Building Numerical Design Matrix and Managing Functional Couplings for Concept Improvement of The Existing Product

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Abstract. Because parametric values are unknown during initial concept generation, the Axiomatic Design Theory uses the binary design matrix (DM) to represent the coupling relationship between functional requirements and design parameters. However, given an existing product, it would be possible to employ the numerical DM that has more detailed information than the binary DM to help improve the design concept. This paper proposed a two-phase method to create a numerical DM in phase I and manage the functional couplings in phase II for concept improvement of existing product. A decomposition-definition-levelling framework and the Puritan-Bennett's 0-1-3-9 level rating are employed to evaluate the system impact of each functional coupling to create the numerical DM of an existing design concept. The Design Coupling Sequence (DCS) approach was extended to use the numerical DM to improve this design concept. Compared with other numerical matrices for product development and the structured approach by Su et al., our method is more generic and faster, providing useful details yet still able to maintain the dominance of the high-level couplings.

1 INTRODUCTION

Matrix formulation has been extensively used in product development research and practice [1-9]. In the Axiomatic Design (AD) Theory [2], for example, the binary design matrix (DM) depicts the functional coupling relationship between functional requirements (FRs) and design parameters (DPs) during concept generation, where upstream objectives (e.g. customer needs) and downstream constraints (e.g. cost, manufacturability, etc.) meet. In authors' prior work [10], the Design Coupling Sequence (DCS) method was developed to manage functional coupling sequences based on the binary DM to help designers achieve the desired balance between upstream and downstream requirements during concept improvement. However, uses of the binary DM, where X denotes nonnegligible relationships and O represents negligible relationships, has been criticised in many studies for lack of necessary details, and that the numerical DM would be better for product development practices [3,7,11]. However, it is impractical to come up with the numerical DM during initial concept generation as the design parameters are lack of numerical values at this early stage. During concept improvement an existing product, however, the task of building the numerical DM that can balance upstream-downstream considerations is still very challenging. This is the motivation of our research described in this paper.

After reviewing the relevant works in Section 2, this paper proposes a new method for designers to build a numerical DM of an existing product and extends the DCS method to include the numerical DM in Section 3.

The practical validation of the proposed method and comparisons with other numerical matrices are discussed in Section 4. Section 5 concludes the paper with potential future works.

2 BACKGROUND

This section reviews different types of numerical matrix used in product design and development, and two sequencing methods for managing functional couplings of design concepts.

2.1. Numerical Matrices for Product Design

Most existing numerical matrices for product design and development have different purposes and ways to number the relationships between the elements of the matrices. This section introduces the background of some popular numerical matrices, including the matrix in House of Quality (HoQ), Design Structure Matrix (DSM), Domain Mapping Matrix (DMM), the Percentage DM, and the numerical DM from Analytic Hierarchy Process (AHP).

The original use of numerical matrix can be traced back to the year of 1972 that Kobe shipyard in Mitsubishi used matrix mapping between customer needs and design attributes in the HoQ in Quality Function Deployment (QFD) for product development. Among many standards of rating the relationship in the HoQ matrix, the Puritan-Bennett's HoQ was a successful application onto an existing product improvement to beat an aggressive competitor, and the relationship was levelled by strong,

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medium, weak, and none corresponding to the values 9, 3, 1, and 0 [1].

Different from rating the relationships in QFD applications, Suh's AD theory uses binary DM mapping between FR and DP domains to represent the design concept [2]. This is useful to represent the functional coupling relationships of a new design because the relationship levels of a new concept are still unclear in such early stage.

In the same decade, DSM was founded by Steward [4] and Warfield [5] as a general product development approach that examines the system interactions among the elements in the same domain (such as DP vs. DP). It was a binary matrix initially, and soon after the numerical DSMs started to appear in many downstream product development studies because it was easy to assess the value of the relationship among same domain elements at downstream and a more-detailed specification is always needed at downstream [12]. Browning [6] suggests 2, 1, 0, -1, -2 to present the required, desired, no, undesired, detrimental couplings in DSM, but the negative numbers haven't had any significant impact to the DSM analysis [13].

DMM developed by Danilovic and Browning is a matrix constructed from two DSMs [8]. In other words, DMM maps between two different domains. Danilovic and Browning used 1, 2, and 3 to value Low, Medium, and High levels in DMM.

A DM can be regarded as a kind of DMM that maps between two domains (i.e., functional domain and physical domain). Dong and Whitney uses a DM to obtain DSM to help designers consider the upstream requirements before developing the product details at downstream [3]. In their research, a percentage DM was used, and the values of the relationship between an FR-DP pair is the percentage of change in fulfilling the FR caused by the unit change of the DP.

In 2003, Su, Chen, and Lin [7] proposed a structured approach to convert the binary DM to the numerical DM and then to find the best execution sequence for it. They used AHP's {1,3,5,7,9} scale to rate the relative contribution through pair-wising process from equally important to extremely important, and then the numerical DM is created by going through multiple processes including eigenvalue evaluation and post-transformation. The best execution sequence are identified by assessing the impact of each execution step and the total loss of contribution freedom for all the possible sequences.

The numerical matrices used in more recent studies for product development are generally in those five types: {0,1,3,9}, {0,±1,±2}, {0,1,2,3}, percentage DM, and numerical DM from AHP. The applicability of those numerical matrices on concept improvement will be discussed in Section 4.1.

2.2 Managing Functional Couplings of Numerical DM to Balance Up-Downstream Requirements

It is commonly known in product development practices that sequencing (or decoupling) functional couplings can improve upstream ideality (i.e., requirement driven) and

modulating design concepts can achieve downstream practicality (i.e., manufacturability, cost, etc) [2,6,7,10]. DCS developed by Wang et al. is an approach to manage functional coupling sequences and use functional sets to modularize design concepts [10]. Designers can use DCS to reach a desired level of balance between upstream objectives and downstream constraints at the same time.

The DCS approach includes an algorithm for decoupling coupled DPs, a formula for listing the best execution sequence(s), and three strategies for optimizing the practice of concept improvement. Although the formula and the strategies are for any type of DM, the previous DCS algorithm was designed for the binary DM only and are not applicable for the numerical DM.

Note, that because DSM only deals with relationships in one domain, existing algorithms for the numerical DSM [12] are unable to balance downstream modularity and upstream decoupling. Furthermore, unlike DCS algorithm that can be used for square and rectangular DM, the structured approach proposed by Su, Chen, and Lin (see Section 2.1) has a sequencing method for the square numerical DM only. The best sequence are obtained with this approach after assessing all the possible execution sequences.

In this paper, we present an extended DCS algorithm that can process both binary and numerical DM (and square and rectangular DM as DCS previously does). This enables us to provide detailed information for sequencing and modularization when improving design concepts of existing products. The new algorithm for numerical DM was validated in Section 4.2 with the best sequence provided in the case study of the numerical DM from AHP.

3 METHOD

Our proposed method has two phases. The first phase is to create the numerical design matrix that is tailored for conceptual design from an existing product. The second phase extends our prior work to the use of numerical DM on the concept improvement of an existing product.

3.1. Phase 1: Numerical DM Built-up

The numerical DM aims to provide more detailed downstream information so that designers can improve the concept with more certain decoupling sequences to trade-off between upstream and downstream. The paper suggests a rating mechanism by following the rating scale of Puritan-Bennett's HoQ.
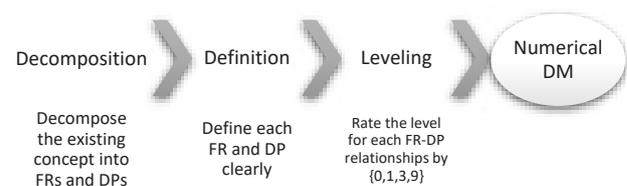

Fig. 1. The steps to obtain the numerical DM.

The steps to obtain the numerical DM from an existing product is as shown in Figure 1. It starts from decomposing the design concept of the product into several DPs and their corresponding FRs. Then a definition step is suggested to help the designer recheck their definitions and take the opportunity to understand each element clearly so that it would become easier to rate the relationship between FRs and DPs in the followed leveling step. In the levelling step, the designer is suggested to rate the level of relationship for each FR-DP. The rating scale uses {0,1,3,9} to represent the {none, low, medium, high} level of the performance change of the FR if the DP varies. The levels are assessed as following:

・None level, 0: There is no any performance change of the FR if the DP varies.

・Low level, 1: There is a little performance change of the FR if the DP varies, but the change may be ignored.

・Medium level, 3: There is some performance change of the FR if the DP varies, and the change is not significant but can't be ignored.

・High level, 9: There is much performance change of the FR if the DP varies, and the change is significant.

After the leveling step, a numerical DM is obtained.

3.2 Phase 2: DCS Algorithm for Numerical DM

Since the values in DM is numerical not binary, the rules of the precedence are adjusted as following:

• The DPs that relate to the FR which has the less impact to the system have higher precedence, and

• The DP that has more impact to the system has higher precedence.

When the above metrics are equal, these DPs have equal precedence. There are two types of equal precedence:

1) If these DPs are functionally independent, the order of these DPs doesn't matter.

2) If there are functional couplings between these DPs, they would be the strongly coupled DPs and should be consider together.

For the functional sets- the completely independent U-set and the insolvably coupled C-set, the definitions are unchanged as it doesn't affect the check of functional coupling. Readers interested in more details of U-set and C-set are referred to DCS approach [10].

The adjusted DCS algorithm uses the same notions as previous algorithm to keep the consistency. The element at row "m" and column "n" in the DM is denoted by DM_{mn}. The sets

$$S\_DP_n: \{m \mid DM_{mn} \neq 0\} \qquad (1)$$

$$S\_FR_m: \{n \mid DM_{mn} \neq 0\} \qquad (2)$$

express the position of the functional coupling in the row or column, and the parameters

$$Sum\_DP_n = \ \Sigma |DM_{mn}| \qquad (3)$$

$$Sum\_FR_m = \ \Sigma |DM_{mn}| \qquad (4)$$

represent degree of the impact to the system if DP_n or FR_m changes. Please note that both sums are obtained from the

absolute value of DM_{mn}. Although the values in the numerical DM obtained in Phase 1 are all positive, doing the absolute values in the algorithm is to accommodate the numerical DM from other methods.

The steps to find the functional sets can be almost the same as the previous steps: 1) ordering DPs in a line by precedence, 2) managing of the equal precedence DPs, and 3) arranging DPs in U-sets.

Step 1: ordering DPs in a line by precedence

The first step is to order the DPs by the precedence rules. It suggests to find the S_FR_i that its Sum_FR_i is the smallest and then to obtain the n in S_FR_i. Then it suggests to add the DP_n in a line and removes the column of the DP from the DM. Repeat this step until all the DPs are in a line.

If there are more than one different n, one is suggested to add these DP_n in the line by its Sum_DP_n from the most to the least, and to mark the DPs with same values of Sum_DP as a group by underlining because of equal precedence.

Step 2: managing of the equal precedence DPs

The second step manages the underlined DPs. The grouped DP_j starting from the second DP in the first underlined group should be checked whether there exists an $x \in S\_DP_j$ of DP_j such that x equals any $y \in S\_DP_k$ of its preceding DP (DP_k).

・ If yes, it suggests to put DP_j in the set (i.e. { , }) with DP_k.

・ If no, it suggests to move DP_j to a new line under DP_k. The checking process with its current preceding DP (i.e. the preceding DP of DP_k) is repeated until it is put into a set or reach the first DP of the group.

Step 3: arranging DPs in U-sets

This step arranges all the DPs (DP_p) into sequences starting from the second DP in the first line. To arrange them one-by-one, the designer should check whether there exists a $u \in S\_DP_p$ of DP_p such that u equals to $v \in S\_DP_q$ of its preceding DP (DP_q) or one of the DPs in the preceding set (DP_q).

・ If yes, it suggests to put a rightward arrow ($\rightarrow$) between DP_p and its preceding DP or set.

・ If no, it suggests to put DP_p to a new line under DP_q. The checking process is repeated until the DP_p is linked by an arrow or reach the first DP in the line.

Since the precedence uses the sum of the numerical value as the impact to the system, the adjustment of the algorithm can be as less as only summing up the numerical values instead of counting the number of the non-zero elements.

4 COMPARISON

This section compares the proposed numerical DM with other numerical matrices and compares the adjusted DCS algorithm with the other sequencing method.

4.1 COMARISON OF NUMERICAL MATRICES

The proposed rating method uses Puritan-Bennett's HoQ rating scale {0,1,3,9} for following reason:
(1) Puritan-Bennett's HoQ was successfully used in the existing product development.
(2) Low, medium, and high levels are intuitive and easy to assess.
     (3) The value of high-level and that of low-level has a huge difference, so the importance of the high functional couplings is not easy to be replaced by a few low-level relationships.

Table 1. The pros and cons of DM with different rating scales.

Ref.	Rating scales	Pros	Cons
Proposed phase 1	{0,1,3,9}	Easy to create, impact of high level is significant	It may not be as detailed as percentage or AHP's DM
[6]	{0,±1,±2}	Easy to create	Few low levels can replace a high level. Negative number is unnecessary.
[8]	{0,1,2,3}	Easy to create	Few low levels can replace a high level
[3]	percentage	It can provide detailed downstream information	Difficult to create, may limit creativity
[7]	AHP & eigen-functions	It can provide detailed downstream information	Difficult to create, may limit creativity

Rating scales {0,±1,±2} and {0,1,2,3} have less gap between low and high levels, and it would appear the issue as explained in reason 3. In addition to no difference of the negative numbers, the high-level relationship may be too easy to be replaced by low-level relationship. For example, the impact of three low-level relationships is equal to one high-level relationship in the scale of {0,1,2,3}, and the impact of two low-level relationships is equal to one high-level relationship in the scale of {0,±1, ±2}. Because the low-level is defined as the relationship that may be ignored, the gap between the values may be too small. In the scale of the proposed {0,1,3,9}, it requires nine low-level relationships to reach one high-level. Therefore, low-level relationship would be regarded as negligible impact to the system but the functional coupling of it still counts according to DCS algorithm.

The percentage DM may provide more detailed information, but it is not easy to obtain unless the design is detailed enough and the unit changes of all the DPs are well defined. In the concept improvement stage, whether the designer is able to give such detailed values is a doubt. In other words, the designer must be able to create the proposed numerical DM if the designer is able to create percentage DM, but the opposite situation doesn't always work. On the other hand, it is also concerned that too detailed of numbers may limit the range of the alternatives. As a result, the new demand from upstream may not be easy to satisfy, and the creativity may be limited.

The numerical DM from AHP comes much more steps and details than the proposed DM does. Thus, the advantages and disadvantages of the numerical DM from AHP are similar to those of the percentage DM.

The comparison table of the pros and cons of the above matrices are displayed as Table 1.

4.2 COMPARISON OF SEQUENCING METHODS

This section demonstrates the adjusted DCS algorithm to the example of one-time-use camera case used in [7], and the comparison results showed the effectiveness of the adjusted algorithm and the usefulness of the numerical matrix.

Following is a list of the FRs and DPs of the one-time-use camera design:
FR_1: able to take picture
FR_2: able to focus on the view
FR_3: able to advance film
FR_4: able to indicate if the flashlight is ready
FR_5: able to show the amount of film left or pictures taken
FR_6: able to recharge for the battery for flashlight
and
DP_1: shutter mechanism
DP_2: lens mechanism
DP_3: rolling mechanism
DP_4: LED indicator
DP_5: wheel-counter mechanism
DP_6: battery recharging system.
The numerical DM of the example obtained by the structured approach in the paper is

$$\begin{bmatrix} FR_1 \\ FR_2 \\ FR_3 \\ FR_4 \\ FR_5 \\ FR_6 \end{bmatrix} = \begin{bmatrix} 0.829 & 0 & 0.104 & 0 & 0.111 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0.136 & 0 & 0.714 & 0 & 0.073 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0.264 & 0 & 0.740 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} DP_1 \\ DP_2 \\ DP_3 \\ DP_4 \\ DP_5 \\ DP_6 \end{bmatrix} \quad (5)$$

Applying the adjusted algorithm, we obtained in the first step:

$$DP_2, DP_4, DP_6, DP_3, DP_5, DP_1 \quad (6)$$

The DP_2, DP_4, and DP_6 have the equal precedence because they all have the sum of 1 in its row and in its column. DP_3 has higher precedence then DP5 because $Sum\_DP_3 = 1.082$ is larger than $Sum\_DP_5 = 0.924$. After applying the second step, we obtained

$$DP_2$$

$$DP_4$$

$$DP_6 \quad (7)$$

because they are functionally independent. After the third step, the result of the U-sets is

$$U_I: DP_2$$

$$U_{II}: DP_4$$

$$U_{III}: DP_6$$

$$U_{VI}: DP_3 \rightarrow DP_5 \rightarrow DP_1 \qquad (8)$$

Hence, it indicates that DP_2, DP_4, and DP_6 can be improved independently, and DP_1, DP_3, and DP_5 should follow the sequence $DP_3 \rightarrow DP_5 \rightarrow DP_1$ to improve the concept.

In Su's paper, the best sequence after the total loss evaluation is the same as our result: $DP_3 \rightarrow DP_5 \rightarrow DP_1$. This proves that the applicability of the proposed algorithm, and the adjusted DCS algorithm is more efficient as it doesn't require to assess all the possible execution sequences.

In addition, we examined the usability of the proposed rating scale in this example. The values in the DM can be converted within the scale of $\{0,1,3,9\}$. The re-rated DM is

$$\begin{bmatrix} FR_1 \\ FR_2 \\ FR_3 \\ FR_4 \\ FR_5 \\ FR_6 \end{bmatrix} = \begin{bmatrix} 9 & 0 & 1 & 0 & 1 & 0 \\ 0 & 9 & 0 & 0 & 0 & 0 \\ 1 & 0 & 9 & 0 & 1 & 0 \\ 0 & 0 & 0 & 9 & 0 & 0 \\ 0 & 0 & 3 & 0 & 9 & 0 \\ 0 & 0 & 0 & 0 & 0 & 9 \end{bmatrix} \begin{bmatrix} DP_1 \\ DP_2 \\ DP_3 \\ DP_4 \\ DP_5 \\ DP_6 \end{bmatrix} \qquad (9)$$

After applying the adjusted DCS algorithm, the result of U-sets is

$$U_I: DP_2$$

$$U_{II}: DP_4$$

$$U_{III}: DP_6$$

$$U_{VI}: DP_3 \rightarrow DP_5 \rightarrow DP_1 \qquad (10)$$

Equation (10) is the same as Equation (8), and this shows that the proposed rating scale $\{0,1,3,9\}$ is detailed enough in this case to provide the detailed execution sequence.

Moreover, we checked the DCS result for the binary DM in this case. The value 0 was converted to O, and other values in the DM were converted to X. The obtained binary DM is

$$\begin{bmatrix} FR_1 \\ FR_2 \\ FR_3 \\ FR_4 \\ FR_5 \\ FR_6 \end{bmatrix} = \begin{bmatrix} X & O & X & O & X & O \\ O & X & O & O & O & O \\ X & O & X & O & X & O \\ O & O & O & X & O & O \\ O & O & X & O & X & O \\ O & O & O & O & O & X \end{bmatrix} \begin{bmatrix} DP_1 \\ DP_2 \\ DP_3 \\ DP_4 \\ DP_5 \\ DP_6 \end{bmatrix} \qquad (11)$$

After applying the adjusted DCS algorithm, the result of U-sets is

$$U_I: DP_2$$

$$U_{II}: DP_4$$

$$U_{III}: DP_6$$

$$U_{VI}: \{DP_3 , DP_5 \} \rightarrow DP_1 \qquad (12)$$

DP_3 and DP_5 became an insolvably C-set because the impact of these two concepts to the system were not specified. Once the designer can have more detailed information to create a numerical DM, it could tell that DP_3 has higher precedence than DP_5.

On the other hand, we also examined the result for the binary DM that obtained by ignoring the low level relationships. The binary DM became

$$\begin{bmatrix} FR_1 \\ FR_2 \\ FR_3 \\ FR_4 \\ FR_5 \\ FR_6 \end{bmatrix} = \begin{bmatrix} X & O & O & O & O & O \\ O & X & O & O & O & O \\ O & O & X & O & O & O \\ O & O & O & X & O & O \\ O & O & X & O & X & O \\ O & O & O & O & O & X \end{bmatrix} \begin{bmatrix} DP_1 \\ DP_2 \\ DP_3 \\ DP_4 \\ DP_5 \\ DP_6 \end{bmatrix} \qquad (13)$$

The result of the U-sets is

$$U_I: DP_3 \rightarrow DP_5$$

$$U_{II}: DP_1$$

$$U_{III}: DP_2$$

$$U_{III}: DP_4$$

$$U_{VI}: DP_6 \qquad (14)$$

The DP_1 was not following DP_5 in the result, but the change of both DP_3 and DP_5 would affect the performance of FR_1, then DP_1 may require a light improvement. It may initially a slight impact, so the adjustment of DP_1 would not be required. Yet after many iterations of the product development, the complexity caused by the coupling would grow and may force the system to redesign. This explains the usefulness of the numerical DM because the low-level coupling can still be taken care during the concept improvement.

5 CONCLUSIONS

The proposed numerical DM uses $\{0,1,3,9\}$ scale to rate the relationship between FR and DP from none, low, medium, to high levels of the performance change of the FR if the DP varies. The DCS algorithm was also adjusted to be applicable on numerical DM by summing up the impact to the system instead of counting the number of non-zero elements. Since DCS approach can be applied to either square or rectangular DM, this makes DCS approach to be a generic method for any design case. Comparing other rating scales for numerical matrix, the proposed DM rating scale is easy to create, and the impact of the high-level relationship is dominant, so the low-level relationships won't be easily replaced the high-level relationship, yet the functional coupling of the low-level relationship is still counted. The camera design case

validates the adjusted DCS algorithm and reveals the usefulness of the proposed method. In the case, the proposed method is easier and faster to obtain the correct detailed execution sequence than the structured approach. The numerical DM also showed more detailed sequencing information than the binary DM in the case. Therefore, the paper successfully proposes a method to build numerical DM and to manage functional couplings with numerical DM for designers to improve the existing concept with detailed information.

References

1. J.R. Hauser, How Puritan-Bennett used the house of quality. Sloan Mana. Rev. **34**, 3 (1993): 61-70.

2. N.P. Suh, *Axiomatic Design*, Oxford Univ. Press, NY (2001)

3. Q. Dong and D.E. Whitney, Designing a requirement driven product development process. Proceedings of the ASME 2001 DETC, DETC2001/DTM-21682 (2001)

4. D.V. Steward, *Systems analysis and management. structure, strategy, and design*. Petrocelli Books, Inc (1981)

5. J.N. Warfield, Binary matrices in system modeling. IEEE Trans. on Sys., Man, and Cyber., **SMC-3**, 5 (1973)

6. T.R. Browning, Applying the design structure matrix to system decomposition and integration problems: a review and new directions. IEEE Trans. on Eng. Mana. **48**, 3 (2001): 292-306.

7. J.C.Y. Su, S.J.G. Chen, and L. Lin, A structured approach to measuring functional dependency and sequencing of coupled tasks in engineering design. Com. Ind. Eng. **45**, 1 (2003): 195-214

8. M. Danilovic and T.R. Browning, Managing complex product development projects with design structure matrices and domain mapping matrices. Int. J. of Proj. Mana. **25**, 3 (2007): 300-314.

9. T.L. Saaty, Decision making with the analytic hierarchy process. Int. J. of Serv. Sci. **1**, 1 (2008): 83-98.

10. C-Y. Wang and S.C-Y. Lu, Managing functional coupling sequence to decrease complexity and increase modularity in conceptual design. Proceedings of MATEC Web Con. & ICAD2018. Vol. 223, pp. 01014. Reykjavik, Iceland, October 9-12 (2018)

11. D.V. Steward, The design structure system: A method for managing the design of complex systems. IEEE Trans. on Eng. Mana. **3** (1981): 71-74

12. T.R. Browning, Design structure matrix extensions and innovations: a survey and new opportunities. IEEE Trans. on Eng. Mana. **63**, 1 (2016): 27-52.

13. J. Bartolomei, M. Cokus, J. Dahlgren, R. De Neufville, R. Maldonado, and J. Wilds, Analysis and applications of design structure matrix, domain mapping matrix, and engineering system matrix frameworks." MIT (2007).