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KINDS OF COUPLING AND APPROACHES TO DEAL WITH THEM

Christopher A. Brown
brown@wpi.edu
Worcester Polytechnic Institute
Worcester, Massachusetts
01609 USA

ABSTRACT

The objective of this paper is to better understand coupling during the axiomatic design process by decomposing coupling into "kinds" based on the causes of coupling. The premises are that coupling can be more readily detected by systematically looking for different kinds, and that there are types of solutions that can be developed to address the kinds of coupling. The paper includes discussions and examples of coupling decomposition, methods to detect the different kinds of coupling, and procedures to find solutions to couplings..
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Keywords:
Axiomatic design, coupling, decomposition, sequential coupling, natural coupling, FR-FR matrix, DP-DP matrix, design matrix.

1 INTRODUCTION

The objective of this paper is to advance the understanding of coupling, or lack of independence, that can affect compliance with axiom one, the Independence Axiom, in axiomatic design. Consideration will focus specifically on coupling within and between the functional and physical domains. The inheritance of coupling from children to parents will also be considered.

Understanding coupling is important because the primary consideration in axiomatic design is to avoid coupling. Coupling occurs when an FR cannot be easily controlled, in that it requires iteration to arrive at its fulfillment. In the case where the iteration does not converge on a solution fulfilling the FR, then the coupling means that the FR cannot be fulfilled. Coupling that goes unnoticed will cause problems with control and adjustability and can lead to unintended consequences. There can be more than one kind of coupling operating in a design, and one kind can mask another, so that one goes unrecognized, and possibly uncorrected. Furthermore, the categorization of kinds of coupling and the systemization of dealing with it will facilitate the development of algorithms that can be run by a computer to develop compliance with axiom one.

The state of the art in understanding coupling is primarily between the physical and functional domains (Suh 1990, 2001) and primarily based on the nature or physics of the interactions between the DPs (Design Parameters, elements of the physical domain) and FRs (Functional Requirements, elements of the functional domain). Suh (1990) also gives attention to FR-FR coupling in considering the formulation of FRs and defining constraints. In practice, coupling is usually addressed in the context of the design matrix, which contains the relations between the FRs and DPs. The elements of the matrix represent the coupling between the FRs and DPs. Frequently, as with Acclaro software (www.axiomaticdesign.com), the presence and absence of coupling for each FR-DP pair is represented with an X or an 0, respectively.

It has been found in the course of using axiomatic design that there are different kinds of coupling; therefore, coupling phenomena can be decomposed. This decomposition is intended to facilitate the recognition of coupling and, once identified, assist in developing ways to eliminating or accommodating that impediment. The approach in the current work is to take a more sophisticated view towards coupling by decomposing it.
There are three elements in axiomatic design: axioms, structure, and process (Brown 2005). Each of these can be decomposed into two smaller elements: independence and information, domains and hierarchy, and zigzagging decomposition and physical integration, respectively. The most important part of axiomatic design is the axioms. The axioms drive the need for the structure, domains, and hierarchical decompositions, so that the axioms can be rigorously applied during development of the design. The structure drives the need for a process so that the design structure can be created (Brown 2005).
Some kinds of coupling need to be identified during decomposition so that the design can be corrected to eliminate or accommodate the coupling. DP-DP coupling can be introduced during the integration phase of the process. The decomposition of coupling and the implementation of the subsequent strategies will suggest modifications to the design process (Brown 2005).
objective purpose of this paper is to explain how Axiomatic Design (AD) can be applied to study the reliability.
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2 METHODS

The coupling is considered from the perspective of fulfilling design functions, FRs. After decomposing coupling into more detailed elements, each element in the decomposition is examined to identify its characteristics. Knowing the characteristics of the kinds of coupling should assist in identifying which kind has been encountered. Strategies for dealing with the different kind of coupling will be identified.

The decomposition of coupling, as with other decompositions in axiomatic design, should be CEME, i.e., collectively exhaustive and mutually exclusive (Brown 2005). The appropriate kind of theme can promote a decomposition that is CEME.

3 FIRST-LEVEL DECOMPOSITION OF COUPLING

In this work, at the highest level, three kinds of coupling are considered, and they are systematic combinations of FRs and DPs: FR-FR, DP-FR, and DP-DP coupling. This kind of systematic theme appears to collectively exhaust all the kinds of coupling, in the context of FRs and DPs. Note that FR-DP coupling is not considered because a function categorically cannot interfere with a design parameter, i.e., a physical element. It is the physical elements, DPs, that interfere with the functions, FRs.

It can be noted that a similar systematic decomposition could probably be applied to DPs and PVs, or FRs and PVs, although in the latter case the interposed elements of the physical domain could introduce other considerations.

3.1 FR-FR COUPLING

FR-FR coupling occurs when one FR overlaps and therefore interferes with another. This kind of coupling is the result of the decomposition of an upper-level FR into child FRs that are not mutually exclusive. FR-FR coupling will be avoided only if the FRs in the decompositions are mutually exclusive. Note that in complying with the rest of the CEME directive, if the children in the decomposition of a parent FR are not collectively exhaustive, then some element or elements are missing, and the parent FR cannot be completely fulfilled.

Designs that have FR-FR coupling will not be uncoupled and, depending on the degree of overlap between the two interacting FRs, may not be decoupled, since the resulting design matrix might not be able to be rearranged to make it triangular. FR-FR coupling needs to be eliminated for the design to comply with axiom one.

FR-FR coupling is best caught during the formulation of the FRs. There are two preemptive responses: reformulate the FRs, perhaps along a better theme, or determine whether an FR is better defined as a constraint. Suh (1990) notes that if an FR seems to be coupled with other FRs, then it could be a constraint. Also, constraints tend to have limits, while FRs should have functional tolerances (Suh 1990).

Examples of FRs that would be better as constraints that Suh (1990) offers are elements including cost, weight, and time. Risk could be another of these kinds of constraints. A good rule for considering if some element is an FR or a constraint is whether or not it requires a DP. If it requires a DP, then it is an FR, and the FRs need to be reformulated in order to avoid coupling. One reformulation might be to take the element in question and formulate it as a constraint, i.e., in such a way that it does not require a DP. One way of dealing with the cost, weight, time, and risk kinds of constraints is to develop a budget between branches of the design.

Unbounded FRs have been proposed, such as "maximize ROI (return on investment)" in decompositions in designing an enterprise (Suh 2001). These unbounded FRs tend not to take on functional tolerances easily. What should be the tolerance on return on investment? Sometimes unbounded FRs can be reconsidered and reformulated. As with "maximize ROI," there are reasonable bounds that could be considered. For a minimum, one might consider what is necessary to stay in business, and a maximum could be based on a benchmark, or past history, something that could suggest realistic expectations.

If there are two unbounded FRs that seem to react similarly to some change in a DP, then these may not be sibling FRs, but parent and child FRs. For example, minimize cost and minimize waste would react similarly to DPs such as inventory reduction initiatives. Reduce waste is probably better regarded as a child of reduce cost than as a sibling.

Whenever an FR, which should be a child of another, is instead proposed as a sibling, then coupling between the two should logically result. In these cases, the FR that would be the child should be demoted. If this demotion results in a parent having only one child, then in order to have a true decomposition, other children must be sought. In a true decomposition, each parent must have at least two children; otherwise, there could be an incomplete decomposition, i.e., not collectively exhaustive, which might demand a renaming of the parent FR. In the later case, the DP for the child would be redundant with the DP for the parent.

When necessary, that is, prompted by difficulty sorting out the FR-FR coupling, the coupling can be mapped in a FR-FR matrix. The FR-FR matrix can use just Xs and 0s to indicate interactions or lack of them. In a decoupled or uncoupled system all FR-FR matrices should be diagonal, i.e., all the off-diagonal terms will be zero. This will occur only when the FRs are fulfilling the mutually exclusive component of the CEME directive. This does not guarantee that the decomposition is collectively exhaustive, however. When an off-diagonal interaction is identified, then the corresponding FRs need to be examined and the cases discussed above considered. An FR that would be better as a constraint should have Xs in a large portion of corresponding rows and columns in an FR-FR matrix and the interactions should be symmetric on the matrix; in other words, whenever FRx is noticed to interact with FRy, and the and the x,y position in the matrix is marked with an X, then FRy should also be interacting with FRx, and the y,x position in the matrix should also be marked. When an FR that should be a child is proposed as a sibling, then it should be interacting with only the FR that should be its parent. If the FR-FR matrix includes more than one level of the hierarchy, which may not be advantageous, then all the children should exhibit coupling in both directions with the parents, that is, FRi.j should interact with FRi and FRi with FRi.j.

3.2 DP-FR COUPLING AND THE DESIGN MATRIX

DP-FR coupling is the most common kind of coupling generally considered in the design process. This coupling occurs when a DP is selected to fulfill an FR, and it interacts with FRs other than the one it was selected to fulfill. When this happens, the most common response is to select another DP. This is the axiom one test for selecting DPs, perhaps the most important application of an axiom to the design process. Selecting DPs that not only fulfill an FR but also do not cause unintended interactions and problems for adjustment and control is arguably the most important contribution of the axioms to the engineering design process.

DP-FR coupling is mapped in the design matrix and is the kind of matrix most frequently proposed;often, this matrix is the only kind considered in the axiomatic design process. Different from the FR-FR matrix discussed above or the DP-DP discussed below, the design matrix is indicative of the essential transformation in the design, as it shows how the DPs act to fulfill the FRs. The simplest embodiment of the design matrix for testing axiom one is to fill it with Xs and 0s. An X in the x,y location in the design matrix indicates that a change in DPy will result in a change in FRx. In other words, the partial derivative of FRx with respect to DPy does not equal zero. Generally, when x equals y, DPx was selected to satisfy FRy. A 0 in the at x,y indicates that the partial derivative of FRy with respect to DPx is zero, or is at least close enough to zero so that any imaginable change in DPy will not take FRx out of tolerance. Conceptually, the elements of the design matrix do not need to be mathematical expressions in the traditional sense. The elements of the design matrix can be thought of as operators that explain how to transform a DP into an FR.

An uncoupled design, indicated by a diagonal matrix, with all the diagonal terms having some value and the off-diagonal terms equal to zero, is the most desirable. Any order of adjustment of the DPs will satisfy the FRs without iteration. A decoupled design, indicated by a triangular matrix, is workable, although in the case of a fully triangular matrix, with the only zeros in half the off-diagonal terms, there is only one order of adjustment of the DPs to satisfy the FRs that does not involve iteration (Suh 1990).

Generally, in devising the design process, the design matrix should be considered after the creation of each level of the FR-DP hierarchy (Brown 2005). FR-DP coupling can be used to evaluate candidate DPs, and after actually fulfilling the intended FR, it is providing for independence of the FRs, i.e., avoiding unwanted coupling, which is the most important criterion in selecting DPs.

When considering coupling in the design matrix, if all the mathematical expressions for the terms are known, and the functional tolerances have been described, then the process is straightforward and involves simply evaluating the partial derivatives, as described above. Frequently, however, in practice, the functional tolerances are not precisely defined, and the mathematical relations between the DPs and FRs have not been formulated. There is a lesser tendency, especially at the higher, more abstract, levels of the design process, to precisely and formally define the tolerances and mathematical relations. The assignment of Xs and 0s to elements in the design matrix can take on some degree of subjectivity.

The decision to assign an X or a 0 to some element in the design matrix can be based on consensus within the design team. The objective is to find an efficient procedure for the design team to use, which is probably one that avoids iteration. One procedure, and maybe the best, is to consider the design matrix elements column by column, this is, look at one DP and systematically consider its influence on one FR after another. Essentially, the design team is relying on the accumulated knowledge inherent in the team. When a consensus is not easily reached, or when there is some doubt about the influence of the DP on a particular FR, then it may be necessary to seek more information, and databases can be consulted. Thought experiments can be proposed. Finally, actual experiments could be designed. The problem with consensus building is that the result is not always consistent with the actual performance. The procedure that builds consensus is sensitive to the interaction of personalities in the design team and individuals' powers of persuasion, which are not always consistent with an accurate assessment of the DP-FR interaction.

Sometimes, particularly at higher levels in the design procedure, the DPs can be generic. This is often desirable, since the specifics are only developed when the details are considered. An upper-level FR could be "provide XYZ," and the corresponding DP could be "device that provides XYZ," or instead of "device" maybe a "system" or a "mechanism". It is not yet decided whether that is a pneumatic device or an electromagnetic device. That will be determined further down in the design. Clearly, at the higher level, it will be difficult to establish coupling if the kind of device is not known. The procedure should be to assume no undesired coupling and to maintain a lack of coupling in the details.

3.2.1 INHERITANCE IN THE DESIGN MATRIX

DP-FR coupling can occur between the children of different branches. This means that DPi.j can be interacting with FRk.l, where $i \neq k$. When this happens, then the coupling is inherited by the parents, so that not only does the k.l, i.j element in the design matrix have an X, indicating the interaction, but automatically the k,l location does as well. If, and only if, there is interaction between the children can there be interaction between the parents.

Since all the children of all the branches can potentially interact, and every potential interaction should be considered to avoid unintended consequences and insure controllability, then there can be many potential interactions to check. Designs of something like an orbital space plane can have, when fully decomposed, over a thousand FRs. This means that there could be on the order of a million DP-FR pairs to evaluate. By the rule of inheritance, not every DP-FR pair needs to be systematically checked for coupling. In theory, only the lowest levels from each branch would have to be checked against each other systematically. It appears that at some point using a computer to analyze the appropriate algorithm and a databank of interactions may be the only practical way to do so extensive and systematic an evaluation when there are many DP-FR pairs.

3.3 DP-DP COUPLING

DP-DP coupling is primarily an issue during physical integration. At this point in the process, the design has been decomposed into its finest functional and physical elements. These elements then need to be integrated into a properly functioning entity. Whenever elements can be physically integrated without compromising the independence of the functions they should be (Suh 1990). Part of the process of physical integration must be verification of the functional independence as the physical elements are integrated.

The DP-DP coupling can be inherent in the DPs, in which case it could be identified during the decomposition. The simplest case happens when the same DP can be selected to fulfill two FRs. If the DP is listed twice in the decomposition, then it might be difficult to identify, since it can appear in the design matrix as if it is not coupled.

Physical contact between DPs does not necessarily mean that there is undesirable coupling. DPs sometimes must be in physical contact in order to fulfill their objectives. Consider ball bearings in races, or wheels on a bicycle. The bearings must roll on the races, and the wheels must be attached to the bicycle in order to accomplish at FR of providing low friction. In these cases the physical contact is required.

During the integration process, the physical interactions can be mapped onto a DP-DP matrix. As with the FR-FR matrix, the diagonal is uninteresting, as it shows that each DP physically interacts with itself. The diagonal could be left blank. Several symbols could be used for the off-diagonal terms in the physical integration matrix. Each position in the matrix could be occupied by more than one symbol. A 0 can be used for no physical interaction. An R can be used to note required physical interactions. A U can be used to note undesirable interactions, those that induce unwanted coupling. And an N can be used to denote physical interactions that are neither required nor undesirable. The matrix will not be symmetric. Because DPx interferes with DPy, does not mean that DPy necessarily interferes with DPx.

The DP-DP matrix can be used to evaluate physical integration alternatives. It can also be used to identify a need for additional FRs that would decouple functions that had been coupled by physical integration. In mechanical devices this FR could be satisfied by a mounting bracket, in computers perhaps by extra RAM. In building the decoupling, FRs might bee satisfied by insulation for sound proofing. Since the design with the minimum number of FRs is the best (Suh 1990), then the best solution to coupling introduced by physical integration would be to find an alternative integration configuration.

4 SECOND-LEVEL DECOMPOSITION OF COUPLING

It is proposed that all three of the above kinds of coupling could be decomposed in the same way, based on their character. One kind of coupling is that which arises from the nature of things. Another kind of coupling arises because the elements of one domain or the other must be fulfilled in sequence and is therefore called sequential coupling. Since no proof can be offered that this second level of decomposition is collectively exhaustive, with only natural and sequential coupling, then a third category could be added, called "other." This at least insures that the decomposition is collectively exhaustive, but it won't be discussed, and therefore adds nothing to the discussion in this paper.

4.1 NATURAL

Natural coupling could result from physical interactions, as through physical juxtaposition, geometry, or universal natural laws like Newton's laws, thermodynamics, and Maxwell's equations. Natural coupling might be revealed through experimental observations of phenomena that presumably are based on natural laws. Addressing natural coupling requires the selection of other FRs and DPs.

4.2 SEQUENTIAL

Sequential coupling is an interesting kind of coupling frequently encountered in process design for things like manufacturing and food preparation. It is worthy of separate consideration.

Sequential coupling occurs in processes that appear to require a certain sequence of operations. In a traditional sense, tapping a hole is dependent on first drilling the hole. If the drilling operation is not working properly, providing, for example, unsatisfactory dimensions or placement, then the tapping cannot correct it and the tapped hole will not satisfy its FR, such as to place a threaded fastener in a certain location. In many cases, the sequential coupling appears to be inherent and unavoidable. Since it can show up so frequently in process designs, it can have a tendency to mask other kinds of coupling that might be addressed separately.

One approach is to consider sequential coupling separately when considering the DP-FR process matrix. This can allow the designer to decouple the kinds of coupling and address potentially more easily avoidable coupling in traditional ways. When there is a set sequence of operations to satisfy the FRs, the design matrix will be triangular. Whenever DPx influences FRx+1 because of the sequence, then a sequential tracking design matrix (FR-DP) could be utilized. This is applicable to FR-FR matrices and DP-DP matrices, as the burden of sequential operations may be noted there. One advantage of this is that these matrices are then left to note natural or other coupling, and the designer can address these coupling problems separately from the sequential issues.

The sequential coupling sometimes can be avoided through more innovative or fundamental changes in the processes or tooling.

For example, the drill and tap can be integrated on the same shaft, which would eliminate drilling and tapping as separate operations. This could reduce the number of situations that could lead to failure to satisfy the FRs and therefore shrink the information content of the process. The caution is that this can introduce unintended consequences. Siting the drill and tap on the same shaft means that the hole will extend past the tapped part, and the drill and the tap must turn at the same speed. Also, this ould be viewed as trading one kind of coupling for another, ;and it increases the complexity of the tool, shifting the burden of maintaining the sequences to tool manufacture. Still, this could reduce the overall information content, since the location only needs to be found once.

Sequential coupling can be address by introducing a new FR as a decoupler. In a transfer line, the decoupler could be a buffer between stations (Suh 2001). This solution is counter to reducing work in process as for lean manufacturing, and therefore could be coupled with another branch of the process or enterprise design.

The sequential coupling should be minimized. The question arises whether eliminating sequential coupling is as important as eliminating natural coupling or reducing the information content. Clearly, if sequential coupling can be eliminated without introducing new FRs, or increasing the information content, it seems that it should be done. However, if there is a cost to eliminating the sequential coupling, and there are no apparent savings resulting from its elimination, then it may be better to leave it. At the worst, sequential coupling results in a decoupled design, which still satisfies axiom one.

5 CONCLUSIONS

This work shows that in theory, at least, it is possible to decompose coupling into several kinds. The first level of the decomposition is based on the kind of pairing between elements of different domains: FR-FR, DP-FR and DP-DP. It is suggested that this system of decomposition could be extended to the elements of the process domain as well. A second level of the decomposition, identical for each of the domain pairs, is based on the character: natural, based on natural laws; sequential, based on a necessary order, although it is not certain that this second level of decomposition is exhaustive. Categorizing potential coupling in this manner could assist in both identifying coupling and in addressing it, and some examples of identifying and resolving coupling have been discussed.

6 REFERENCES

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