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INTEGRATION OF THE CONTACT AND CHANNEL MODEL WITH AXIOMATIC DESIGN

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ABSTRACT

The Contact and Channel Model (C&CM) is a design approach developed since 1999 at the Institute of Product Development of the University of Karlsruhe, in Germany. It considers that any design can be described in terms of Working Surface Pairs (WSPs) and Channel and Support Structures (CSSs). The WSPs are all the pair-wise interfaces between components, or between a component and its environment, that contribute to the transformation of energy, material and information occurring in a technical system. The CSSs are the components or fields connecting only two WSPs, and are responsible for the transference or storage of energy, material and information from one WSP to another. The C&CM approach assumes that the functions are carried out by the WSPs, but also that the fulfillment of a functional requirement for a given system depends on the properties and interactions of at least two WSPs and one CSS connecting them. Moreover, C&CM incorporates concrete heuristic solutions and specific drawings and graphical symbols to help designers come up with a better understanding of the relationships between the description of the functions and the physical embodiment of the system, at any level of detail.

In this paper we analyze how C&CM and Axiomatic Design can be integrated, by comparing both approaches and identifying their similarities, differences and synergies. Other authors' research revealed advantages derived from integrating Axiomatic Design with other methods, like TRIZ, DFMEA, or Robust Design, among others. Here we conclude that synergies between C&CM and Axiomatic Design can also be explored to benefit the design process. Namely, such an integration can facilitate the design synthesis, when mapping from the functional domain to the physical domain, and increase our comprehension about how each possible design parameter may impact over each functional requirement. Furthermore, the C&CM heuristics may be useful in decoupling a coupled design. Two examples of application are presented, in order to illustrate these points and the benefits associated with the combined use of C&CM together with Axiomatic Design. Finally, we show how the C&CM approach can fit within the context of a Design for Six Sigma (DFSS) roadmap.

Keywords: Axiomatic Design, Contact and Channel Model, design synthesis, design analysis, Design for Six Sigma.

1 INTRODUCTION

Design is a key phase within the life cycle of any type of technical system, be it is a product, service, business model or a process. The decisions made during this phase deeply affect quality, cost and life cycle properties (safety, serviceability, manufacturability, maintainability etc.). In spite of its importance, the design process has often been treated more as an art than a scientific and systematic approach.

To overcome such a situation, and since design is recognisably a complex process, design models have been developed over the last decades, especially related to engineering and product design, although more recently some of them have also been adapted to other system morphologies, such as software, services or transactional processes.

One of those models is Axiomatic Design, a general theory that aims to guide the designers in their decisions by establishing the principles that should govern the design process. A strength of Axiomatic Design is its flexibility, allowing it to be used in conjunction with other design models.

The Contact and Channel Model (C&CM) is a much more recent design approach. Its main contribution consists of breaking fixations of designers on already existing solutions, by creating an abstract mental model that enables a better knowledge to be acquired about the interrelation between the functions that must be performed by the technical system and its physical elements.

This paper identifies the main similarities and differences between Axiomatic Design theory and C&CM, and explores the potential benefits of integrating them. The long-term goal of this work is to bring together these two approaches in order not just to help the designers during the conceptual stage of the design process, but also to contribute to possible synergies that can lead to a fruitful improvement of the engineering design science in the future. Moreover, we want to integrate this framework into a Design for Six Sigma methodology.

We start by reviewing the basics of Axiomatic Design and C&CM. In section 3, we identify the main common concepts, differences and potential synergies between both models. In Section 4 we present two examples of application that illustrate the synergies between C&CM and Axiomatic Design. Finally, in section 5, we show how and where C&CM can be applied in the context of a Design for Six Sigma (DFSS) project.

2 LITERATURE REVIEW

2.1 AXIOMATIC DESIGN THEORY

Axiomatic Design builds on the following four key elements: domains, hierarchies, zigzagging and axioms.

DOMAINS

According to Suh [1990], the world of design consists of the four domains represented in figure 1. Each domain on the right side answers how one can achieve the objectives or goals defined on its left adjacent domain, through appropriate design mappings..

Although these names are mainly based on the case of product design, other authors have demonstrated their applicability in the design of other types of technical systems, like software [Do and Suh, 2000], lean management [Cochran *et al*, 1999], supply chain management [Schnetzler and Schönsleben, 2006], strategic planning [Engelhardt and Nordlund, 2000], home building industry [Psilander, 2002] or even ergonomics [Suh, 2007]. In such cases the name and/or the number of the domains may differ from the standard ones.

HIERARCHIES

Design activities must be often simplified by breaking them down into lower levels of abstraction. In doing so, each domain considered will be decomposed into sublevels of increasing detail (less abstraction). As depicted in figure 1, the hierarchy in each domain is similar to a tree diagram.

Apart from the customer domain wherein the decomposition process is usually not considered, the remaining domains may have several levels of abstraction that jointly describe the technical system architecture.

The lowest levels in each branch of the hierarchy are commonly called "leaf levels". The sub-FRs not requiring further decomposition are the leaf-FRs. Similar reasoning is applied to the design parameters (DPs) in the physical domain and to the process variables (PVs) in the process domain.

Please note the index structure used to identify the FRs, DPs and PVs in the design hierarchy represented in figure 1.

A way to look at the domains/hierarchy relationship is by considering two dimensions: breadth and depth [Gonçalves-Coelho *et al*, 2005]. Breadth is the scope of the design process, conveyed namely by the number of domains considered. Depth, on the other hand, represents the level of detail attained during the decomposition process.

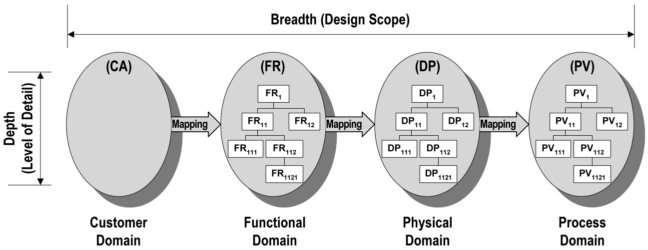

Figure 1. Axiomatic Design domains and hierarchies.

ZIGZAGGING

The decomposition process in Axiomatic Design is achieved according to a zigzag procedure. The zigzagging decomposition tells us that the hierarchy in the domains is defined by zigzagging back and forth between at least two adjacent design domains, depending on the breadth of the design process. This means that, before breaking down a given FR into their correspondent sub-FRs, a decision about the design parameter (DP) that will achieve that FR must first be made. That is to say that the decisions made at the higher levels in the hierarchy, for a certain design breadth, have consequences at the lower levels (Lindholm *et al* [1999]).

A decomposition example using the zigzagging approach for the design of an automatic washing machine, is depicted in figure 2. Given the FR "Wash clothes", before proceeding with the decomposition in the functional domain, one has to define a DP that will satisfy this FR. The sub-FRs depend on which DP is selected. In this example, an automatic washing machine was chosen, but the option could be for instance to use a washtub. After zigging from the functional into the physical domain, one needs to zag on the opposite direction but now to a lower level in the hierarchy to define de sub-FRs, by asking "what FRs does the automatic washing machine need to perform?".

Note that each FR is described in a solution neutral manner, using the "verb + noun" rule from Value Engineering. Moreover, the FRs should have an operational definition, in order to assure they are both verifiable and attainable.

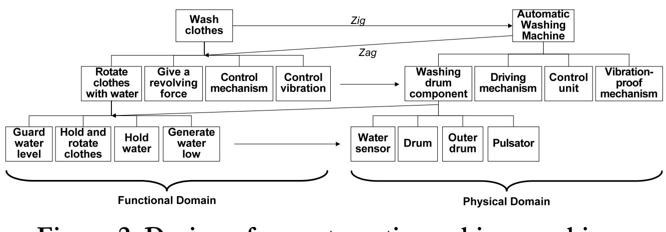

Figure 2. Design of an automatic washing machine (adapted from Yamashina et al, 2002]).

AXIOMS

Axiomatic Design comprises two axioms established by Nam P. Suh to govern the design process: the Independence Axiom and the Information Axiom. From these axioms, a set of theorems, corollaries and guidelines were developed.

a) *Axiom 1 – Independence Axiom*: Maintain the independence of the functional requirements.

When we perform the mapping from the functional into the physical domain, the choice of the DPs should be done in such a way that each FR can be satisfied without affecting other FRs. If the mapping occurs from the physical into the process domain, one should choose the process variables (PVs) that ensure the independency of the DPs.

The mapping between two adjacent domains can be represented by a design equation. When mapping from the functional to the physical domain, the design equation is:

$$\{\mathbf{FR}\} = [\mathbf{A}]\{\mathbf{DP}\} \tag{1}$$

where {**FR**} and [**DP**} are respectively the functional requirement vector and the design parameter vector, whereas [**A**] is the design matrix for this mapping. The design matrix displays the relationship between each FR_i and each DP_j:

$$A_{ij} = \partial FR_i / \partial DP_j \tag{2}$$

If there are *m* functional requirements and *n* design parameters, the general format for the design matrix is:

$$\begin{bmatrix} A_{11} & \cdot & A_{1j} & \cdot & A_{1n} \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ A_{i1} & \cdot & A_{ij} & \cdot & A_{in} \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ A_{m1} & \cdot & A_{mj} & \cdot & A_{mn} \end{bmatrix} \tag{3}$$

Ideally a square design matrix is obtained, with an equal number of FRs and DPs ($m = n$), which you might the case depicted in figure 2. If this matrix is diagonal, the off-diagonal elements can be assumed to be zero ($A_{ij} \cong 0$, where $i \neq j$), so an uncoupled design is obtained, and the first axiom is satisfied.

If the design matrix is triangular, the independency of the FRs is assured if and only if the adjustment of the values of the DPs is made in the order indicated by the design matrix. This is the case of a decoupled design

Any other case of a square design matrix that is neither diagonal nor triangular, is said to be a coupled design, in which the Independence Axiom cannot be satisfied.

When the number of FRs is larger than the number of DPs (m > n), the result is either a coupled design, or the non-fulfilment of all the FRs.

If there are fewer FRs than DPs ($m < n$), the design may be uncoupled or decoupled, but in both cases we say that we are in the presence of a redundant design.

The values of the elements of the design matrix (A_{ij}) can assume one of three formats: binary, percentage or function.

In the binary format, the values of the design matrix are "0" or "X", where the first indicates no relationship between a certain FR_i-DP_j pair, and "X" indicates a relationship between them. Sometimes, it is possible to use a "1" instead of an "X".

The percentage format admits values for the design matrix elements between "0" and "1", according to the strength of the relationship that is believed to exist for each FR_i-DP_j pair.

The third possibility is that the design matrix elements are a quantitative expression (transfer function) of the relationship between each FR_i-DP_j pair.

The design equation for the mapping from the physical domain to the process domain is given by equation 4.

$$\{\mathbf{DP}\} = [\mathbf{B}]\{\mathbf{PV}\} \tag{4}$$

The second axiom states the following:

b) *Axiom 2 – Information Axiom*: Minimize the information content of the design.

The first aim is to ensure the satisfaction of the Independence Axiom When multiple designs satisfying the first axiom are available, the Information Axiom is used to choose the one with minimum information content.

The information content is normally computed using the probability of success of the FRs [Park, 2007]. The less the information content of a proposed design, the less its complexity is.

In the simple case of a single FR-DP pair, the information content (*I*) is defined by equation 5, where usually logarithms of base 2 ($x = 2$) are used [Gonçalves-Coelho *et al*, 2005].

$$I = log_x\left(\frac{\text{Area of the system range}}{\text{Area of the common range}}\right) \tag{5}$$

The design range corresponds to the specifications established for the operational definition of the FR. The design range is commonly also known as the translation of the "Voice of the Customer" into technical terms.

The system range is the real performance range associated to the FR. Its area is the entire area under the probability density function (pdf) of the FR. For generic purposes, the pdf of figure 3 does not correspond to a Normal distribution. The system range is also known as the "Voice of the Process".

The area of the common range is the overlap between the design range and the system range areas. If both areas are equal, the information index is minimum with a value of zero.

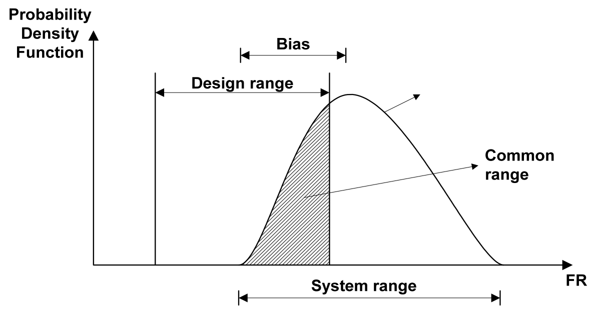

Figure 3. Probability of success using the probability density function of a single FR.

If an uncoupled design with *m* FRs, and each FR_i has a probability of p_i to be satisfied, then the total information content of the system is:

$$I_{\text{Total}} = \sum_{i=1}^{m} log_2\left(1/p_i \right) = \sum_{i=1}^{m} I_i \tag{6}$$

Frey *et al* [2002] proved that for decoupled designs, equation 6 is not applicable and propose a method to compute the total information content for these cases.

Park [2007] says that the information content is usually not computed for a coupled design, as it violates the first axiom.

2.2 Contact and Channel Model (C&CM)

The core of the C&CM approach is an orderly assignment of the functions of a product to their shape, which enables designers to break up with rigid, pre-fixating representations of products. C&CM product models by means of Working Surface Pairs (WSP) and Channel and Support Structures (CSS) force users to think about products in a more abstract way [Eckert *et. al*, 2004].

HOW THE C&CM WORKS

By using C&CM it is possible to isolate an individual problem from the remaining technical system at any time of the design process and at any level of detail, to solve it and to integrate the solution into the entire system to check the effects of the changes on the entire system.

The Contact & Channel Model describes engineering products in terms of Working Surface Pairs and Channel and Support Structures [Matthiesen 2002]. Every function of the product resides in a particular set of Working Surface Pairs (WSPs) and Channel and Support Structure (CSS), because a function cannot be applied other than through these interfaces. This enables designers to think about abstract functions in a concrete way, because they can picture them at a set of WSPs.

In terms of the C&CM approach, descriptions are generated for a particular problem through assigning a set of Working Surface Pairs and Channel and Support Structure to a specific function and searching for solutions on this clearly assigned level. The C&CM approach then picks and groups elements of the existing description in a new way, exploring the inherent ambiguity of how elements of a description are grouped (see [Stiny 2000]).

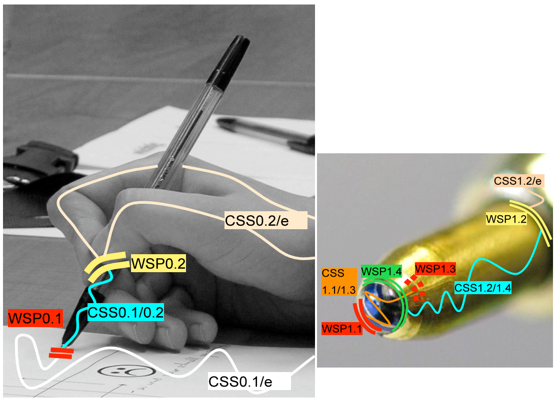

Figure 4. Function of a ballpoint pen.

For example the function of a ballpoint pen (see figure 4) cannot be fulfilled unless WSP0.1 between paper and pen, WSP0.2 between pen and hand and the CSS0.1/0.2 represented by the body of the pen exist. If one of these elements is not build up correctly the function cannot be fulfilled. For example if somebody tries to write on glass, WSP0.1 does not work correctly. Reasoning on a lower level of detail it remains to clarify why the function cannot be obtained. What effect prevents writing on glass? Is there not enough friction in order to turn the ball, or do the properties of the liquid ink prevent a wetting of glass through ink? Are there other reasons? To clarify such a case remains then in the hands of the designing engineer who might be given the task of creating a ballpoint pen for labelling glass-surfaces.

Thus, C&CM models can be applied on different levels of detail always in the same way, so that the same type of mental model can be applied at different levels of hierarchy. The CSS0.1/0.2 of the ballpoint pen can be split up into further WSPs and CSSs, which represent the structure of parts in relation to the structure of functions contributing to the principal function. The model can be dynamically adjusted in its degree of detail, according to the problem posed by a product.

3 COMPARISON OF AXIOMATIC DESIGN AND CONTACT AND CHANNEL MODEL

Several research studies, relating the comparison of Axiomatic Design with other design methods have been carried out for some time, demonstrating the interest this subject has within the design community.

For example, Yang and Zhang [2000] compared Axiomatic Design with TRIZ and identified mutual relationships to be explored, Dong and Whitney [2001] proposed a technique to obtain a Design Structure Matrix (DSM) from a design matrix, whereas Melvin and Deo [2002] highlighted the importance of identifying noise factors during the conceptual stage of the design process, by means of Axiomatic Design.

On the next paragraphs we will explore the similarities, differences and possible synergies between Axiomatic Design theory and the Contact and Channel Model.

3.1 MAIN SIMILARITIES

INTER-DOMAIN APPROACH

Both Axiomatic Design and C&CM outline the design process as a mapping between two domains. The C&CM is a product model that can save and relate both insights on product architecture, the functional level and the form responsible for it [Alink, 2005]. In doing so, although C&CM is not by itself a matrix-based method, this procedure is equivalent to a design mapping between the functional domain and the physical domain of the Axiomatic Design theory.

LEVELS OF ABSTRACTION

Similarly to Axiomatic Design, C&CM addresses the possibility of performing design analysis at any level of abstraction, within the hierarchy of the technical system.

The design analysis, using the design axioms, is performed at each level of detail. The C&CM approach also works on all levels of detail, applying the same basic modelling elements [Albers *et al*, 2004]. In doing so, C&CM can be applied in each of those levels needed to carry out the synthesis of the DPs.

LEVEL OF MATURITY OF THE SYSTEM

Both Axiomatic Design and C&CM are applicable to different degrees of innovation, ranging from incremental design to radical design. Within the TRIZ vocabulary this is so called "level of innovation". In this paper we denominate it the "level of maturity" of a technical system.

Tate [1999] describes how design activities, both within and between design detail levels, based on Axiomatic Design theory can be applied to the design of a new technical system, to the redesign of an existing one and to perform design object analysis for a current technical system. In the same direction, Park [2007] refers that Axiomatic Design can be applied in the following areas: creative design, analysis of an existing design, and design improvement.

Similarly, C&CM is able to help the designers to think about existing and new solutions [Albers *et al*, 2005a],.as well as to analyse a current system based on object analysis.

ENABLER OF INNOVATION

Both approaches stimulate the search for different solutions, in order to satisfy the functional requirements and design constraints. This enhances value creation of the proposed solution and its potential of innovation.

Within the Axiomatic Design framework, at each level of the hierarchy, different sets of possible DPs that independently satisfy the FRs, are developed and subsequently evaluated, according to the Information Axiom.

C&CM also helps designers to come up with new ideas, by breaking their fixations on current design solutions, and thinking about the problem in new ways.

CONCEPT OF COUPLING

According to the first axiom, coupling occurs when the design goals (left domain) are not independently achieved by their respective design solutions (right domain). Referring to the mapping between the functional domain and the physical domain, Suh [1990] distinguishes functional coupling from physical coupling, as Corollary 3 of Axiomatic Design states that one may integrate DPs in a single physical part (chunk) if their respective FRs can be independently satisfied. Suh [1990] demonstrates this using the beverage can example.

Causes for the non-independency between FRs can be grouped into two main reasons (figure 5):

1. The adjustment or modification of one of the DPs directly affects one or more of its non-respective FRs (situation a)).
2. The adjustment or modification of one of the DPs affects one or more of the other DPs, because their correlation cannot be neglected. This correlation will indirectly affect the other FRs that would not be directly affected by the change of the original DP (situation b)).

To illustrate this reasoning, let us consider the simple case, where we have a coupled design with two FRs and two DPs, given by the following design equation:

$$\begin{Bmatrix} FR_1 \\ FR_2 \end{Bmatrix} = \begin{bmatrix} X & X \\ X & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \end{Bmatrix}$$

Both situations depicted in figure 5 can cause this coupled design. In situation a) coupling occurs because each DP directly satisfies both FRs, whereas for situation b), in spite of the fact that each DP does only satisfy its respective FR in a direct way, coupling derives from the strong correlation between the two DPs that will indirectly affect the other FR.

From the perspective of the Theory of Inventive Problem Solving (TRIZ), situation a) may be regarded as a technical contradiction, whereas case b) can often be viewed as a physical contradiction, causing a technical contradiction.

Matrix-based methods, such as the roof of the House of Quality or a Design Structure Matrix (DSM) can be used to capture interactions (correlations) between each pair of DPs. Multi-vari studies are often useful as well for this purpose.

C&CM also accommodates the concept of coupling. Functional coupling may occur when one same WSP is adjacent to two or more functions, because a change performed in one function can impact the other function(s) through this linkage [Alink, 2005]. This situation may be seen as similar to case b) depicted in figure 5.

Alink [2005] also proves that two functions, with their corresponding two WSPs and one CSS, sharing the exact same physical location, are said to be coupled. This is similar to situation a) in figure 5.

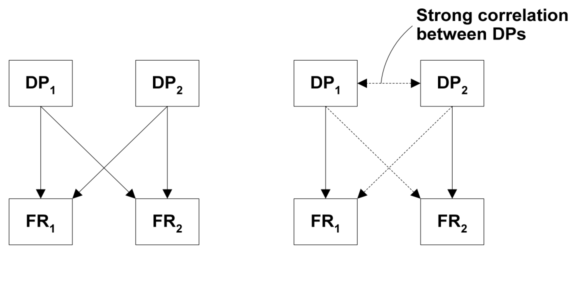

Figure 5. Design of an automatic washing machine.

CONCEPT OF COMPLEXITY

Complexity in Axiomatic Design is related to the information content of the design. The more complex a technical system is, the larger its information content is.

According to El-Haik [2005], complexity is a compound measure consisting of variability, correlation and vulnerability. Variability is due to the variability inherent to the DPs that will achieve the FRs, correlation accounts for the statistical correlation between the DPs, and vulnerability depends on the topology of the design matrix, in particular on the sensitivities of the A_{ij} elements.

Corollary 2 of Axiomatic Design states that the number of FRs and design constraints should be minimised, because it increases the information content of the design.

C&CM also incorporates the definition of complexity. Alink [2005] shows that complexity of systems increases when several functions need to be fulfilled. This author underlines that complexity depends on the architecture of the system, i.e. on the arrangement of its forms and functions. This includes the correlation and vulnerability elements referred by El-Haik [2005].

For example, corollary 3 of Axiomatic Design states that the information content may be reduced through the physical integration of DPs into the same part if the functional independency can still be assured. In C&CM, two functions, with their basic elements located on the same chunk, can still be performed independently, as will be seen in the example of the carpenter's hammer that we will provide later on.

3.2 MAIN DIFFERENCES

INDICATION OF THE SEQUENCE OF ADJUSTMENT THAT ASSURE FUNCTIONAL INDEPENDENCY

C&CM does not directly capture the adjustment sequence of the design elements that assure the functional independency. However, a method to deal with the temporal independence of the functions is being developed at IPEK (see [Albers *et al*, 2008a] and [Albers *et al*, 2008a]).
On the other hand, Axiomatic Design indicates the right sequence of adjustment through the design matrix.

MORPHOLOGY OF THE TECHNICAL SYSTEMS

As opposed to Axiomatic Design, the C&CM is basically applied to support the design of physical systems, although very recent research [Wynn and Clarkson, 2008] demonstrated its applicability to software design as well.

Because Axiomatic Design is a more mature theory, along the years has been applied to design different types of technical system, as was referred in section 2.1.

REPRESENTATION OF SYSTEM ARCHITECTURE

In addition to the design equations, where design analysis can be performed, and the tree diagrams, that represent the hierarchical structure of FRs, DPs and PVs, Axiomatic Design can also capture the system architecture through Module-Junction Diagrams and Flow Diagrams (see [Suh, 1998]).

Drawings and notations to represent the architecture of the technical system in the context of the C&CM approach have been developed (see [Albers *et al*, 2005b]), but these representations are very different from those of Axiomatic Design. C&CM Drawings enable the visualisation of the WSPs and CSSs, and the representation of their properties through the use of a set of graphical symbols. These drawings, and their symbols, can be used to describe the system architecture at different levels of detail.

DECOMPOSITION

The C&CM approach currently does not provide rules, nor guidelines, to coherently perform the functional and physical decomposition during the system design, although recent research (see [Albers *et al*, 2008a] and [Albers *et al*, 2008a]) is being undertaken to perform functional and structural decomposition in the context of C&CM.

Tate [1999] developed a set of rules, guidelines and tools to better execute the design activities that are part of the decomposition process.

3.3 MAIN SYNERGIES

Table 1 explores the potential benefits from integrating Axiomatic Design with C&CM.

Table 1. Synergies between Axiomatic Design and the Contact and Channel Model.

Axiomatic Design	Contact and Channel Model (C&CM)
<u>Concept of Design Parameter (DP)</u>: Suh [1998] defines design parameters (DPs) as the key physical (or other equivalent terms in the case of software design, etc.) variables in the physical domain that characterize the design satisfying the specified FRs. The DPs can be allocated into physical or logical parts, depending on the morphology of the technical system	<u>Basic C&CM elements to fulfil a function</u>: A technical function in terms of C&CM needs two Working Surface Pairs (WSPs) and a structure that connects them (a Channel and Support Structure – CSS). A DP can then be described under these terms of two WSPs and one CSS, together with the properties of these elements.
<u>Axiomatic Design activities at one level of abstraction</u>: Tate [1999] distinguishes the design activities that occur at one level of detail from those related to the decomposition process. The first type of activities comprises design synthesis of the DPs, comparison of the DPs versus constraints, design analysis according to the two axioms, and decoupling of a coupled design.	<u>Element model C&CM support activities</u>: C&CM can play an important role in the activities that occur at a certain level of abstraction. In particular, it supports the thinking process both during design analysis and synthesis. Moreover, C&CM can also be useful when we do intend to decouple a coupled design using the C&CM heuristic solutions.
<u>Theorem 1 (Coupling due to insufficient number of DPs)</u>: When we have less DPs than FRs the result is a coupled design or the non-satisfaction of all the FRs. <u>Theorem 2 (Decoupling of coupled design)</u>: When a design is coupled due to the number of FRs being greater than DPs ($m > n$), it may be decoupled by the addition of new DPs, so as to make the number of FRs and DPs equal to each other, if a set of the design matrix containing $n{\times}n$ elements constitutes a triangular matrix.	<u>C&CM synthesis four basic principles</u>: The principles "Adding WSP and CSS", "Changing properties of CSS", and "Changing properties of WS or WSP" are 3 of the 4 basic principles of the C&CM framework, that can be applied to create a sufficient number of DPs.
<u>Theorem 3 (Redundant design)</u>: When there are more DPs than FRs, the design is either a redundant design or a coupled design.	<u>C&CM Heuristics</u>: A set of solution principles within C&CM approach can help the designers to change the properties of the technical system, in order to improve its conceptual design. The heuristic solution to overcome the problem "Add an additional function to an existing system" (same problem stated in theorem 3) is either "Insert (at least) one additional WSP that fulfils the additional function" or "Change the properties of an existing WSP, so that this WSP can fulfil the additional function".
<u>Theorem 5 (Need for new design)</u>: When a given set of FRs is changed by the addition of a new FR, or substitution of one of the FRs by a new one, or by the selection of a completely different set of FRs, the design solution given by original DPs cannot satisfy the new set of FRs. Consequently, a new design solution must be sought.	<u>C&CM basic rules</u>: The addition of a new FR, or substitution of one of the FRs by a new one, means that the description of the previous system, in terms of the basic rules of C&CM, is not applicable anymore, so that a new description is needed. The description based on the C&CM basic rules is useful to conceive a new design based on the connection of functions (FRs) and forms (DPs).

Corollary 1 (Decoupling of coupled designs): Decouple or separate parts or aspects of a solution if FRs are coupled or become interdependent in the design proposed.	Decoupling by understanding the C&CM concept of coupling: Functional coupling may occur either when a linkage (an adjacent WSP) between two functions exists, or when their corresponding two WSPs and one CSS do share the exact same physical location. Similarly to Axiomatic Design's corollary 1, decoupling or separation of parts or solution elements can remove those linkages or those allocated WSPs and CSS on the same physical location.
Corollary 2 (Minimization of FRs): Minimize the number of FRs and constraints. This corollary derives from the Information Axiom, because the higher the number of FRs and constraints a design has to fulfil, the larger its complexity will be. This corollary reminds the designer to design for maximum simplicity.	Concept of complexity of the C&CM: According to C&CM complexity also increases when several functions need to be fulfilled.
Corollary 3 (Integration of physical parts): Integrate design features in a single physical part if the FRs can be independently satisfied in the proposed solution.	Integration of different WSPs and CSSs in one physical part: One same chunk can accommodate several independent functions by integrating their corresponding basic elements (WSPs and CSSs), if two WSPs and one CSS of at least two functions do not share the exact same physical location.

4 EXAMPLES OF APPLICATION

CARPENTER'S HAMMER

We will now consider the case of a carpenter's hammer. This technical system has two main functions to perform, which are satisfied by two design parameters:

FR_1: Insert nail.
FR_2: Remove nail.

DP_1: Flat end on the head.
DP_2: Forked end on the head.

Although both DPs are allocated in the same physical part (the hammer's head), the design matrix of this technical system concepts tells us that the Independence Axiom is assured. This in accordance with corollary 3.

$$\begin{Bmatrix} \text{Insert nail} \\ \text{Remove nail} \end{Bmatrix} = \begin{bmatrix} X & 0 \\ 0 & X \end{bmatrix} \begin{Bmatrix} \text{Flat end on the head} \\ \text{Forked end on the head} \end{Bmatrix}$$

We can take a deeper look into the relationship between forms and functions by analysing this design using the C&CM approach (figure 6).

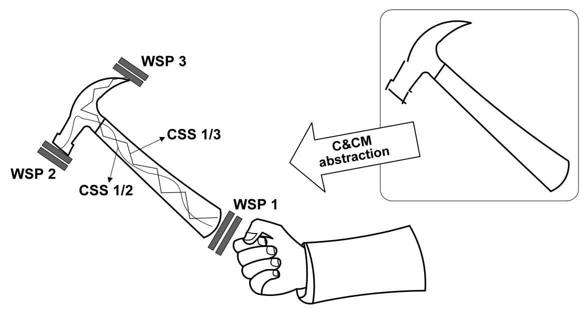

Figure 6. Design analysis of the carpenter's hammer using de C&CM approach.

The function "insert nail" is fulfilled through two WSPs (WSP 1 and WSP 2) and one CSS (CSS 1/2) connecting them. This is equivalent to DP_1.

The function "remove nail" is fulfilled through WSP 1 an WSP 3,with CSS 1/3 linking them. This is equivalent to DP_2.

WSP 1 is formed by the interface between the carpenter's hand and the WS of the hammer's handle; WSP 2 is also the interface between the flat end on the head and the nail's head.

Both functions share one common WSP (WSP 1), but the design is not coupled because WSP 2 and WSP 3 are not located on the exact same physical location. If they did, they would also share the exact same CSS, and this design would be functionally coupled.

BEAM ADJUSTER FOR A LASER MARKER

This example is described in Park [2007]. A laser marker is a machine that engraves characters or logos on the surface of semiconductors. To adjust the visible diode laser, a device called "beam adjuster" is used. The current design of the beam adjuster is depicted in figure 7. Park [2007] analysed this existing design using Axiomatic Design, and concluded that the FRs for this beam adjuster were as follows:

FR_1: Align the vertical position of the diode laser beam.
FR_2: Align the vertical angle of the diode laser beam.
FR_3: Align the horizontal position of the diode laser beam.
FR_4: Align the horizontal angle of the diode laser beam.
FR_5: Fix the beam alignment.

And that the corresponding DPs were the following:

DP_1: Vertically moving component.
DP_2: Supporting block.
DP_3: Fixing screw.

There are less DPs than FRs. According to theorem 3, this is either a coupled design or the non-satisfaction of all the FRs. The design equation reveals a design matrix showing that this current design is a coupled one:

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \\ FR_4 \\ FR_5 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ X & 0 & 0 \\ 0 & X & 0 \\ 0 & X & 0 \\ 0 & 0 & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{Bmatrix}$$

Figure 7 describes the current beam adjuster design according to the C&CM model, at the highest level of abstraction, the same level of detail described by the previous design matrix.

We see that FR_1 and FR_2 are coupled, because their WSPs (WSP 1 and WSP 2) and CSS (CSS 1/2) are located on the same physical location. That is to say that both FRs are fulfilled by the same DP (DP_1).

In a similar manner, FR_3 and FR_4 are coupled by DP_2, so that both functions have their WSPs (WSP 3 and WSP 4) and CSS (CSS 3/4) located on the same physical location.

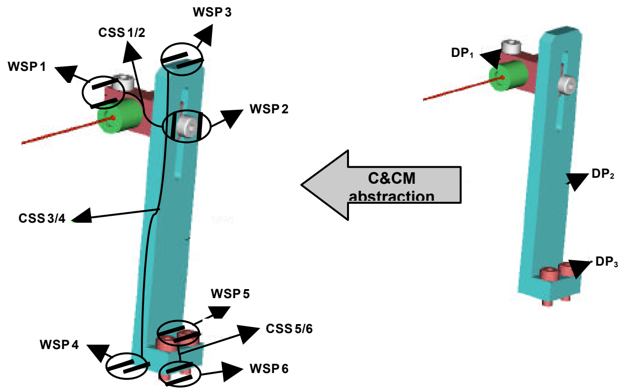

Figure 7. Description of the current beam adjuster design using the C&CM (adapted from [Park, 2007]).

Table 2 translates the DPs identified using Axiomatic Design from the perspective of the C&CM approach.

Table 2. Description of the DPs for the current beam adjuster design according to the C&CM approach.

FR	DP	Equivalent description of DP in C&CM
FR_1, FR_2	DP_1	WSP 1 (interface between the vertically moving component and the hand of the person that is adjusting the beam) and WSP 2 (interface between the vertically moving component's screw and the support block's hole) linked by CSS 1/2 (the vertically moving component's body)
FR_3, FR_4	DP_2	WSP 3 (top surface of the supporting block and the hand of the person that is adjusting the beam) and WSP 4 (interface between the base of the supporting block and the surface in which this block can horizontally slide) linked by CSS 3/4 (the supporting block's body)
FR_5	DP_3	WSP 5 (interaction between the screw's head and the top surface of the beam adjuster's base) and WSP 6 (interface between the bottom surface end of the fixing screw and the surface in which the supporting block can be fixed) linked by CSS 5/6 (the body of the screw)

When two or more functions have their correspondent WSPs and CSS sharing exactly the same physical location, and their inherent properties are no different, they can be viewed as having the same WSPs and CSS connecting them. This means those functions are fulfilled by the same DP.

According to table 1, one can use three out of the four C&CM synthesis basic principles to decouple this design.

For example, FR_1 and FR_2 can be decoupled by adding one WSP and one CSS that links this new WSP to an existing WSP. Alternatively, two new WSPs can be added, linked by a new CSS. The same reasoning may be applied for the case of FR_3 and FR_4. Decoupling each of the two coupled functions can be viewed as changing one WSP from one physical location to another.

A new design was proposed (figure 8). Two DPs were added, so that the number of DPs and FRs are now the same.

The new set of DPs is:

DP_1: Upper rear screw.
DP_2: Upper front screw.
DP_3: Side rear screw.
DP_4: Side front screw.
DP_5: Fixing screw.

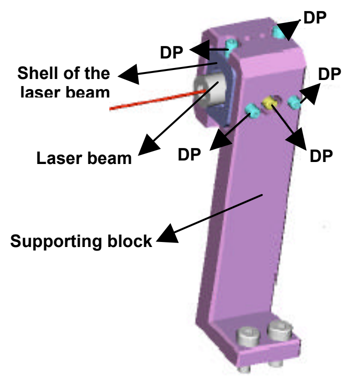

Figure 8. Description of the new beam adjuster design in terms of its DPs (adapted from [Park, 2007]).

By analysing the corresponding design matrix, one can conclude that this is a decoupled design, because the angles can be adjusted after the adjustment of the positions.

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \\ FR_4 \\ FR_5 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 & 0 \\ X & X & 0 & 0 & 0 \\ 0 & 0 & X & 0 & 0 \\ 0 & 0 & X & X & 0 \\ 0 & 0 & 0 & 0 & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \\ DP_4 \\ DP_5 \end{Bmatrix}$$

Figure 9 shows the front view of the new beam adjuster. Because this is a front view, the figure depicts the C&CM description of the front screws (DP_2 and DP_4) that fulfil FR_2 and FR_4.

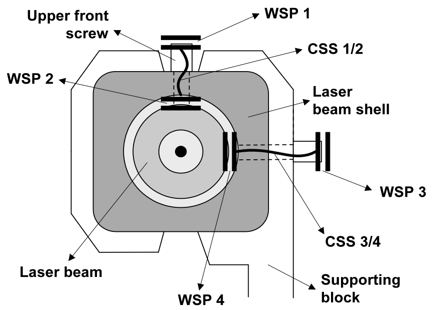

Figure 9. Description of the front design elements of the new beam adjuster using the C&CM approach.

FR_2 is fulfilled through two WSPs (WSP 1 and WSP 2) linked by one CSS (CSS 1/2), so that these elements together are equivalent to DP_2. WSP 1 is formed by the interaction between the hand of the person that is adjusting the beam and the head of that upper front screw. WSP 2 is the interaction between the surface of the laser beam outside diameter and the bottom surface end of the upper front screw.

The C&CM description of the elements that fulfil FR_4 is also depicted in figure 9 and follows the same reasoning.

Table 3. Description of the DPs for the new beam adjuster design according to the C&CM approach.

FR	DP	Equivalent description of DP in C&CM
FR_1	DP_1	One WSP (interaction between the upper rear screw head and the hand of the person that is adjusting the beam) linked by one CSS (the body of the upper rear screw) to another WSP (interaction between the surface of the laser beam outside diameter and the bottom surface end of the upper rear screw)
FR_2	DP_2	One WSP (interaction between the upper front screw head and the hand of the person that is adjusting the beam) linked by one CSS (the body of the upper front screw) to another WSP (interaction between the surface of the laser beam outside diameter and the bottom surface end of the upper front screw)
FR_3	DP_3	One WSP (interaction between the side rear screw head and the hand of the person that is adjusting the beam) linked by one CSS (the body of the side rear screw) to another WSP (interaction between the surface of the laser beam outside diameter and the bottom surface end of the side rear screw)
FR_4	DP_4	One WSP (interaction between the side front screw head and the hand of the person that is adjusting the beam) linked by one CSS (the body of the side front screw) to another WSP (interaction between the surface of the laser beam outside diameter and the bottom surface end of the side front screw)
FR_5	DP_5	One WSP (interaction between the fixing screw head and the hand of the person that is fixing the beam) linked by one CSS (the body of the fixing screw) to another WSP (interaction between propped end of the fixing screw and the surface of the laser beam outside diameter)

Table 3 depicts the equivalent description of the new set of DPs from the perspective of the C&CM approach. The functions FR_1, FR_2, FR_3 and FR_4 share one same WS (surface of the laser beam's outside diameter), although in distinct physical locations. This new design is not coupled because the WSPs and the CSSs correspondent to the different FRs are located in different physical locations.

5 C&CM IN THE CONTEXT OF A DESIGN FOR SIX SIGMA ROADMAP

Design for Six Sigma (DFSS) is a recent branch of the Six Sigma philosophy, whose main purpose is to design technical systems with world-class levels of performance in all its the critical to quality (CTQ) characteristics. It can be used to redesign existing systems or to design completely new ones.

DFSS is a methodology that commonly uses a four-phase roadmap, known by the acronym ICOV. It uses a set of tools in a structured way to achieve high standards of conceptual and operational robustness for the technical system during its life cycle. A formal design review, usually entitled "tollgate", takes place, in order to evaluate if the project milestones and design objectives are being properly accomplished, if any adjustments are needed, and also to plan the activities that will take place during the next phase.

Figure 10 depicts the ICOV roadmap that is used during the execution of the DFSS projects. The Contact and Channel Model can be very useful during the Characterise phase, where it can also be used in combination with Axiomatic Design as well other tools of this phase.

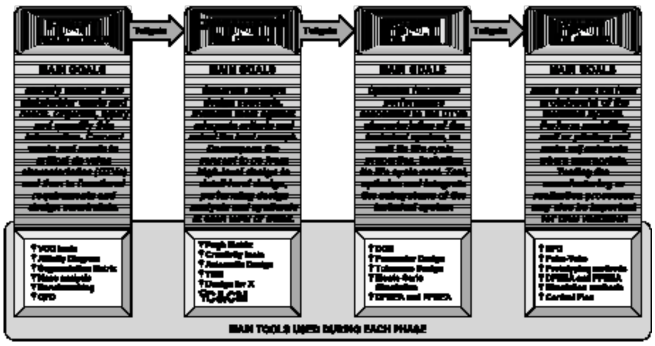

Figure 10. C&CM can be easily fitted into a DFSS project.

6 CONCLUSIONS

This is the first paper where the Axiomatic Design theory and the Contact and Channel Model are formally compared and their use in conjunction is explored.

The similarities and differences between the two design approaches were first identified.

We concluded that both design approaches relate the functional perspective of a technical system with its solution elements, that will fulfil the functional requirements. Furthermore, both can be used to perform design analysis at any level of detail. Other similarity is the fact that the two approaches stimulate creativity and innovation by searching for alternative solutions that fulfil the functional requirements. Both can be applied to different types of design projects (e.g. design object analysis, incremental design, new design). Finally, both C&CM and Axiomatic Design share the concepts of coupling and complexity, although C&CM does not directly indicate the right sequence of adjustment of the design parameters when the design is a decoupled design.

C&CM is essentially used when the technical system to be designed is a physical one, i.e. hardware, whereas Axiomatic Design has already been applied to the design of several morphological types of systems. Both approaches also differ in the way they represent the technical system's architecture.

The main synergies between Axiomatic Design and C&CM were presented in a table format, where the integration between several of the underlying theorems and corollaries of the Axiomatic Design theory and the C&CM approach was explored. The two examples of applications, also presented, demonstrate how an integration of both approaches can be made possible.

Finally, it was shown that the C&CM model can be used during the Characterize phase of a Design for Six Sigma (DFSS) program.

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