Matrix based approach in assessing optimum robust product architectures

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1 Abstract

This paper proposes a matrix based approach with aim to help mechanical designers tackle the problem of risk emerging in assessing product architecture under the uncertain operating conditions in early design stages. The presented approach combines existing matrix based methods - Quality Function Deployment (QFD) and Multiple-Domain Matrix (MDM) methods with the Function-Based Failure Propagation (FBFP) method. The QFD method is an integrated set of tools for recording user requirements, engineering characteristics that satisfy these requirements, and any trade-offs that might be necessary between the engineering characteristics, while the MDM method is applied to model structural arrangements and dependencies between the domains and within themselves. The FBFP method is applied at the functional level providing information of potential failure based on product functions during conceptual design in product subsystems. As a result of the proposed approach, risk analysis of subsystems becomes possible and feedback on structural analysis of product architecture could be provided. To obtain the optimum robust product architectures from available alternative solutions a continuous risk analysis of the system is proposed. The analysis is performed through all stages from initialization through later refinements with several evaluation criteria: complexity, interdependency and process duration.

The following section presents the background of this research, related work and research motivation. Third section will provide more detailed description of proposed matrix based approach. Fourth section four will provide to evaluate and test validity of the proposed matrix approach. A real case study will be presented here. Conclusions and future research close this paper.

Zusammenfassung

Diese Foeschungsarbeit schlägt die matrixbasierte Betrachtungsweise vor, mit dem Ziel, den Mechanikdesignern zu helfen, das Problem der Risikoerscheinung in der Bewertung der Produktarchitektur unter unsicheren Arbeitsbedingungen in den frühen Desingphasen zu lösen. Die dargestellte Betrachtungsweise kombiniert die bestehende matrixbasierten Methode – die Gütefunktionsaufstellung (QFD), und die mehrfachen Matrix domainmethoden (MDM) mit der funktionsbasierte Fehleraufbreitungsmethode. Die QFD Methode ist ein integrierter Satz von Werkzeugen, die Benutzeranforederungen aufnehmen, wie auch Ingenieureigenschaften, die diese Anforderungen treffen, und auch alle Abstimmungen, die zwischen den Ingenierueigenschaften nötig sein könnten, wenn die MDM Methoden gebraucht werden, um Strukturanordnungen und Abhängigkeiten zwischen den Domains und innerhalb derjenigen zu modellieren. Die FBFP Methode wird anderseits auf der funktionellen Ebene verwendet, sie sichert die möglichen Fehlerinformationen auf Grund von Produktfunktionen während des konzeptuellen Dessings in Produktsubsystemen. Als Ergebnis der vorgeschlagenen Betrachtungsweise wird die Rizikoanalyse von Subsystemen möglich, und das Feedback zur Strukturanalyse des Systems wird vorgeschlagen. Die Analyse wird in allen Phase durchgeführt, von der Initialisierung durch weitere Verbesserungen mit einigen Bewertungskriterien: Komplexität, Abhängigkeitsverhältnis und Prozessdauer.

2 Introduction and motivation

The product architecture can have major impacts on all phases of its lifecycle, but its qualitative nature means that it is not easy to define a "design space" of architectures [1]. It is typically established during the concept development phase of product development [2]. During conceptual design stage, an abstract description of the product is created that serves as the basis for subsequent design stages and decisions. It is recognized that the initial stages of design are most influential on the quality and success of the product [3]. System architects in most product development cases start with the existing architecture of the product (or a similar one) and modify it to map the added functionality into the product [4]. Matrix-based architecture models are the most conventional representations and have the great advantage to provide a common modelling tool for product architecture. It represents the system structure (list of its elements and their relationships) as a matrix. The dependencies between components or modules within a product explain changes in which module will have effect on which other modules. Effectively managing risks in new product architecture development can reduce the likelihood of cost, schedule, and performance deviations during execution. How to make a robust plan for new product architecture development has become an important concern for enterprises, especially for the hi–tech industry. To provide this a systematic approach is needed in product architecture development and evaluation.

3 Proposed matrix approach

Matrix based approach (see Figure 1), presented in this paper is based on Theory of Technical Systems (TTS) [5] and VDI 2206 standard [6]. It focuses on making the system performance immune to variations, under uncertain operating conditions. Variations are everywhere, wanted and unwanted, but the unwanted variations can lessen the quality of the provided products. The aim with a robust design is not to try and eliminate the variations, but rather to make the product insensitive to them. The steps in the approach are introduced as follows:

1. Forecast the overall customer requirements

Mapping of the overall design requirements regarding market segmentation grid is the first step. The market segmentation grid is an attention-directing tool providing a link between management, marketing and engineering designers to help identify potential opportunities. Thus, the overall design requirement could be generated by integrating all of the market segmentation. In product definition phase, marketing and data collection work should be complete before modelling the procedure beginning.

2. Customer requirements/ Market segment

Here is try to determine the overall customer requirements, for each group within customer base. It includes different requirements from different market segment grid. Customer base is given from the generated list from the first step. Market segmentation grid is created based on the size of the product family. Importance data is given corresponding to the customer requirements and market segment (some importance is set to zero to represent that there is no requirement).

3. QFD analysis – phase I

In this step is importing the overall customer requirements (CRs) rating and customer requirement to House of Quality (HoQ) [7] to obtain the engineering characteristics. On the left side of QFD matrix, the importance value is presented by the overall rating from the previous step. The engineering requirements (ERs), which can satisfy customer requirements, are determined as shown on top and the relationships between them are given.

4. QFD analysis – phase II

Following the QFD procedure [7], input the engineering requirements (ERs) with weighting to the left side of QFD phase II, and the parts characteristics are determined and the relationships between engineering requirements and parts characteristics (PCs) are also obtained. Further, the interdependencies between parts characteristics are represented on the roof of QFD phase II.

5. Product functional modelling

Functional modelling is a design tool that describes a product or system in terms of the functions it performs [8]. Our model is based on the function of a product.

6. Multiple Domain Matrix (MDM) analysis

According to the procedure of structural complexity management [9], the system definition was carried out first, using the Multiple-Domain Matrix (MDM). The key domains that can be found here are namely: requirements, technical processes, functions and components (according to the Theory of Technical Systems – TTS [5]). In the next step, the types of dependencies between domains (inter-domain) were defined. As we can see from Figure 5, the dependency meanings have not been indicated for all possible domain combinations represented by the matrix subsets. That, which are not shaded, indicate that dependency information which is available, but here is not required for further system investigation (architecting and refinement). Finally, meanings for the intra-domain dependencies of components, functions, technical processes and requirements were defined.

7. Functional dependency matrix

To perform the function-based failure propagation method [10], a functional dependency matrix is generated from the functional model of the system using the flows as the common interface. Functions are directly dependant on the functions that are connected to them by one or more flows. The functional dependency matrix is then populated with the likelihoods of a failure propagating to a particular function from one it is dependent on. The initiating functions are the functions that fail initially, and the dependent functions are those that the failure propagates to. For this method, the likelihood values are decimal values between zero and one, zero denoting no likelihood of propagation, and one representing certain propagation of the failure. This is done to allow the use of Boolean operators [11] in the calculation of the total likelihood of propagation. In places where there is no dependency, there is no likelihood of propagation, and thus the place filled in with a zero or left empty (see Figure 7).

8. Propagation tree

Next, using the functional dependency matrix [10], propagation trees are built for each function in the model. These trees trace the path of a potential failure to each possible function that can propagate its failure to the end function. Each branch represents a different starting function, travelling to the same "root".

9. Total likelihood of risk propagation

Finally, the total likelihood of risk propagation is calculated. Using the direct likelihoods generated from the functional dependency matrix and the propagation trees, the total propagation likelihood is calculated using the Boolean operators "AND" and "OR" [11]. Wherever there are multiple functions that failures can propagate from, the "OR" calculation is used. If a branch can only propagate a failure to a single function, the "AND" calculation is used. In order to properly use this method, historical data pertaining to failure propagation must exist. Finally, these failures were then tabulated into a matrix showing the number of times that each function pair had appeared. These numbers were then normalized, using the most frequently occurring failure propagation pair as the normalizing factor. In this way, each value collected becomes a decimal value between zero and one. It is unlikely for each possible failure mode that a function might fail by has the same likelihood of propagation. Some failure modes might have higher or lower likelihoods of propagation than others. However, for ease of calculation of those likelihoods, each failure mode for a function is assumed to have the same likelihood. Using a modified form of the likelihood mapping from [12], the likelihood of each function pair was then calculated (see Table 1).

10. Evaluation of product parts and properties

Evaluation is based on three information (evaluation criteria) obtained from QFD and MDM analysis: complexity, interdependency and process duration [13] (see Table 2). We choose these criteria for the early evaluation for product properties. The degrees of complexity are determined by the designer's experience. On the other hand, process duration data is adopted from activity based DSM (technical process domain in MDM), while interdependency is adopted from the D-value (sum of columns) from component based DSM (component domain in MDM) (see Figure 4).

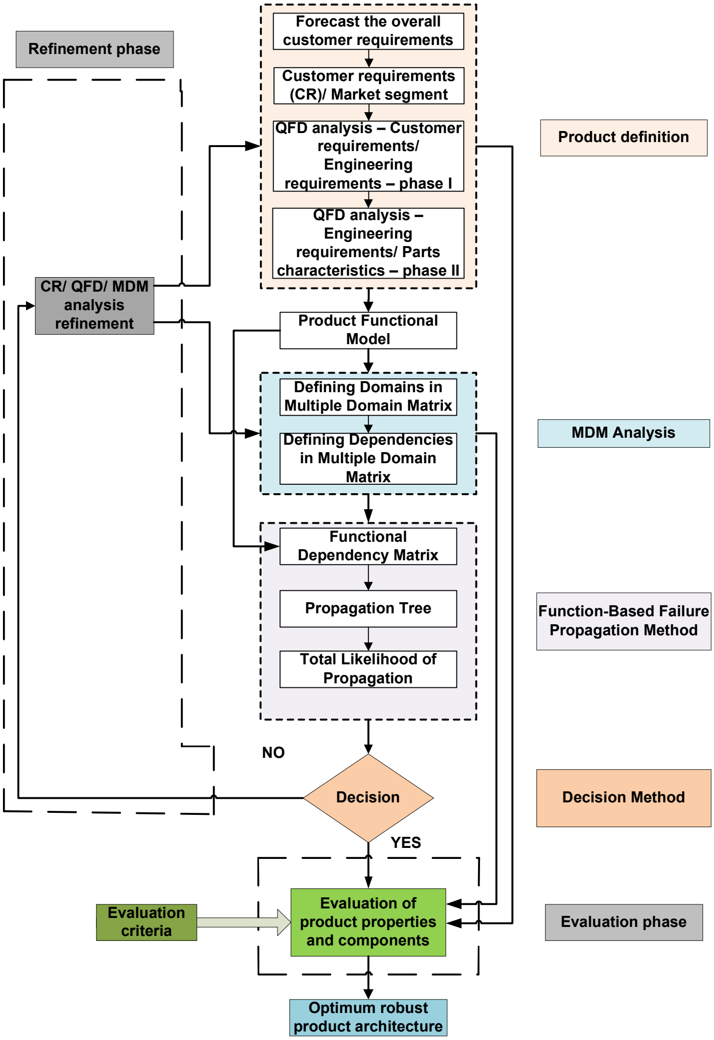

Figure 1: Schema of matrix approach

Each data is converted to the level of importance (see Table 2). Then we input the importance data to the upper side of the QFD phase II, the rating corresponding to each part characteristics is obtained by summing up the value in the column. The lowest row and the rightmost column is calculating with the level of importance, the ratings for evaluation criteria, and relationship between engineering requirements and parts characteristics, the summed up ratings of each engineering requirements and parts characteristics are obtained (from which we can see critical components and critical properties).

4 Case study

The objective of the case study is to show how the proposed matrix approach can support mechanical designers during conceptual designing. For this purpose we used the example of a climate chamber, which is very often an integral part of HVAC systems for large objects (e.g. office buildings). Here we start with the initial climate chamber concept with operating conditions based on designer experience (see Figure 2). Our goal in the case study was to propose architecture for such operating conditions through the given procedure.

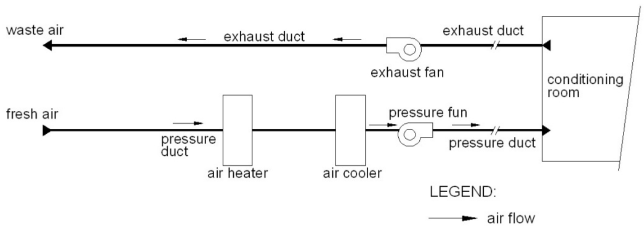

Figure 2. Simplified schema of initial concept of climate chamber

In OFD phase I, is input customer requirements in relation to the engineering requirements that can meet them. According to the calculation of the importance of customer requirements, the engineering requirements that can meet them were determined and shown on the top and their mutual relationships are provided. Phase I of the QFD procedure contains a roof, which represents the correlations between engineering requirements. These data are not relevant in this research, so the roof part has been removed. During phase II of the QFD procedure, the engineering requirements with a weighting factor are put to the left side and the parts characteristics are then determined. This was followed by determining the relationships between engineering requirements and parts characteristics. Furthermore, the interdependencies between parts characteristics are represented on the roof of phase II of the QFD procedure. After presenting a functional model of the system, an MDM analysis was provided (using LOOMEO® software). Here is started with domains for our initial climate chamber concept (see Figure 2). This case study presents a component-based DSM (component domain) for the final climate chamber concept (see Figure 3), after a few steps of refinement. After determining the dependencies between domains (inter and intra), we can start to build a functional dependency matrix for our model of the initial climate chamber concept (see Figure 4). In Figure 4, the initiating functions are shown across the top of the matrix and the dependent functions are listed along the side. Next, based on the propagation tree created and starting from the "top" function and linking it to each function, we are able to calculate total likelihood for each system. Each of these chains (branches) is linear because they have only one path from the initiator to the top function. Table 1 presents the failure propagation data collected for final climate chamber concept, after a few steps of refinement. As we can see in Table 1, if we follow this procedure (as a Function-Based Failure Propagation Method), we can see for the entire tree (our proposed system with subsystems) the individual likelihoods of each branch and determine which branch of the tree has the highest likelihood. Based on this, we can add some new elements through our refinement phase (see Figure 1).

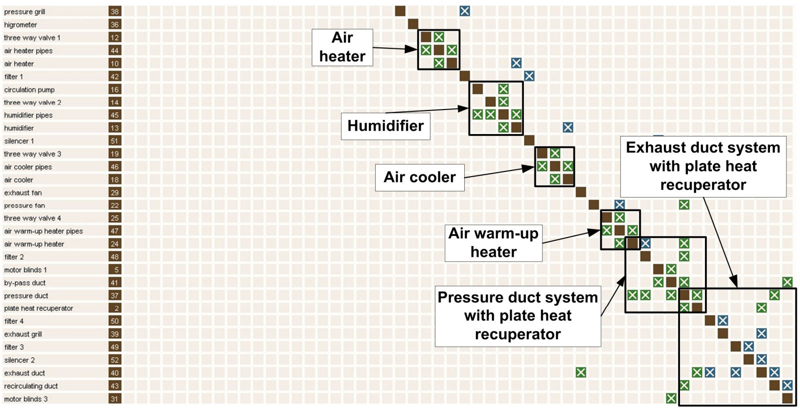

Figure 3. Component domain representation in MDM with possible modules (subsystems) identified in proposed product architecture for final concept of climate chamber (screenshots from LOOMEO®)

We obtain an improved model after several feedback loops within the proposed framework to reduce risk likelihood and build our system that will fulfil our initial operating conditions (see the matrix representation of the system with its subsystems after clustering [14]). The problem can be solved by adding some new elements: a heat regenerator, a bypass duct, a recirculation duct, a humidifier and an air warm-up heater. The final climate chamber concept after a few feedback loops in the refinement phase is presented in Figure 5. In this current research stage, the feedback loop is performed manually based on the results given from the Total Likelihoods in Function-Based Failure Propagation Method.

Table 1. Collected failure propagation data for final concept of climate chamber

Branch	**Total likelihood**
F0 – F1	0,1
F0 – F1 – F6 – F7 – F8 – F13 – F14	0,000054
F0 – F5 – F6 – F7 – F8 – F13 – F14	0,000108
Full tree	0,100162

As we can see, each data element (see Table 2) is converted to a value to represent a level of importance (9 stands for strong, 3 stands for medium and 1 stands for weak). Using the information provided in Table 2, we can determine critical properties and critical parts of our proposed product architecture through QFD phase II.

		Likelihood *I*													
		Initiating function													
Dependent function		F0	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13
	F0- bring waste air														
	F1 – separate share of waste air	0,1													
	F2 - accept device														
	F3 – secure device against relegation														
	F4 – bring air														
	F5 – regenerate heat to air	0,3				0,3									
	F6 – exploit waste heat to air		0,3				0,2								
	F7 – transfer heat to air							0,3							
	F8 – humidify air								0,1						
	F9 – absorb noise														
	F10 – absorb vibrations														
	F11 – absorb noise														
	F12 – absorb vibrations														
	F13 – transfer heat to air									0,2					
	F14 – bring hot air to the conditioning room														0,3

Figure 4. Functional dependency matrix for final concept of climate chamber

Putting the given criteria information on the upper side of QFD phase II, we can recalculate rating for all engineering requirements, as well as rating for all parts characteristics.

Table 2. Importance level for criteria information

Components	Process duration		Interdependency		Complexity	
	Day	Importance	Degree	Importance	Degree	Importance
12	5	3	1	1	Medium	3
44	1	1	10	9	Low	1
10	10	9	3	1	High	9
42	4	3	0	1	Medium	3
16	15	9	1	1	High	9
14	5	3	1	1	Medium	3
45	1	1	13	9	Low	1
13	14	9	18	9	High	9
51	4	3	1	1	Medium	3
19	5	3	1	1	Medium	3
46	1	1	10	9	Low	1
18	10	9	10	9	High	9
29	15	9	0	1	High	9
22	15	9	0	1	High	9
25	5	3	1	1	Medium	3
47	1	1	19	9	Low	1
24	10	9	2	1	High	9
48	4	3	10	9	Medium	3
5	4	3	3	1	Medium	3
41	2	1	13	9	Low	1
37	2	1	20	9	Low	1
2	12	9	1	1	High	9
50	4	3	1	1	Low	1
39	2	1	3	1	Medium	3
49	4	3	1	1	Medium	3
52	4	3	1	1	Medium	3
40	2	1	5	3	Low	1
43	2	1	4	3	Low	1
31	4	3	4	3	Medium	3
Importance: High 9 Medium 3 Low 1						

5 Conclusion and future research

This paper proposes a matrix-based approach, which could help designers to obtain the optimum robust product architectures through the continuous risk analysis through all stages from initialization to later refinements with several evaluation criteria: complexity, interdependency and process duration in early design stages. The Function-Based Failure Propagation method used here has great importance in analysing failure chains using functions present in the system and may be applicable before a designated product assumes its physical form, to present functions not only as separate events, but also as dependent on other functions based on their connection with flows.

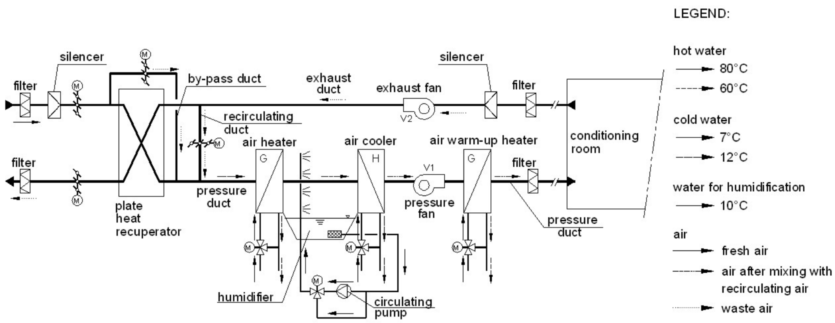

Figure 5. Simplified schema of final concept of climate chamber

It helps us determine a single likelihood of propagation for each function as well as calculate the likelihood of propagation of any function into another for our proposed model. Depending on that, designers could make refinements to the existing subsystem structures, adding new features to them. Based on the proposed framework, it is possible to analyse different product architecture arrangements of function interactions against the changes in product architecture using risk propagation. By using the Multiple-Domain Matrix, designers could also see the impact of the whole analysis on other domains (requirements, technical processes and components) to enable their refinement and changes. The framework also enables designers to evaluate robust design alternatives using the evaluation phase. Future research could be continued through several options. One of them could extend the approach to all types of product development, not only the modular or the present one. The second option could involve elaboration and implementation of the decision method in the approach on which it will be based, if it is necessary to make refinements in the QFD and MDM methods.

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