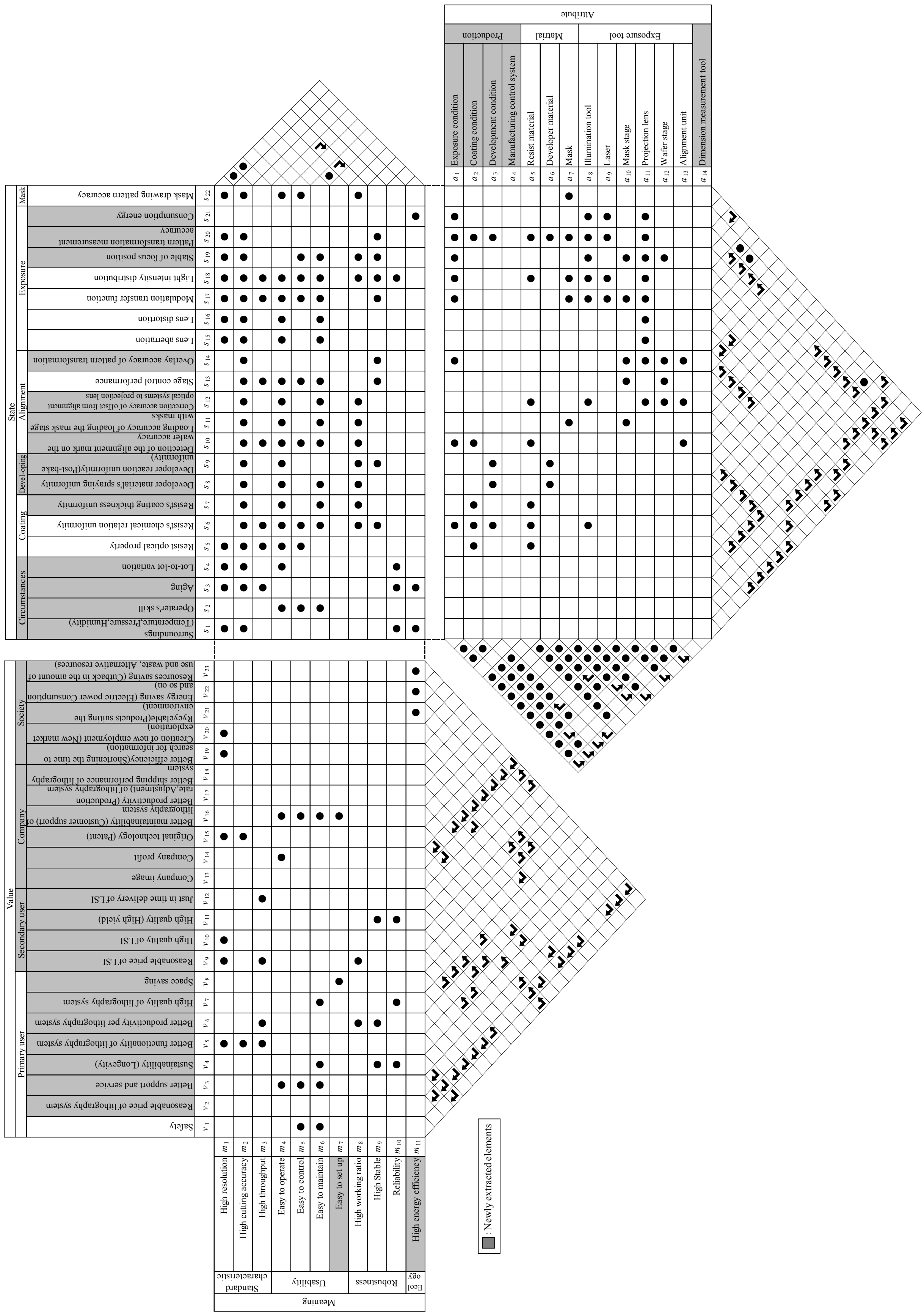
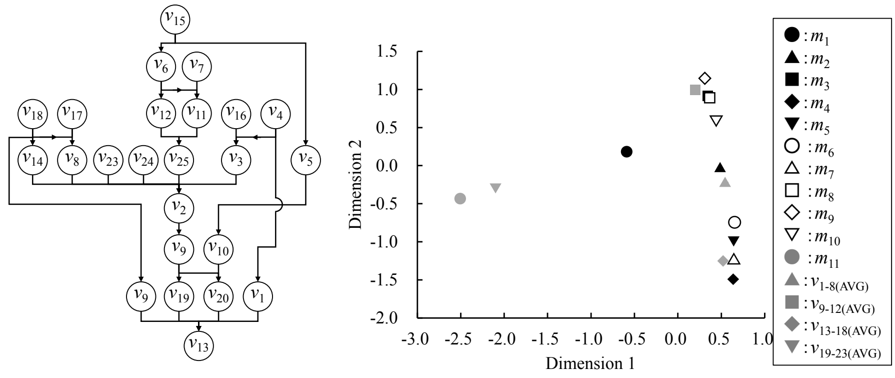


Figure 7. Result of M-QFD about lithography system



	$v_{1\text{-}8}$	$v_{9\text{-}12}$	$v_{13\text{-}18}$	$v_{19\text{-}23}$
m_1	0.125	0.500	0.167	0.400
m_2	0.250	0.250	0.167	0
m_3	0.250	0.500	0.000	0
m_4	0.125	0	0.333	0
m_5	0.250	0	0.167	0
m_6	0.500	0	0.167	0
m_7	0.125	0	0.167	0
m_8	0.125	0.250	0	0
m_9	0.125	0.500	0	0
m_{10}	0.250	0.250	0	0
m_{11}	0	0	0	0.600
m_{12}	2.125	2.250	1.167	1.000

Data for input correspondence analysis

Figure 8. Result of ISM and correspondence analysis about lithography system

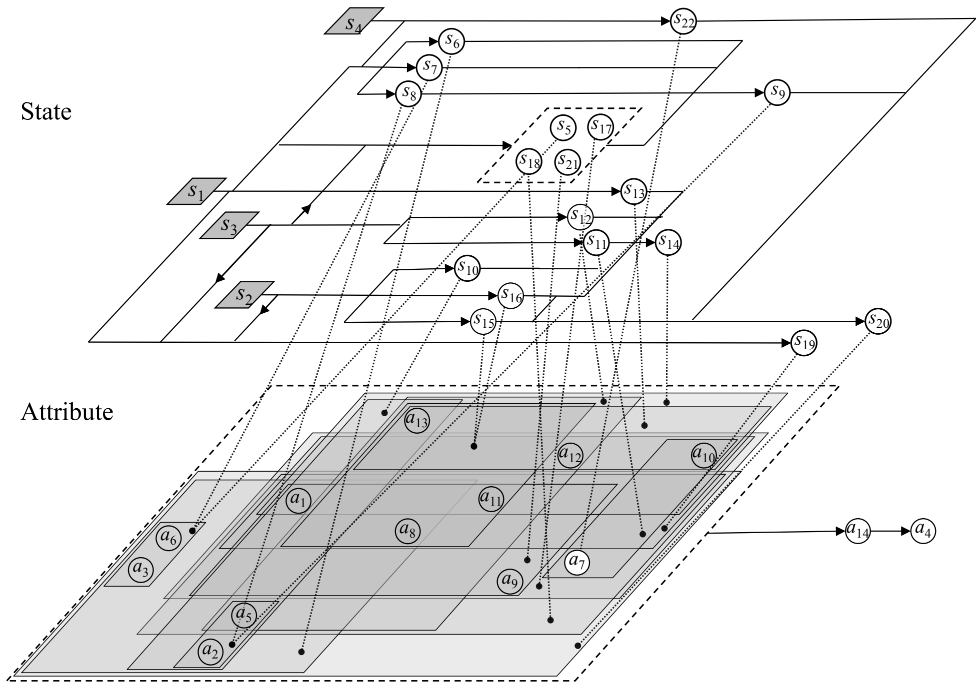


Figure 9. Result of ISM about lithography system

4 CONCULUSIONS

This paper introduces M-QFD and its analytical methods and illustrates their application to a lithography system design to confirm the effectiveness. M-QFD is comprised of four deployment charts, which correspond to the four spaces (value, meaning, state, and attribute) in the multispace design model. M-QFD enabled designers to extract the design elements based on diverse requirements (requirements of the customer, company, society, etc.) and the circumstance of the design objects (user physique, ambient temperature, etc.). In addition, the analytical methods for M-QFD (correspondence analysis, ISM, DSM, and MDM) enabled them to easily understand the design element relationships. The results of the application show the benefits of M-QFD. To confirm the versatility of the M-QFD and the analytical methods applied thereto, future work will implement design applications, including novel design, redesign, and improvement design.

ACKNOWLEDGEMENT

This study was supported by the Japan Society for the Promotion of Science, Grant-in-Aid for Young Scientists (B) (26750005).

REFERENCES

Akao, Y. (1990) Quality function deployment. New York:Productivity Press.

Akao, Y. and Mizuno, S. (1994) QFD: The customer-driven approach to quality planning and deployment. Tokyo:Asian Productivity Organization.

Ashihara K. and Ishii K. (2005) Application of quality function deployment for new business R&D strategy deployment. In: Proceedings of 2005 ASME International Mechanical Engineering Congress and Exposition, Orlando, 5th-11th Nov. 2005, pp. 279-287.

Barad M. (2008) Strategy maps as improvement paths of enterprises. International Journal of Production Research, Vol. 46, No. 23, pp. 6627-6647.

Benzécri, J.P. (1992) Correspondence Analysis Handbook. New York:Marcel Dekker, Inc.

Chen L.H. and Ko W.C. (2011) Fuzzy nonlinear models for new product development using four-phase QFD processes. IEEE Transaction on Systems, Man, and Cybernetics, Vol. 41, No. 5, pp. 927-945.

Diehl H., Hellenbrand, D. and Lindemann U. (2008) Transparent 3D visualization of mechatronic system structures. In: Proceedings of International Design Conference – Design 2008, Dubrovnik, 19th-22nd May. 2008, pp. 1255-1262.

Eppinger, S.D. and Browning, T.R. (2012) Design structure matrix methods and applications (Engineering Systems). Massachusetts:MIT Press.

Hsiao S.W. (2002) Concurrent Design Method for Developing a New Product. International Journal of Industrial Ergonomics, Vol. 29, No. 1, pp. 41-55.

Huang G.O. and Mak K.L. (2002) Synchronous quality function deployment (QFD) over world wide web: Computers & Industrial Engineering. Vol. 42, No. 2/4, pp. 425-431.

Iwata K. and Hayashi A. (2008) A redundancy-based measure of dissimilarity among probability distributions for hierarchical clustering criteria. IEEE Transactions on Pattern Analysis and Machine Intelligence, Vol. 30, No. 1, pp. 76-88.

Kato, T., Horiuchi, S., Sato, K. and Matsuoka, Y. (2013) Quality function deployment based on the multispace design model. Bulletin of JSSD, Vol. 60, No. 1, pp. 77-86.

Kato, T., Horiuchi, S., Sato, K. and Matsuoka, Y. (2014a) Multispace quality function deployment using interpretive structural modeling. Bulletin of JSSD, Vol. 61, No. 1, pp. 57-66.

Kato, T., Noguchi, S., Yoshinaga, K. and Hoshino, Y. (2014b) Multispace quality function deployment for modularization. Bulletin of JSSD, in press.

Kuo T.C., Wu H.H. and Shieh J.I. (2009) Integration of environmental considerations in quality function deployment by using fuzzy logic. Expert Systems with Applications, Vol. 36, pp. 7148-7156.

Lindemann U., Maurer M. and Braun T. (2009) Structural complexity management: An approach for the field of product design. Berlin:Springer.

Matsuoka, Y. (2010a) Design science. Tokyo:Maruzen.

Matsuoka, Y. (2010b) Multispace design model as framework for design science towards integration of design. In: Proceedings of International Conference on Design Engineering and Science 2010, Tokyo, 17th-19th Nov. 2010, Tokyo:Japan Society for Design Engineering.

Miwa T. and Ishii K. (2009) Product development task planning using worth flow analysis. ASME Journal of Computing and Information Science in Engineering, Vol. 9, No. 3, 034502.

Miwa, T. and Aoyama, H. (2012) Evaluation method of product development process with technology risk using product worth flow analysis. Transactions of the JSME C, Vol. 78, No. 785, pp. 312-326 (in Japanese).

Olsen A.S. (1982) Group planning and problem-solving method in engineering management. New York:Wiley.

Reich, Y. (1995) A critical review of General design theory. Research in Engineering Design, Vol. 7, No. 1, pp. 1-18.

Warfield J.N. (1976) Societal systems: planning, policy and complexity. New York :Wiley.

Yeh C.H., Huang J.C.Y. and Yu C.K. (2011) Integration of four-phase QFD and TRIZ in product R&D: a notebook case study. Research in Engineering Design, Vol. 22, No. 3, pp. 125-141.

Yoshikawa, H. (1991) General design theory. Industrial Design, No. 155, pp. 56-60.

Zhang Y., Wang H.P. and Zhang C. (1999) Green QFD-Ⅱ: A life cycle approach for environmentally conscious manufacturing by integrating LCA and LCC into QFD Matrices. International Journal of Production Reserch, Vol. 37, No. 5, pp. 1075-1091.