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A TRIZ Based Methodology for the Analysis of the Coupling Problems in Complex Engineering Design

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Abstract

Conceptual design is a critical and innovative stage in engineering product and system design. In the conceptual design process, it would be ideal if all functional requirements are maintained independently according to the law of Axiomatic Design theory. However, in practice, especially in complex engineering product and system design, more often the requirements are not independent (or coupled), and this makes conceptual design more difficult. In this paper, a coupling analysis methodology, framework and related techniques are proposed which integrate axiomatic design with the theory of inventive problem solving (TRIZ), in order to identify and analyse the coupling problems existing in conceptual design. An illustrative example is also presented.

Keywords:

New product design, Coupling analysis, Axiomatic design, TRIZ

1 INTRODUCTION

Conceptual design, seen as a critical part of new product and system development, is getting more attention both in academia and industry. Many techniques have been proposed in the past decades in order to improve the effectiveness and efficiency of conceptual design. Some of them, such as Quality Function Deployment, Axiomatic Design [1], and the Theory of Inventive Problem Solving (TRIZ) [2], are proven successful in conceptual design of engineering products and systems and are widely used in industrial applications. Axiomatic design provides an effective approach to developing products and systems throughout the whole design domains, including the customer domain, the functional domain, the physical domain and process domain. The zigzagging developing process and two axioms of axiomatic design theory developed by Suh [1] are widely adopted, especially in mapping functional requirements to design parameters at the conceptual design stage. During the zigzagging process, function requirements and design parameters are acquired with corresponding design matrices. By populating design matrices, uncoupled, decoupled and coupled solutions can be identified and further measures can be carried out to eliminate couplings. However, this is not viable in some complex engineering products and systems in the real world [3,4,5]. Firstly, current techniques of coupling analysis are implemented on a qualitative basis. The strengths of couplings existing in the solution can not be obtained. For example, when there are many couplings and not all of them can be solved all together, the critical couplings need to be identified, prioritised and solved in order to improve the effectiveness and efficiency of design. Therefore, it is important to find a methodology that can analyse and quantify the strengths of couplings. Secondly, the original theory of axiomatic design is inefficient when the scale of design matrix gets very large. Generally, decoupling of design is conducted in two steps, i.e., (i) the design matrix is populated so that couplings existing in the design are identified; and (ii) the design matrix is rearranged to adjust the sequence of functions and design parameters in order to make the design decoupled. However, when the number of functional requirements increases, the number of combinations will grow in a geometric progression and the rearrangement of design matrix will be extremely time consuming [1], and this is difficult to implement in industry. Thirdly, resources, in terms of development costs, lead-time, staffing and so on are always precious and need to be allocated properly in most projects. The scale and complexity of some large engineering projects are enormous and solutions of these couplings are not easy to be obtained. Therefore, it is unacceptable to spend too much resource in resolving the less critical coupling issues (some are even harmless). Instead, the critical couplings should be identified and resolved with intensive efforts.

In summary, a more practicable and efficient coupling analysis approach is needed to analyse the couplings existing in design solutions, which is able to identify couplings quickly and enables engineers to make more efforts on solving critical couplings that are most harmful to the implementation of required functions. In addition, the progress of the project may be speeded up and unnecessary costs may be reduced by leaving the less critical or even harmless couplings unsolved.

2 LITERATURE REVIEW

2.1 Axiomatic Design

The theory of axiomatic design is proposed by Suh [1], which is dedicated to constructing a design framework with a scientific basis and improving design activities with a logical and analytic thinking process. Basically, there are three essential parts of the axiomatic design that are widely used in academic research and industrial applications, namely the zigzagging design process, design axioms and the design matrix. The Axiomatic design theory divides the design world into four domains, i.e., the customer domain (CAs), the functional domain (FRs), the physical domain (DPs) and the process domain (PVs). The design is gradually realised by mapping from one domain to another. Typically, the mapping process between functional domain and physical domain is studied more often in literature than others because the conceptual design is mostly undertaken at this stage. As depicted in Figure 1, the mapping system works in a top-down way. Each design parameter (DP) in the physical domain corresponds to each functional requirement in the functional domain at the same level. Then design parameters in this level derive functional requirements in the next level until it reaches the leaf level so that functions and solutions are decomposed and obtained during this process.

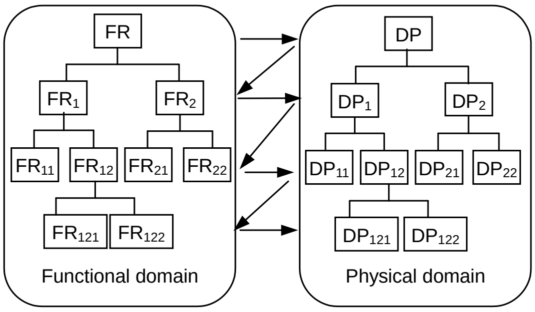

Figure 1: Zigzagging mapping process between functional domain and physical domain [1]

There are two axioms recognised in design, namely independent axiom and information axiom, companied by related theorems and corollaries. Design axioms are the elementary part of axiomatic design and deemed as the basis of good design, which are used to guide the design process and evaluate alternative solutions. The independent axiom indicates that the function requirement should always be maintained independently so that any change of the corresponding DP of one FR will not affect functionalities of other DPs. As the basis of the axiomatic design theory, the independent axiom takes effect throughout the design process. The information axiom indicates that the best design solution should contain minimum information content. More information means being more complicated and more possible that the design parameter can’t satisfy the functional requirement.

Design matrix is a technique used to analyse the coupling relationships between a group of FRs and their corresponding DPs. Normally the matrix is populated in a binary way so that all the coupling relationships are recognised qualitatively. According to the independent axiom, only uncoupled and decoupled designs are acceptable. However in the design of some complex engineering products and systems, it is impossible to keep all FRs independent of DPs. Quantitative analysis of coupled elements should be carried out. A practical approach is needed to clarify the coupling relationships within these designs so that the direction of improvement can be pointed out.

2.2 The Substance-Field Model of TRIZ

TRIZ is the Russian acronym of Theory of Inventive Problem Solving [2]. Since TRIZ was proposed, it has been widely used in industrial applications to solve technical problems due to the fact that TRIZ is a result from the analysis of thousands of patents. Recently, many researchers and practitioners are trying to apply TRIZ in other non-technical areas, such as management, education, environment and politics. Although there are a considerable set of techniques in the theory of TRIZ, such as contradiction matrix, inventive principles, knowledge/effects and ARIZ, the Substance-Field (shortly Su-Field) analysis model is picked up in this project in order to clarify the coupling relationships during the zigzagging design process of Axiomatic design. The Su-Field analysis model is based on the minimal technological system which is also known as the triad ‘object-tool-energy’. The triad system is composed of a tool, an object and the energy and describes that the tool performs action on the object by the force coming from the energy. Through the analysis of the triad system, interactions between elements within this system can be clarified. Along with the triad system, four kinds of actions are also identified which include unspecified action, specified action, inadequate action and harmful action. For example, the Su-Field analysis model of driving nail into the wall is depicted in Figure 2. In this system, mechanical force is performed on the hammer by the user, and then the hammer performs mechanical force on the nail.

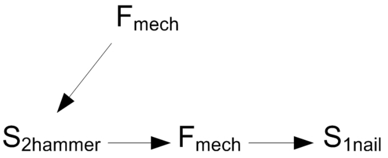

Figure 2: Su-Field model example

In this project, direct or indirect interactions between DPs in the Axiomatic design methodology may be identified using the Su-Field analysis method. Fields existing in interactions can be clarified as well so that effects caused by fields can be estimated by specific expertise. This is important to identify the couplings between DPs and FRs.

2.3 Integration of Axiomatic Design and TRIZ

Many attempts at integrating TRIZ and Axiomatic design together have been made by researchers, in order to improve the product development process. Comparison between Axiomatic design and TRIZ is carried out to identify advantages and disadvantages of the two theories. The possibility of complementary integration of axiomatic design and TRIZ is also discussed [6,7,8]. It is found that, on one hand the Axiomatic design is powerful in functional analysis and provides a logical thinking approach to devising conceptual design in a zigzagging and hierarchical structure. On the other hand, although it is effective to identify functional conflicts underlying the solutions, there is a lack of specific tools in the Axiomatic design theory for problem solving [9]. Based on a wide range of analysis of a large number of patents, TRIZ becomes a sophisticated methodology for physical and technological problem solving. However, it is relatively less powerful in complex system analysis [6, 10]. With the advantages of TRIZ, it is possible to improve the ability of problem identification and solving within the Axiomatic design theory.

In the light of the above discussions, many methodologies have been proposed to enhance the capability of product design by making Axiomatic design and TRIZ work together [5,8-13]. Particularly, some methodologies are devised, from different perspectives, for coupling analysis recently. Su and his colleagues [4] developed a methodology to deal with coupling analysis of engineering system design in a quantitative way. A comparative approach and a scale algorithm are proposed in order to transfer the binary design matrix into a quantitative one on an analytical basis. Zhang et al [5] proposed a conceptual framework by integrating TRIZ with axiomatic design. Some tools of TRIZ, such as contradiction analysis, separation principles, inventive principles and effects, are used to solve constraints and coupling problems. Shin and Park [13] classified the coupled designs into six patterns. Tools of TRIZ, such as standard solutions, scientific and technical effects, contradiction matrix, separation principles and ARIZ, are used in each pattern respectively or combined, to solve different coupling problems. Kang [12] proposed an uncoupling methodology using contradiction matrix and inventive principles. Within this methodology, coupling problems are formulised as contradictions and FRs are converted into standard characteristics, and then inventive principles are applied to solve all the contradictions.

By reviewing the above methodologies regarding the integration of Axiomatic design and TRIZ, it is found that there still exits a weakness in using these methodologies in conceptual design. TRIZ is good at solving technical and physical problems, but in conceptual design, detail design parameters are still vague and it is difficult, and also time-consuming, to solve problems using the principles or standard solutions in TRIZ. The aim of this project is to identify the coupling relationships within solutions and find critical paths for designers to focus on. As an ongoing project, although not all the coupling problems will be solved in the proposed methodology directly, it provides an efficient way for designers to find which path is most valuable to take for improvement.

3 THE PROPOSED COUPLING ANALYSIS METHODOLOGY

Functional design is to find an object or a group of objects that can realise the function requirements by some properties of them or by interactions between them. In other words, the function is the outcome of the operation of the triad system, in terms of TRIZ. Design parameter is one kind of properties of these objects that can be used to drive the realisation of required functions. Any unexpected actions will affect the realisation of functions. In this project, expected interactions within and between design elements that are used to realise functions are not considered. Instead, unexpected interactions are focused on because they are most possible to cause unexpected couplings. Different from the term “contradiction”, unexpected interactions are not contradictions or conflicts from a technical point of view. They are just functional interactions, but out of the expectation of designers.

The approach to analysing couplings in the zigzagging design process is depicted in Figure 3. As the product design is organised in a hierarchical structure by the zigzagging process, design parameters (DPs) in lower levels should be consistent with their parent ones (parent-DPs) in upper levels. In other words, characteristics of design parameters in lower levels will reflect characteristics of those in upper levels. Given the coupling analysis is carried out in the second level of the zigzagging process, design parameters DP_{11} and DP_{12} are identified as coupled in this solution. On account of the lack of design details at this stage, although the qualitative results of impact of this coupling can be roughly estimated by the inputs and outputs of DP_{12} and DP_{11}, the more accurate and quantitative strength of coupling can not be obtained yet. Provided that the third level is the leaf level of this design, the corresponding child design parameters of DP_{11} are DP_{111}, DP_{112} and DP_{113}, and likewise, the corresponding child design parameters of DP_{12} are DP_{121} and DP_{122}. At the leaf level, behaviours of these child design parameters are analysed by the Su-Field analysis model, so that couplings between design parameters derived from the same parent parameters are identified and quantified. At the same time, couplings between child parameters of different parent parameters are also identified. Pointing to the second level, by analysis of the third level of design parameters, not only couplings within DP_{11} and DP_{12} can be calculated by specific algorithms but also coupling between DP_{11} and DP_{12} , which is caused by F_{12}(o’), can be determined by analysing behaviours between their child parameters (i.e. F_{121}(o)’ and F_{122}(o)’).

Due to the fact that this project primarily focuses on the analysis of coupling relationships between design parameters, the Su-Filed method is partially used. Conventionally, Su-Field method is used to analyse problems and guide designers to solving problems with standard solutions [2]. In this project, standard solutions are not involved, because no efforts will be made to solve coupling problems at this stage. In other words, the triad analytical model is the only part that is used to clarify interactions within solutions. Discussion of using standard solutions or laws of system evolution to suggest or predict the measure of improvement is out of the scope of this project.

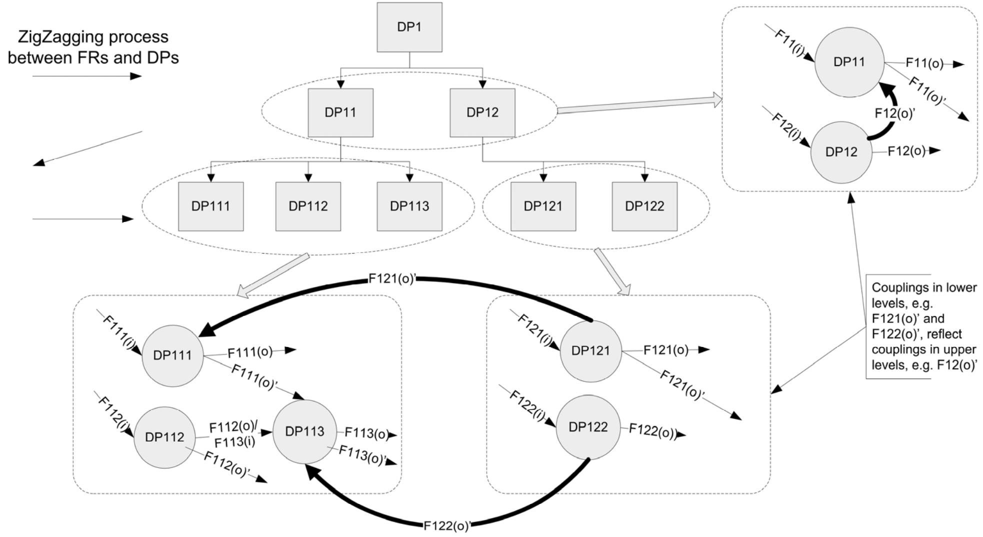

Figure 3: Analysis in the Zigzagging design process

4 COUPLING ANALYSIS TECHNIQUE WITH SU-FIELD METHOD

In order to formulate the coupling analysis process, the framework of coupling analysis methodology is developed (see Figure 4), which is mainly composed of 8 steps. In this section, every step of this framework will be described and related techniques used in each step will be clarified.

Step1: Complete the zigzagging design process. The zigzagging design process is conducted by designers at the beginning of product design. Hierarchical design structures of functional requirements (FRs) and corresponding design parameters (DPs) are constructed with current design capability of the team. A qualitative design matrix is populated and rearrangement of the matrix is conducted so that uncoupled and decoupled functions are identified [14]. Meanwhile, coupled blocks existing in the binary design matrix are identified as well, which are looked into in this project. Unlike the conventional axiomatic design approach that does not decompose coupled blocks, in the proposed methodology, each coupled block in the design matrix is decomposed further until it reaches the leaf level and interactions between constituent elements are analysed in step 2 by the Su-Field analysis method.

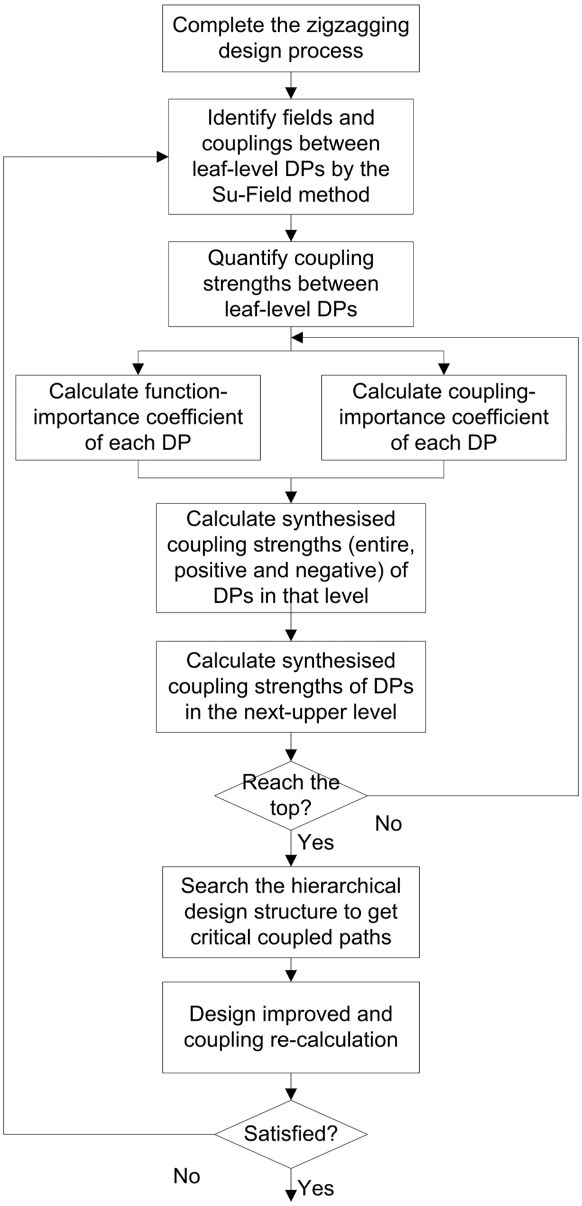

Figure 4: The framework of coupling analysis

Step2: Analyse couplings between leaf-level DPs by the Su-Field method. The coupling analysis method in this project is built upon the Su-Field analysis method which is used to clarify interactions between design elements and their effects caused by these interactions. For example, as depicted in Figure 5, there are three DPs and their interactions are expressed in the way of Su-Field analysis. In this coupling analysis model, Fields are denoted by F(i), F(o) and F(o)', and Substances are denoted by DP.

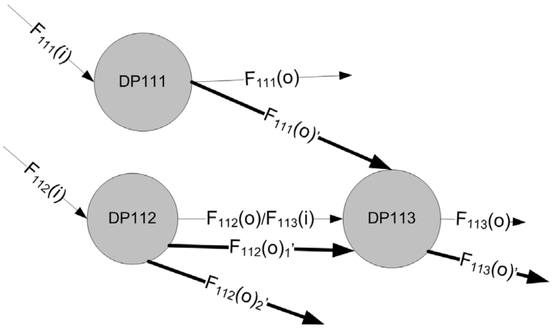

Figure 5: Su-Field analysis of couplings among Design Parameters

F(i) denotes the expected input field of a DP, which is designated when the DP is designed. F(i) could be fields coming from out of the system, like actions from users or environments, or fields coming from other DPs in the system. F(o) is the expected output field of a DP. Similarly to the F(i), F(o) is also designated when the DP is designed. The F(o) is what the system wants in order to realise the function corresponding to the DP. F(i) and F(o) are necessary for the realisation of functions, so in this paper the couplings caused by F(i) and F(o) are not considered. Another output field is F(o)' which is not expected by the initial design of the system. In other words, F(o)' is the factor that may be out of control and cause unexpected couplings between DPs. So the analysis of F(o)' will clarify what the coupling of DPs is, how the coupling happens.

Another important factor in this model is the DP. Strictly according to the theory of Axiomatic design, DP means a feature that can satisfy the realisation of functional requirement. The carrier of desired feature may be an object or a particular part of an object. For simplicity, here, 'DP' denotes an object or a part of an object that has these design parameters so that the expression can be consistent with the theory of Su-Field analysis as well. In terms of design parameters, their expected states are controlled by F(i)s and their carriers. However, with influence made by F(o)'s from other design parameters, their states may vary. Thus, by comparing the state influenced by F(o)'s with the initial state expected by design, changes of these states of DPs are looked into. The effects of functional performance caused by changes of DP's states can be quantified by a scale system so that strengths of couplings can be obtained.

Step3: Quantify coupling strengths between leaf-level DPs. Due to the fact that couplings are caused by unexpected fields, i.e., F(o)', acting on DPs, the effort of calculating coupling strength is focused on the influence that F(o)'s make on DPs. To achieve that, a scale system is developed. The strength of coupling is scaled by engineering experts according to the effect that one DP performs on another DP in every level of the zigzagging design process. The relationship between coupling strengths and effects can be learnt from Table 1. Taking the system in Figure 5 as an example, if $F_{113}(o)'$ performs a negative effect on DP_{113}, which significantly reduces it's performance, then the scaled coupling strength will be marked as -5 on DP_{113}; if the $F_{112}(o)_1'$ performs a positive effect on DP_{113}, which slightly improves it's performance, then the scaled coupling strength will be marked as 1 on DP_{113}, as depicted in Figure 6. Along with the progress of zigzagging design, the scale system expresses the coupling strength in a more accurate way, because there are more details emerged from top level to lower level design until the leaf level. In turn, more accurate estimation of coupling strength in lower levels can improve estimation of coupling strength in upper levels with the help of an estimating algorithm.

Coupling Strengths	Descriptions of Coupling Strengths
9	Necessity of function
7	Extreme performance improvement
5	Significant performance improvement
3	Moderate performance improvement
1	Slight performance promotion
0	No effect
-1	Slight performance reduction
-3	Moderate performance reduction
-5	Significant performance reduction
-7	Extreme performance reduction
-9	Function damaged

Table 1: The scale system of coupling analysis

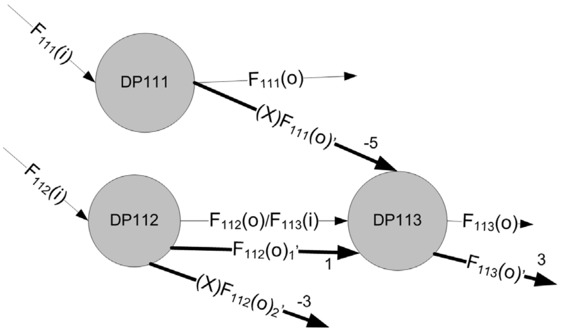

Figure 6: Example of scaled coupling strength

Step4: Calculate relative importance of each DP. Before calculating the coupling strength of a DP, the importance of each DP needs to be clarified, due to the fact that DPs have different importance compared to each other. DPs with different importance will be considered differently when their coupling strengths are calculated. In this project, there are two kinds of importance need to be analysed, which are the functional importance and the coupling importance.

Step 4.1: Calculate the functional importance. Among the child design parameters of the same parent parameter, one child parameter is expected to realise one child function of the corresponding parent function. Obviously, these child functions play different roles in realising the parent function therefore there is different relative importance existing. To obtain the relative importance of each child function, the Analytical Hierarchical Process method (AHP) [15] is used to deal with a pair-wise comparison between these child functions of a parent function. As a result, each child parameter will get a relative importance coefficient which will be used in calculating its coupling strength. For DP_l, its relative importance coefficient is denoted as ε_l, where $\varepsilon_l \in (0,1)$ and DP_l means a certain DP in the hierarchical structure, e.g. DP_{113} in Figure 5.

Step 4.2: Calculate the coupling importance. When a DP performs actions on another DP, it means this DP has the ability to influence others. Given that there is a DP_1 performing actions on DP_2, in other words there is a coupling between them, the outcome of DP_2 will be influenced by DP_1. Furthermore, the outcome of DP_2 will act on other DPs that are coupled with DP_2. Thus, it is important to consider the ability that how one DP can influence others before calculating its coupling strength. The coupling importance coefficient of DP_l is denoted as λ_l which can be calculated as follows:

Provided that DP_l has *K* F(o)'s act on *H* DPs, each single coupling strength resulting from $F_k(o)'$ acting on DP can be denoted as f_k and the functional importance of each DP that is acted on by F(o)'s is denoted as ε_h, where $k \in K$ and $h \in H$. Then, the original coupling importance can be calculated as:

$$\hat{\lambda}_l = \sum_{(h-1)|k}^{H} \sum_{k=1}^{K} |f_k| \bullet \varepsilon_h \tag{1}$$

In order to be consistent with functional importance, the importance coefficient should be a number between 0 and 1. Thus, the original coupling importance needs to be normalised. The normalised coupling importance coefficient can be calculated as:

$$\lambda_l = \frac{\hat{\lambda}_l}{\sum_{l=1}^{L'} \hat{\lambda}_l} \tag{2}$$

where *L'* denotes the number of child parameters of DP_l's parent parameter.

Step5: Calculate synthesised coupling strengths of DPs. The coupling of DP_l can be expressed by $C_l(ct)_{cn}^{cp}$, where ***cp*** means the aggregate coupling strength caused by positive effects performed on DP_l, ***cn*** means the aggregate coupling strength caused by negative effects performed on DP_l, and ***ct*** means the aggregate coupling strength caused by all effects performed on DP_l. For example, if there are *n* fields act on DP_l, *p* of them make positive effects on DP_l and *q* of them make negative effects on DP_l. Then cp_l and cn_l can be calculated as follows:

$$cp_l = \varepsilon_l \bullet \lambda_l \bullet \sqrt{\sum_{i-1}^{p} f_i^2} \tag{4}$$

$$cn_l = \varepsilon_l \bullet \lambda_l \bullet \sqrt{\sum_{j=1}^{q} f_j^2} \tag{5}$$

where $i \in \{0,...,p\}$, $j \in \{0,...,q\}$, $p+q=n$ and f means the coupling strength caused by a field; The aggregate coupling strength can be calculated by this equation:

$$ct_l = \sqrt{cp_l^2 + cn_l^2} \tag{6}$$

Step6: Calculate synthesised coupling strengths of DPs in the next-upper level. For the parent design parameter, its coupling strength can be calculated easily by integrated coupling strengths of child parameters together. For example, if DP_p has R child parameters, then the coupling strength can be calculated as follows:

$$cp_p = \sqrt{\sum_{r=1}^{R} cp_r^2} \tag{7}$$

$$cn_p = \sqrt{\sum_{r=1}^{R} cn_r^2} \tag{8}$$

$$ct_p = \sqrt{cp_p^2 + cn_p^2} \tag{9}$$

where cp_p denotes the aggregate positive coupling strength of the parent DP, cn_p denotes the aggregate negative coupling strength of the parent DP, cp_r denotes the aggregate positive coupling strength of a child-DP, and cn_r denotes the aggregate negative coupling strength of a parent-DP. The coupling strength of every DP in each level is calculated until it reaches the top level. Before calculating the coupling strength of each upper level, relative importance coefficient needs to be calculated first.

Step7: Search for the hierarchical design structure to get critical coupled paths. After obtaining all the coupling strength of every DP in each level, a searching algorithm is used to identify critical coupling paths in this hierarchical design structure. Designers can get the most coupled path by searching coupling strengths *t* from the top level to the leaf-level in order to get the most promising route to improve the design. Designers can also get the most negative coupled path by searching negative coupling strengths *cn* in the structure in order to get the most valuable way to eliminate critical problems existing in the design. Additionally, designers can get the most positive coupled path by search for the positive coupling strength *cp* of every DP so that they can decide whether some parts of the design can be integrated together.

Step8: Design improved and coupling re-calculation. By recognising some most valuable paths for improving the design, improvements need to be implemented and the design is refined. If the design is still not satisfactory, recalculation of the coupling strength of the design is carried out and further improving work needs to be done.

5 AN ILLUSTRATIVE EXAMPLE

In this section, an example is demonstrated to show how the methodology works to identify and quantify the coupling relationship between FRs and DPs in an engineering system. The engineering system chosen in this paper is the reactor cavity cooling system (RCCS) of General Atomics' Gas Turbine-Modular Helium Reactor (GT-MHR) nuclear reactor which is described in the GT-MHR conceptual design description report [16,17] and is further studied by Jeff Thielman et al [3,18] in order to evaluate and optimise the system with Axiomatic design theory. The RCCS is one of the cooling systems of the GT-MHR and works in a passively natural circulation cooling condition to remove decay heat when the reactor is shut down (see [10] and [12] for details). Although there are seven sub-FRs and seven sub-DPs of the DP3.2.2 in Jeff Thielman's research, for the purpose of demonstrating the proposed methodology in the simplest way, only three FRs and their corresponding DPs are selected in this paper, which can be found in Table 2.

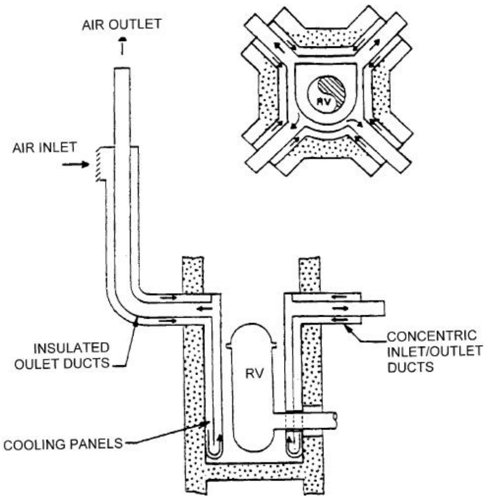

Figure 7: The reactor cavity cooling system [18]

Sub-FRs of FR3.2.2	Sub-DPs of DP3.2.2
Air exit temperature	Riser Width
Air velocity in riser	Riser Height
Maximum riser wall temperature	Outlet Area

Table 2: Selected FRs and DPs of RCCS

There are three functional requirements selected in this demonstration, namely air exit temperature, air velocity in riser, and maximum riser wall temperature. In the conceptual design of the RCCS, the air exit temperature is supposed to be maintained as low as possible. The value of air velocity in riser needs to be kept as high as possible so that there will be more heat taken from the reactor. Obviously, the maximum riser wall temperature is designed to be as low as possible due to the fact that high temperature is negative to the safety of the reactor.

The operation model of the RCCS system is simply built up using the Su-Field analysis method, as depicted in Figure 8. Obviously, it can be learnt that Reactor is the source of heat and it delivers heat to risers by radiation. The riser, therefore, is heated and delivers forward the heat to the circulating air in the riser. By the nature of air, the heated air drives air in the riser to rise up and go outside of the riser. Finally, the exit air is led by the outlet duct and gets into the atmosphere.

Beside these expected actions, there are also some actions that are not expected by the original design. For example, with increase of the width of riser, the air inside the riser is heated more effectively so that the velocity of air in riser increases. Meanwhile, the temperature of the riser wall decreases because there is more heat taken from the reactor. Another fact is when the height of riser increases the temperature of exit air and the maximum temperature of the riser wall increase because when the height of riser increases the damp of air circulation increases as well and the performance of releasing heat decreases. The outlet area also affects functions of air exit temperature and air velocity in riser by control of the exit of air. Thus, the coupling diagram can be obtained based on the analysis of Su-Field method and engineering expertise, which is shown in Figure 9. By analysing the effects caused by unexpected actions, relative coupling values are obtained according to the scale system of coupling analysis.

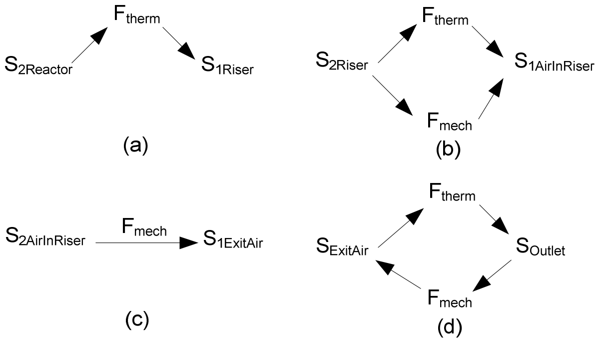

Figure 8: Su-Field analysis of heat removal

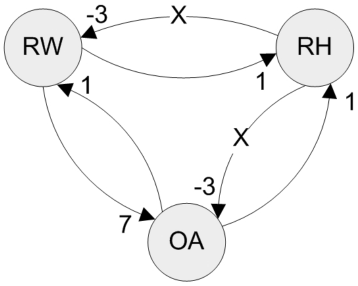

Figure 9: Interactions and couplings between objects

After obtaining the coupling relationship between design elements, step 4 of the coupling analysis framework needs to be carried out to calculate the relative functional importance and relative coupling importance of each element. By the algorithm of AHP (Analytical Hierarchical Process), the relative functional importance can be calculated as in Table 3.

	Air exit temperature	Air velocity in riser	Maximum riser wall temperature	Relative Importance
Air exit temperature	1	2	1/2	0.297
Air velocity in riser	1/2	1	1/3	0.164
Maximum riser wall temperature	2	3	1	0.539

Table 3: Relative functional importance

According to the results of coupling analysis in Figure 9 and the relative functional importance in Table 3, the relative coupling of each design element can be obtained by equation 1 and equation 2, which is shown in Table 4.

	RW	RH	OA
Relative coupling importance	0.57	0.067	0.363

Table 4: Relative coupling importance

Furthermore, the coupling value of each design element can be calculated by equation 4, 5, 6. The results are shown in Table 5.

	Positive coupling (cp)	Negative Coupling (cn)	Total coupling (ct)
RW	0.169	-0.508	0.535
RH	0.011	-0.011	0.016
OA	1.37	-0.587	1.49

Table 5: Coupling strengths of design elements

Finally, the coupling strength of the parent element, DP3.2.2, can be calculated by equation 7, 8, 9. The result of coupling strength of DP3.2.2 is displayed in Table 6. It needs to be noticed that the coupling strengths of DP3.2.2 below are not the actual values because there are only three pairs of FRs and DPs selected to demonstrate in this example.

	Positive coupling (cp)	Negative Coupling (cn)	Total coupling (ct)
DP3.2.2	1.38	-0.776	1.583

Table 6: Coupling strength of DP3.2.2

By calculation of coupling strengths of three design elements, the coupling problem can be learnt from the result intuitively. From Table 5, the design element OA is supposed to the critical element that gets coupled in the system with others because both the strongest negative coupling and the strongest total coupling occurred on OA. Thus, some proper improving efforts should be assigned to the design of OA in order to effectively reduce the couplings of the solution. If the full decomposition of the design structure and the coupling analysis of all design elements are completed, there would be a hierarchical structure of coupling analysis results where a comparative algorithm can be applied to search the strongest couplings in each level in a top-down way. As a result, critical paths for system improvement are identified to facilitate the effectiveness and efficiency of product design.

6 CONCLUSIONS

The theory of Axiomatic design is widely used in new product and system design, especially at the conceptual design stage. According to the Independence Axiom, it is critical to maintain the independence of functions that minimises the disturbance to realisations of other functions when anyone of design parameters changes. However, in the real world, it is almost impossible to maintain the complete independence of all functions at an acceptable cost in some complex engineering systems. In this project, a methodology of coupling analysis is proposed by integrating TRIZ with Axiomatic Design. Su-Field method, an important part of TRIZ, is used to identify and analyse the couplings existing in design solutions. With the assistance of this methodology, coupling relationships within the designs are clarified and quantified. It is much easier for designers to find out clues to improve the system. Furthermore, if the number of design parameters is large, it is impossible for designers to carry out a rearrangement of the design matrix. Therefore this method can help to find critical coupled elements that affect the performance of the system. Also, it can help to improve the effectiveness and efficiency of engineering design because critical coupled paths can be found by searching in the hierarchical structure based on the coupling analysis results. The design team can make more efforts to improve the critical aspects of the system (and less efforts on less important or harmless couplings) and resources can thus be allocated more properly.

7 DISCUSSION AND FURTHER WORK

Although the proposed methodology provides a new way to analyse coupling issues in conceptual design, some uncertainties and shortcomings also appear, which are worthy of further discussion and consideration. From the perspective of TRIZ, substance in the Su-Field method indicates “thing” or “entity” which normally is a physical object. In this project, the carrier of design parameters is considered as an object or a part of an object which possesses the feature that can realise the corresponding function. Therefore, design parameter is used to represent that object or that part of the object or carrier. However, the carrier may have more than one feature to realise different functions. Thus, further analysis needs to be carried out to clarify which action is performed on a certain feature and what is the effect. This analysis is done by individual designers in this paper. A further research of mapping between physical Su-Field analysis and abstract coupling analysis is interesting to be looked into. Another issue is that the scaling system of coupling strength is used to quantify the coupling based on the expertise of individual engineers, which may make the estimation of couplings inconsistent if there are engineers in the team with different levels of experience. The scientific and technical effects of TRIZ are possible to be helpful to estimate the coupling strength by analysing the interactions. In this paper, the coupling strength of design element is the value that denotes the effects caused by other design elements acting on the current design element. But the effect, which is caused by the current design element acting on other design elements, has not been considered. Further research needs to be done in order to clarify the strengths of effects that the current design element acts on other design elements. The illustrative example in this paper is based on a complex engineering system. However, due to progress of the current research, the system has not been decomposed in details so that coupling analysis is not based on a rigorous engineering analysis and coupling analysis in upper-levels is not demonstrated. Thus, further research on the reactor cavity cooling system needs to be carried on. A real industrial case study is planned in the next stage of this project.

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