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Proceedings of

The Eighth International Conference on Axiomatic Design

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FOREWORD

This is the second time that Universidade Nova de Lisboa hosts the International Conference on Axiomatic Design in Campus de Caparica. The International Conference on Axiomatic Design series (ICAD), which is the topmost international forum on the matter, started in Cambridge, MA (ICAD 2000), in the year of 2000. Since then, the conference was held again in Cambridge, MA (ICAD 2002), Seoul, KR (ICAD 2004), Firenze, IT (ICAD 2006), Campus de Caparica, PT (ICAD 2009), Daejeon, KR (ICAD 2011) and Worcester, MA (ICAD 2013).

From the seven previous editions, we have got a heritage of 251 articles, to which now we are joining 28 more that were prepared by 52 authors and co-authors of 17 countries from all the continents of the World but Antarctica. The reader will find here a wide range of matters that includes design of sustainable buildings, machine and structural design, road traffic design, industrial design, design maturity and complexity, higher education, manufacturing technologies, engineering consultancy and sustainable governance.

Historically, Axiomatic Design (AD) was introduced in 1978 by Nam P. Suh and co-authors, at the MIT, which was published in their well-known seminal paper (Suh, N.P., Bell, A.C. and Gossard, D.C., On an Axiomatic Approach to Manufacturing and Manufacturing Systems, Journal of Engineering for Industry, Transactions of ASME, 100(2):127-130), but the spread of AD worldwide had to wait until 1990, when Professor Suh published his first book on the subject (Suh, N.P., The Principles of Design, Oxford University Press, N.Y., 1990). Since then, many scientific texts on AD have been published and, just for example, a search in the Thompson-Reuters Web of Knowledge under the topic "Axiomatic Design" currently reveals more than 480 entries, beginning in 1992 and including journal papers, reviews and editorials, books, meeting papers and patents.

On the education point of view, in the 1990s Axiomatic Design began being lectured in the MIT to post-graduate students, then other universities adopted it, mostly in doctoral and postgraduate courses. However, only in the 21st century we could see, for the first time, Axiomatic Design being thought to freshmen at the KAIST.

The Organising Committee hopes that the reader could find this volume useful, and gratefully acknowledges the Conference sponsors for their valuable support. Furthermore, we are thankful to the authors and co-authors, to the International Program Advisory Committee, to the Session Chairs and to the Administrative Staff, whose contributions have made possible the realization of ICAD 2014.

Campus de Caparica, September 10, 2014

António M. Gonçalves-Coelho

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AXIOMATIC DESIGN APPROACH TO THE DESIGN OF A DEVICE FOR WIRE ELECTRICAL DISCHARGE MACHINING

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ABSTRACT

This paper presents a few considerations concerning to product design. As an application, it focuses on the study of a device that was designed to improve the material removal process in wire electrical discharge machining. The main objective of the research is to assess the device in the light of the independence axiom of Axiomatic Design. The device was intended for the experimental study of the material removal process. The functional requirements concern essentially to the ability for changing the machining process input factors, the device adaptability to a specific machine tool and the usual economics, safety, reliability, and easy-to-repair requirements. The problem under analysis is focused on functional requirements and design parameters and the results show that the principles of axiomatic design are valid in the case of the designed device and highlighted some interesting aspects to be addressed in future research.

Keywords: axiomatic design, wire electrical discharge machining, wire electrode tool, wire travelling speed.

1 INTRODUCTION

The design process was divided by [Pahl, 1994] in four distinct phases: 1) *Formulation of the requirements*; 2) *Conceptual design*; 3) *Embodiment design* and 4) *Detail design*. Within each stage, the process could be presented as a flow diagram. The basic trends of embodiment design should be "clarity, simplicity and reliability". Moreover, some of the principles of embodiment design are as follows: principle of the division of tasks, principle of self-help, principle of force and energy transmission and principles of safety and reliability, but some times these principles are not easy to apply.

The researchers elaborated methodologies for systematization of the design process. Some of these methodologies are based on algorithms and others on diverse approaches that cannot be generalized. Each stage of the iterative process is based on the designer experience and intuition. Usually, the morphological approaches use a matrix to highlight all possible design options, from which the designer must choose the best one [Pahl, 1994], [Slătineanu *et al.*, 2011]. This last task could be problematic because one could pass aside the most suitable solutions.

The distinct possible solutions could be evaluated by using weighted factors for the technical or economical meanings. An overall evaluation of the design can be obtained through the relation [Pahl, 1994]:

$$W_j = \frac{\sum_{i=1}^{n} w_{ij}}{w_{\max} \cdot \sum_{i=1}^{n} g_i} \qquad (1)$$

where: i is the number of evaluating criteria, j - the number of evaluated possible solutions, w_{ij} - the numerical evaluation value of the jth solution regarding to the ith criterion, w_{max} - the maximum value of the evaluation values and g_i the value of the element corresponding to the ith criterion.

Using such a methodology, the decision is based on exact data but it is still possible to obtain a solution that is not the best one. It is possible to have a solution with a high total value, but with one or more specific weak points, which is clearly worst than a different solution with an overall lower total value but with better distributed specific values for the different criteria.

Usually, in the industrial practice, the potential infinite number of different solutions is reduced to 2 or 3, which are analysed in the above-described manner, in order to select the best one.

Other authors present the design process as a problem of optimization, by considering all the existing constraints [Arora, 2004]. The process supposes the identification of a set of design variables, establishing an objective function to be optimized, as well as the constraint functions.

In [Suh, 1990] and [Suh, 2001], the design process was presented as a process with clear rules, design axioms (independence and information), corollaries, theorems and a methodology for decomposing the hierarchical structure, in order to obtain good designs. The approach represents a breakthrough in terms of design process based on scientific methods and evaluation of the solutions. The founder of axiomatic design proposes a general framework to assist in the decision-making at any instance of the designing process. The unique "zigzagging" process allow including the multiple design solutions into three basic categories (uncoupled, decoupled and coupled) and, in the end, to select the best alternative with the maximum probability of success [Suh, 1990].

The main objective of the research presented in the paper is to test if the principles specific to axiomatic design are valid in case of a device designed for activating the material removal process in wire electrical discharge machining.

2 WIRE ELECTRICAL DISCHARGHE MACHINING

The *wire electrical discharge machining* (WEDM) is used mainly in industry for obtaining accurate and intricate parts made of conductive materials, such as parts of dies and molds, parts of sintering presses, geared elements, profiles for cutting tools, etc.

WEDM takes advantage of thermodynamic, electromagnetic, hydrodynamic and electrodynamic phenomena. The material removal is caused by pulsating electrical discharges generated by a power supply at a frequency in the range of 20000-30000 Hz. The discharges occur between the electrodes that are formed by the workpiece and by a wire that plays the role of tool. The electrodes are separated by a thin layer of dielectric liquid and material is removed from both electrodes. Yet, the aim of the machining process is the material removal from the workpiece, the removal from the wire being an annoying wearing process that should be minimized. Due to the plasma channels that buildup between the anode and cathode, a part of the kinetic energy of the subatomic particles in motion is transformed in thermal energy; subsequently, the generated heat is distributed by conduction to the electrodes and to the dielectric fluid. The temperatures have values in the range of 8000-20000 °C. Because of such a high temperature, the process of melting and vaporization of the surface layers of the two electrodes is initiated. When the electric discharge is turned off, the plasma channels break down, the temperature suddenly decreases and the circulating dielectric fluid flushes the re-solidified particles of the electrodes in the form of microscopic debris.

WEDM allows manufacturing parts having various contours, and due to the machining scheme it makes it possible to obtain only ruled surfaces (Figure 1). The wire tool electrode travels from a reel to a take-up reel and the workpiece has numerical controlled movements in a plane perpendicular to the electrode axis. Some manufacturers of machine tools propose an additional controlled movement of the upper support of the wire guide, making it possible to obtain conical surfaces, or even ruled surfaces similar to conical surfaces.

The feeding motion of the wire electrode is required to compensate for the wear that is generated by the electrical discharges. In order to obtain intricate shapes with small fillet radii, one has to use wire electrodes with diameters in the range of 0.01 – 0.3 mm. The wire feed is also necessary to completely avoid the wire breakage due to the wear that occurs during the machining process.

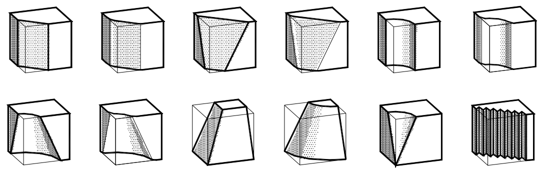

Figure 1. Example of WEDM ruled surfaces.

The typical WEDM technological characteristics are the cutting rate, the material removal rate, the accuracy, the surface roughness, and the thickness of the heat-affected zone. The current machine tools allow obtaining a feed rate of 300 mm^2/min for 50 mm thick steel plate workpieces, and of 750 mm^2/min for 150 mm thick aluminum plate workpieces [Patel and Vaghmare, 2013]. The machining accuracy and surface roughness are considered as corresponding to the current machining requirements. Due to the deionized water used as a dielectric fluid, which allows a certain anodic dissolving of the workpiece material, the surface roughness could reach values for the *Ra* parameter equal to or higher than 0.1 μm. The deviation from straightness could be less than 2 μm for a 100 mm thick workpiece and the slope of the machined surfaces is in range of ten seconds.

2.1 ACTIVATING THE WEDM PROCESS

It is widely accepted that WEDM is appropriate for manufacturing parts made of hard or extra-hard materials with high precision and shape complexity. However, most of the known literature is focussed on the problem of increasing the productivity in a condition of high cost and/or low accuracy [Boothroyd and Knight, 2006].

The main trends of research aiming at improving WEDM can be grouped in three classes: improving the machine tool architecture and constructive details, improving the technology by optimizing the operation input parameters and improving the activation of the material removal process.

Analyzing the first research direction, one can notice that the known literature mainly concerns to the limitations of the machine tool components (such as the dc power supply subsystem, the wire electrode tool, the dielectric fluid supply subsystem or the mechanical subsystem) [Dauw and Albert, 1992].

The second trend, which is specific to each machine tool, is based on establishing the best working conditions to accomplish certain criteria under some restrictions. Usually, the optimization criteria refer to maximizing the machining feed rate (expressed in mm/min), while minimizing both the surface roughness and the total specific machining cost [Dodun, 2000].

As for the activation of the material removal process, it could be achieved in various ways. Some researchers presented various approaches mostly based on overlapping the electrical discharge machining process while applying a magnetic field or using a high injection pressure of dielectric liquid. Other researchers referred to methods based on vibrating or extra movements of the tool electrode [Patel and Vaghmare, 2013]. In order to improve the overall machining consistency, the material removal rate and the performance, Ho *et al.* described a solution that uses an orbiting movement of the tool electrode around the workpiece [Ho *et al.*, 2004].

This additional motion of the tool electrode facilitates the material removal from the work zone, due to the easier penetration of the dielectric liquid in the work gap. In this way, a better evacuation of the eroded particles from the work gap is achieved.

3 CASE STUDY

The main goal of this paper was to test the appropriateness of the solution that was found for a device adaptable to the traveling wire tool electrode system of a Japax L250A machine from the point of view of axiomatic design (Figure 2). The *customer needs (CNs)* correspond to a device that must allow changes of the wire motion parameters, in order to optimize the process of material removal from the workpiece by wire electrical discharge machining. Thus, the top level *functional requirements (FRs)* are concerned to allowing the wire motion, as well as ensuring the adaptability of the device to the Japax wire travelling system and the usual economical, safety, reliability, and easy-to-repair requirements.

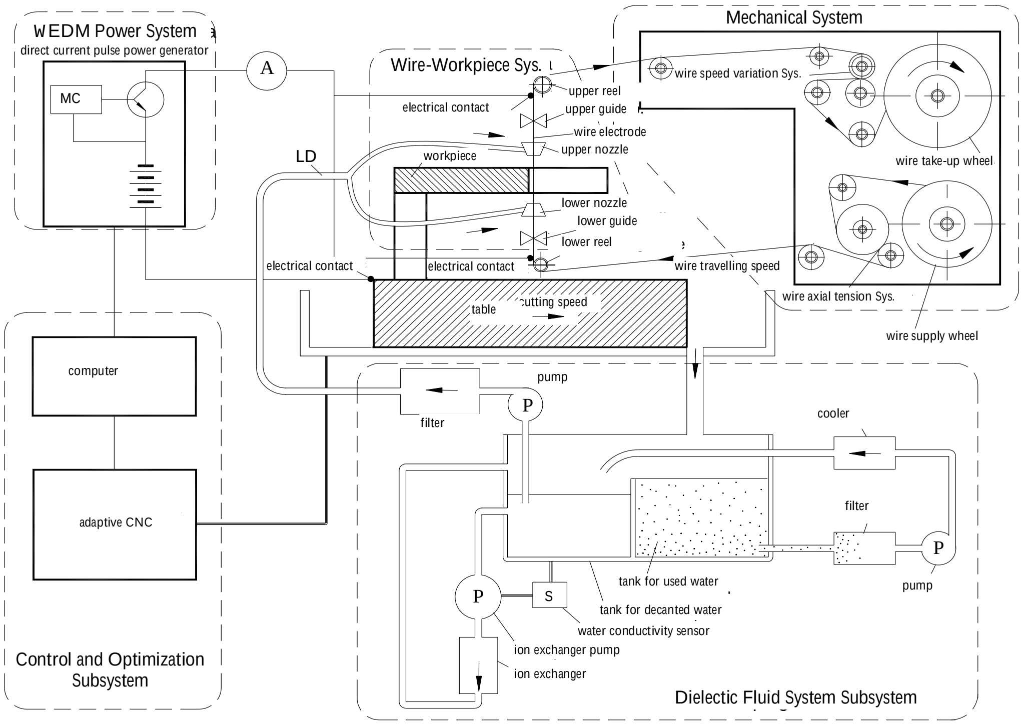

Figure 2. The wire electrical discharge system.

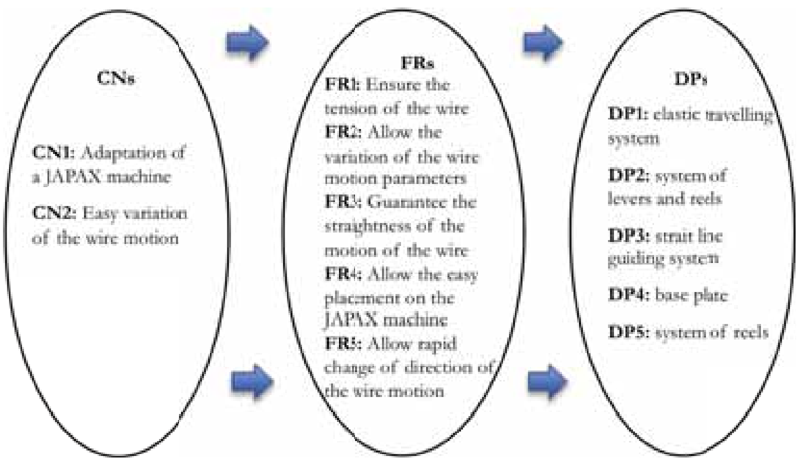

Figure 3. The design domains of the device for studying the wire electrical discharge process.

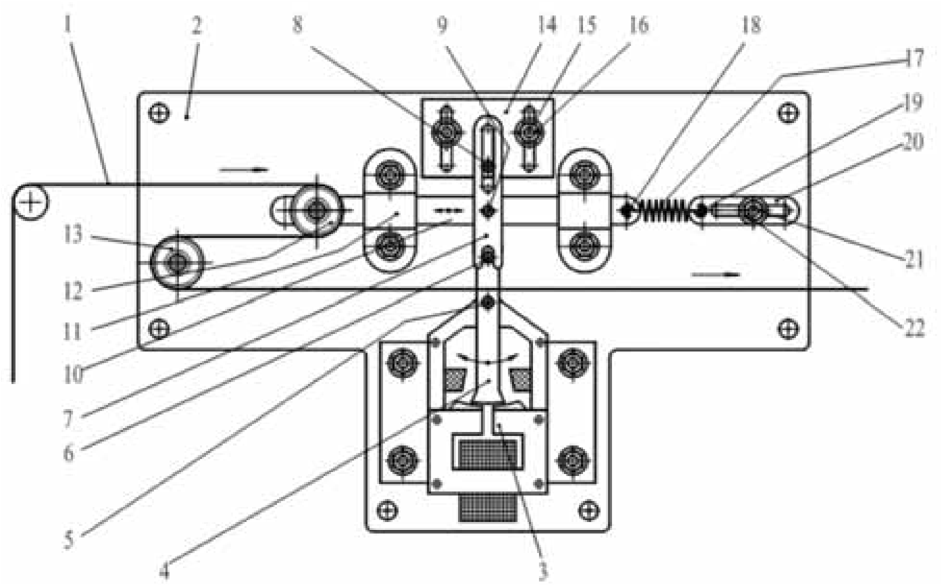

Figure 4. The structure of the device for studying the WEDM process.

Zigzagging was performed to establish the functional requirements and finding the design parameters and Figure 3 shows the top-level result of this process.

By loosely using the independence axiom, the mapping between the customer and the functional domain yielded to the following *functional requirements*:

FR1: Ensure the tension of the wire tool;

FR1.1: Provide tension in wire;

FR1.2: Allow the correct adjustment of the axial tension in wire;

FR2: Allow the variation of the wire motion parameters;

FR2.1: Ensure easy changing of excitation frequency;

FR2.2: Ensure easy changing of the wire vibration amplitude;

FR3: Guarantee the straightness of the motion of the wire;

FR3.1: Ensure the change of the initial reciprocating circular movement into a reciprocating rectilinear one;

FR3.2: Ensure the rectilinear displacement of the wire support;

FR3.3: Ensure the power source for performing the motion;

FR4: Allow the easy placement of the device on the electrode wire travelling subsystem of the JAPAXtype machine;

FR5: Allow rapid change of direction of the wire motion;

The constraints could be defined as:

C1: Ensure a high wear resistance;

C2: Ensure low energy consumption;

C3: Ensure a lightweight;

C4: Ensure a simple solution (minimum number of parts of the device);

C5: Ensure an easy manufacturing;

C6: Ensure safety in operation;

C7: Diminish the possibility of wire breakage;

C8: Ensure an easy access to wire tool electrode in case of breakage;

C9: Ensure a minimum cost of device.

The achieved *design parameters DPs* for those functional requirements are the following:

DP1: elastic travelling system

DP1.1: spring subsystem;

DP1.2: system of changing the tensioning force of the spring (groove, supporting plate, nut and threaded rod);

DP2: system of levers and reels;

DP2.1: electromagnetic subsystem (magnetic circuit, coil, frequency generator);

DP2.2: system of modifying the lengths of the levers (groove, pin, supporting plate, nut and threaded rod);

DP3: strait line guiding system;

DP3.1: mechanical levers;

DP3.2: guiding subsystem for the rectilinear motion;

DP3.3: electric power source;

DP4: base plate including the necessary components and its placing on the machine tool;

DP5: system of reels on which the wire travels.

	DP1	DP1.1	DP1.2	***DP2***	DP2.1	DP2.2	***DP3***	DP3.1	DP3.2	DP3.3	***DP4***	***DP5***
FR1	X											
FR1.1		X										
FR1.2			X									
FR2				X								
FR2.1					X							
FR2.2						X						
FR3							X					
FR3.1								X				
FR3.2									X			
FR3.3										X		
FR4											X	
FR5												X

Figure 5. The design matrix for the WEDM device.

The result of the zigzagging is presented in the matrix of Figure 5. The relationships between *FRs* and *DPs* are denoted by the letter *X*, and one might notice that the design is uncoupled.

4 THE ACCOMPLISHED SOLUTION

The embodiment of the solution introduced in the previous section is described here.

In order to ensure the variation between some pre-established limits for the speed of the wire tool electrode motion at any given frequency (or even to reverse the direction of the wire motion), the achieved device was based on the design parameters presented in Figure 4 [Dodun and Lungu, 2005].

The device includes a base plate 2 (design parameter DP4), on which there is an electromagnetic subsystem 3 (coil, magnetic circuit and frequency generator that generates the periodical motion of lever 4 around the axis of bolt 5 (design parameter DP2.1). Bolt 6, which is placed at the end of lever 4, generates the periodical rotation motion of lever 7 around the axis of bolt 8, which is fixed to the base plate 2. Bolt 9 (design parameter DP3.1) that links lever 7 and the prismatic bar 10 generates a rectilinear-alternative motion of bar 10 (design parameter DP3.2), which is guided by linear guides 11.

In order to adjust the amplitude of the rectilinear-alternative motion of bar 10, bolt 8 can be moved together with its supporting plate 14 along two grooves machined in plate 14. The required position of supporting plate 14 can be achieved by means of two cylindrical threaded end bars 15 and two matching nuts 16 (design parameter DP2.2). An electric power source and a frequency generator (which are not included in the schematic representation of Figure 4) are used to materialize design parameter DP3.3).

The wire tool electrode 1 travels on pulley 12, situated at the end of bar 10, and on pulley 13 (design parameter DP5), which axis is fixed on base plate 2. The rectilinear-alternative movement of bar 10 ensures conditions for the periodical change of the wire tool electrode travelling speed.

In order to create the tension force in the wire tool electrode, as well as to obtain a smooth motion of the squared bar 10, one used spring 17 (design parameter DP1.1), which has an end fixed on bolt 18 on the squared bar 10. The other end of spring 17 is fixed on bolt 19.

In order to easy modify the value of tension in the wire tool electrode by means of the spring tensioning, the bolt 17 could be moved with its supporting plates along a groove existing in the supporting plate 20 (design parameter DP1.2). The supporting plate 20 is fixed on the base plate 2 by means of a nut 21, found on the threaded end of the bar 22. This bar 22 passes through a groove existing in the supporting plate 20 and it is fixed on the base plate 20.

5 CONCLUSIONS

The wire electrical discharge machining process can be activated by providing an additional motion to the wire tool electrode. Axiomatic Design's independence axiom was used to evaluate a device that allows changing the translation speed of the wire between certain speed limits and with a specific frequency.

Specifically, a device that was designed some time ago to improve the performance of the Japax L250A wire electrical discharge machine was assessed in the light of the AD's independence axiom. The conclusion is that the device is a typical case of uncoupled design, a condition that can explain its good behavior in service. Retrospectively, one could say that the design of the presented solution would be much easier if the designers were aware of the AD's independence axiom.

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WHERE IS THE 'WHY' IN AXIOMATIC DESIGN?

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ABSTRACT

Axiomatic Design (AD) Theory describes the design process as a mapping of 'what' to 'how' across four design domains. Every decision during this process is made deliberately, from the highest-level functional requirements to the lowest level process variables. However, it is unclear how and where to document that information within the AD framework. This paper investigates where and how the goals, motivation, values, and rationale of a design project – the 'why' – are, could, and should be specified within AD. It presents three options for where to find the goals and motivation (the highest-level 'why') of a design project. It explores the various 'whys' associated with the requirements and mapping and decomposition processes. The design domains are then viewed as a whole and a new model that defines the relationship between 'why,' 'what,' and 'how' information in AD is presented.

Keywords: Axiomatic Design, design rationale, product development, decomposition.

1 INTRODUCTION

In Axiomatic Design Theory, "a rigorous design approach must begin with an explicit statement of "what we want to achieve" and end with a clear description of "how we will achieve it"" [Suh, 2001]. The transformation of an "abstract intent (i.e. 'what') to a concrete instantiation (i.e. 'how')" [Lu and Liu, 2011a] that satisfies the perceived needs of the stakeholders is achieved through a mapping between the design domains and through the decomposition of information within each domain [Suh, 1990]. Every decision made during this process is deliberate, from the definition of the highest-level functional requirements (FRs) to the choice of the lowest level process variables (PVs). Documenting these decisions ensures that the design task is not carried out in an ad hoc manner. It allows the decision process to be reconstructed if necessary [Krause et al., 1993]. It can also help to plan and perform maintenance [Suh, 1997], to determine "the causes of system failures or [detect] impending failures" [Suh, 1998] and to improve or modify an existing design [Suh, 1997; Lee *et al.*, 2001; Brissaud *et al.*, 2003].

Unfortunately, it is unclear how to document those decisions in the AD framework. As a result, many authors present only their final decompositions with no discussion of their choices beyond the necessity to adhere to the design axioms [Lee *et al.*, 2001; Gu *et al.*, 2001; Peck *et al.*, 2010; Melvin and Suh, 2002; Matt and Rauch, 2013] or with the design rationale included as supplementary information in the text [Cha and Cho, 1999; Kim *et al.*, 2004; Kim *et al.*, 2011; Ouellet and Vadean, 2013]. Examples like Ferreira *et al.* [2013], where multiple design options are developed and compared, are rare.

This work investigates where and how the goals, motivation, values, and design rationale of a design project – the 'why' – are, could, and should be specified within AD. It begins by presenting three options for where to find the goals and motivation (the highest-level 'why') of a design project. Next, it explores the various 'whys' associated with the requirements and mapping and decomposition processes. The design domains are then viewed as a whole and a new model that addresses the relative nature of why-type information is presented. Finally, the documentation process in Axiomatic Design Theory is considered.

2 PROJECT GOAL AND MOTIVATION: DEFINING THE HIGHEST-LEVEL 'WHY'

The goal or motivation is the reason why a design project is undertaken. From a decomposition perspective, it can be thought of as the highest-level 'why'. This section considers three different motivations for the development of an artifact and proposes where to find the highest-level 'why' for each.

2.1 THE HIGHEST-LEVEL 'WHY' IS DEFINED IN THE CUSTOMER DOMAIN OF THE ARTIFACT

The overall goal of a project can be to satisfy the customer needs (CNs) and to bring about customer (client, user, stakeholder, etc.) satisfaction. For example, most design consultancy firms design artifacts either to satisfy their clients or their clients' customers. In these cases, the highest-level 'why' for the design project is not explicitly defined but is implicit in the information contained within the customer domain. This is consistent with Lu and Liu's [2012] claim that the design intent or "highest overall goal to achieve" is "conceptually equivalent" to customer needs in Axiomatic Design Theory.

2.2 THE HIGHEST-LEVEL 'WHY' IS DEFINED IN THE HIGHEST-LEVEL FUNCTIONAL REQUIREMENTS OF THE ARTIFACT

In some cases, an artifact's functionality is its reason to exist. For example, many early flying machines were designed because their designers wanted to fly. In these cases, the highest-level 'why' is synonymous with the highest-level 'what' and is contained within the highest-level FRs of the artifact. This is consistent with Suh's statement that the "objective of design is always stated in the functional domain" [Suh, 1990], Alting *et al.'s* [2003] assertion that the "expected benefits of [a] product are expressed in terms of functional requirements", and Lee *et al.'s* [2001] claim that the highest level FRs serve as the "mission statement" for a design project.

2.3 THE HIGHEST-LEVEL 'WHY' IS DEFINED IN THE FUNCTIONAL REQUIREMENTS OF A HIGHER (PARENT) LEVEL SYSTEM

However, many artifacts are a means to an end rather than the end itself. For example, most consumer products are designed to increase a company's return on investment (i.e. profit). Different artifacts could be chosen to satisfy this FR, each with different customers, customer needs, and functional requirements. In these cases, the highest-level 'why' cannot be defined at the artifact level. Instead, the design domains must be viewed as a continuum that extend beyond the boundaries of the artifact (Fig. 1). This allows the designer to see that highest-level 'why' is often defined by the FRs of a higher-level (parent) entity. This is consistent with Thompson's [2013a] assertion that many procedural errors in the definition of functional requirements stem from a conflation of the FRs of the artifact and of related higher-level systems.

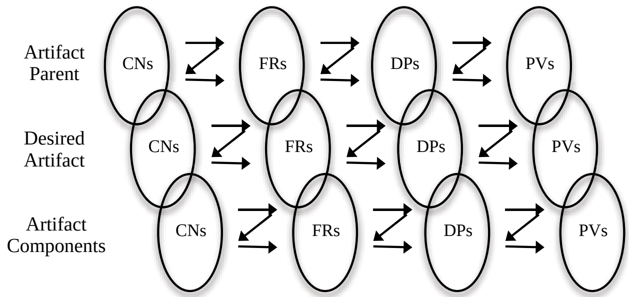

Fig. 1 Design domains of an artifact, its parent system and its components.

3 DEFINING THE REQUIREMENTS

Once the motivation for a project is established and the customer needs have been defined, the CNs are mapped to the highest-level FRs and used to define other types of requirements information. This section addresses how and why those decisions are made.

3.1 WHY THESE HIGHEST-LEVEL FRS?

At the highest-level of a decomposition, FRs are included because they are intrinsic to the artifact and its intended use, because they are needed to satisfy the customer needs, and/or because they are needed to fulfill the requirements of the parent entity. The intrinsic functions are those associated with what Kano *et al*. [1984] describe as basic and performance needs. They are derived directly from the goals and motivation of the project. For example, all mobile phones must send and receive phone calls. These FRs represent many of the project's ends. Thus, there is no need to document their rationale independently from the project's goals and motivation.

However, non-essential functions, like those intended to excite or delight users and increase the attractive qualities of an artifact [Kano *et al.,* 1984], are usually a means of accomplishing a higher (parent-level) end. For example, many mobile phones also take photos, access the Internet, and provide navigation instructions in order to increase the competitiveness of the product. Usually, multiple means are available to achieve these ends so there will be multiple highest-level FR options to consider and select from. Unlike their intrinsic counterparts, these FR options and the reasons for their inclusion or exclusion are an important part of the design strategy and should be documented during the design process.

3.2 WHY THESE CONSTRAINTS?

Constraints in Axiomatic Design Theory "represent the bounds on an acceptable solution" [Suh, 1990]. Like the highest-level FRs, some constraints are intrinsic to the artifact and its environment. For example, all artifacts must obey the laws of nature. Similarly, an artifact that is intended to function as a component in a larger system will have physical constraints (size, connection points, etc.) imposed by that system. An artifact that is intended for use by humans must take into account their limitations. And, many artifacts are subject to legal constraints such as building regulations [Albano *et al*., 1993] and emissions standards [Dandy *et al.,* 2008]. The rationale for these constraints is usually obvious and requires no explanation. However, providing some background for each constraint will help to document how it was identified (e.g. what issues were considered) and reduce the chances of missing other constraints during the requirements process.

Constraints are also derived from the customer needs and/or the parent-level requirements. For example, bounds on size, weight, and cost can all be chosen to satisfy the customer and/or to increase an artifact's competitive advantage. However, unlike the highest-level FRs, these constraints are often comparative and/or contextual. For example, in commercial markets, the features and performance of existing artifacts set the minimum baseline for the development of new artifacts. In order for a new product to be competitive, it must be somehow better (smaller, lighter, cheaper, etc.) than the alternatives. The rationale for these decisions should appear in the documentation of the benchmarking activities performed during the background and stakeholder research phase of the conceptual design process.

3.3 WHY THIS DESIGN RANGE?

In Axiomatic Design Theory, a design range specifies the bounds on the acceptable performance of a function [Suh, 2001]. Some functions are binary; they are either performed or they are not. In these cases, there is no meaningful design range and thus nothing to document. All other design ranges represent a choice by the designer. Like constraints, many design ranges are derived directly from the customer needs and the parent-level requirements. For example, improved performance may be chosen as a means to achieve a parent-level end such as increased sales. And like constraints, the values for many design ranges are comparative or contextual. For example, the improvement of a function will often be defined relative to a previous version of the artifact or to a competitor. As a result, some of the rationale for a design range will appear in the benchmarking documentation. However, it is often necessary to balance stakeholder satisfaction with the techno-socio-economic realities that are reflected in the constraints. The factors that were considered during the definition of a design range, how they were prioritized, and why the final decision was made should be documented as a part of the design process.

3.4 WHY THESE SELECTION / OPTIMIZATION CRITERIA?

Selection criteria (SCs) are used to choose between different design concepts, while optimization criteria (OCs) are used to refine and improve the final artifact [Thompson, 2013a]. They often address the same qualities as constraints (cost, weight, efficiency, etc.) but indicate which to minimize or maximize rather than setting a hard limit on their values. SCs and OCs are derived directly from the customer needs and the parent-level requirements. But because they imply a ranking or a prioritization, they always require choices on the part of the designer. The reason why some criteria were chosen over others and why a given number of criteria were chosen should be documented as part of the design process.

4 MAPPING AND DECOMPOSITION

Once the highest level FRs and the other requirements information have been defined, the mapping and decomposition process can begin.

4.1 WHY THESE DPS?

The process of defining design parameters (DPs) is essentially the same at every level of decomposition. Multiple options for satisfying each FR are generated or are retrieved from knowledge bases [Suh, 2001]. These options are screened [Ulrich and Eppinger, 2008] for feasibility [Kim *et al.*, 2006] and to ensure that they do not violate the constraints [Suh, 2001; Kim *et al.*, 2006]. The remaining concepts are scored or ranked based on performance criteria [Chen and Lin, 2002] and one option is chosen for inclusion in the final decomposition. Although this mirrors the divergent-convergent nature of more general engineering and product design processes, the AD design process differs in two ways: the generation and selection is done for each individual DP instead of for collections of DPs (i.e. design concepts) and both processes are strongly affected by the design axioms.

The generation of design concepts and design parameters depends on the designer's creativity [Suh, 1990], his or her knowledge and experience, and the design tools and methods (brainstorming, morphological charts, analogy, design from first principles, reverse engineering, etc.) used [Suh, 2001]. The generation of DPs is also guided by the need to maintain the independence of the FRs [Suh, 1990]. As a cognitive process, ideation is not well understood. Thus, designers themselves may not be aware of why a given DP option was proposed. However, most of the time a solution is proposed because the designer knows that it has performed well in another form or another context. If this information is available, documenting it may help to inspire the generation of other options and/or to inform the selection process. But this particular 'why' is normally left unaddressed.

The (rational) selection of design concepts and design parameters in engineering and product design usually relies on some kind of weighted decision matrix to rate and rank the design concepts for selection [Slocum, 1992]. In Axiomatic Design Theory, the design axioms should be applied prior to this step and can be thought of as a pre-condition for selection. In an ideal situation, only DPs that lead to designs that satisfy the Independence Axiom and have zero Information Content will be put forward for selection. In these cases, the design rationale is contained in the selection criteria and the weights assigned to them. The design axioms do not answer why a particular DP has been chosen but they can explain why another has not. If the axioms have not been satisfied, then they can be used as selection criteria (i.e. the least coupled design and/or the design with the lowest Information Content should be chosen). In these cases, the design axioms do represent part of the design rationale. However, the 1st Axiom implies that it is better to return to the decomposition and attempt to locate and remove the source of coupling.

4.2 NO 'WHY' FOR SOME UPPER-LEVEL DPS

There are some exceptions to the scenario discussed above. At the highest-level(s) of the decomposition, design parameters often represent "conceptual entities" or the "design intent" rather than specific solutions [Suh, 2001]. As a result, designers sometimes define DPs that perform the desired functions by definition but otherwise have no meaning. For example, if FR1 is to "dry <something>" then DP1 can be defined as a "dryer" or a "drying system". These 'place-holder' DPs are important because they satisfy the 1:1 mapping required by the Independence Axiom and allow the design process to proceed. But they do not require any options to be generated and do not permit any choices to be made. Thus, there is no why-type information associated with theses DPs.

4.3 WHY THESE LOWER LEVEL FRS?

After all of the design parameters for a given level have been defined, the FRs for that level can be decomposed. This process can be viewed in three ways. First, the lower level FRs (FRij) can be viewed as defining the goals or motivation of the object or solution (DPi) that will perform the function required (FRi). From this perspective, the definition of lower level FRs is the same as the definition of the highest-level FRs and the why-type information is found in the same places. While this method may result in a good decomposition, it greatly increases the size of the design space and thus reduces the efficiency of the design process.

Second, the decomposition process can be thought of as an analytical or reverse engineering process that seeks to identify the functions that are commonly performed by the specified DP. For example, many dryers (DP1) heat air (FR11) and then blow the hot air onto a wet medium (FR12). This type of decomposition is often ill advised because it does not allow the FRs to be defined in a solution-neutral environment. This leads to increased opportunities for fixation and bias and thus less potential for innovation. However, it may be useful in cases where the parent DP is well defined and requires decomposition only to specify the interactions between its sub-components and other parts of the artifact.

Finally, the decomposition process can be thought of as a divergent-convergent process in the functional domain that mirrors the one that occurs in the physical domain. In this case, multiple options for each sub-FR are generated (or are retrieved from knowledge bases). These options are then evaluated and one option is chosen for inclusion in the final decomposition. In this case, the design rationale for the lower level FRs is contained within the criteria used to select between the different functional solutions. If the decomposition process is viewed in the third way, the question is not "what functions must the higher-level DP perform?" but rather "how will the higher-level FR be achieved functionally?"

5 THE 'WHY' IS RELATIVE

Thus far, the discussion in this paper has focused on the various stages of the design process. This section considers the 'why' in the design process as a whole.

5.1 THE 'WHY' IS RELATIVE AND REVEALED BY THE BACKWARDS HORIZONTAL MAPPING OF WHAT-TO-HOW

Each design domain in AD represents 'what we want to achieve' relative to the domain on its right and 'how we propose to achieve it' relative to the domain on its left [Suh, 2001]. Thus, the design process can be thought of as a series of what-to-how mappings between each of the four design domains. Lu and Liu [2011a] claim that a backwards mapping of the what-to-how relationship is a how-to-what relationship. However, each PV is present because it is needed to create its associated DP(s). Similarly, each DP exists because it is needed to perform its associated function(s). And, each FR is included to satisfy one or more customer or stakeholder needs. Thus, it might be more accurate to say that a reverse mapping in Axiomatic Design Theory actually represents a what-to-why relationship (Fig. 2). Similar observations have been made in the AD literature [Sohlenius *et al.*, 2002; Moon, 2011; Marques *et al.*, 2013), by Cross [2000] in the context of objective trees, and by Otto and Wood [2001] in association with the FAST method.

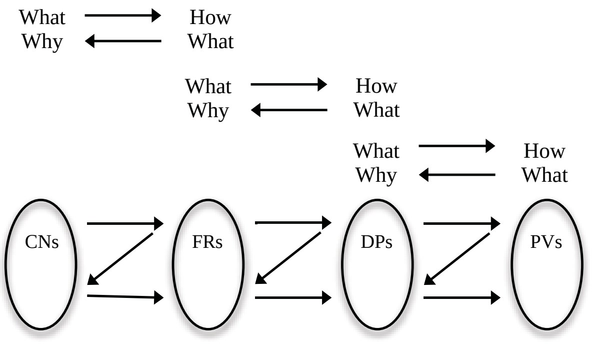

Fig. 2 Forward what-to-how and backwards what-to-why mapping between design domains.

5.2 THE 'WHY' IS RELATIVE AND REVEALED BY THE BACKWARDS VERTICAL DECOMPOSITION OF WHAT-TO-HOW

In their discussion of a logic-based foundation for Axiomatic Design Theory, Lu and Liu [2011b] also claim that the horizontal mapping across domains represents a synthetic "means-of" relationship while the vertical decomposition represents an analytic "part-of" relationship. Each sub-FR, sub-DP, and sub-PV is part of its parent entity from a forward decomposition perspective. Based on this logic, parent entities can be viewed as the reason why each child entity exists. This implies that backwards vertical decomposition can also be thought of as a mapping of what-to-why within each of the design domains (Fig. 3).

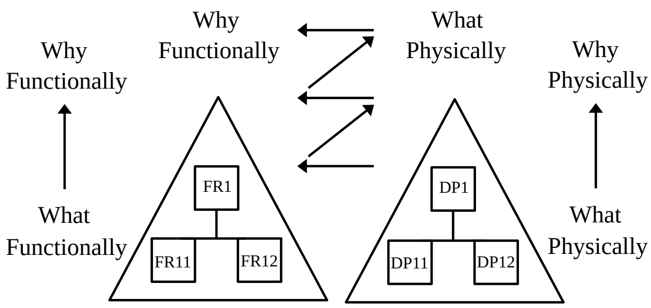

Fig. 3 Backward two-dimensional what-to-why mapping and decomposition.

If the mapping and decomposition process demonstrates a symmetric property of equality, then sections 5.1 and 5.2 indicate that a forward what-to-how mapping also takes place within the design domains (Fig. 4). This is supported by the third view of functional decomposition discussed in section 4.3.

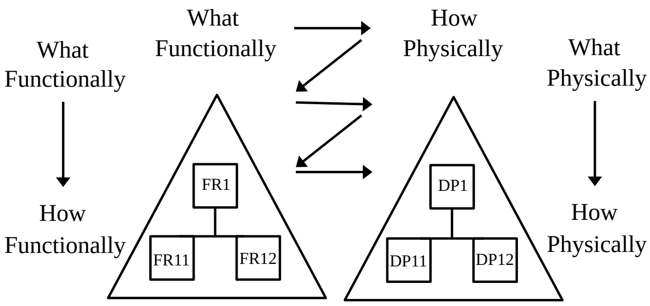

Fig. 4 Forward two-dimensional what-to-how mapping and decomposition.

These views of the relationships within and between the design domains are consistent with the earlier observations that the 'why' appears in the customer domain, the functional domain, and the extended requirements categories [Thompson, 2013b] as well as with observations that it affects all aspects of the design process. This model also explains why the 'why' is so completely integrated into the design process and why it has traditionally been so invisible.

6 WHERE AND HOW TO DOCUMENT THE EXTRINSIC 'WHY'?

This paper has argued that much of the why-type information in the design process is intrinsic to the artifact and/or contained within the design domains, the extended requirements categories, and the relationships between them. However, it has also argued that some why-type information is not directly incorporated into the Axiomatic Design framework. Traditional engineering and product design captures this information in the form of mission statements, mind maps, concept classification and combination trees, morphological charts, Pugh charts, concept screening matrices, etc. Rather than extending the Axiomatic Design framework to incorporate this information in other ways, the connections between AD and traditional engineering and product design processes and methods could be strengthened so the existing tools can be used more easily with both. Existing Axiomatic Design software [Do and Suh, 1999; Suh and Do, 2000] can also be used and improved to automate the documentation process.

7 SUMMARY AND CONCLUSIONS

This paper has investigated where and how why-type information is specified within the AD framework. It was claimed that the highest-level 'why' can be found in the CNs, the highest-level FRs of the artifact, and/or the FRs of a parent-level entity depending on the design task. Within the requirements process, some why-type information is intrinsic to the artifact while other information must be documented separately. Within the mapping and decomposition process, specific why-type information can either be unknown, contained within the requirements information, or documented outside of the AD framework. Finally, it was claimed that the 'why' is a relative property and represents the relationships between different types of information. Why-type information that is not currently contained within the AD process can be documented using traditional design tools and methods and/or AD software.

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EXTROVERTED, NON-VERBAL, AND PSEUDO-DISCOMFORTING STIMULATORS FOR RECOGNIZING DESIGN TARGETS

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ABSTRACT

This paper proposes a method for recognizing design targets. We looked into the origin of the design process and found that stimulating the designer to feel discomforts can help the designer identify design targets. In other words, we propose extroverted (to receive stimulation from the external surroundings), non-verbal (not expressed with words), and pseudo-discomforting (to give the designer anxiety) stimulators (to make the designer excite internally) for recognizing design targets, and we confirmed the effect through design education and product design.

Keywords: Decision making, Innovation management, Product development.

1 INTRODUCTION: THE PROCESS OF HUNTING FOR DESIGN TARGETS

In the modern world, up to 2014, designers spend much time in identifying the design target [Lu and Liu, 2012], i.e., “what to design” in the beginning of a design project. Before this time, the design target was usually given to the engineer. As Suh explained, for example, in the thinking process of Axiomatic Design [Suh, 2001; Thompson, 2013], shown in the right side of Figure 1 (a), the engineer analyzes the given design target to find the followings; the customer’s needs at first, and the detailed functional requirements of “what to do” in the functional domain, the design parameters of “how to make,” and finally the process variables in the physical domain. And when a problem happens, the engineer goes back to the left side of the functional requirement or the design target with a kind of inspiration of “why not?”.

The thinking process in this paper, however, is at the origin of the whole process shown at the left in the figure. This upstream process is the engineer’s act of hunting the design target of “what to design”. In other words, it is that of finding what the “big-bang” is to start the design

n thinking process in the emotional domain. This paper looks a “beyond design basis” against Axiomatic Design for engineers. But according to the authors’ experience to teach young students, it is only a “piggy back” of the conventional design methods; namely, one of the extensional business applications in the all thinking structure of Axiomatic Design. Without the overall engineering knowledge of physics, chemistry, production technologies, and the conventional Axiomatic Design, any engineering products cannot be designed as explained later in the discussion of Chapter 5 of this paper.

The next example illustrates our proposal. Conventionally, as the right side of Figure 1 (b) shows, the design target is given in the defined form of a functional requirement, e.g., “rescue a physically handicapped person from the emergency stairs in case of an earthquake or fire.” The planner implied to the engineer a solution “evacuation chair” as a design parameter that is well accepted in the market. And then the engineer starts his task of designing a physical improvement. Recently, however, the boundary between the engineer and planner is fading out. The task given to the engineer is more abstract and comprehensive, e.g., “design a building tender to the physically impaired.” An engineer full of the engineering mind, cannot imagine such tender buildings. Finally, he or she fails to find the design target like evacuating chair, voice guide or smart cane.

The authors, in an effort to bring such ideas to the engineers’ minds, stimulated their brains in a manner not tried before. For example, as shown in the figure, we blindfolded half of the students so they can experience the anxiety of the vision impaired during evacuation. The other half, of course, guided the blindfolded partners for safety. Such discomforts that students would not experience in the normal course of school life stimulate their minds, and function as the driving force for developing design targets. Of course, candidates for a design target may be easily found on the Internet with logical and detail structures. In the case of such a product design, however, they often end up being the subject of patent infringement lawsuits. Or moreover, products that the human mind imagines without any experience are often blocked by unforeseen constraints. For example, the largest limitation with evacuation chair is its storage when not in emergency use. Caretakers often end up putting them in the back of the storage area if they cannot be folded up in a compact size.

In the 21st century, many companies started to give abstract and comprehensive assignments to engineers. The reasons are sudden changes in the market caused by dramatic shifts in the customer taste, M&A of companies, or catastrophic natural disasters. Under such circumstances, that the market may suddenly change, manufacturers are always after new design targets as part of their strategies. Through

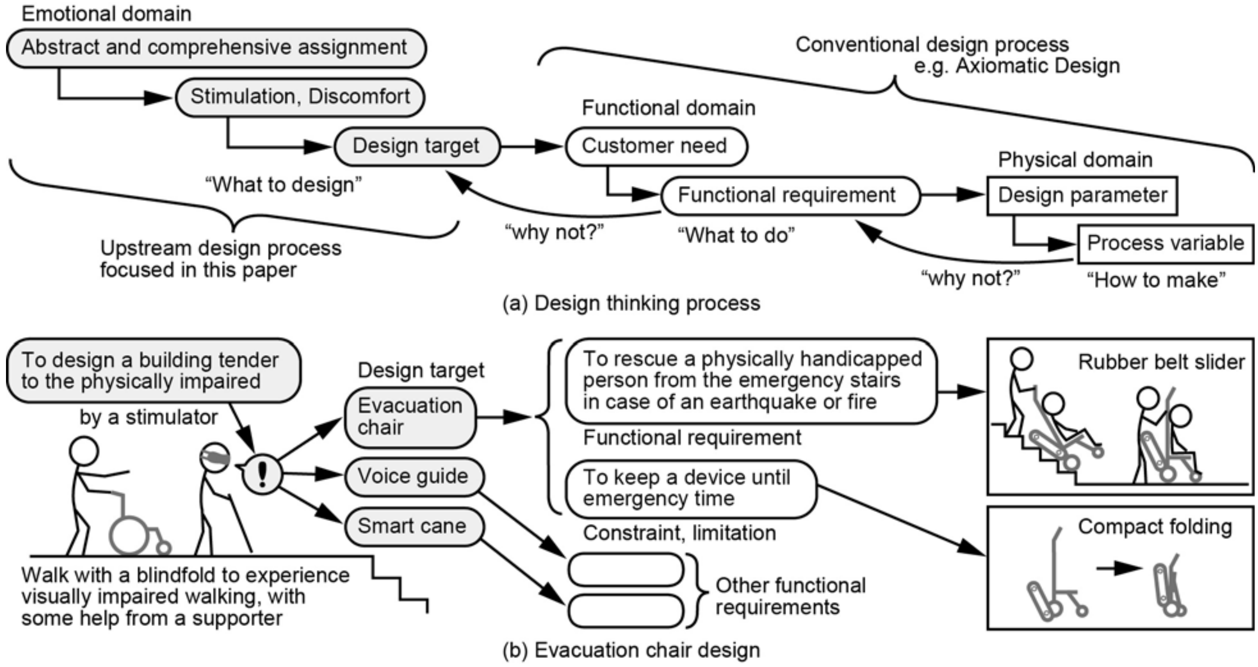

Figure 1. Upstream design process of hunting design targets.

our experience in education, however, the authors have found that new design targets are hard to recognize with conventional methods such as brain storming, market research, or portfolio analysis. The reason is, in many cases, collecting members that grew up in the same educational system and have spent lives in the same culture. It result in a homogeneous "same old same old" thinking pattern, and could only come up with ideas that are merely slight modifications over past products.

This trend led us to hire instructors who were industrial designers or art oriented creators. Such non-engineering minds trust their own emotions, feel inconvenience, pleasure, and discomforts that engineers would not even recognize. People with art-oriented work value emotional discomforts outside one's knowledge. In contrast, the engineer would search through past knowledge, apply standards, and aim for logically reliable designs. The mindsets are completely different.

In recent years of engineering, we started to study the originating process of design. Liefer in the d.school at Stanford University teaches the first steps in conceptual design to engineers [Liefer, 1998; Institute of Design at Stanford, 2011]. The school describes the design process with the 5 steps of empathize, define, ideate, prototype, and test. For the very first step of "empathize", the school lists the methods to observe (watch the user and his reactions), engage (communicate with the user through an interview), and immerse (experience for yourself). Looking at the design cases, however, this education is only effective after the design target has been set and the main user is known.

Riel et al. called this initial process the fuzzy-front-end and derived the success factors from manufacturing literature review and expert interviews [Riel et al., 2013]. They claimed that success factors for ideation, for example, are involvement of top management, defined focus, stakeholders networks, resources with high creativity and entrepreneurship, and organizational orientation. These factors are clearly effective for fast corporate product development once the design target has been set, however, the study does not address if they are important in the originating process of finding the design target.

The authors studied the design motivation for products that had won the Good Design Award and found that 67% of the designs originated from negative discomforts of "hard to use," "dirty," or "cumbersome," and 33% from positive feeling of "beauty", "health," or "ecology" [Nakao, 2012]. That is to say the artists find design targets from such weak stimulation to their bodies like discomfort. Engineering education, on the other hand, does not systematically describe which stimulator can arouse such recognition for the designer.

The rest of this paper has the following chapters; Chapter 2 proposes three methods for engineers to improve their skills in recognizing design targets, namely extroverted, non-verbal, and pseudo-discomforting stimulators, Chapter 3 shows case study results of our education in our university and Chapter 4 the results with industrial product design.

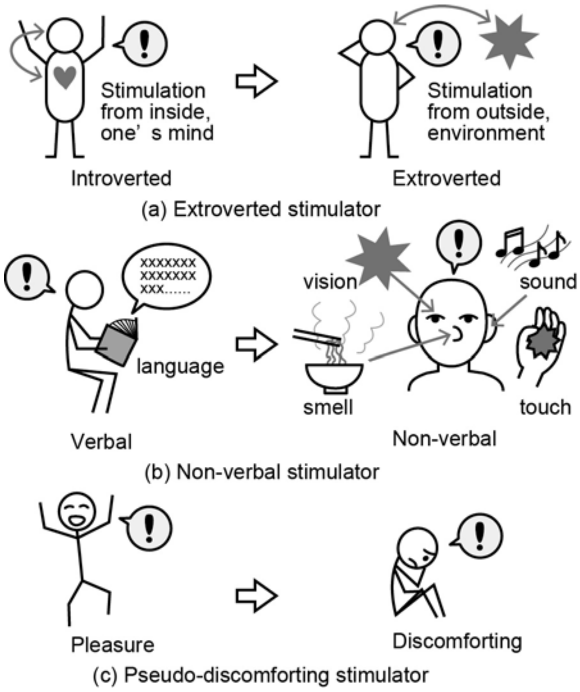

Figure 2. Effective stimulators in hunting design targets.

2 PROPOSAL: EXTROVERTED, NON-VERBAL, AND PSEUDO-DISCOMFORTING STIMULATORS

This chapter proposes three stimulators so engineers can feel the sensation to better recognize design targets as shown in Figure 2.

(1) Extroverted stimulator: We call this method "extroverted" because the origin is in the outside environment which stimulates the brain to generate sparks to recognize design targets. The most effective extroverted stimulator is to travel around in foreign countries to receive influence from different cultures. Many of us have the experience of an exciting walk in a foreign country where we find everything new and different. Introverted stimulator, on the other hand, hardly raises discomforts in the mind, except for maybe highly trained artists, because its origin is within one's mind. Stimulations that originate from the inside are usually dull because our emotions are so used to them.

(2) Non-verbal stimulator: Engineers go through a thorough education to verbalize concepts and think logically. Artists, on the other hand, value such non-verbal qualities like sound, color, shape, sent, and touch that directly affect human minds. Non-verbal stimulator takes advantage of such non-verbal qualities. A sketch, illustration, photograph, or rhythm can directly stand for general concepts that describe the stimulation. If the target product is a piece of art, the design solution can stay non-verbal; however, in case of an industrial product, the design target has to be described verbally in detail, so others can produce it on the factory floor.

(3) Pseudo-discomforting stimulator: Placing an engineer in an artificial situation that he feels anxiety, and forcing him to find his way out, or move on within the awkward state often enlightens him to find a design target. It is probably due to the human nature that never gives up and always strives to move upwards. Placing him in a happy situation may have the same effect, however, most people would feel their hearts fulfilled and would no longer seek for discomforts.

3 EDUCATIONAL RESULTS OF STIMULATORS

This chapter reports our results of actually applying stimulator in machine design lectures. The tasks that we gave to student were, unlike making minor improvement on existing products, targeted at developing new major advancement in arbitrary product fields, e.g., "to design a new transportation to ease your commute," or "design a system so elderly can enjoy meals." As shown in Figure 1(b), the customer, in most cases, lays out some constraints in the assignment like "tender to the physically impaired". Without such constraints, like a project to "design a city that keeps every member happy" would be too broad and the engineer's brain would just keep turning without anywhere to land. It is the role of top management to confine the target within an appropriate range.

(1) Extroverted stimulator: The previous chapter discussed the effect of having an engineer first experience life in a foreign country. Through our classes, we found that similar effects can be obtained by forcing the class into situations that are first experiences for them.

For example, we blindfolded the student so they can experience blindness while trying to make their ways through and around buildings as mentioned in Figure 1[b]. All five groups in the class found Braille blocks along the aisles were insufficient and they wanted more directions about what was in which way and where there was a door to a classroom. Two out of the five groups reached the design target of notifying the vision impaired with voices activated by signals from their canes about orientations and which classroom they were in front of. This simulating exercise to feel the anxiety from blindness was also an application of pseudo-discomforting stimulator.

Another example was to simulate an elderly when he tries to have a meal. We had the students put thick gloves on and take a meal. All of the students found difficulty handling thin chopsticks, and wanted spoons with thick handles and plates that stay in place even when they were pushed by the spoon.

(2) Non-verbal stimulator: For our hands-on sessions, we had the students express their ideas and thoughts with sketches and photographs. These exercises lower the psychological block the students have about hunting for design targets.

Two of the authors Nakao and Iino offered a design class to about 30 graduate students. The first assignments were to take five photographs of subjects the students felt discomfort with to present to the class. The authors were more intrigued by the findings photographs of the foreign students, probably because the homework had them experience the extroverted stimulator. They presented some discomforts; e.g., many Japanese people wearing surgical masks in the winter, or sliding and pivoting doors having the same handles in our

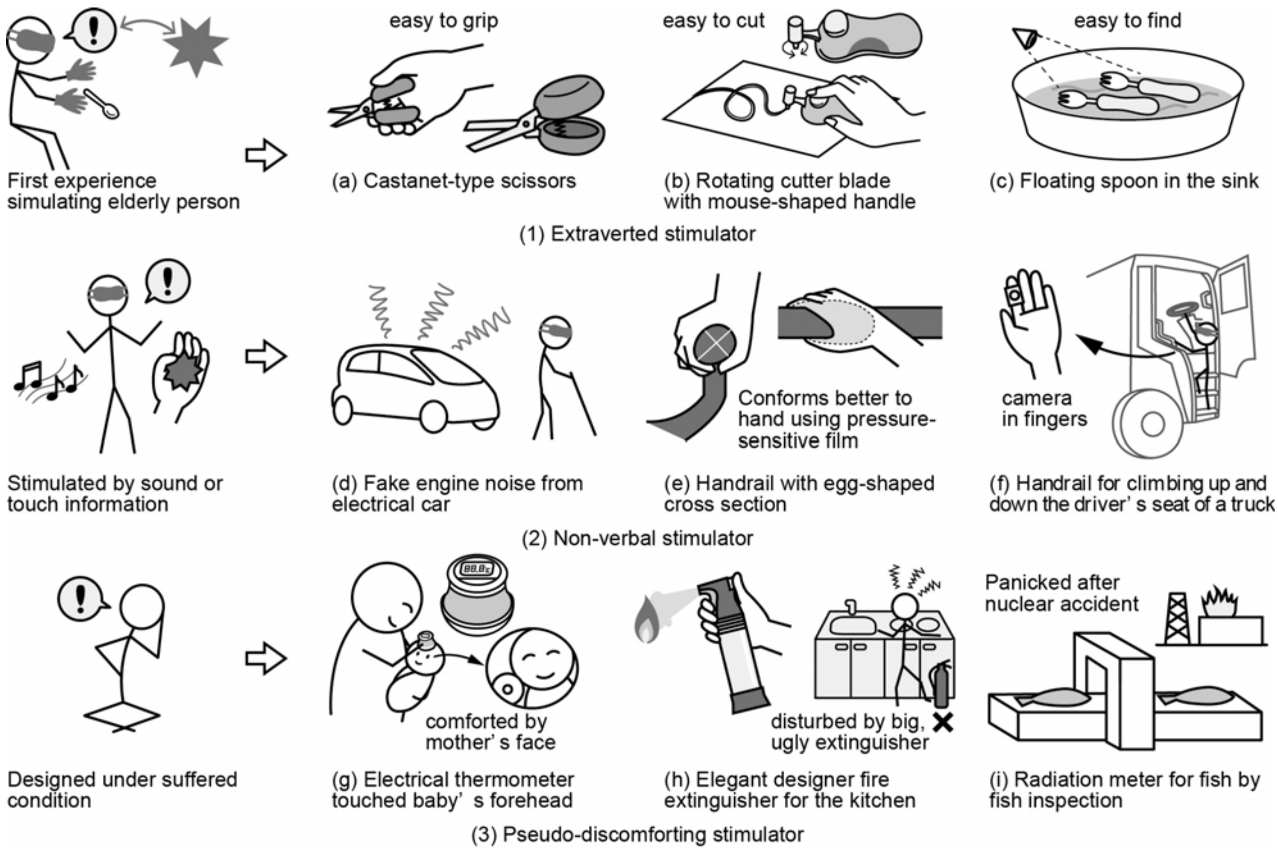

Figure 3. Designed products used by the processed stimulator.

university. When told, natives would also feel the same awkwardness; however, we probably have gotten used to the discomfort and not even recognize them. We then had the students analyze their discomforts to come up with design targets. Some prototyped a transparent surgical mask saying that the awkwardness came from hiding most of the face, and others designed different door handles for different type actions; flat plate when to push, easy to grab handles when to pull, and vertical handles when to slide.

Most Japanese students, in contrast, found discomfort in subjects from their state of mind at the time, e.g., flowers on the sidewalk when heartbroken, or red traffic-light when late to an appointment. These subjects were largely affected by the observer's state of mind at the time, and were hard to explain to others, thus, mostly inappropriate as design targets.

One of the authors Nakagawa was in charge of a 30-student freshman class. He demonstrated that even engineers could brush up their five senses. For example he had students sniff a flagrance and express it with color, had them listen to music and shape it with wire bending art, had them form the feeling of superiority or envy with clay, and sketch the transition of time with lamp shades. At the end of this course, the students found themselves, equipped with keener sensitivity; e.g., some noted discomfort with too many power cables that blocked the sky view, or annoying echoing sound in the student cafeteria. It would have been ideal if they could set the design targets of running the cables underground or installing sound absorbing walls in the cafeteria, however, we also found that, without the basics of engineering, the students' thinking process stopped upon only finding the problems.

(3) Pseudo-discomforting stimulator: Since the 2011 Great East Japan Earthquake, it is now realistic to assume circumstances that will give us strong anxiety, e.g., "what action can we take in case Mt. Fuji erupts," or "how can we survive a direct earthquake in Tokyo" and hunt for design targets that will ease our minds. With such natural disasters in mind, we assigned a project to "design a system so we can survive a week of power outage." All the students remembered what happened at the time of the great earthquake and realized that, with the power outage, they could lose water supply, gas, traffic lights, or ways of remote communication. Almost half of the 130 students of a junior class, listed design targets: e.g., installing solar battery panels on residence housing, or designing a private vehicle mounted communication systems.

4 DESIGN RESULTS OF STIMULATORS

This chapter shows industrial design results by one of the authors Nakagawa. Figure 3 shows some samples after applying stimulators discussed in Chapter 2.

(1) Extroverted stimulator: Nakagawa simulated an elderly life as described above for an extended time and produced (a) castanet-type scissors that do not require sticking fingers in

the holes, and (b) a paper cutting knife with a rotating blade and a computer-mouse-like body to hold so the user can just trace curves to make cuts, and (c) floating silverware so you do not have to search for sunken knives and forks inside the sink with elderly weak vision during dishwashing.

(2) Non-verbal stimulator: Electrical vehicles are quieter than gas-engine ones and pedestrians, without noticing their approaches, get hit by them more frequently. We tested if blindfolded pedestrians, relying more on audible sound in the surroundings, would recognize (d) fake engine noise. We found the negative side effect that the monotonous sound makes the driver sleepy. To prevent elderly from dropping from stairs, we designed (e) a handrail with egg-shaped cross sections. An engineer pasted pressure-sensitive film on gloves to find the feel of contact to design gloves with bigger contact area. Next, drivers of large trucks sometimes fall from the high driver's seat when they try to climb up to it. We experimented with a test driver with eye-masks and camera on their fingers to check where or how to grab something, and found that he tried to hold the steering wheel as a handle for climbing to the driver's seat. We then produced (f) a steering wheel/handrail for climbing up and down the driver's seat of a truck.

(3) Pseudo-discomforting stimulator: When a baby is crying, it is hard to measure its temperature. We cannot ask a baby what the matter is, so we put a camera in a baby figure to find how the mother's face eased the baby's mind. Our study led to producing (g) an electrical thermometer that takes measurement within 1 second with the mother holding her hand against the baby's forehead. We spent time in an experimental setting with the anxiety of having to extinguish a kitchen fire. We then, like the aforementioned evacuation chair, found discomfort at times when the tool was not in use. Consumers would want to get rid of products that were hard to store, and we produced [h] an elegant designer fire extinguisher that looked nice in the kitchen. Next one is a realistic anxiety; we helped a fisherman town suffering from the threat of radioactivity after the Great East Japan Earthquake for (i) a 100% radiation inspection of captured fish without damaging them. After setting this design target, we found a high sensitive radiation sensor for breast cancer and were able to push the development into a product.

5 DISCUSSION

We applied three stimulators in classroom assignments and confirmed these stimulations enhance the sensitivity of all students against discomforts. Some students, however, still weak with their engineering background, could not extract design targets from their experiences and we could not reach quantitative conclusions. For examples, in the evacuation project of Figure 1, some non-engineering students introduced a parachuting "umbrella" for jumping from the window, or a flying "carpet" to slide even on the stair. They were interesting, but some mere imaginary tools in a cartoon without any concrete designs for material, power or control. Our stimulators cannot improve their ability for the product design without any engineering knowledge.

We also found that these stimulators are more powerful for experts. For example, young researchers often struggle with the search of "what to research" to win grants. The most effective trigger in such searches is extroverted stimulator of visiting overseas research labs or researchers in different fields and have discussions. Other effective sparks include non-verbal stimulator of looking for discomforts in sound, heat, color, or flow when watching experiments, and pseudo-discomforting stimulator of trying a challenging project like aiming at 10 times better results.

6 CONCLUSION

Three types of stimulator, namely, extroverted, non-verbal, and pseudo-discomforting mildly stimulate the engineer and help him at the very origin of the design process, i.e., hunting for a design target. Successful applications have been demonstrated with university courses and product development.

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SIZE UNIFORMING PROCESS OF MINUTE SPHERES BASED ON AXIOMATIC DESIGN

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ABSTRACT

Modern micro droplet reactors and nanoparticle processing require uniform minute spheres. They, however, often face difficulty in collecting minute spheres with the same diameter. The difficulty comes from the bottom-up process of growing small seeds, instead of breaking larger ones. The bottom-up process ends up with the byproduct of spheres smaller than the target size due to variation in temperature, pressure, and concentration of the system. Moreover, when the minute sphere size is smaller than the filter pore or the opening of the pipette tip, separating them into different sizes is difficult. One will have a hard time even in selecting out the right sized ones visually. For our study we report with this paper, we set the primary functional requirement to “Produce minute spheres” and the secondary functional requirement to “Homogenize minute spheres” and applied axiomatic design theory to develop a design solution that satisfies the two functional requirements by “suppressing the growth of secondary cores.”

Keywords: axiomatic design theory, independence axiom, process control, minute sphere, byproduct core.

1 INTRODUCTION

Minute spheres in this paper are spheres or hemispheres with diameters under 1mm. Minute spheres offer a number of advantages in engineering processes; i.e., the large surface area for the same volume makes enzyme particles highly reactive, or the low heat capacity produces chemical field with high heat response. These properties, however, are easily affected with the minute sphere size and often require “uniform size” spheres.

In general, however, when the target sphere size is smaller, supplying spheres with the same diameter is more difficult. One of the main reasons is their bottom-up production process. Bottom-up methods often have the byproduct of cores with diameters smaller than the target. The reason is spatial and timeline based variation in the temperature, pressure, and concentration within the production pool. Also, when multiple cores stick together, they turn into aggregated cores with undesired size. When the target diameter is 1mm or larger, homogenizing uniformity with the sphere size is fairly easy. They can be classified and separated with filters with small pores or hand-picked one by one with pipettes. Separating out minute spheres of smaller size, however, is in general not easy. Filters with 100nm pores are not in the market and if the minute sphere has active surface, it will stick to the filter surface to hinder the separation process.

In our study, we applied axiomatic design theory and set the primary functional requirement (FR_1) to “Produce minute spheres”, “Supply minute spheres” or “Enlarge spheres from seeds or embryo”. And we set the secondary functional requirement (FR_2) to “Homogenize minute spheres”, “Select minute spheres” or “Sort minute spheres into same size”.

In the next Section 2, we will derive a method to suppress the growth of minute spheres with off-target sizes to satisfy the two functional requirements of FR_1 and FR_2 without relying on filtering or hand-picking. In Section 3, we apply the method to the design of a method to maintain micro droplet size, and in Section 4, to designing a particle control system for copper nanoparticles.

2 METHOD FOR SUPRESSING OFF-TARGET SIZED PARTICLES

The design equation for our system is equation (1).

$$\begin{Bmatrix} FR_1\text{: Produce minute spheres} \\ FR_2\text{: Homogenize minute spheres} \end{Bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \end{Bmatrix} \quad (1)$$

DP_1 is the design parameter to satisfy FR_1 about our target primary cores. DP_2 is the design parameter to satisfy FR_2 about the byproduct secondary cores. We selected our DP_1 and DP_2 following the independence axiom so that the system is uncoupled with both a_{12} and a_{21} being 0, or at least one is zero so the system is decoupled [Suh, et al., 2001].

We can make a_{12} and a_{21} go to zero by selectively removing the byproduct secondary cores if we select filtering or hand-picking for DP_2. As we discussed above, however, there are hardly any filters or pipettes that work for minute spheres. Applying other bottom-up methods for DP_1 would allow smaller new cores to generate one after another and the diameter distribution would never converge to the target size ($a_{21} \neq 0$).

So for our study, we assigned a way of suppressing the core generation to DP_1. The suppression cancels the growth and the sphere diameter distribution does not expand ($a_{21} \rightarrow 0$).

If, however, we apply growth suppression to the entire system, the chamber that produces all, that is target primary cores and byproduct secondary cores, is the same and it would suppress the growth of byproduct secondary cores ($a_{12} \to 0$), however at the same time, the production of target primary cores would also be suppressed ($a_{11} \to 0$). To avoid this tradeoff, we developed a mechanism to selectively suppress the growth of byproduct secondary cores but not the target primary cores ($a_{12} \to 0$, but at the same time, $a_{11} \neq 0$).

From the above discussion, we derived the following guidelines for our *DP*s.

-Guideline 1 for DP_1: Suppressive generation of all spheres

-Guideline 2 for DP_2: Selectively suppressive growth against secondary cores

In the following sections, we report our findings from applying these guidelines, derived from axiomatic design theory, to a couple of processes. If we can find design solutions that resolve past problems, the guidelines will be proved effective. The two processes are “maintaining micro droplet size” for liquid and the “copper nanoparticle production” for solid. Analogically speaking, these guidelines can apply to a policy of developing countries. The government decides the suppressive birth control and financial support for poor people in order to make all people happy.

3 MAINTAINING MICRO-DROPLET SIZE

3.1 PROCESS DESIGN

Combinatorial experiments have the need for devices with multiple droplets arranged in a lattice array on an open substrate [Kim, et al., 2012]. With the micro droplet defining the field of chemical reaction, its small size allows small quantity of reagent or blood sample with shorter reaction time proportional to the square of the size ratio. Also, preparing the micro droplets on an open substrate makes the injection of a variety of reagents easier. From the above guidelines, we set the design equation for handling micro droplets on an open substrate as following equation (2):

$$\begin{Bmatrix} FR_1\text{: Produce micro droplet} \\ FR_2\text{: Homogenize micro droplets} \end{Bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \begin{Bmatrix} DP_1\text{: Wet droplets with spray} \\ DP_2\text{: Dry secondary droplets with electrolysis} \end{Bmatrix} \quad (2)$$

If we hold the micro droplets on an open dry substrate, evaporation would shrink the droplet size. So, we set DP_1 to "Wet all droplets with spray" on open dry substrate. This solution, however, would result in condensing seeds for micro droplets in areas that are “not reserved” for the experiment, i.e, byproduct secondary droplet's cores. To avoid forming unwanted droplets, we set DP_2 to decompose the byproduct secondary droplet's cores by electrolysis. The target primary droplets are sitting on reserved seats that that are masked and they do not reduce in size ($a_{21} \to 0$). In other words, DP_1 cancels out the effect of evaporation with humidification to maintain the target primary droplets diameter, and DP_2 eliminates byproduct secondary droplet's cores with electrolysis and the target primary droplets continue to keep the target diameter ($a_{12} \to 0$, but at the same time, $a_{11} \neq 0$).

Another DP_1 would be to add liquid for the amount evaporated using a pipette and maintain the target primary droplets diameter so that FR_1 and FR_2 are both satisfied. This solution, however, would cause cross contamination among cores with the pipette, thus, is unwanted for a combinatorial device. Also, adding humidity and removing the byproduct secondary droplet's cores with a pipette is another conceptual design solution, however, searching for byproduct secondary droplet's cores with a microscope and removing them with a constantly shivering pipette is not an easy task. And the smaller the size of the droplet is, the larger contamination to the droplet from the impurities on the opening of the pipette tips have.

3.2 EXPERIMENT

We built an electrochemical device shown in Figure 1. Two electrode films (Carbon nano tube 13wt%, PolyVinylidene DiFluoride 33wt%, 1-Butyl-3-methyl-imidazolium Tetrafluoroborate 54wt%) sandwich an electrolyte film (PolyVinylidene DiFluoride 40wt%, 1-Butyl-3-methylimidazolium Tetrafluoroborate 60wt%) in between. The surface was masked with a lattice array of circles where electrolysis could not reach across; they were the “reserved seats” for target primary cores.

We produced this device by first preparing the three layer sandwich, covering one side with porous fluoric resin for hydrophobic treatment, attaching hydrophilic polyimide resin stages and then placing target primary cores on the stages. The cores were not “placed” one by one, but the whole structure was submerged under the solution and then lifting the structure formed a target primary core on each hydrophilic stage. The experiment proceeded by humidifying the whole structure while decomposing the byproduct secondary cores with electrolysis. DP_1 performed a 30 second spray of mist for every 3 minutes in dry air. The mist volume measured 2mL/hour over a roughly 30cm square plane. The environment was open with a 0.5m/sec wind, thus, without the spray, the cores would have reduced their sizes by evaporation. DP_2 applied 4V step voltage to the device from the beginning of the experiment.

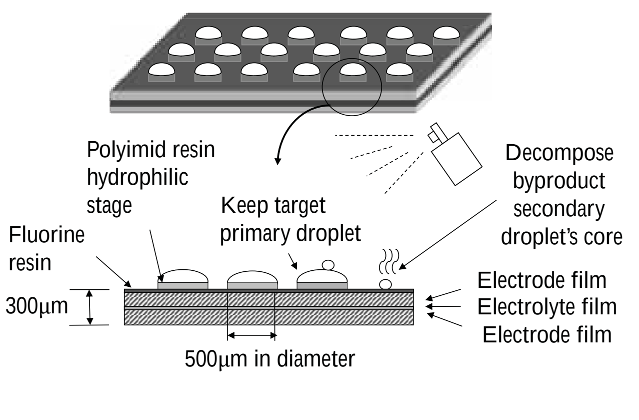
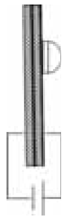
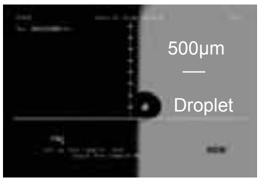
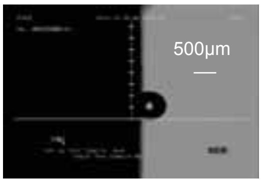
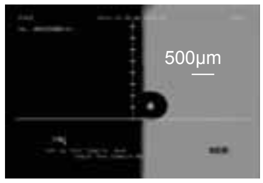
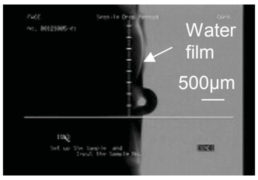
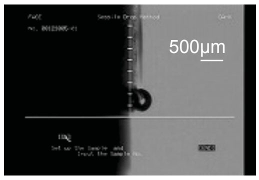
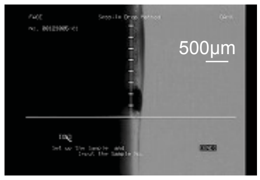
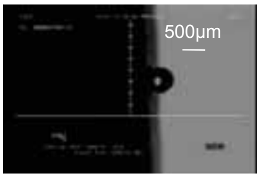
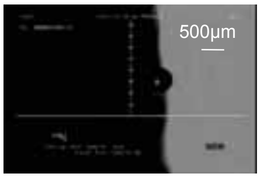
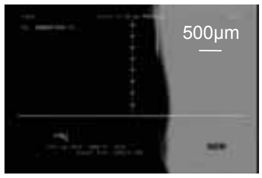
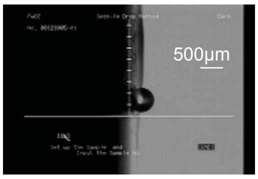
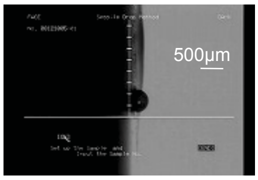
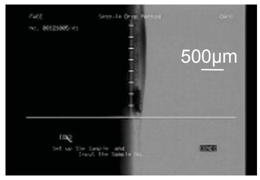


Figure 1. Cross section of the electrochemical device.

Table 1. Results of the first case (Humidification and Electrolysis).

Condition	DP_1: Wet with spray	Results FR_1 on primary droplet	Interference of DP_1 for FR_2	Initial state 500μm 	Mid state 500μm	End state 500μm
	DP_2: Dry with electrol-ysis	Results FR_2 on byproduct droplet	Interference of DP_2 for FR_1			
1	Yes	Satisfied: Survived more than 60 min.	No interfered $a_{21} = 0$			
	Yes	Satisfied: Evaporated immediately after generation.	No interfered $a_{12} = 0$			
2	No	Unsatisfied: Evaporated in 4min. 50sec.	No interfered $a_{21} = 0$			
	Yes	Satisfied: No generation. (Incidentally placed water film for this case was evaporated.)	No interfered $a_{21} = 0$			
3	Yes	Unsatisfied: Aggregated with secondary core into a large droplet	Interfered $a_{21} \neq 0$ Droplet grew			
	No	Unsatisfied: Aggregated with primary core into a large droplet.	No interfered $a_{12} = 0$			
4	No	Unsatisfied: Evaporated in 7 min. 40 sec.	No interfered $a_{21} = 0$			
	No	Satisfied: No generation.	No interfered $a_{21} = 0$			

3.3 RESULTS

We ran cases with both DP_1 (Wet droplets with spray) and DP_2 (Dry secondary droplet's cores with electrolysis), and three reference cases; two with one of the two design parameters missing, and one with both *DP*s missing. Table 1 shows the results. The time the target primary micro droplet maintained its size on stage is the average of 4 measurements. The substrate was held vertically for observation. The photographs show the actual particles during the experiment.

As Table 1 shows, only with Condition 1, the micro droplet on its stage kept the same diameter even after 60 minutes into the experiment and byproduct secondary droplets did not grow. In other words, DP_1 and DP_2 designed with the guidelines satisfied FR_1 and FR_2. As the target primary droplet survived and the secondary droplet's cores evaporated, the experimental result agreed, at least, with the original design equation. Condition 2, without spray, evaporated the primary target micro droplet in less than 5 minutes; FR_1 was not satisfied. For this particular Condition 2, we placed a film of water away from the target primary micro droplet. The water film disappeared as the experiment proceeded demonstrating that electrolysis decomposed water as well as byproduct secondary micro droplets. Condition 3, without DP_2 electrolysis, formed byproduct secondary micro droplets around the target primary droplet, and they aggregated to form a large aggregate droplet. The resulting large droplet diameter violated FR_2; DP_2 interfered FR_1. Condition 4 ran without both the humidification DP_1 and electrolysis DP_2 to evaporate the target primary micro droplet in less than 8 minutes, thus, did not meet FR_1.

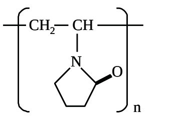
4 PRODUCTION OF COPPER NANO-PARTICLE

4.1 PROCESS DESIGN

Wiring technology using metal slurry inkjet requires uniform size copper nanoparticles in the ink for smaller gaps between slurry particles, thus, higher conductivity. Reduction of copper ions with non-electrolytic plating within a solution added with high-polymer electrolyte like polyvinylpyrrolidone (PVP) produces copper nanoparticles.

This copper nanoparticle process, however, fails to control the particle size because the non-uniform process parameters like temperature or concentration result in late generation of byproduct secondary cores that grow after target primary cores are formed. Furthermore, surface active

Table 2. Composition of Material for copper nanoparticle production.

Name	Formula	Amount
Polyvinylpyrrolidone (PVP)		5mM/mL
Sodium tetrahydroborate	$BaH_4 \cdot NaOH$	30mM/mL
Copper acetate	$Cu(Ch_3OO)_2$	15mM/mL
Water	(H_2O)	(500mL)

nano-sized particles adhere to particle size classifier walls and filters to hinder their classification. We then set the design equation (3) to the following from the above guidelines.

$$\begin{Bmatrix} FR_1\text{: Produce nanoparticles} \\ FR_2\text{: Homogenize nanoparticles} \end{Bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \begin{Bmatrix} DP_1\text{: Suppressive generation of nanoparticles by suppressor } (Na^+) \\ DP_2\text{: Selectively growth of secondary cores with wide active surface area per volume } (CuOH_2) \end{Bmatrix} \quad (3)$$

We chose a suppression method to add sodium ion to the above solution. The method canceled the Cu growth to keep the distribution of particle diameters under control ($a_{21} \rightarrow 0$), i.e., adding sodium hydroxide where PVP was present suppressed the grown of both the target primary cores and byproduct secondary cores ($a_{11} \rightarrow 0$, $a_{12} \rightarrow 0$) [Nishimura, et al., 2010], [Hirayama, 2013]. Table 2 shows the composition of the solution. It had 30mM/mL of sodium ion at minimum, and when we ran a control case without the sodium ion, the reaction itself no longer took place.

To lessen the effect of target primary core suppression, we controlled the initial core production to small size so byproduct secondary cores would be selectively suppressed. PVP and sodium ions react with the very surface of cores and smaller byproduct secondary cores have larger surface area per volume. Then particles with smaller diameters are subject to stronger effect of growth suppression than those with larger diameters ($a_{12} \rightarrow 0$, $a_{11} \neq 0$). The keep the core size small, we applied classical core generation theory that keeping the degree of supersaturation low will produce smaller size cores. So, we used copper hydroxide with smaller copper ion solubility compared to copper acetate to keep the degree of supersaturation low. Figure 2 sketches the difference of copper nanoparticle generation with copper acetate and copper hydroxide. Copper hydroxide can make smaller embryos. Using copper hydroxide for the material, byproduct secondary core generation proceeds with that of target primary cores, however, secondary cores are strongly suppressed to leave just the primary cores in the solution.

4.2 EXPERIMENT AND RESULTS

The initial copper reduction process proceeded with sodium borohydride solution dripping_in the solution. To wait for the copper to complete reacting with the sodium borohydride, we stirred the solution at room temperature while sending nitrogen into the solution. Then we poured the additional sodium hydroxide in the solution before generating the copper cores. To wait for the copper to complete reacting with the sodium borohydride, we stirred the solution at room temperature while sending nitrogen into the solution.

After we produced the copper nanoparticles, we degassed the solution for an hour with nitrogen gas at 10 degrees Celsius for preventing the oxidation. We determined the reaction time by measuring the amount of byproduct hydrogen until it saturated.

Table 3 shows the results of this experiment. We tried the reference case of no Na^+ for DP_1, however, as we explained above, the conditions resulted in no reaction. Condition 3 was the conventional process condition which still produced copper nanoparticles to meet FR_1, however, with an average diameter of 14.6nm with a standard deviation of 3.6nm.

When we used copper hydroxide to reduce the initial core size with lower degree of supersaturation (Condition 1), the average nanoparticle diameter dropped to 11.0mm to still satisfy FR_1 and it additionally satisfied FR_2 with a smaller standard deviation of 2.8mm. The experimental result agreed, at least, with the original design equation.

To further improve FR_1, we added sodium borohydride after the process and as Conditions 2 and 4 show, both cases of copper acetate and copper hydroxide gave longer reaction times of factors 1.5 to 1.7. These conditions resulted in larger nanoparticle diameters of 23.4nm and 19.1nm to meet FR_1 and, however, the standard deviation values also grew to 4.2nm and 4.5nm. The longer reaction time let the small number of target primary cores to grow larger and resulted in degrading FR_2.

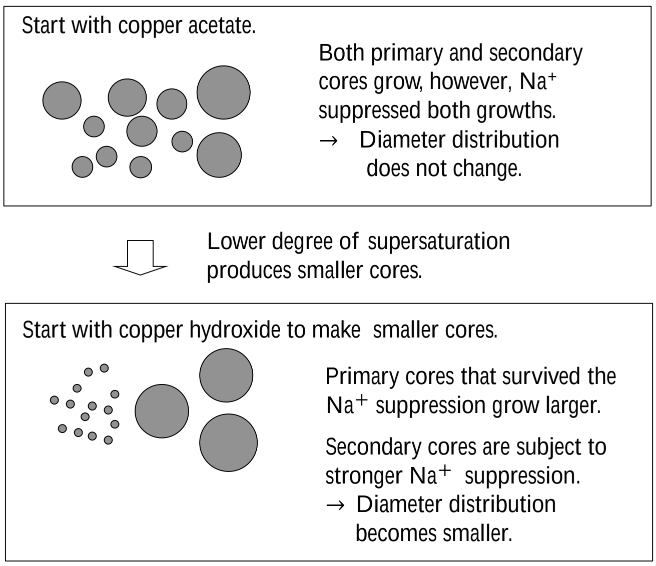
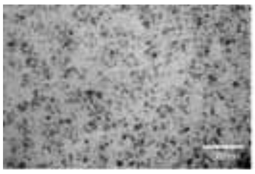
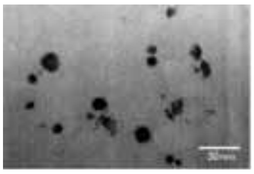
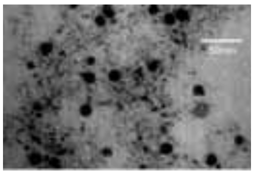
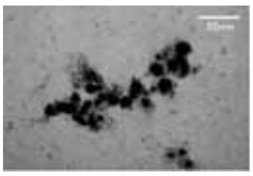


Figure 2. Growth and suppression of primary and secondary cores.

Table 3. Copper nanoparticle average diameter and reaction time.

Condition	DP_1 (Na^+) (mM/ ml)		DP_2 (CuOH)	Particle photo 50nm	Reaction time(min)	FR_1 Average diameter (nm)	FR_2 Standard deviation (nm)	Interference of DP_1 for FR_2 / Interference of DP_2 for FR_1
1	*NaOH*	0	Copper hydroxide		45 min	Acceptable 11.0 nm	Satisfied 2.8	→ 0
	BaH_4 ·*NaOH*	30						→ 0 Making the degree of supersaturation lower
2	*NaOH*	30	Copper hydroxide		70 min	Satisfied 23.4 nm	Unacceptable 4.2	≠ 0 Making reaction time longer
	BaH_4 ·*NaOH*	30						→ 0 Making the degree of supersaturation lower
3	*NaOH*	0	Copper acetate		10 min	Acceptable 14.6 nm	Acceptable 3.6	→ 0
	BaH_4 ·*NaOH*	30						≠ 0 Making the degree of supersaturation larger
4	*NaOH*	30	Copper acetate		17min	Acceptable 19.1 nm	Unacceptable 4.5	≠ 0 Making reaction time longer
	BaH_4 ·*NaOH*	30						≠ 0 Making the degree of supersaturation larger

In comparing results, we took several photographs for measurement and the average diameter change with copper hydroxide was 11.0nm to 23.4nm, while, that for copper acetate was 14.6nm to 19.1nm. When we used copper hydroxide, the degree of supersaturation was low and the active surface area of per volume of secondary cores was wide. As a result, the interference of DP_2 for FR_1 (a_{21}) was small. The long reaction time of 70 minutes for copper hydroxide, compared to 17 minutes with copper acetate, caused the target primary cores to grow huge.

5 DISCUSSION

As we showed in Section 3 and 4, the design guidelines of setting DP_1 to growth suppression and DP_2 to selective application to byproduct secondary cores are applicable to designing minute spheres. These design guidelines are also

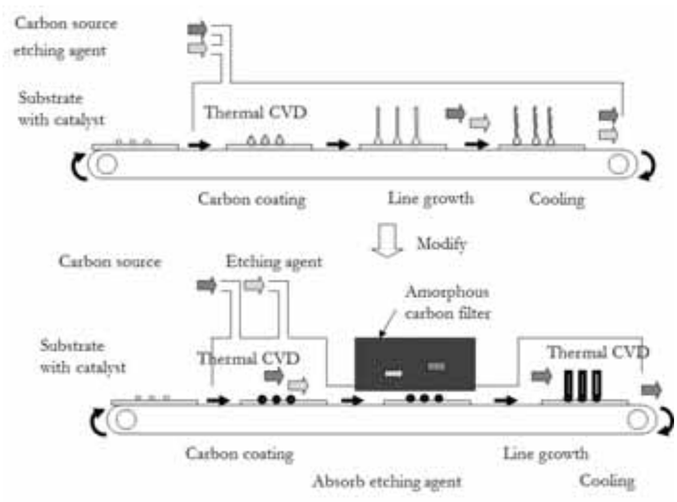


Figure 3. Sketch of CNT production process.

applicable to minute linear structures that start from minute spheres and grow in one direction.

For example, in designing carbon nanotubes (CNT), adding a small amount of water as etching agent for DP_1 suppresses the overall reaction [Yamada, et al., 2008]. If we introduce the etching agent water to both the upstream process of coating carbon to the catalyst and the downstream process of linearly growing the tube, we can suppress the generation of byproduct core amorphous carbon, however, at the same time, we will end up introducing flaws to the target primary core CNT itself by etching it. We can then apply the guidelines to this design to reach the following design equation(4):

$$\begin{Bmatrix} FR_1\text{: Supply CNTs} \\ FR_2\text{: Homogenize CNTs} \end{Bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \begin{Bmatrix} DP_1\text{: Suppressive generation by etchant } (H_2O) \\ DP_2\text{: Selectively flawless growth under etchant free condition. (Amorphous carbon filter)} \end{Bmatrix} \quad (4)$$

Figure 3 shows our design with DP2 of applying the etching agent only to the upstream process and an amorphous carbon filter to the downstream process to absorb the etching agent. The etchant free condition of the downstream process can produce flawless CNTs. Although still in the prototyping stage, it promises to satisfy both FR_1 and FR_2.

6 CONCLUSION

We applied axiomatic design to derive the design guidelines for producing minute spheres with a uniform diameter, i.e., FR_1 is to produce minute spheres and FR_2 is to keep the sphere diameter uniform. The design solution we reached were DP_1 to suppress the particle growth for the entire system and DP_2 to apply the suppression selectively to byproduct secondary cores. This solution provides the design guideline for uniform minute sphere generation. We demonstrated the effect of this guideline with two designs; one for maintaining micro-droplet size and the other for copper nanoparticle diameter control.

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AXIOMATIC DESIGN APPROACH FOR THE CONCEPTUAL DESIGN OF SUSTAINABLE BUILDINGS

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ABSTRACT

Architectural design needs systematic approaches to manage complexity in the early design process stage and to address sustainable building requirements. Architects often use previous experiences and knowledge to stimulate the early conjecture of possible solutions repeatedly until a satisfactory solution is defined. Possible use of an engineering design framework such as Axiomatic Design (AD) is studied with a case study on a small sustainable house design. High-level requirements are defined and decomposed into a manageable set of requirements. This study shows the potentialities of applying AD to support the initial architect's decision-making activity for the development of sustainable solutions.

Keywords: axiomatic design, sustainable building, decision-making

1 INTRODUCTION

The complexity of architectural design has been ever increasing due to the need for designers to address environmental and energy issues along with social-economic considerations. As the demand for sustainable buildings continues to increase, the need for a better understanding of how these buildings are designed has also increased. In the sustainable building design, the aim is to reach an overall sustainability in which design solutions satisfy the specified requirements regarding quality, cost, time and also efficient use of resources and consideration of context, environment and local culture [European Community Commission, 2005]. Therefore several aspects have to be considered right from the initial phase of the design process. The solution has to be optimized with consideration for a large number of different (sometimes conflicting) requirements and constraints, and it has to be selected from different available alternatives.

In order to address the key issues explained above, the design phases of the architectural design reviewed by the Royal Institute of British Architects (RIBA) is considered and shown in Table 1 [RIBA, 2012].

Table 1 Architectural design process [RIBA, 2012]

1	Development of Initial Project Brief according to project objectives, client's business case, sustainability aspirations and other constraints	
2	Preparation of Concept Design including proposals for mechanical, structural design, site landscape, specifications and preliminary cost plan along with environmental strategies.	
3	Preparation of Developed Design including coordinated and updated proposals for structural design, services systems, site landscape, outline specifications, cost plan and project strategies.	
4	Preparation of Technical Design information including all architectural, structural and mechanical services information and specifications	

In the initial and concept design phases, the design activity is more important and challenging than in the later design phases since architects have the greatest opportunity for good decisions as well as the risk of bad decisions for addressing the complexity of sustainable building design and influencing the project outcomes. Usually, during this initial phase of the design process, architects use previous experiences and knowledge and define a rather simplified problem in order to stimulate the early conjecture of possible solutions (Figure 1) [Marchesi et al, 2013].

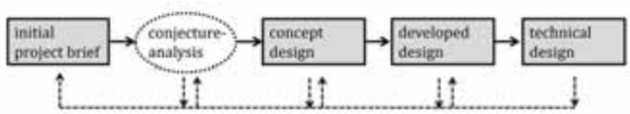

Figure 1. Concept generation in the architectural design process

Therefore very early in the design process, architects identify a rough quick concept based on a limited set of design objectives and developed by a conjecture-analysis cycle in which both problem and solution are refined in parallel

[Marchesi et al, 2013]. During these loops of iteration, the form of the building is slowly generated. The conjecture-analysis cycle often results in serial formulation of design problems and iterative search for solutions. Initially defined problems are constantly reformulated, co-evolving together during the design process until the relevant issues of the specific task and the related design solution are defined [Marchesi et al, 2013]. This approach is explained below by a case study analysis of a roof concept generation, the Lord's Cricket School roof, reviewed by its own designers [Spence et al, 2013]. The crucial requirement for this project was a high and steady degree of natural lighting inside the building. In order to guarantee this requirement, saw-tooth north-lights were proposed on the roof. Then the designers proposed to soften the roof-light shape for improving the internal reflections of the daylight. Afterwards the design solution was redefined moving the light glass line according to the requirement of daylight entrance improvement. Since in this last solution the sunlight enters directly, an internal solar blinds layer was proposed that obstructs the sunlight, but allows the daylight entrance.

Systems design tools and methods in engineering can be useful to minimize this kind of serial and iterative design process in architectural design [Sohlenius, 2000; Sohlenius and Johansson, 2002]. AD, one of these engineering design approaches, is distinguished from other systematic design methods by having a framework for mapping through top-down and zigzagging decomposition between functional and design parameter domains and two design axioms that guide the decision-making activity during the design process, especially in the early design phase, towards good design decisions [Suh, 1990, 2001]. In order to demonstrate the benefits of applying AD to the architect's approach, AD is applied to the roof design case study. Using AD, a minimum set of independent FRs is defined for a sustainable building design: supporting of loads, optimization of daylight inside and protection from rainwater among others. Then, a solution is conceptualized by mapping between domains, from the functional domain to the physical domain and it is expressed in terms of design parameters (DPs) that satisfy the established FRs. Later, coming back in the functional domain, a lower level is generated, and the process is pursued until the design is completed. A comparison between architect's approach and AD approach is showed in Figure 2.

In general, architectural design approach emphasizes intuition and experience during the co-evolving and iterative concept design phase. But often designer's knowledge and experience are not sufficient due to the complexity of sustainable building design. In addition, the architects have to consider and satisfy also other requirements such as water protection and structural stability. Most of the available tools for designing sustainable buildings are to support late design development and evaluate the sustainability of detailed building projects providing an indication of their performances [Marchesi et al, 2013]. Architect's experience should be supported by systematic approaches to design in order to manage complex problems starting from the early phase of the process.

Using AD, a designer is able to consider all requirements, including sustainable requirements, since AD begins with the definition of a minimum set of independent functional requirements (FRs). In AD, the formulation of the problem and the solutions are developed together with constant shuttling to-and-from problem (what) and solution (how), moving down and decomposing into a hierarchy [Suh, 1990, 2001]. Also, in the architectural design, the decision-making activity is performed by intuition and experience, making decisions among conflicting parameters, defines necessary compromises and optimizes design decisions regarding a varied and complex set of requirements. In contrast, AD provides two design Axioms for designers to make decisions not to couple the FRs and not to make the design too complex. This is especially beneficial in the conceptual phase of the design of sustainable buildings.

In order to show the potentiality of applying AD to the design of sustainable buildings, the conceptual design of a small sustainable house is reviewed. Requirements defined according to the customer needs, urban and building regulations and a sustainable building protocol, CasaClima Nature are progressively considered during the design process. This analysis results in an initial design framework, supported by decision criteria, to address early the design solution toward the established objectives in a systematic way and to assure the design decision consistency along the decomposition process. The research presented in this paper intends to propose the development of a decision-making tool in a Building Information Modelling (BIM) process in which high level design decision support system for architects is integrated in a multi-disciplinary digital information store by a suitable representation [National Institute of Building Sciences, 2007]. In a BIM tool, AD may improve the decision-making activity of sustainable buildings design from the initial phase to the detail technical design phase.

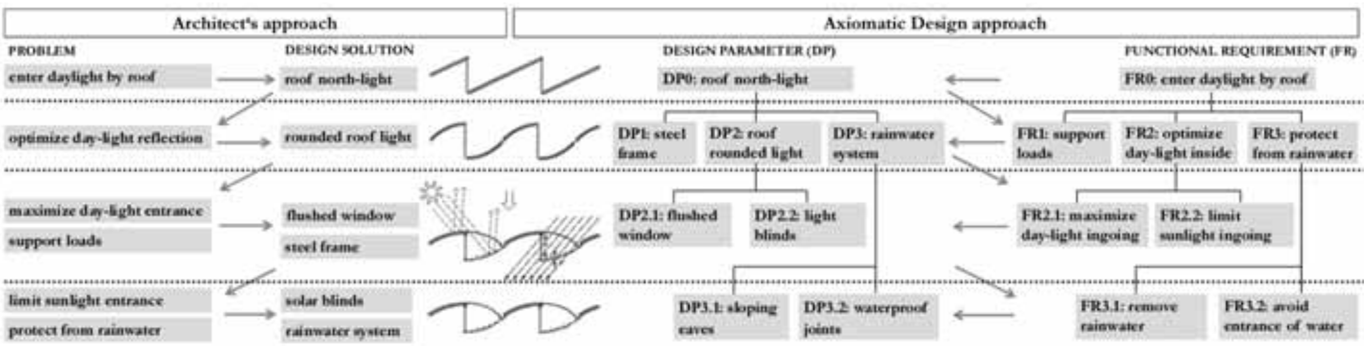

Figure 2. Comparison between architect's approach and AD approach on a roof design case

2 CONCEPTUAL DESIGN DEVELOPMENT OF A SUSTAINABLE BUILDING

The conceptual design development of a sustainable building case study is reviewed using AD: the design requirements and the related design solution are decomposed down coherently in a systemic way transforming the design goals into a concept design solution through the process of mapping, zigzagging and decomposition. AD decomposition is performed starting from the defined customer attributes (CAs). In order to ensure that all needs are addressed, all people involved in the design process should be initially considered. In this case study, the initial set of CAs is defined collecting data from the end users that are also those who make the buying decision about building and maintenance, the government and local municipality and the sustainable building assessment agency. The owners require a sustainable house for 2 people in a timber panel structure with zero energy consumption and zero carbon emissions annually, also known as a zero net energy building (NZEB). It should be an energy efficient house with passive energy use and grid connection, enabled to generate energy from renewable sources to compensate for its own energy demand. Moreover the customers require that the design is pleasantly integrated in the natural and architectural context; the cost is less than 200 000 euro and the construction is built within 3 year The design solution must also satisfy design requirements defined by local and national rules regarding safety (earthquake risk), comfort (thermal, hygrometric, acoustic, light) health (radon, electromagnetism, air quality pollution) usability, maintenance and energy efficiency [Comune di Bolzano, 2005, 2013; Repubblica Italiana, 1991, 2000, 2001, 2008]. In order to satisfy the demand for a certified sustainable design solution, a green building certification assessment, CasaClima Nature, developed by Agenzia CasaClima in Italy, is adopted. CasaClima Nature protocol consists of a set of eight requirements regarding skin energy efficiency, overall energy efficiency, environmental impact of construction materials, water impact, indoor air quality, daylight comfort, acoustic comfort, radon protection expressed in terms of parameters and limit values [Agenzia CasaClima, 2013]. Specifications about the site and context where the design is located are collected in order to generate a solution integrated in the surrounding and to define specific site features according to urban, building and environmental regulation requirements. The site is a rectangular piece of land in a semi-rural and low density zone on the border of the city in the north Italy composed of green spaces and sparse rural constructions. Typical local architecture is characterized by rock basement, timber balcony at upper levels and timber pitched roof. The area presents a low risk of earthquake and no-risk of landslips with loose and low resistant ground. The climate is evaluated cold (E climate zone) according to the national climate zone classification [Repubblica Italiana, 1993]. The site is oriented toward south; it is a well-sunny area without visual obstructions. The area benefits by regular wind from south in summer and occasional wind from north in winter and spring. Regarding the renewable energy sources available, in the site it is possible to have available energy by solar energy panels and photovoltaic panels, by ground probe and by biomass. In regard to environment aspects, the presence of radon is low in this area and specific protection measures are not required. The noise level is also low and the electromagnetism does not exceed the law limits above which specific measures are compulsory. Anyway there is a problem of air quality pollution in winter due to the smog stagnation for absence of wind.

Based on customer's requests, the top-level design goal is described in terms of FR, and the corresponding DP as follows:

FR0 = provide a sustainable house for two people, energy efficient, grid connected, able to generate renewable sources energy to make up for its own energy demand

DP0 = sustainable NZE solar two-room house project

According to the Italian technical rule UNI 10838-1999 [UNI, 1999], a building must provide usable space to accommodate the user activities and assure the permanence of safe, healthy and comfortable conditions for the users with regard to varying behavior of the external environment. Building design is composed of two systems: space system and technology system. Space system defines a combined set of inside-outside usable spaces in their functions, dimensions, shape, reciprocal position and position with consideration for the site. It includes the circulation within these spaces to allow the flow of habitants and things and the connectivity between inside and outside. Technology system consist of an integrated set of building components providing partially or totally specific functions to guarantee and maintain conditions of safety, health and comfort. Space and technology systems should be composed together and in relation with the physical surroundings to create aesthetic harmony. The aesthetic quality of architectural design is given from proportion, light, texture and color of both systems combined in an ordered form and integrated with the surrounding [Ackerman, 2013].

The top-level FR0 for a chosen DP0 is decomposed:

FR1 = accommodate client's living activities for two people

FR2 = support client's activities (protect the internal environment, relate to the external environment, provide resources and equipment)

At the highest level of the design process, a design solution determined by the architects must satisfy the two FRs by a physical system that combines space and technology into a harmonious entity. The definition of the design solution is constrained by urban and building regulations regarding maximum height, maximum covered surface and minimum inside surface and by user's aesthetic requirements such as the maintaining of some features such as inclined roof typical of the local traditional architecture (Table 2).

Table 2 First level Cs

C1	made by a timber technology *(customer need)*
C2	guarantee volume smaller than 400 m3 to limit cost to 200.000 euro *(customer need)* and at least minimum dwelling volume of 20 m3 *(building regulation)*
C3	provide renewable source energy to integrally cover its own energy demand *(customer need)*
C4	adopt typological features of local architecture: pitched roof and well-oriented balcony *(customer need)*
C5	use a semi-prefabricated technology to construct building within 3 year *(customer need)*
C6	observe plan regularity *(building regulation)* and limit span to 5 m to optimize structure construction cost *(customer need)*
C7	be oriented toward south with openings toward south to optimize passive solar energy use *(building regulation)* and south-north to foster natural ventilation *(customer need)*
C8	observe maximum built index (2 m3/m2), maximum height (10.5 m), maximum cover surface rate (33%) and minimum distance from borders (5 m) and from existing buildings (10 m) *(building regulation)*
C9	if ratio between thermal loss surface and volume is lower than 0.2, overall energy efficiency in winter (EPw) should be lower than 46.8 kWh/m2yr; if S/V is bigger than 0.9, EPw limit should be lower than 116 kWh/m2yr.. Intermediate values are defined by linear interpolation *(building regulation)*
C10	supply renewable source energy (by sun, ground, wind or biomass) *(building regulation)*
C11	integrate any photovoltaic and solar energy systems on the pitched roof *(building regulation)*
C12	locate any solar energy system on the roof surface oriented toward south *(building regulation)*
C13	obstruction absence on 60% involved roof surface in case of solar energy system (*building regulation*)
C14	use construction materials with environmental impact index smaller than 300 points *(CasaClima)*

According to the defined FRs and constraints (Cs), a rough volume is proposed. Based on the initial mapping, the DPs that satisfy the defined set of FRs are chosen as:

DP1 = two-room house
DP2 = building body in timber panels with an integrated active solar energy systems

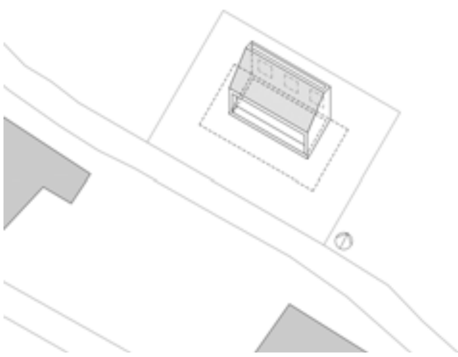

Figure 3. Initial design solution

The defined volume (Figure 3) is located on the site in relation to the access from the road, observing specific distances from the propriety line and roads according to the conditions required by the local urban plan.

In order to build an energy self-sufficient building, the volume is oriented towards south to optimize the passive and active uses of the solar energy. Also CasaClima requirements impose constraints in the initial decomposition: low environmental impact of the construction materials should be guaranteed.

In order to check the coupling of the DPs chosen, the corresponding design matrix (DM) is developed (Table 3).

Table 3 First level DM

	DP1	DP2
FR1	X	-
FR2	X	X

The resulting DM is triangular: the FRs are decoupled which implies that FRs can be satisfied only when FR1 is determined before FR2. Therefore if the planned space is adjusted first, the function of providing safe and comfortable conditions could be met without affecting the planned space.

The FRs and DPs are decomposed into lower level ones using the framework proposed by Italian organizations for residential building CER [CER, 1984] and the Italian organization for standardization UNI [UNI, 1981]. Regarding space aspects, the customers specify further their needs: a small dwelling area, an open area for outside living activities and a parking area for a car. The solution should provide a bright and sunny place for living.

The FR1 is decomposed further to a lower level FRs in order to provide specific areas for the user's activities. The lower level of FR1 is defined as follows:

FR1.1 = accommodate dwelling activities
FR1.2 = accommodate outside living activities
FR1.3 = accommodate outside service activities: waste collecting and car parking.
FR1.4 = connect outside-inside
FR1.5 = connect activities

The design solution is subjected to constraints imposed by the users and the local building rules as showed in the following Table 4.

Table 4 Second level Cs - FR1

C1.1	locate outside living activities towards south *(customer need)*
C1.2	guarantee at least a dwelling volume of 15 m3 for each bed *(building regulation)*
C1.3	guarantee circle maneuver space of 1.5 m (diameter) in the entrance area for people with motor disabilities *(building regulation)*
C1.4	guarantee at least a pedestrian path with 1.2 m wide of and 12% slope ramp in case of level difference for motor disability people *(building regulation)*
C1.5	waste collection space must be accessible to users and waste collection service *(building regulation)*

A solution is defined according to the FRs and observing the set Cs (Figure 4). The solution is developed considering the user requests and the defined Cs. The dwelling area is located in the site observing the set distances from the propriety line and roads according to the local urban plan. The outside living activity area is placed in front of the dwelling facing toward south and connected with the dwelling. A site entrance for pedestrian and vehicular is provided with an adjacent waste collection area.

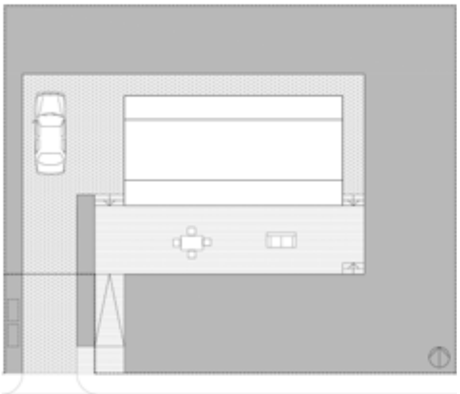

Figure 4. Site space system

The related DPs that satisfy the FRs listed above are:
DP1.1 = dwelling area
DP1.2 = paved area toward south
DP1.3 = service area composed of waste collecting area near the road and parking area
DP1.4 = pedestrian-vehicular site entrance on road side
DP1.5 = pedestrian-vehicular path

The evaluation of the Cs compliance is performed. The check of the DM is shown in Table 5.

Table 5 Second level DM FR1

	DP1.1	DP1.2	DP1.3	DP1.4	DP1.5
FR1.1	X	-	-	-	-
FR1.2	-	X	-	-	-
FR1.3	-	-	X	-	-
FR1.4	-	-	-	X	-
FR1.5	-	-	-	-	X

The resulting DM is diagonal: the Axiom one is satisfied.

The customers provide further specifications regarding their functional needs. It is requested: a pleasant living open space with kitchenette and a study area, a private area with bathroom and double bedroom, and a loggia. The main spaces should be sunny, well-lighted and ventilated.

The FR1.1 is decomposed further to a lower level FRs in order to provide specific areas for the user's activities. The lower level of FR1.1 is defined as follows:
FR1.1.1 = accommodate cooking-dinning-living activity
FR1.1.2 = accommodate study/work activity
FR1.1.3 = accommodate cleaning activity
FR1.1.4 = store service systems/things
FR1.1.5 = accommodate sleeping activity for a couple
FR1.1.6 = accommodate living activities outside in a sheltered place
FR1.1.7 = connect inside-outside
FR1.1.8 = connect inside activities

The design is subjected to constraints specified by the customers or imposed by the building regulation (Table 6).

Table 6 Third level Cs - FR1.1

C1.1.1	locate living activities towards south *(customer need)*
C1.1.2	locate openings on the windward and leeward sides *(customer need)*
C1.1.3	provide a double-height living space with zenith light *(customer need)*
C1.1.4	guarantee average interior height of 2.70 m, area of 9 m2 for single bedroom, 14 m2 for double-bedroom and living room, width of 1.10 m for corridor *(building regulation)*
C1.1.5	total opening surface regarding each room (living room, kitchen and bedroom) should be at least 1/8 of the room area and even at least equal to 1 m2 *(building regulation)*
C1.1.6	guarantee circle maneuver space of 1.5 m (diam.) for motor disability people (living room and bathroom) *(building regulation)*
C1.1.7	guarantee at least door passage width of 0.80 m for motor disability people *(building regulation)*

According to them, each activity must provide adequate space that observes defined minimum dimensions (area and height); each space must be sized to be equipped with system networks and terminals, fixtures and furniture. Some spaces (access, living room and bathroom) must be planned to allow the accessibility of people with physical disabilities. Finally the definition of the space solution is bounded by aesthetic requirements also. A solution is defined according to the CAs and observing the set local rules and Cs (Figure 5).

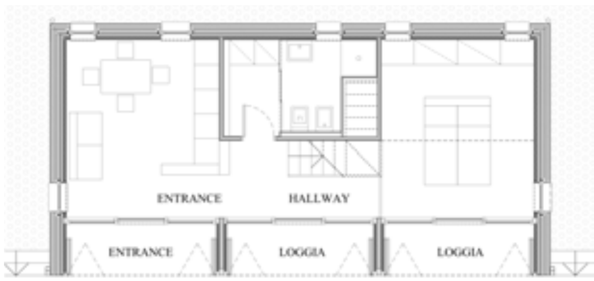

Figure 5. Building space system

The related DPs that satisfy the FRs listed above are:
DP1.1.1 = living-room on south with kitchenette
DP1.1.2 = study-room at mezzanine with a skylight
DP1.1.3 = bathroom
DP1.1.4 = storage room
DP1.1.5 = double bedroom
DP1.1.6 = loggia toward south
DP1.1.7 = entrance and openings
DP1.1.8 = hallway and staircase

The corresponding DM is shown in Table 7.

Table 7 Third level DM - FR1.1

	DP 1.1	DP 1.2	DP 1.3	DP 1.4	DP 1.5	DP 1.6	DP 1.7	DP 1.8
FR1.1	X	-	-	-	-	-	-	-
FR1.2	-	X	-	-	-	-	-	-
FR1.3	-	-	X	-	-	-	-	-
FR1.4	-	-	-	X	-	-	-	-
FR1.5	-	-	-	-	X	-	-	-
FR1.6	-	-	-	-	-	X	-	-
FR1.7	X	-	-	-	-	X	X	-
FR1.8	-	-	-	X	-	-	-	X

The resulting DM is triangular. This solution is acceptable as long as DP1.7 is defined after DP1.1 and DP1.6, and DP1.8 is set after DP1.4. An alternative solution with similar DPs is evaluated to reduce couplings (Figure 6).

Figure 6. Building space system - alternative

The corresponding DM is shown in Table 8.

Table 8 Third level DM - FR1.1

	DP 1.1	DP 1.2	DP 1.3	DP 1.4	DP 1.5	DP 1.6	DP 1.7	DP 1.8
FR1.1	X	-	-	-	-	-	-	-
FR1.2	-	X	-	-	-	-	-	-
FR1.3	-	-	X	-	-	-	-	-
FR1.4	-	-	-	X	-	-	-	-
FR1.5	-	-	-	-	X	-	-	-
FR1.6	-	-	-	-	-	X	-	-
FR1.7	-	-	-	-	-	-	X	-
FR1.8	-	-	-	X	-	-	-	X

Regarding the technology system, customers require high comfort, energy efficiency and independence and context integration using local typical materials and technologies.

According to the decomposition proposed by UNI [UNI, 1999], the FR2 is decomposed into a lower level FRs to provide conditions of safety, health and comfort and to supply resources. The lower level FR2 is defined:

- FR2.1 = support loads and external actions
- FR2.2 = separate inside from outside
- FR2.3 = divide inside spaces
- FR2.4 = divide outside spaces
- FR2.5 = provide and distribute resources (energy and materials) to support user's living
- FR2.6 = support inside client's living activities
- FR2.7 = support outside client's living activities

The technology system is mostly constrained by the local building rules and CasaClima protocol (Table 9).

Table 9 First level Cs - FR2

C2.1	provide renewable energy equal to the building energy demand *(customer need)*
C2.2	be connected to urban energy supply *(customer need)*
C2.3	adopt local vegetation and typical features (pitched roof and well-oriented balcony) and materials (roof tiles, wall plaster) of local architecture *(customer need, building regulation)*
C2.4	guarantee a load-bearing structure able to resist to the provided loads and the peak ground acceleration due to a seismic action equal to 0.05 g *(building regulation)*
C2.5	guarantee envelope energy efficiency in winter smaller than 50 kWh/m2yr *(building regulation, CasaClima)*
C2.6	observe envelope energy efficiency in summer smaller than 30 kWh/m2yr *(building regulation)*
C2.7	guarantee overall energy efficiency in winter (EPw) smaller than 110 kWh/m2yr *(building regulation)* that is smaller than 20 kg CO2eq/m2 yr *(CasaClima)*
C2.8	provide at least heating system, water-sanitary system, mechanical ventilation (in space without windows) and disposal system *(building regulation)*
C2.9	at least 1.2 kW photovoltaic energy system power if provided *(building regulation)*
C2.10	guarantee global average seasonal energy efficiency of plant greater than (75 + 3 log Pn)%, (Pn = rate output power) *(building regulation)*
C2.11	provide a rainwater gutter system connected to the urban disposal system *(building regulation)*
C2.12	observe ground water permeability index RIE equal to 4 *(building regulation)*
C2.13	use materials with environmental impact index smaller than 300 points *(CasaClima)*
C2.14	observe the formaldehyde limit of 0.05 ppm in the indoor air emitted by pasted wood products, the formaldehyde limit of 10 ppm, without heavy metals, organic compounds and risk warnings emitted by interior paints and the VOCs limit smaller than law limit *(CasaClima)*
C2.15	guarantee water impact index greater than 35% *(CasaClima)*

According to national and local building regulations, structural safety must be guaranteed and building shell and service systems must assure the high energy efficiency and internal minimum conditions for thermal, daylight, acoustic comfort and air exchange. Building service systems must generate the demanded energy by renewable sources. Moreover in order to build a sustainable building according to CasaClima Nature, additional restrictive bounds relative to water impact and low environmental impact of construction materials limit the design solution. Finally the definition of the solution is bounded by aesthetic requirements also.

A design solution is proposed that satisfy the specified FRs and imposed Cs (Figure 7).

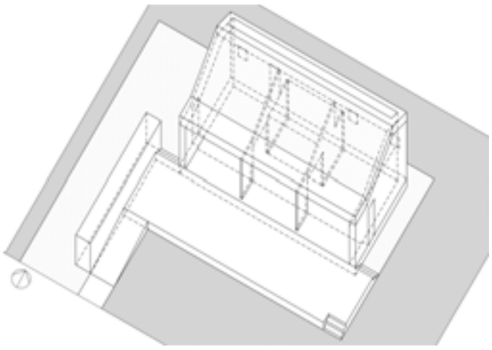

Figure 7. Technology system

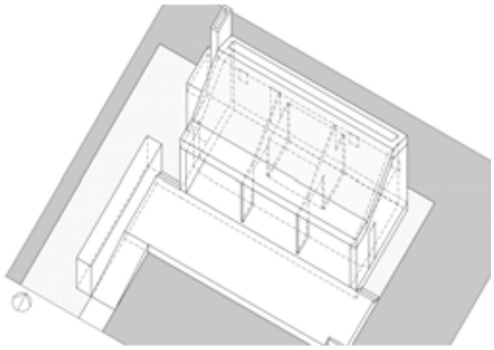

Figure 8. Technology system - alternative

The corresponding DPs are defined as follows:

DP2.1 = load-bearing structure in wood beams
DP2.2 = high energy efficient building shell with big openings toward south
DP2.3 = interior walls
DP2.4 = hedge of local bush and perimeter fence
DP2.5 = service systems with solar and photovoltaic energy systems integrated on the roof
DP2.6 = interior furniture and finishing with low indoor emissions
DP2.7 = outside finishing with high ground water permeability and vegetation

The DM is shown in Table 10.

Table 10 Third level DM - FR2

	DP 2.1	DP 2.2	DP 2.3	DP 2.4	DP 2.5	DP 2.6	DP 2.7
FR2.1	X	-	-	-	-	-	-
FR2.2	X	X	-	-	-	-	-
FR2.3	-	-	X	-	-	-	-
FR2.4	-	-	-	X	-	-	-
FR2.5	-	X	-	-	X	-	-
FR2.6	-	-	-	-	-	X	-
FR2.7	-	-	-	-	-	-	X

Some couplings are noticed: the continuous load-bearing structure contributes also the separation from inside-outside; the roof dimensions influence the functions of proving solar energy because the solar energy system is integrated in the roof. The solution is acceptable if DP2.2 is defined after DP2.1, and DP2.5 is set after DP2.2. In order to reduce the coupling between the supply of the demanded energy by renewable energy sources and the available shell area for the integration of the energy system, an alternative solution is evaluated.

This solution (Figure 8) is based on biomass energy source and solar hot water source; a further space for the biomass storage on the site and a roof surface for the solar energy panels are required.

The DP2.5 is changed and is expressed as follow:

DP2.5 = service systems with biomass energy source and solar hot water panels

The resulting DM is similar to Table 10, but in this case the coupling is simpler: only the hot water supply by renewable energy source is bound by the roof. This means that the energy supply is just influences by the roof slope.

Regarding the shell, customers require closures able to generate comfortable and energy efficient spaces. Moreover building appearance should contribute to the context integration using local materials and techniques.

According to the decomposition proposed by UNI [UNI, 1981], the FR2.2 is decomposed into a lower level FRs to provide safe, healthy and comfortable conditions. The lower level FR2.2 is defined as follow:

FR2.2.1 = divide spaces from outside vertically
FR2.2.2 = divide spaces from ground
FR2.2.3 = divide spaces from outside horizontally

The design of the envelope is mostly constrained by the building rules and CasaClima protocol (Table 11).

Table 11 Second level Cs - FR2.2

C2.2.1	adopt typical materials of local architecture: roof tiles, wall plaster and timber *(customer need)*
C2.2.2	guarantee static transmittance of each building component smaller than 0,8 W/m2K *(CasaClima)*
C2.2.3	observe dynamic transmittance smaller than 0.10 W/m2K and phase shift greater that 12h for vertical opaque closure and horizontal opaque closures *(building regulation)*
C2.2.4	provide external shadings on windows *(building regulation)*
C2.2.5	rainwater must be moved away from the building *(building regulation)*
C2.2.6	the number of air changes per hour should be less than 0.6 h-1 when the indoor ambience is subjected to a pressure of 50 Pa above the atmosphere *(CasaClima)*
C2.2.7	any interstitial condensation should result lower than the law limit according to the material type *(building regulation)*
C2.2.8	internal superficial temperature on building joints should be bigger than 17°C *(CasaClima)*
C2.2.9	average daylight factor in the main spaces should be bigger than 2% *(building regulation - CasaClima)*
C2.2.10	guarantee envelope acoustic insulation bigger than 40 dB *(building regulation)*
C2.2.11	exterior walls must be plastered *(building regulation)*
C2.2.12	use materials with environmental impact index smaller than 300 points *(CasaClima)*

A design solution is proposed that satisfy the specified FRs and imposed Cs (Figure 9).

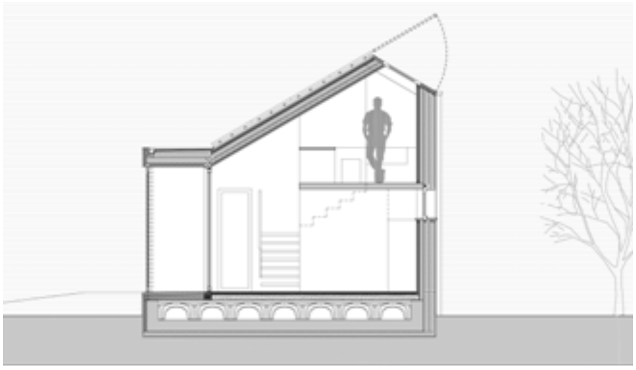

Figure 9. Building shell

The corresponding DPs are defined as follow:
DP2.2.1 = opaque and transparent vertical closures
DP2.2.2 = floor on the ground
DP2.2.3 = pitched roof and skylight
The check of the DM is shown in Table 12.

Table 12 Second level DM - FR2.2

	DP2.2.1	DP2.2.2	DP2.2.3
FR2.2.1	X	-	-
FR2.2.2	-	X	-
FR2.2.3	-	-	X

On the base of the DM, the design is defined uncoupled. In case of traditional technology solutions, this DM results commonly.

3 DISCUSSION AND CONCLUSIONS

In general, architectural design approach emphasizes intuition and experience during the co-evolving and iterative concept generation. Architects tend to identify a rough concept quickly based on a limited set of design objectives. Then the initially defined problems are constantly reformulated, co-evolving together during the design process until the relevant issues of the specific task and the related design solution are defined. This kind of serial and iterative approach makes sustainable building design a complex design problem due to the numerous requirements and constraints that architects must consider in the early stage of the design process. In this stage, decisive design decisions regarding performances, appearance and also sustainability are to be made. In order to improve the conceptual design generation in the sustainable building design, AD approach is proposed and the conceptual design development of a sustainable building case study is reviewed. In this case study, a minimum set of independent FRs is defined based on all requirements including sustainable issues. Performing the AD approach through decomposing the initially defined functional requirements in a systematic manner requires extensive amount of technical and regulatory information during the design process. At the same time, searching for the corresponding design solution to satisfy the specified requirements requires a decision base how to make good decisions at the early stage of design. This study shows the potentialities of applying AD to the architectural design to support the full inclusion of all the requirements and architect's decision-making activity for the development of sustainable solutions starting from the initial phase of the process. This research intends to propose this kind of framework for a design support in a BIM tool in order to improve the decision-making activity in the initial phases of the design process. The application of the AD approach allows performing the control of process and solution quality. In the next future, the research intends to evaluate and compare alternative solutions.

In engineering design, solution concepts are synthesized only after rigorous and exhaustive analysis of user requirements and other basic features of the problem while architecture stresses the importance of generating solution concepts early in the design process, drawing upon presuppositions. As the complexity of architectural design is increasing due to the need for addressing more environmental and energy requirements along with social-economic considerations, an approach able to integrate both perspectives could be effective. In this way, this paper describes the effort to apply AD to the conceptual design of sustainable buildings for designing buildings in which form, function and efficiency are consistent combined according to the stakeholder needs and the existing context.

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APPLICATION OF AXIOMATIC DESIGN TO ELECTRIC BICYCLES

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ABSTRACT

Market conditions and the situation inside electric bicycle producing companies require a product development process which ensures that customer requirements are met and problems in product design are identified at an early stage. Therefore, this research takes an analytical approach towards the development of electric bicycles by applying Axiomatic Design, which offers both a holistic framework for product development as well as analytical mapping in between the individual steps of the design process. The application is done as a case study at a German electric bicycle manufacturing company and based on a collection of customer feedback as well as the contribution of the company's management. In the design process, functional requirements and design parameters are formulated and a design matrix is created to identify and resolve coupling issues. Further, constraints such as price, weight and ease of use are taken into account and process variables for practical implementation are suggested. The study results in recommendations for a specifications sheet of a new electric bicycle model. It is concluded that Axiomatic Design is of substantial advantage to the case company's product development. Future research is suggested to improve the level of detail and quality of electric bicycles designed by Axiomatic Design.

Keywords: axiomatic design, electric bicycles, market requirements specification

1 INTRODUCTION

A central issue in product design is the fulfilment of customer needs. At the same time, efficient engineering of products is important to avoid rework and reduce product life cycle cost. Both of these factors are especially true for the development of electric bicycles at Third Element GmbH & Co. KG (further referred to as 'Third Element'). First, the market for electric bicycles is rapidly growing, dynamic and diversified (ZIV 2013: 63). This makes it challenging to design products that successfully address customer needs, especially for small companies such as Third Element, which do not have the resources for extensive market research. Second, it is crucial for those companies to organize their development processes in an efficient way in order to avoid rework. Recalls of electric bicycles and bankruptcies of firms in the industry have shown that the complexity of electric bicycles is often underestimated and mistakes in their design are recognized too late (myStromer: 2013).

Axiomatic Design has the potential to address both of these issues. The importance of customer needs is addressed by putting customer feedback at the very beginning of the design process and effectiveness is pursued by taking an analytical approach to transform those requirements into functions and physical properties of a product. The advantages of this methodology are better matching of product functions with customer requirements, better consistency in between functions and physical parts and, thus, more efficiency and less cost during the life-cycle of a product (Axiomatic Design Solutions 2014).

There are numerous studies connected to electric bicycle design using other methods than Axiomatic Design. Hsu, Liu and Chan (2012) have studied power management of electric bicycles based on reinforcement learning. Xiao, Liu, Du, Wang and He (2012) have applied topology optimization to frame design of electric bicycles. Wu and Sun (2013) have designed and analysed a novel speed-changing wheel hub with an integrated motor for electric bicycles, using analytical modelling. Liang, Lin and Chang (2006) have used a fuzzy logic and single chip approach to develop an intelligent control for electric bicycles. Hua, Kao and Fang (2011) have designed a regenerative braking system for electric bicycles by experimenting with digital signal processing. Further studies apply Axiomatic Design to the design of non-electrical bicycles, for example the case study conducted by Guo, Jiang, Zhang and Tan (2012). However, little research has been done on the combination of Axiomatic Design and electric bicycles.

In order to fill this gap and to explore how Axiomatic Design can help to deal with the issues in the field, two questions are addressed in this study: "How does an Axiomatic Design based electric bicycle look like?" as well as "What are the opportunities and limitations of Axiomatic Design with this case?" The first question marks the main goal of this study, the creation of a proposal for an electric bicycle which fulfils the needs of Third Element's customers in the best possible way. The second question aims at a brief evaluation of the approach taken, possibly helping the case company with the decision on further pursuing this matter.

In the following, information on the background of this case is presented. Subsequently, the data collection is described, followed by the application of the Axiomatic Design framework: The formulation of functional requirements, design parameters, process variables and constraints as well as the creation of a design matrix. Finally, the results of this process will be presented and discussed.

2 BACKGROUND

This research is based on the case of Third Element, an original equipment manufacturer (OEM) of electric bicycles located in Gauting, greater area of Munich, Germany. Third Element was founded in 2009 when prototypes of a newly developed electric bicycle were tested. This model combined a full suspension mountain bike with a powerful electrical assist, which was an innovation to the market at the time. In 2011, the company received the official listing from the Federal Office for Motor Traffic Germany as a certified manufacturer, enabling the company to series production also of such electric bicycles that require a type approval. In 2012 Third Element presented a new model line-up, adding hard tail mountain bikes and bicycles for urban use to the existing models of full suspension mountain bikes. With this step the company made a move to becoming a full-range bicycle manufacturer. (Third Element 2014a.)

Third Element's products are positioned in the premium segment of the electric bicycle market. The premium status is claimed by using quality components and manufacturing in Germany as well as superior appearance and technology with „the aim of giving users the possibility of moving in a modern, stylish and highly efficient way" (Third Element 2014a). With the numerous customer expectations for premium products on the one side, and the high cost for quality components and manufacturing on the other, Third Element often faces the challenge of keeping their products both attractive and profitable.

Figure 1. An electric bicycle by Third Element.(Third Element: 2014b)

3 METHOD

This research was carried out as a single company case study for Third Element in Munich, Germany. The proceeding was divided into four steps: First, a data collection on customer feedback was conducted within the case company in order to assess the needs of their customers. Second, a preliminary design was made and presented to the General Manager of Third Element. Third, a mid-term review was held, in which the General Manager added his comments and suggestions to the preliminary design. Last, the authors improved and finalized the design.

3.1 DATA COLLECTION

The Axiomatic Design process starts with the customer domain, which assesses the needs of customers. In order to familiarize with the needs of Third Element's customers, an extensive data collection was conducted within the company. All data used in this research is secondary data from organisational records of Third Element. The records comprise notes from trade fairs and exhibitions, test drive evaluations, emails from retailers and users, internal evaluations and a survey among retailers conducted by a consultant agency. The oldest document taken into account was an employee's note from May 2010 and the newest was a test drive evaluation from November 2013. Based on this material, a total of 440 customer statements were identified, which originated eiter from consumers, business customers or internal evaluations.

Sorting and processing of the data was done manually. Due to the number of customer statements, redundancy, and varying impact on decision-making, a 'sort and combine' approach was taken. This means that statements to the same topic were sought and if suitable, condensed into a functional requirement (FR) or design parameter (DP) as illustrated by the example given in Figure 2.

Id.	Customer statement
49	"Quite a lot of force needs to be applied to the brake levers to generate an acceptable deceleration."
62	"The brakes were still sufficient, although you could feel that they were stressed."
217	"Insufficient brakes."

FR_7: Stop sufficiently
A function that provides sufficient power to stop the vehicle, giving the user a feeling of control and safety.

Figure 2. Combination of multiple customer statements into one FR.

3.2 DESIGN

Based on the 440 customer statements collected and the expertise of the General Manager, FRs and DPs were formulated. The structure of the modules follows the company's modular framework for electric bicycles (Third Element: 2012b).

3.2.1 TOP-LEVEL FRS AND DPS

Table 1. Top-level parameters for electric bicycle design.

Index	FR	DP
1	Provide basic structure	Frame assembly
2	Allow movement	Wheel set
3	Drive electrically	Electric drive assembly
4	Drive mechanically	Mechanical drive assembly
5	Interact with user	Human interaction components
6	Suit individual user needs	Flexible accessories packages
7	Stop sufficiently	Quality hydraulic disc brakes
8	Allow use in darkness	Lighting package, frame mount

The design equation is given by

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \\ FR_4 \\ FR_5 \\ FR_6 \\ FR_7 \\ FR_8 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ X & X & 0 & 0 & 0 & 0 & 0 & 0 \\ X & X & X & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & X & X & 0 & 0 & 0 & 0 \\ 0 & X & 0 & 0 & X & 0 & 0 & 0 \\ X & 0 & 0 & 0 & 0 & X & 0 & 0 \\ X & 0 & X & 0 & 0 & 0 & X & 0 \\ X & 0 & 0 & 0 & 0 & 0 & 0 & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \\ DP_4 \\ DP_5 \\ DP_6 \\ DP_7 \\ DP_8 \end{Bmatrix}. \quad (1)$$

3.2.2 DECOMPOSITION OF FR_1 AND DP_1

Table 2. Decomposed parameters for frame design.

Index	FR	DP
11	Provide strong support	Frame composed of closed-section aluminium members
12	Smooth surface	Quality weld seams
13	Frame shock absorption	Suspension front fork
14	Unique design	Double top-tube
15	Easy to clean	Wet paint

The design equation is given by

$$\begin{Bmatrix} FR_{11} \\ FR_{12} \\ FR_{13} \\ FR_{14} \\ FR_{15} \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 & 0 \\ 0 & X & 0 & 0 & 0 \\ 0 & 0 & X & 0 & 0 \\ 0 & 0 & 0 & X & 0 \\ 0 & 0 & 0 & 0 & X \end{bmatrix} \begin{Bmatrix} DP_{11} \\ DP_{12} \\ DP_{13} \\ DP_{14} \\ DP_{15} \end{Bmatrix}. \quad (2)$$

3.2.3 DECOMPOSITION OF FR_2 AND DP_2

Table 3. Decomposed parameters for wheels design.

Index	FR	DP
21	High tyre shock absorption	Large diameter tyres
22	Low rolling resistance	Low friction profile

The design equation is given by

$$\begin{Bmatrix} FR_{21} \\ FR_{22} \end{Bmatrix} = \begin{bmatrix} X & 0 \\ 0 & X \end{bmatrix} \begin{Bmatrix} DP_{21} \\ DP_{22} \end{Bmatrix}. \quad (3)$$

3.2.4 DECOMPOSITION OF FR_3 AND DP_3

Table 4. Decomposed parameters for electrical drive design.

Index	FR	DP
31	Propulsion	Motor-/gearbox unit with integrated controller
32	Interaction with electrical drive	High value display
33	Speed metering	Speed sensor, spoke magnet based method
34	Innovative charging	Inductive charging system
35	Control of the electric drive	Controller software
36	Assist during walking	Walking assist
37	Good gearshift performance	Gear sensor
38	Sufficient range	Lithium-ion battery

The design equation is given by

$$\begin{Bmatrix} FR_{31} \\ FR_{32} \\ FR_{33} \\ FR_{34} \\ FR_{35} \\ FR_{36} \\ FR_{37} \\ FR_{38} \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & X & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & X & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & X & 0 & 0 & 0 & 0 \\ 0 & 0 & X & 0 & X & 0 & 0 & 0 \\ 0 & 0 & X & 0 & X & X & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & X & 0 \\ X & X & 0 & 0 & X & X & 0 & X \end{bmatrix} \begin{Bmatrix} DP_{31} \\ DP_{32} \\ DP_{33} \\ DP_{34} \\ DP_{35} \\ DP_{36} \\ DP_{37} \\ DP_{38} \end{Bmatrix}. \quad (4)$$

FR_{32} and DP_{32} may be further decomposed as:

Table 5. Third level display design.

Index	FR	DP
321	Intuitive operation	Graphical user interface (GUI)
322	Good visibility	High contrast screen
323	Sufficient functionality	3 drive modes

The design equation is given by

$$\begin{Bmatrix} FR_{321} \\ FR_{322} \\ FR_{323} \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ 0 & X & 0 \\ 0 & 0 & X \end{bmatrix} \begin{Bmatrix} DP_{321} \\ DP_{322} \\ DP_{323} \end{Bmatrix} \quad (9)$$

FR_{36} and DP_{36} may be further decomposed as:

Table 6. Third level walking assist design.

Index	FR	DP
361	Software function	5 km/h limiter software module
362	User control	On/off button

The design equation is given by

$$\begin{Bmatrix} FR_{361} \\ FR_{362} \end{Bmatrix} = \begin{bmatrix} X & 0 \\ 0 & X \end{bmatrix} \begin{Bmatrix} DP_{361} \\ DP_{362} \end{Bmatrix}. \quad (5)$$

3.2.5 DECOMPOSITION OF FR_4 AND DP_4

Table 7. Decomposed parameters for mechanical drive design.

Index	FR	DP
41	Control application of power	Derailleur gears
42	Compatibility with electric drive	Single speed crank set

The design equation is given by

$$\begin{Bmatrix} FR_{41} \\ FR_{42} \end{Bmatrix} = \begin{bmatrix} X & 0 \\ 0 & X \end{bmatrix} \begin{Bmatrix} DP_{41} \\ DP_{42} \end{Bmatrix}. \quad (6)$$

3.2.6 DECOMPOSITION OF FR_5 AND DP_5

Table 8. Decomposed parameters for human interface design.

Index	FR	DP
51	Saddle shock absorption	Comfortable saddle
52	Steering control	Quality grips

The design equation is given by

$$\begin{Bmatrix} FR_{51} \\ FR_{52} \end{Bmatrix} = \begin{bmatrix} X & 0 \\ 0 & X \end{bmatrix} \begin{Bmatrix} DP_{51} \\ DP_{52} \end{Bmatrix}. \quad (7)$$

3.2.7 DECOMPOSITION OF FR_6 AND DP_6

Table 9. Decomposed parameters for accessories design.

Index	FR	DP
61	Protection from dirt	Quality mudguards without reflector mount
62	Protection from oil and grease	Quality chain protection
63	Goods transport capability	Carrier without light mount
64	Multi-media functions	Mobile phone interface

The design equation is given by

$$\begin{Bmatrix} FR_{61} \\ FR_{62} \\ FR_{63} \\ FR_{64} \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 \\ 0 & X & 0 & 0 \\ 0 & 0 & X & 0 \\ 0 & 0 & 0 & X \end{bmatrix} \begin{Bmatrix} DP_{61} \\ DP_{62} \\ DP_{63} \\ DP_{64} \end{Bmatrix}. \quad (8)$$

3.3 CONSTRAINTS

Table 10. Constraints table.

Index	Constraint	Impacts FR							
		1	2	3	4	5	6	7	8
1	Cost	-	-	-	-	-	-	-	-
2	Weight	-	-	-	-	-	-	-	-
3	Creates fun	-		-	-	-	-		
4	Easy to use	-	-	-	-	-	-	-	-
5	Legal requirements	-	-	-	-			-	-

Table 10 shows the constraints of the design and was adopted from the example of the mechanical design of a chemical-mechanical-planarization machine as described by Suh (2001: 407-440). The constraints are shown on the left side, while the FRs, which may be affected by a constraint are shown on the right side. For example with C_3 (“Creates Fun”), numerous customer statements were found either praising or criticizing the structural behaviour (FR_1) of a bike, while no comments were found regarding FR_2. Therefore, it can be assumed that for the goal of creating a joyful user experience, attention to the emotional perception of FR_1 has to be paid, while with FR_2 it would be sufficient to concentrate on technical requirements only.

The constraints should be understood as an underlying element, which affect all corresponding design decisions. Furthermore it is suggested to create more constraint tables, one for each design level. While Table 10 shows the constraints for the top-level FRs, similar tables should be created for each step in the decomposition process to add more detail to the design.

3.4 DESIGN MATRIX

Mapping in between the functional domain and the physical domain resulted in the design matrix shown in Figure 3. The layout of the design matrix used in this research is a combination of the matrices used by Carnevalli, Miguel and Calarge, (2010: 6) as well as Suh (2001: 282-283). The FRs, as formulated in the previous sections, can be found in rows while the DPs are shown in columns. An "X" at the intersection of a FR and a DP indicates dependence in between both elements, while an empty cell means that there is no dependence. Cells on the diagonal are highlighted in grey, making it easier to see that the result is a lower triangular matrix, which corresponds to a decoupled design. Thus, the design is not coupled but there are interdependencies. For example, FR_{21} (high tyre shock absorption) is not only affected by DP_{21} (large diameter tyres) but also by DP_{11} (frame composed of closed-section aluminium members) and DP_{13} (suspension front fork), because frame and fork dimension have to fit together with tyre dimensions.

FRs \ DPs	1.1	1.2	1.3	1.4	1.5	2.1	2.2	3.1	3.2.1	3.2.2	3.2.3	3.3	3.4	3.5	3.6.1	3.6.2	3.7	3.8	4.1	4.2	5.1	5.2	6.1	6.2	6.3	6.4	7	8
1.1	x																											
1.2		x																										
1.3			x																									
1.4				x																								
1.5					x																							
2.1	x		x			x																						
2.2							x																					
3.1	x							x																				
3.2.1									x																			
3.2.2									x	x																		
3.2.3											x																	
3.3												x																
3.4	x												x															
3.5												x		x														
3.6.1												x		x	x													
3.6.2												x		x		x												
3.7																	x											
3.8	x						x	x	x		x			x				x										
4.1								x									x		x									
4.2								x												x								
5.1						x															x							
5.2																						x						
6.1	x		x																				x					
6.2																								x				
6.3																									x			
6.4																										x		
7	x		x					x																			x	
8			x																									x

Figure 3. Design Matrix.

3.5 Suggestions for PVs

Following the mapping in between the functional and the physical domain, the authors also investigated the process domain. While it was not possible to formulate all process variables (PVs) at the time this research was conducted, suggestions for the realization of those DPs were made, which had enough information available:

- PVs for DP_{12} (quality weld seams) may comprise values related to the welding process such as welding method, type of filler material and degrees of freedom during the welding process (Weman 2012 :210).
- DP_{15} (wet paint) may be further defined by variables relevant to the tasks done in the paint shop, for example the number of layers applied.
- DP_{21} (large diameter tyres) and DP_{22} (low friction profile) may result either from automated or manual ('hand-made') tyre manufacturing processes.
- Since DP_6 (flexible accessories packages) and all of its sub-components are optional parts, it is advisable to define inventory control parameters for the manufacturing process, such as safety stock to meet fluctuations in demand (Hopp and Spearman 2011: 73).
- With DP_7 (quality hydraulic disc brakes) it can be relevant to choose either manufacturing in Germany or manufacturing in other parts of the world.

3.6 Example of Calculating the Information Content

With FR_{13} (suspension front fork) the requirement for a "reasonable amount of travel" (cf. 3.2.2) was discussed. With this wording, it should be questioned what is 'reasonable' and how can the requirement be quantified? The solution can be found in the calculation of the information content.

Assumed that the majority of customers considers a travel of up to 100 mm as reasonable, the system range for this FR is 0-100 mm. Further it is assumed that Third Element wanted to investigate two design options: Fork 1 with 80 mm maximum travel and fork 2 with 100 mm maximum travel.

In case of fork 1 the design range overlaps with the system range by 80 %, which means that the possibility $P_{13\ (Fork\ 1)}$ to meet the requirement is 0.8. Using formula (4), the information content of FR_{13} equals to

$$I_{13\ (\mathrm{Fork}\ 1)} = \log_2 \frac{1}{0.8} = 0.32. \qquad (9)$$

In case of fork 2, $P_{13\ (Fork\ 2)} = 1$ and the information content is

$$I_{13\ (\mathrm{Fork}\ 2)} = \log_2 \frac{1}{1} = 0. \qquad (10)$$

Thus, the information content of fork 1 is higher than that of fork 2, the latter should be become part of the design if this would not violate any constraints.

Calculations of this kind should be done for each element of a design, and the overall information content of the design as a whole should be calculated as well.

4 RESULTS

4.1 THE AXIOMATIC DESIGN BASED THIRD ELEMENT ELECTRIC BICYCLE

Figure 4. Proposed concept.(Agentura repro 2014, Ralf Bohle 2014, Electric Cyclery 2014, Selle Italia 2014, SEW-EURODRIVE 2012, SRAM 2014, Third Element 2012a, Third Element 2014c, Trelock 2014)

A concept for a novel electric bicycle was created that is defined by the following main characteristics:

- An uniquely shaped frame which clearly distinguishes the vehicle from competitor's products,
- a combination of an effective front suspension, comfortable saddle and shock absorbing tyres which provides riding comfort, even though the frame is a rigid construction,
- a gear sensor which makes shifting of gears easily possible even under load conditions, turning a major weakness of electric bicycles into an advantage,
- reduced complexity and the possibility for increased customization by a fully modular arrangement of components and component groups, especially concerning the speed detection system and accessories,
- an innovative and reliable charging system which makes charging of the battery easy and convenient and,
- additional multi-media functions for better human-machine interaction, thereby improving key functionalities such as driving range as well.

The proposed concept further comprises a rigid frame which ensures stability and gives the user a feeling of control and safety, a graphical display providing exactly defined functionality, a speed sensor without interdependencies to other component groups, and intelligent controller software which further improves a variety of performance factors.

All of the above-mentioned characteristics are based on original customer feedback as well as professional expertise, which make the design likely to please the user. The technical realization exhibits reduced dependencies and complexity due to the use of the Axiomatic Design mapping principles. Due to the constraints, which have been paid attention to, legal requirements are still met and price and weight are kept within reasonable limits. Overall, these factors contribute to a design that is likely to be superior to solutions not based on Axiomatic Design.

4.2 OPPORTUNITIES AND LIMITATIONS OF AXIOMATIC DESIGN WITH THIS CASE

All in all, Axiomatic Design showed to be of advantage to electric bicycle development at Third Element.

The application of Axiomatic Design to the case of Third Element's electric bicycle development showed to have substantial opportunities. In his feedback on the results of this study, Third Element's General Manager (2014) pointed out that "Axiomatic Design helps to analyse the capabilities and visualizes the dependencies of the single components" and that "many mistakes can be shown at an early stadium, so time can be saved without getting these results too late in a more advanced stage". He added that fewer mistakes will be done and problematic dependencies can be avoided, especially when teams work together at different departments. Further the General Manger agreed with the starting point of the process, which is user feedback, or – in case of products or components that are completely new to the market – a mix of personal experience, market research, or pilot studies. (General Manager, Third Element (2014.)

Limitations with the application of Axiomatic Design to this case exist, but are minor in their impact and can be dealt with. One limitation may be seen in the workload that comes with the quantitative assessment of the Information Axiom, which appears to be a well-known problem in research on complexity. Already in the 1990s, Calinescu, Efstathiou, Schirn and Bermejo (1998: 724) warned that the task of measuring complexity is time-consuming, requires a lot of involvement and might not be carried out thoroughly. Therefore, an exact calculation of the information content might exceed the resources of small companies like Third Element. As a work-around, the Information Axiom could be assessed in a qualitative way, as done by the authors. Another difficulty comes with mapping from the customer domain to the functional domain. This step can be time-consuming if the number of customer statements is large. Additionally, the mapping process from CAs to FRs is not of the analytical kind as with the other domains, so that designers are asked to come up with their own ideas of defining FRs in the best possible way. This freedom of choice of FRs leaves room for criticism. For example Mann (2002: 4) pointed out that – despite the arguments put forth by users of Axiomatic Design – a large number of freezers with vertically hinged doors had been sold, concluding that the FRs chosen for that design could not be the requirements most important to customers.

5 CONCLUSION

The collection and review of 440 individual customer statements marked the starting point for this case study. Based on the dataset, Axiomatic Design was applied to electric bicycle development at Third Element. This comprised the definition of FRs and DPs, their analytical mapping in order to create the design matrix, the formulation of PVs and constraints, as well as the discussion of the information content. As the result, a novel electric bicycle concept was presented.

Concerning the question on how an Axiomatic Design based electric bicycle is specified, it can be answered that a vehicle design following this approach is defined by six main characteristics organised in a decoupled design with reduced complexity. The main characteristics comprise a uniquely shaped frame, which distinguishes the vehicle from competitor's products, while a combination of comfort elements ensure pleasant riding capabilities. Further the use of a gearshift sensor and the possibility for an inductive charging system are innovative features, which pave the way to the future. In addition to that, flexible accessory packages and additional multi-media functions broaden the customer base and contribute to better human-machine interaction. The Independence Axiom is taken into account by a fully modular arrangement of components, leading to the additional benefit of numerous possibilities for customization. The Independence Axiom has also helped to resolve existing and future coupling problems. The qualitative use of the Information Axiom has led to overall reduced complexity.

The question on the opportunities and limitations of Axiomatic Design with this case was addressed by the collection of feedback from the case company as well as the critical reflection of the design process. It can be concluded that Axiomatic Design bears substantial advantages to electric bicycle development, especially towards two aspects: First, Axiomatic Design helps to translate customer requirements into product specifications by providing an all-encompassing design framework. Second, analytical methods within this framework visualize dependencies in between components of the design. Both aspects together support designers in creating products that meet customer expectations better and require less rework during the development process. Difficulties occurred with the processing of customer statements and the quantitative application of the Information Axiom. With customer statements it was challenging to manually translate them into FRs due to their large number. The quantitative assessment of the information axiom was difficult to realize due to the in-depth system knowledge required on the one hand, and limited resources on the other hand.

Taking into account the challenges identified with mapping from the customer domain to the functional domain, future research may investigate how to combine Axiomatic Design with methods that enable effective processing of large amounts of customer data. If this was possible, the result would contribute towards an even broader framework for analytical product and service design.

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AXIOMATIC DESIGN PRINCIPLES IN TEACHING MANUFACTURING TECHNOLOGY DESIGN - PRELIMINARY APPROACH

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ABSTRACT

The future specialists in the field of manufacturing technologies of mechanical equipments must have adequate knowledge about the possibilities to design and materialize the manufacturing processes. In order to fulfill this requirement, the university curricula include activities in which the students learn to design manufacturing technologies for various parts. Since one is talking about a design problem, one can formulate the question of applying the principles of axiomatic design (AD) for approaching and developing the design of manufacturing processes. The analysis of the stages corresponding to designing manufacturing processes facilitated the definition of the functional requirements. Solutions for approaching these stages were considered as design parameters. The initial analysis showed that a coupled matrix corresponds to the current way of designing manufacturing processes. Some investigations were developed in order to remove the use of the same design parameters for many functional requirements. An uncoupled matrix was thus elaborated and some remarks were formulated in order to find better solutions for design of manufacturing process.

Keywords: axiomatic design, manufacturing process design, functional requirements, design parameters.

1 INTRODUCTION

Manufacturing refers to the process in which raw materials, components, or parts are converted into finished goods that correspond the to customer's expectations or specifications [Manufacturing, 2014, Kalpakjian and Schmid, 2008]. On the other hand, from a technological point of view, manufacturing consists of application of physical and chemical processes in order to change the geometry, properties, and/or appearance of a given workpiece, as a means to make parts or products [Groover, 2007].

A process is the succession of stages through which a product or a phenomenon passes consecutively. Thus, the manufacturing process can be considered as a succession of processing operations or assembling operations through which a certain product is obtained. Within *a processing operation*, a workpiece is transformed from one state of completion to a more advanced state, considered as being closer to the final desired product [Groover, 2007].

Because of the continuous increasing request for new and improved products, manufacturing engineering currently has a high developing dynamics. From the point of view of manufacturing engineering, one can consider two stages:

a) Design of manufacturing technologies and
b) applying manufacturing technologies.

Both activities could be coordinated by specialists in the field of manufacturing engineering.

Since there is a design problem, one could stress that the principles of axiomatic design could be applied for designing processing operations, as a part of the more general concept of *manufacturing technologies*. Another question concerns to the possibility of applying axiomatic design in the training of future engineers in the field of designing manufacturing processes. We do not propose an immediate solution to these problems, but, to begin with, just a more complete formulation of these problems, an analysis of the possibilities of using axiomatic design principles for solving some aspects specific to teaching how to design and optimize manufacturing technologies.

2 DESIGN ACTIVITIES STRUCTURE IN THE CASE OF COLD MANUFACTURING TECHNOLOGY

In the negotiation for manufacturing a certain product, a brief technology study is made, in order to establish/estimate the price of the product; only later the manufacturing technology is developed in detail. Usually, there is the interest of manufacturer to make the product at low cost, in order to maximize the profit and, if it possible, in a short time, so that the problem of manufacturing other products could be also addressed. This study is more detailed when the exigencies are higher or when the number of products to be manufactured is higher; for example, if in the case of low-quantity production, the main technological document is a master process sheet, but in the case of high production, an operation sheet (process plan) for machining is used.

In accordance with some accepted conventions, cold manufacturing technologies are usually executed in workshops where the workpieces are processed by cutting and by plastic deformation at temperatures not higher than 30% of their melting temperature. Yet, the temperature reached by the work zone could exceed the above-mentioned value in some cold processes. For example, in case of grinding processes or electrical discharge machining processes, the temperature in the work zone could reach 900 ^{o} C, or even more, but such processes are usually performed in workshops for cold manufacturing technologies.

There are various points of view concerning the stages of designing the manufacturing technology of a part. From a didactic point of view, when training students in the field of designing manufacturing technologies, one should take into account the following stages: *1)* Analysing the product technical drawings and verifying its manufacturability; *2)* Establishing the type of raw material to be used; *3)* Determining the machining allowances and intermediate dimensions; *4)* Determining the values of processing parameters (here, substages are addressed to select the machine tool, the tools and the devices for processing operations); *5)* Determining the operations time durations; *6)* Evaluating the selected technology from the technological and the economical points of view, or selecting the most appropriate one if two or more technologies were considered; *7)* Elaborating the relevant technical documents (master plan sheet or process plan, list of tools and fixtures, etc.).

In the manufacturing engineering practice, many of these stages are overlapped or more succinctly solved, but from didactical point of view, one considers that the student must know and apply fundamental knowledge about the above-mentioned stages.

Reynal and Cochran noticed that during the attempt to implement lean manufacturing, complementary or contradicting concepts are sometimes used in an ad-hoc basis; they proposed to apply the axiomatic design and developed a methodology in order to establish a sequence of implementation steps of lean changes [Reynal and Cochran, 1996].

Muñoz-Avila and Weberskirch considered that the main tasks that must be performed during the process planning of conventional machining could be: *1*. Identification of the processing areas; *2*. Selection of the machine tools; *3*. Sequencing of tool sets; *4*. Grouping of set-ups; *5*. Selection of machining operations and their sequence; *6*. Selection of the cutting tools; *7*. Selection of clamping devices and positions, and datum surfaces; *8*. Calculation of cutting conditions; *9*. Determining the path of the tools; *10*. Determination of cutting times, non-machining times and costs; *11*. Generation of the NC (numerical control) program to produce the part [Muñoz-Avila and Weberskirch, 1999].

Cochran *et al.* [2000] pondered that a possible solution for optimizing the design of production systems is the segmentation of the manufacturing enterprise in small, flexible and decentralized production units on the basis of an axiomatic design framework; in this way, they took into consideration the decentralization of production control functions to operators found in certain working areas.

N. P. Suh emphasized that manufacturing systems are complex and methods of reduction complexity should be applied. Such a reduction could be achieved by transformation of time–dependent combinatorial complexity into periodic complexity [Suh, 2005].

Amaitik considered that the steps in designing manufacturing technologies could be: Identification of part specifications; Selection of blanks or stock; Selection of machining operations; Selection of machine tools; Selection of cutting tools; Calculation of cutting parameters; Generation of setup plans; Selection of work holding devices (fixtures); Calculation of times and costs; Generation of process plans [Amaitik, 2005].

C. Brown showed that some difficulties specific to teaching traditional design could be avoided or diminished by applying axiomatic design [Brown, 2005]. When the axiomatic design is applied to the manufacturing engineering, he noticed that it is difficult to decouple the functional requirements concerning the cost from other functional requirements. He concluded that the main functional requirements applied to manufacturing processes could be maximizing the value added and minimizing the cost [Brown, 2011].

Gonçalves-Coelho and Mourão developed an AD-based procedure that could be applied to match a product with the most appropriate manufacturing process; they showed that there is a strong correspondence between the design of the products and the manufacturing technology that should be selected to achieve their cost-effective fabrication [Gonçalves-Coelho and Mourão, 2007].

Jeon et al. combined axiomatic design and Taguchi method, in order to solve a multi-response problem corresponding to the manufacturing of insulation for coaxial cables; they considered that the development of manufacturing processes and finding adequate responses for each process variable are possible [Jeon *et al.*, 2008].

Wisk appreciated that the stages for the case of computer-aided process planning are the following: *a)* raw material selection; *b)* process selection; *c)* tool selection; *d)* feed, speed selection; *e)* operation selection; *f)* setup planning; *g)* fixture planning; *h)* part programming [Wysk, 2009].

Housmand and Mokhtar used axiomatic design to create a universal manufacturing platform in an enterprise; they defined the functional requirements and developed design matrixes and equations that characterize the manufacturing platform [Housmand and Mokhtar, 2009].

Weng and Jenq formulated the problem of selecting an appropriate machine tool and related equipment on a basis of axiomatic design. They took also into consideration other aspects that are specific to the design of the manufacturing process (such as machining time, labor cost, machining cost, consumption cost, product quality, etc.); they proposed a hierarchical decision-making model for equipment selection in agile manufacturing units [Weng and Jenq, 2012].

M. K. Thompson highlighted the significance of axiomatic design for the stakeholders in the field of manufacturing processes (manufacturing teams), as stages that are placed just in the design process, inclusively by considering the lean production [Thompson, 2013b].

In addition, M. K. Thompson highlighted five classes of common procedural errors that can be made in the definition of the functional requirements. She appreciated that the investigation of experts' errors in this matter could generate new questions about the axiomatic design research and, in this way, could contribute to the improvement of design education methods [Thompson, 2013a].

3 TEACHING DESIGN OF MANUFACTURING TECHNOLOGIES ON THE BASIS OF AXIOMATIC DESIGN PRINCIPLES

The direct or close customer of the manufacturing technologies designers is the manufacturing workshop. The further customer could be considered the buyer of the product that results from the designed manufacturing technologies.

The main needs of the direct customer and, in fact, the request of the company leaders is the design of cost-effective technologies and, if possible, with high production rates (the last customer need could help the company to manufacture other products in the immediate future period).

There are yet other customer needs to be considered when the customer is the manufacturing workshop: for example, *a)* the designed technology must be adequate to the equipment existing in the workshop, in the manufacturing company or in external operators; *b)* In the first part of the manufacturing route, the operations aiming to prepare the technological bases could placed; *c)* If possible, a maximum number of machining steps could be performed at a single clamping of the workpiece; if this condition is met, a higher machining accuracy and a diminished time required per operation should be possible); *d)* If possible, a minimum number of workpiece fixings could be preferred, also in order to ensure higher machining accuracy and labor productivity; *e)* If possible, the operations should be grouped by considering the machine tools placement in the workshop; *f)* If possible, an optimized batch size should be used, etc.

The quality of the product will not be discussed here since technologies that do not allow obtaining the product in accordance with the quality requests is not taken into consideration.

The practice of designing manufacturing technologies proved that the problem is not simple and usually some simplifications are adopted.

Thus, in teaching designing manufacturing technology, just the first-level functional requirements that result from the customer needs are initially taken into consideration.

An equation for calculus of the production cost C of a single product (manufacturing cost) in the manufacturing workshop could be written by simplifying a more complex relation [Balakshin, 1971] as follows:

$$C = M + W + L \quad (1)$$

where M is the cost of materials required per unit of production, W is the sum of the wages expended per unit of production and L is the overhead expenses.

One can compute the sum of wages, S, by considering the sum of the products obtained by multiplying the standard times T_{pi} per piece at the ith machining operation by the salaries expressed per minute, $S_{min\,i}$, of the involved workers:

$$S = \sum T_{pi} S_{\min i} \quad (2)$$

In the first stage, the overhead expenses L can be estimated by means of the equation:

$$L = kS \quad (3)$$

where k is the fraction that results from distributing the overhead expenses.

In this way, the second-level functional requirements that goes after the first-level functional requirement concerning to the necessity to ensure a minimum cost C of the designed technology (FR1: Minimize the cost of designed technology) could be:

FR1.1: Minimize the row material cost;
FR1.2: Minimize the admissible machining allowances;
FR1.3: Minimize the number of processing operations;
FR1.4: Minimize the cost of using machine tools;
FR1.5: Minimize the tools costs;
FR1.6: Minimize the expenses of the necessary fixtures (in the education system applied in Romania and in other East European countries, there is the concept of *technological system* which is considered as including machine tool, fixture, jigs and workpiece);
FR1.7: Minimize the cost of the jigs;
FR1.8: Minimize the workers' salaries;
FR1.9: Minimize the overheads.

The labor productivity for the operation ith can be estimated by means of the standard output, Q_i, by taking into account the time T_{pi} required per operation [Balakshin, 1971]:

$$Q_i = \frac{1}{T_{pi}} \quad (4)$$

In turn, the time required per operation T_{pi} is considered [Balakshin, 1971] as being:

$$T_{pi} = \frac{T_{su}}{n} + \sum t_m + \sum t_a + t_s + t_f \quad (5)$$

where T_{su} is the setting-up time, n the number of pieces in a batch (batch size), t_m the basic processing time (machine time), t_h the handling time, t_s the time for servicing the workplace, t_f the time required for personal needs and for resting in case of strenuous work (fatigue allowance). The times for servicing the workplace, for personal needs and for resting are usually calculated as percentages of the machine time or of the sum including the machine times and handling times.

The machine time t_m can be determined [Balakshin, 1971] by taking into consideration the required length L (mm) of travel of the cutting tool at the working feed in reference to the workpiece (or the opposite, workpiece travel in reference to tool), rotation speed n, rpm (or the number of full strokes per minute, strokes/min) and the feed rate per min f of the tool or workpiece, mm/min:

$$t_m = \frac{L}{nf} i \quad (6)$$

i being the number of passes or cuts necessary to remove the established machining allowance A_m. One can determine the number i of passes by means of the equation [Danilevsky, 1973]:

$$i = \frac{A_m}{a_p}, \quad (7)$$

where a_p is the depth of cut.

The first-level functional requirement concerning the *labour productivity Q of the manufacturing process under design (FR2:* Maximize the labor productivity)*)* leads to the following second-level functional requirements:

FR2.1: Establish the machine tools;

FR2.2: Establish the scheme for locating and clamping the workpiece;

FR2.3: Establish the fixtures;

FR2.4: Establish the tools;

FR2.5: Establish the jigs;

FR2.6: Maximize the depth of cut;

*FR*2.7: Maximize the feed rate;

*FR*2.8: Maximize the cutting speed;

*FR*2.9: Minimize the setting-up time;

*FR*2.10: Minimize the machine time;

*FR*2.11: Minimize the handling time;

The third first-level functional requirement concerning *the adequacy of the designed manufacturing technology to the available equipments and operators (FR3:* Use available equipment and operators*)* could be divided in the following second-level functional requirements:

*FR*3.1: If possible, use the available machine tools;

*FR*3.2: If possible, use the available fixtures;

*FR*3.3: If possible, use the available jigs;

*FR*3.4: If possible, use the available tools;

*FR*3.5. Use the available operators.

One does not divide the fourth first-level functional requirement (the requirement that the designed manufacturing technology should ensure, if possible*, a maximum number of processing operations achieved in the available workshop – FR*4).

According to the above mentioned structure for designing the manufacturing technology, the main steps in the design process in which the student/the engineer must make a decision consists in the selection of the design parameters of first or second level, which could be:

- Verifying the working drawings and the product manufacturability;
- Selecting the kind of blank (raw material);
- Planning the sequence of machining operations and operations elements;
- Determining the machining allowances;
- Determining the intermediate dimensions (these dimensions correspond to the blank/workpiece dimensions for the various machining operations that are applied to the same workpiece surface);
- Establishing the necessary dimensions of the blank and selecting, if possible, a blank having normalized dimensions;
- Selecting the machine tools;
- Selecting schemes for locating and clamping workpiece;
- Selecting fixtures;
- Selecting tools;
- Selecting jigs;
- Determining the depth of cut;
- Determining the rate of feed;
- Determining the cutting speed;
- Verifying the cutting forces, moments and effective powers;
- Determining the setting-up times;
- Determining the machine times;
- Determining the handling times;
- Determining the times for servicing the workplace, for personal needs and for resting;
- Determining the time required per operation;
- Determining the per-unit cost of the product;
- Comparing the per-unit cost of the product with the contract cost or with the expected one;
- Elaborating the final technological and economical documents.

If one takes into consideration the objectives proposed to be solved by the student in each of the stages, one can propose the appropriate design parameters for planning the manufacturing processes.

As design parameters corresponding to the functional requirement FR1 (minimize the cost of designed technology), one can consider DP1: Procedures for determining the elements of the cost:

DP1.1: Procedure for establishing the type of raw material;

DP1.2: Procedure for establishing the sequence of operations;

DP1.3: Procedure for determining the machining allowances;

DP1.4. Procedure for determining the dimensions of the blank .

The design parameter corresponding to the functional requirement FR2 (Maximize labor productivity) could be (DP2: Procedures for maximizing labor productivity), and:

DP2.1: Procedure for establishing the scheme for locating and clamping the workpiece;

DP2.2: Procedure for establishing the machine tool;

1					Design parameters DPs																	
2					Design parameters of first level																	
3					*DP1*				*DP2*								*DP3*					*DP4*
4					Design parameters of second level																	
5				**Functional requirements**	*DP1.1:* Procedure for establishing the type of blank	*DP1.2:* Procedure for establishing sequence of operations	*DP1.3:* Procedure for determining the machining allowances	*DP1.4:* Procedure for determining dimensions of blank	*DP2.1:* Procedure for establishing schema for locating and clamping workpiece	*DP2.2:* Procedure for establishing machine tool	*DP2.3:* Procedure for establishing tools	*DP2.4:* Procedure for establishing fixtures	*DP2.5:* Procedure for establishing jigs	*DP2.6:* Procedure for establishing depth of cut	*DP2.7:* Procedure for establishing feed rate	*DP2.8:* Procedure for establishing cutting speed	*DP3.1:* Procedure for establishing set-up time	*DP3.2:* Procedure for establishing machine time	*DP3.3:* Procedure for establishing handling time	*DP3.4:* Procedure for establishing the workers qualification levels	*DP3.5:* Procedure for determining time per operation	*DP4:* Procedure for establishing the operations to be achieved in the available workshop
	2	3	4	*5*	6	7	8	9	10	11	12	14	15	16	17	18	19	20	21	22	23	24
7	Functional requirements of first level	*FR1:* Minimize the cost of machining	Functional requirements of second level	*FR1.1:* Minimize the cost of the row material cost	X	X	X															
8				*FR1.2:* Minimize the admissible machining allowances			X															
9				*FR1.3:* Minimize the cost of using machine tools		X				X												
10				*FR1.4:* Minimize the tools costs					X		X											
11				*FR1.5:* Minimize the fixtures costs					X			X										
12				*FR1.6:* Minimize the jigs costs					X				X									
13				*FR1.7:* Minimize the salary costs										X	X	X	X	X	X	X	X	X
14				*FR1.8:* Minimize the overheads						X	X	X	X	X	X	X	X	X	X	X	X	X
15		*FR2:* Maximize the labour productivity		*FR2.1:* Establish the machine tools		X				X												
16				*FR2.2:* Establish the schema for locating and clamping workpiece					X													
17				*FR2.3:* Establish the fixtures								X										
18				*FR2.4:* Establish the tools							X											
19				*FR2.5:* Establish the jigs									X									
20				*FR2.6:* Maximize the depth of cut										X								
21				*FR2.7:* Maximize the feed rate											X							
22				*FR2.8:* Maximize the cutting speed												X						
23				*FR2.9:* Minimize the setting-up time													X					
24				*FR2.10:* Minimize the machine time														X				
25				*FR2.11:* Minimize the handling time															X			
26		*FR3:* Use available equipments and operators		*FR3.1:* If possible, use the available machine tool		X				X												
27				*FR3.2:* If possible, use the available fixture					X			X										
28				*FR3.3:* If possible, use the available jigs					X				X									
29				*FR3.4:* If possible, use the available tools							X											
30				*FR3.5:* Use the available operators		X				X										X		
31		*FR4:* Achieve a maximum number of operations in the available workshop		FR4.1:Maximize the number of the processing operations achieved in the available workshop		X														X		X

Figure 1. Initial design matrix.

DP2.3: Procedure for establishing tools (standardized cutting tools, which must be purchased or tools which must be designed and achieved);

DP2.4: Procedure for establishing the fixtures; these fixtures could be the standardized/purchased ones or fixtures which must be designed and manufactured;

DP2.5: Procedure for establishing the jigs (the statements corresponding to fixtures are valid for jigs);

DP2.6: Procedure for establishing the depth of cut;

DP2.7: Procedure for establishing the feed rate;

DP2.8: Procedure for establishing the cutting speed.

In the case of FR3 (Use available equipments and operators), one can take into consideration as design parameters DP3 (Procedures for use the available equipments and operators), and:

DP3.1: Procedure for establishing the set-up time;

DP3.2: Procedure for establishing the machining time;

DP3.3: Procedure for establishing the handling time;

DP3.4: Procedure for establishing the workers qualification level;

DP3.5: Procedure for determining the time per operation

For the functional requirement FR4 (Achieve a maximum number of operations in the available workshop), one can take into consideration the design parameter:

DP4: Procedure for establishing the operations to be achieved in the available workshop. .

The design parameters *DP2.1*- *DP3.5* are valid for each processing operation.

The first version of the matrix corresponding to these functional requirements and design parameters is presented in figure 1; this version was elaborated by considering some requirements associated to the manufacturing technology design for a certain part by the student and the derived problems specific to solving each stage. One can see that there are many aspects that do not match the principles of axiomatic design. Firstly, one can notice that the matrix is not a square matrix, because there are 25 functional requirements and only 19 design parameters. In addition, there is many design parameters for some of the functional requirements. As a result, we have a *coupled design.*

During the process of the matrix elaboration, one noticed that there are dependencies between the considered functional requirements; for example, in order to diminish the raw material cost, one can act during selection of raw material type (laminated, cast, forged etc.), by diminishing the machining allowances and by establishing optimized dimensions of the blank. One can also notice that the salary costs are dependent on the cutting parameters, on the times affected to various components of time per piece, and on the level of qualification of workers; a similar statement could be formulated about the overheads, taking into account that these overheads can be estimated on the basis of salary costs. As the equation (3) shows, the overhead expenses depend on the salary expenses and on the service cost of machine tools, tools, fixture and jigs. There are also situations where the same design parameter is used to fulfill two or many functional requirements. For example, the selection of a certain machine tool must consider the necessity of diminishing the cost of the machine tool, which have to be considered in the final cost of the part; the possibility of using a machine tool already available at the workshop; and the necessity to ensure a certain distribution of the work tasks between several operators (workers) of the workshop (there is a match between the number of workers and their qualification levels, as well as the types and number of available machine tools). The above-mentioned contradictions to the axiomatic design principles determined us to reanalyse the problem through zigzagging as in order to find a better solution.

As a result, a second design matrix was elaborated (fig. 2). This is a 11x11 square matrix, and one can see that the number of functional requirements was diminished, by taking into account some specific aspects of the previous formulation.

For example, when the machine tool is selected, on can take into consideration the necessity of minimizing the cost of machine tool service, the technical possibilities to materialize the machining of a certain part on the selected machine tool, the existence of this machine tool in the workshop, etc.

The zigzag could be also completed by applying specific methods in order to optimize some design parameters. Thus, the method of dynamic programming could be applied in order to optimize the the sequence of operations. Other procedures can be used to find the optimal values for the cutting parameters (Monte Carlo method, linear mathematical programming, Taguchi method, etc.). Various methods could be also applied to find adequate solutions for multi-response problems (multi-criteria analysis, Grey analysis, etc.).

During the zigzagging, the diminishing of the time per piece T_{pi} at the *i*th operation could be taken into consideration; it is known that diminishing the value of a certain component of the time per piece could ensure conditions that, in a next step, makes it possible to diminish other components of the time per piece.

Additional problems appear in the case the design of technologies that use computer numerical controlled machine tools. In such a situation, establishing optimal tool path for each operation element could be a functional requirement needing adequate design parameters.

4 CONCLUSION

The design of manufacturing processes has a significant influence on the product price and on the time necessary for obtaining the product. Being considered as a design process, the problem of applying the axiomatic design principles was formulated. Various aspects specific to the use of the axiomatic principles in design of manufacturing or machining processes were investigated by the researchers interested in such problems. Taking into consideration the necessity of teaching the use of axiomatic design in didactic activities concerning the design of machining/manufacturing processes, the functional requirements and design parameters were investigated in correspondence with the stages solved by the students in their didactic projects. In this context, a first design matrix was elaborated. The analysis of this initial matrix highlighted that the principles of axiomatic design were not met. The functional requirements and design parameters were reanalyzed and a second uncoupled design matrix was elaborated. In the future, there is the intention to take into consideration a larger zigzagging path, in order to find ways to

Li-ne no. 1	Functional requirements				Design parameters *DPs*										
2					Design parameters of first level										
3					*DP1*		*DP2*					*DP3*			*DP4*
4					Design parameters of second level										
5					*DP1.1*: Procedure for establishing the type of raw material	*DP1.2*: Procedure for determining the machining allowances	*DP2.1*: Procedure for establishing the machining schema	*DP2.2*: Procedure for establishing the machine tool	*DP1.3*: Procedure for establishing tools	*DP1.4*: Procedure for establishing fixture	*DP2.5*: Procedure for establishing jigs	*DP3.1*: Procedure for establishing depth of cut	*DP3.2*: Procedure for establishing rate of feed	*DP3.3*: Procedure for establishing cutting speed	*DP4*: Procedure for establishing the workers qualification levels
6 Col. no. 1	2	3	4	5	6	7	8	9		10	11	12	13	14	15
7	Functional requirements of first level	*FR1*	Functional requirements of second level	*FR1.1:* Minimize the cost of raw material	X										
8				*FR1.2:* Minimize the admissible machining allowances		X									
9		*FR2*		*FR2.1:* Provide adequate machining schema			X								
10				*FR2.2*: Provide adequate machine tools				X							
11				*FR2.3:* Provide adequate tools					X						
12				*FR2.4:* Provide adequate fixtures						X					
13				*FR2.5:* Provide adequate jigs							X				
14		*FR3*		*FR3.1:* Maximize the depth of cut								X			
15				*FR3.2*: Maximize the rate of feed									X		
16				*FR3.3*: Maximize the cutting speed										X	
17		*FR 4*		*FR4:* Provide available operators having the necessary qualification level											X

Figure 2. Second design matrix.

optimize various stages of selecting the design parameters and process parameters that are specific to the activities of manufacturing process design.

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AXIOMATIC DESIGN AND DESIGN STRUCTURE MATRIX MEASURES FOR RECONFIGURABILITY & ITS KEY CHARACTERISTICS IN AUTOMATED MANUFACTURING SYSTEMS

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ABSTRACT

In recent years, the fields of reconfigurable manufacturing systems, holonic manufacturing systems, and multi-agent systems have made technological advances to support the ready reconfiguration of automated manufacturing systems. While these technological advances have demonstrated robust operation and been qualitatively successful in achieving reconfigurability, limited effort has been devoted to the measurement of reconfigurability in the resultant systems. Hence, it is not clear 1.) to which degree these designs have achieved their intended level of reconfigurability 2.) which systems are indeed quantitatively more reconfigurable and 3.) how these designs may overcome their design limitations to achieve greater reconfigurability in subsequent design iterations. Recently, a reconfigurability measurement process based upon axiomatic design and the design structure matrix has been developed. This paper now builds upon these works to provide a set of composite reconfigurability measures. Among these are measures for its key characteristics of integrability, convertibility, and customization, which have driven the qualitative and intuitive design of these technological advances. These measures are then demonstrated on an illustrative example followed by a discussion of how they may be practically applied in large automated manufacturing systems.

Keywords: Reconfigurability, axiomatic design for large flexible systems, design structure matrix, reconfigurable manufacturing systems, multi-agent systems

1 INTRODUCTION

Manufacturing has became increasingly characterized by continually evolving and ever more competitive marketplaces. In order to stay competitive, manufacturing firms have had to respond with a high variety products of increasingly short product lifecycle[Mehrabi et al. 2002; Pine 1993]. One particularly pertinent problem is the need to quickly and incrementally adjust production capacity and capability. To fulfill the needs of enterprises with extensive automation, reconfigurable manufacturing systems have been proposed as a set of possible solutions[Mehrabi et al. 2000]. They are defined as:

Definition 1. Reconfigurable Manufacturing System[Koren et al. 1999]: "[A System] designed at the outset for rapid change in structure, as well as in hardware and software components, in order to quickly adjust production capacity and functionality within a part family in response to sudden changes in market or regulatory requirements."

Over the last decade, many technologies and design approaches each with their respective scope have been developed to enable reconfigurability in manufacturing systems[Dashchenko 2006; Setchi & Lagos 2005]. This is a cyber-physical challenge requires the careful design of functions, components and their interfaces be they of a material, energetic or informatics nature. Some of this work includes modular machine tools [Heilala & Voho 2001; Landers et al. 2001; Shirinzadeh 2002] and distributed automation[Brennan & Norrie 2001; Vyatkin 2007; Lepuschitz et al. 2010]. Additionally, a wide set of IT-based paradigms such as Multi-Agent Systems[Shen & Norrie 1999; Shen et al. 2000; Leitao 2009; Leitao & Restivo 2006; Leitao et al. 2012; Ribeiro & Barata 2013], Holonic Manufacturing Systems[Babiceanu & Chen 2006; Marik et al. 2002; McFarlane & Bussmann 2000; McFarlane et al. 2003] have emerged. While these technological advances have demonstrated robust operation and been qualitatively successful in achieving reconfigurability, there has been comparatively little attention devoted to design methodologies of these reconfigurable manufacturing systems and so their ultimate industrial adoption remains limited[Marik & McFarlane 2005].

One major challenge in the development of a reconfigurable manufacturing system design methodology is the absence of a reconfigurability measurement process. Hence, it is not clear 1.) the degree to which previous designs have achieved their intended level of reconfigurability, 2.) which systems are indeed quantitatively more reconfigurable 3.) how these designs may overcome their inherent design limitations to achieve greater reconfigurability in subsequent design iterations. Recently such a measurement process has been developed upon the foundation of axiomatic design for large flexible systems and the design structure matrix. Collectively, these works show that a high degree of reconfigurability is achieved by fostering greater reconfiguration potential through axiomatic design as well as greater reconfiguration ease. This paper now integrates these prior works to provide measures for reconfigurability and its key characteristics of integrability, convertibility, and customization.

This paper follows a five part discussion. Section 2 provides the foundation to this work. It uses axiomatic design for large flexible systems and the design structure matrix to provide measures of reconfiguration potential and ease respectively. Section 3 then demonstrates how these measures may be used to synthesize more complex measures that address reconfigurability and its key characteristics: integrability, convertibility, and customization[Mehrabi et al. 2000b]. Section 4 then applies these measures to an illustrative example. Section 5 concludes the work.

Prior to proceeding, this paper restricts its discussion to the shop-floor activities of automated manufacturing systems as defined in Levels 0-3 of ISA-S95[ANSI-ISA 2005]. For simplicity, productions systems are assumed to have physically allocated distributed automation and control. Production systems with centralized controllers have been previously addressed in [Farid 2008]. Furthermore, this paper defines reconfigurability as:

Definition 2. Reconfigurability[Farid & McFarlane 2007]: The ability to add, remove and/or rearrange in a timely and cost-effective manner the components and functions of a system which can result in a desired set of alternate configurations.

2 BACKGROUND: FOUNDATIONS OF RECONFIGURABILITY MEASUREMENT

The composite measures presented in the next section are built upon a reconfigurability measurement process based upon axiomatic design for large flexible systems and the design structure matrix. While a deep treatment of the reconfigurability measurement process is not feasible here, the interested reader is referred to the background references for the details of the mathematical developments in this work [Farid & McFarlane 2008; Farid 2008a; Farid 2013; Farid 2008b; Farid 2014a; Farid 2014b; Viswanath et al. 2013; Farid & Covanich 2008; Baca et al. 2013; Farid & McFarlane 2006; Farid & McFarlane 2007; Farid 2007]. Figure 1 shows a conceptual representation of a reconfiguration process.

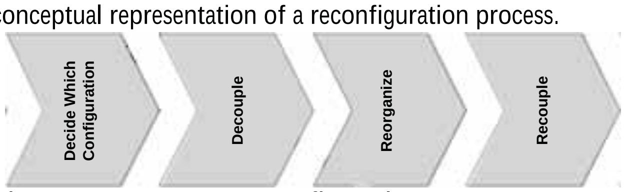

Figure 1. A Four Step Reconfiguration Process

Facilitating the potential for such a process can be achieved through axiomatic design while fostering reconfiguration ease can be achieved through the design structure matrix. The former is linked to the number of possible configurations of the system in a measure called production degrees of freedom. The latter is linked to the effort required to pull apart and reconnect interfaces in a measure of modularity. This section introduces the concept of a reconfigurability measurement process and then presents a set of definitions and measures for use in the following section.

2.1 MEASURABLES & MEASUREMENT METHODS

As shown in Figure 2, the measurement of reconfigurability is naturally an indirect measurement process[Cerni & Foster 1962]. It requires that measurables be directly measured with measurement methods and then placed into models from which formulaic measures can give the desired measurement property of reconfigurability. In this work, the measurables are the production system's processes, resources, and their interfaces. These may be counted manually once the measurer has determined a consistent ontological basis for defining them[Gasevic et al. 2009]. However, with the advent of model-based systems engineering, this work instead assumes that there exists a virtual model of the production system and its control implemented in a language such as SysML[Friedenthal et al. 2011]. In such a case, the measurables of production processes, resources, and interfaces can be automatically extracted.

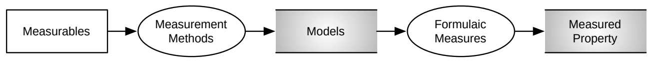

Figure 2. A Generic Indirect Measurement Process

2.2 AXIOMATIC DESIGN MEASURES: PRODUCTION DEGREES OF FREEDOM

Suh [2001] defines large flexible systems as systems with many functional requirements that not only evolve over time, but also can be fulfilled by one or more design parameters. In production systems, the high level design parameters are taken as the set of production resources. DP={Production Resources}. These resources $R=M\cup B\cup H$ may be classified into value adding machines $M=\{m_1\ldots m_{\sigma(M)}\}$, independent buffers $B=\{b_1\ldots b_{\sigma(B)}\}$, and material handlers $H=\{h_1\ldots h_{\sigma(H)}\}$ where $\sigma()$ gives the size of a set. The set of buffers $B_S=M\cup B$ is also introduced for later simplicity. Similarly, the high level functional requirements are taken as a set of production processes. FR={Production Processes}. These are formally classified into three varieties: transformation, transportation and holding processes and are defined as:

Definition 3. Transformation Process[Farid & McFarlane 2008]: A machine-independent, manufacturing technology-independent process $p_{\mu j}\in P_\mu=\{p_{\mu 1}\ldots\ p_{\mu\sigma(P_\mu)}\}$ that transforms raw material or work-in-progress to a more final form.

Definition 4. Transportation Process[Farid & McFarlane 2008]: A material-handler - independent process $p_{\eta u}\in P_\eta=\{p_{\eta 1}\ldots\ p_{\eta\sigma(P_\eta)}\}$ that transports raw material, work-in-progress, or final goods from buffer b_{sy1} to b_{sy2}. There are $\sigma^2(B_S)$ such processes of which $\sigma(B_S)$ are "null" processes where no motion occurs. Furthermore, the convention of indices $u=\sigma(B_S)(y_1-1)+y_2$ is adopted.

Definition 5. Holding Process[Farid & McFarlane 2008]: A material-handler and end-effector-independent process $p_{\varphi g}\in P_\varphi=\{p_{\varphi 1}\ldots\ p_{\varphi\sigma(P_\varphi)}\}$ that holds raw material, work-in-progress, or final products during the transportation from one buffer to another.

These production processes and resources may be related through the use of the axiomatic design equation for large flexible systems[Suh 2001].

$$P = J_S \odot R \tag{1}$$

where $\odot$ is "matrix Boolean multiplication"[Farid & McFarlane 2008] and J_S is the production system knowledge base.

Definition 6. Production System Knowledge Base[Farid & McFarlane 2008]: A binary matrix J_S of size σ(P)xσ(R) whose element $J_S(w,v) \in \{0,1\}$ is equal to one when event e_{wv} exists as a production process p_w being executed by a resource r_v.
In other words, the production system knowledge base itself forms a bipartite graph which maps the set of production processes to production resources. J_S can then be reconstructed straightforwardly from smaller knowledge bases that individually address transformation, transportation, and holding processes. $P_\mu = J_M \odot M$, $P_\mu = J_H \odot R$, $P_\gamma = J_\gamma \odot R$. J_S then becomes[Farid & McFarlane 2008]

$$J_S = \begin{bmatrix} J_M & | & \mathbf{0} \\ & J_{\bar{H}} & \end{bmatrix} \quad (2)$$

where in order to account for the simultaneity of holding and transportation processes[Farid 2013]

$$J_{\bar{H}} = \left[J_\gamma \otimes \mathbf{1}^{\sigma(P_\eta)} \right] \cdot \left[\mathbf{1}^{\sigma(P_\gamma)} \otimes J_H \right] \quad (3)$$

and ⊗ is the Kronecker product and 1^n is a column ones vector length n.

In order to differentiate between the existence and the availability of a given production system capability, a production system scleronomic (i.e. sequence-independent) constraints matrix is introduced.

Definition 7. Production System Scleronomic Constraints Matrix[Farid & McFarlane 2008]: A binary matrix K_S of size σ(P)xσ(R) whose element $K_S(w,v) \in \{0,1\}$ is equal to one when a constraint eliminates event e_{wv} from the event set.
It is calculated analogously to the production system knowledge base:

$$K_S = \begin{bmatrix} K_M & | & \mathbf{1} \\ & K_{\bar{H}} & \end{bmatrix} \quad (4)$$

where

$$K_{\bar{H}} = \left[K_\gamma \otimes \mathbf{1}^{\sigma(P_\eta)} \right] \cdot \left[\mathbf{1}^{\sigma(P_\gamma)} \otimes K_H \right] \quad (5)$$

From these definitions of J_S and K_S, follows the definition of sequence-independent production degrees of freedom.

Definition 8. Sequence-Independent Production Degrees of Freedom[Farid & McFarlane 2008]: The set of independent production events E_S that completely defines the available production processes in a production system. Their number is given by:

$$DOF_S = \sigma(E_S) = \sum_w^{\sigma(P)} \sum_v^{\sigma(R)} \left[J_S \ominus K_S \right](w,v) \quad (6)$$

where A⊖B is "Boolean subtraction" or equivalently $A \cdot \bar{B}$. Note that the Boolean "AND" is equivalent to the hadamard product and $\bar{B} = not(B)$.

In addition to these sequence-independent production degrees of freedom, it is necessary to introduce a measure for the sequence-dependent capabilities of the production system given that constraints often arise between two events [Farid & McFarlane 2008].

Definition 9. Sequence Dependent Production Degrees of Freedom[Farid & McFarlane 2008]: The set of independent production strings $z_{\varphi\psi} = e_{w1v1}e_{w2v2} \in Z$ of length 2 that completely describe the production system language. Their number is given by:

$$DOF_\rho = \sigma(Z) = \sum_\varphi^{\sigma^2(P)} \sum_\psi^{\sigma^2(R)} \left[J_\rho \ominus K_\rho \right](\varphi,\psi) \quad (7)$$

where J_ρ and K_ρ are defined below.

Definition 10. Rheonomic production system knowledge base[Farid & McFarlane 2008]: A binary matrix J_ρ of size $\sigma^2(P)x\sigma^2(R)$ whose element $J(\varphi,\psi) \in \{0,1\}$ are equal to one when string $z_{\varphi\psi}$ exists. It may be calculated directly as:

$$J_\rho = \left[J_S \cdot \bar{K}_S \right] \otimes \left[J_S \cdot \bar{K}_S \right] \quad (8)$$

This implies the index relations: $\varphi = \sigma(P)(w_1 - 1) + w_2$, and $\psi = \sigma(R)(v_1 - 1) + v_2$. The availability of these strings is reflected in an associated constraints matrix.

Definition 11. Rheonomic Production Constraints Matrix K_ρ[Farid & McFarlane 2008]: a binary constraints matrix of size $\sigma^2(P)x\sigma^2(R)$ whose elements $K_\rho(\varphi,\psi) \in \{0,1\}$ are equal to one when string $z_{\varphi\psi}$ is eliminated.

In addition to the above, it is necessary to introduce the concept of product degrees of freedom as those production degrees of freedom applicable to a product line. A given enterprise may have a whole product line $L = \{l_1, \ldots, l_{\sigma(L)}\}$. Each product l_i has its associated set of product events $e_{xli} \in E_{li}$ which when all are completed result in a fully manufactured product.

Definition 12. Product Event[Farid & McFarlane 2008]: A specific transformation process that may be applied to a given product.
The relationship between product events and scleronomic transformation and transportation degrees of freedom is achieved with production feasibility matrices.

Definition 13. Product Transformation Feasibility Matrix $\Lambda_{\mu i}$ [Farid 2008]: A binary matrix of size $\sigma(E_{li})x\sigma(P_\mu)$ whose value \$$\Lambda_{\mu i}(x,j)=1$ if e_{xli} realizes transformation process $p_{\mu j}$.

Definition 14. Product Transportation Feasibility Matrix $\Lambda_{\gamma i}$ [Farid 2008]: A binary row vector of size 1x $\sigma(P_\gamma)$ whose value $\Lambda_{\gamma i}=1$ if product l_i can be held by holding process $p_{\gamma g}$.

From these definitions, it is straightforward to assess the number of product transformation and transportation degrees of freedom[Farid 2013].

$$DOF_{LM} = \langle \Lambda_{ML} \cdot J_M, \bar{K}_M \rangle_F \quad (9)$$

$$DOF_{LH} = \langle \Lambda_{HL} \cdot J_{\bar{H}}, \bar{K}_{\bar{H}} \rangle_F \quad (10)$$

where

$$\Lambda_{ML} = \bigvee_i^{\sigma(L)} \bigvee_x^{\sigma(E_L)} \Lambda_{\mu i}^T \mathbf{1}^{\sigma(M)T} \quad (11)$$

$$\Lambda_{HL} = \left[\left(\bigvee_i^{\sigma(L)} \Lambda_{\gamma i} \right) \otimes \mathbf{1}^{\sigma(P_\eta)T} \right]^T \mathbf{1}^{\sigma(R)T} \quad (12)$$

The intuitive form of product degrees of freedom in Equations (9) and (10) shows that the product line effectively selects out the production degrees of freedom provided by the production system. The former is ultimately a subset of the latter as a product naturally restricts the scope of a production system[Farid 2008].

This subsection has used axiomatic design for large flexible systems to produce production degree of freedom measures that represent the reconfiguration potential of a production system. The following subsection shifts its attention to reconfiguration ease.

2.3 Design Structure Matrix Measure: Modularity

In this subsection, modularity is addressed as one of the key characteristics of reconfigurable manufacturing systems. As shown in Figure 3, the decoupling and coupling of products and resources must be considered not just physically but at all of the ISA-S95 control levels.

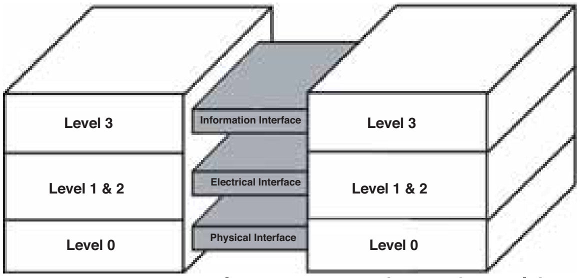

Figure 3. Conceptual Representation of Multi-Level Interfaces of Production Resources & Products

Here, the production design structure matrix[Farid 2008] is used to produce a modularity measure to suitably represent reconfiguration ease. It has a block form for all of the production system entities including products, buffers, material handlers, and value-adding machines. It is shown in Figure 4. The associated measure of modularity is given by

$$\Gamma = \left[\frac{a_d}{V_d}\right] - \left[\frac{a_o}{V_o}\right] \tag{13}$$

where a_d is the total cohesion defined as the sum of all of the elements along the block diagonal, a_o is the total coupling defined as the sum of all of the elements outside the block diagonal, V_d is the total possible cohesive interaction defined as the number of elements in the block diagonal, V_o is the total possible coupling interaction defined as the number of elements outside the block diagonal[Farid 2008]. From this foundation, the discussion can turn to the introduction of the composite reconfigurability measures.

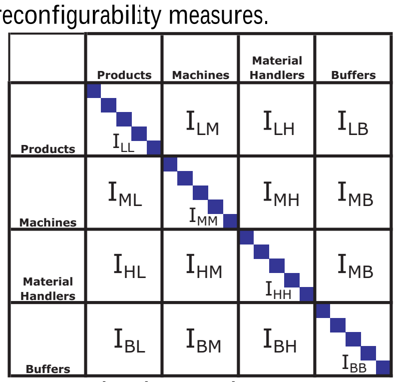

Figure 4. Production Design Structure Matrix

3 COMPLEX RECONFIGURABILITY MEASURES

The previous section summarized two sets of reconfigurability measures: one for reconfiguration potential and another for reconfiguration ease. This section now demonstrates how these measures may be used to synthesize more complex measures that address reconfigurability and its remaining key characteristics: integrability, convertibility, and customization[Mehrabi et al. 2000b]. Each of these is now discussed in turn.

3.1 Integrability

As the second of four key reconfigurability characteristics, it has been described as[Mehrabi et al. 2000b]:

Integrability: The ability with which systems and components may be readily integrated and future technology introduced.

In the context of this work, this description is interpreted as the ability to add or remove resources.

As shown in Figure 1, such a reconfiguration requires two resources to be first determined and then subsequently pulled apart or put together. Rheonomic production degrees of freedom quantifies the first step with a mathematical description of the resource and their associated capabilities. The effort required for the second step can be quantified using the modularity of the pair of resources. Then, the pair of resources must be considered as their own system with a design structure matrix composed of four blocks from the larger DSM. Finally, to eliminate the effect of cohesion on reconfiguration ease, the cohesion term is replaced with unity. The resulting measure of integrability is:

$$I = \sum_{\psi}^{\sigma^2(R)}\left[1-\frac{a_{o\psi}}{V_{o\psi}}\right]\sum_{\varphi}^{\sigma^2(P)}[J_\rho \ominus K_\rho](\varphi,\psi) \tag{14}$$

This equation shows that the integrability of a system is measured in terms of the effort saved to integrate the rheonomic production degrees of freedom of a pair of resources summed overall resource pairs. Seen a different way, each degree of freedom is discounted by the amount of effort required to integrate it into the rest of the system. The system integrability can be normalized by its maximal value which it reaches in the absence of rheonomic constraints and inter-resource coupling.

3.2 Convertibility

The convertibility of a manufacturing system can be addressed similarly. It is described as[Mehrabi et al. 2000b]:

Convertibility: The ability of the system to quickly changeover between existing products and adapt to future products.

This description, within the scope of the desired reconfigurations, can be interpreted as the ability to add or remove products from the product line. Such a reconfiguration requires that a product and resource be chosen and then be pulled apart or put together. Scleronomic product degrees of freedom quantifies the first step with the resource-product feasibility. To do this, one must recall that the relationship between product and transportation and transformation degrees of freedom is fundamentally different.

As a result, two convertibility measures are developed. The effort required for the second step can be quantified using the modularity of the resource-product pair. The resulting convertibility measures are:

$$C_M = \sum_i^{\sigma(L)} \sum_j^{\sigma(P_\mu)} \sum_k^{\sigma(M)} \left[1 - \frac{a_{oik}}{V_{oik}}\right] \left[\Lambda_{Mi} \cdot J_M \cdot \bar{K}_M\right](j,k) \quad (15)$$

$$C_H = \sum_i^{\sigma(L)} \sum_\varrho^{\sigma(P_{\bar{\eta}})} \sum_v^{\sigma(R)} \left[1 - \frac{a_{oiv}}{V_{oiv}}\right] \left[\Lambda_{Hi} \cdot J_{\bar{H}} \cdot \bar{K}_{\bar{H}}\right](\varrho,v) \quad (16)$$

where

$$\Lambda_{Mi} = \left[\bigvee_x^{\sigma(E_L)} \Lambda_{\mu i}\right]^T \mathbf{1}^{\sigma(M)T} \quad (17)$$

$$\Lambda_{Hi} = \left[\Lambda_{\gamma i} \otimes \mathbf{1}^{\sigma(P_\eta)T}\right]^T \mathbf{1}^{\sigma(R)T} \quad (18)$$

These measures show that the convertibility of a system is measured in terms of the effort saved to integrate the scleronomic product degrees of freedom of a product-resource pair summed over all product-resource pairs. Much like integrability, each degree of freedom is discounted by the amount of effort required to integrate it into the rest of the system. The two convertibility measures can be normalized by their respective maximal values which it reaches in the absence of sceleronomic constraints and product-resource coupling.

3.3 CUSTOMIZATION

In many ways, the characteristic of customization has already been addressed in terms of product degrees of freedom. It is described as[Mehrabi et al. 2000b]:
Customization: The degree to which the capability and flexibility of the manufacturing system hardware and control match the application (product family).
This description suggests that customization is a relative measure that compares scleronomic product degrees of freedom versus scleronomic production degrees of freedom. A customization measure may be formulated as:

$$C = \frac{DOF_{LM} + DOF_{LH}}{DOF_S} \quad (19)$$

Such a measure over zero to one clearly expresses how many of the manufacturing system's capabilities are being used by the existing production line. In such a way, it may be used to rationalize either the expansion of the product line, or the removal of excess capabilities.

3.4 RECONFIGURABIITY

Given the measures for the four the key characteristics of modularity, integrability, convertibility and customization, a measure for reconfigurability can be synthesized. Within this work, reconfigurability is defined as in the introduction and the desired set of alternate configurations includes the addition and/or removal of products and resources. These two types of reconfigurations have already been addressed independently in terms of integrability and convertibility. Hence, a reconfigurability measure can be reasonably synthesized as the sum of the two characteristics.

$$R = I + C_M + C_H \quad (20)$$

This measure marks the completion of the reconfigurability measurement process on the dual foundation of axiomatic design for large flexible systems and the design structure matrix. The former gives a sense of productions systems' reconfiguration potential while the latter gives a sense of its reconfiguration ease.

4 ILLUSTRATIVE EXAMPLE: STARLING MANUFACTURING SYSTEM

To demonstrate the reconfigurability measure and its key characteristics, the "Starling Manufacturing System" is taken as a test case for its functional heterogeneity and redundancy, its resource flexibility, and its moderate size. The interested reader is referred to earlier references on reconfigurability measurement for fully worked examples on this test case[Farid 2007; Farid & McFarlane 2008; Farid & McFarlane 2006a; Farid & McFarlane 2007; Farid & Covanich 2008; Farid 2008a; Farid 2008b; Farid & McFarlane 2006b). Here, the essential aspects of the test case are included before presenting the associated quantitative results.

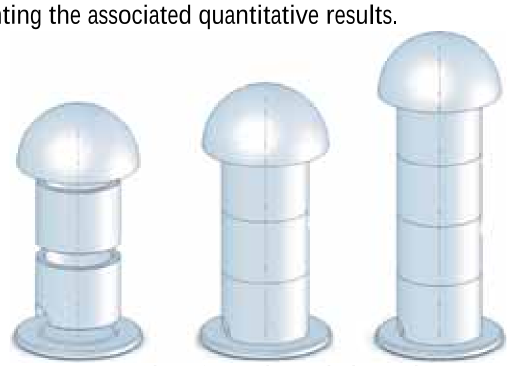

Figure 5. CAD Model of Starling Bird Feeders

The system produces customized bird feeders from cylindrical wooden components. The customer can choose between small, medium, and large bird-feeders which have two, three, or four cylinders respectively. Any of the product configurations can be offered in red, yellow or green. Thus, nine product types are regularly offered. Finally, all of the bird-feeders have an injection moulded dome roof and base which doubles as a bird perch. These two components are manually snapped onto the cylindrical birdfeeders after production and are not further discussed in this example. Figure 5 shows the four component parts and how they may be assembled into three possible configurations of the product line. In addition to this regular range of products, a seasonal "specialized product" from time to time is added. It is composed of independently painted red, yellow and green cylinders with large radii.

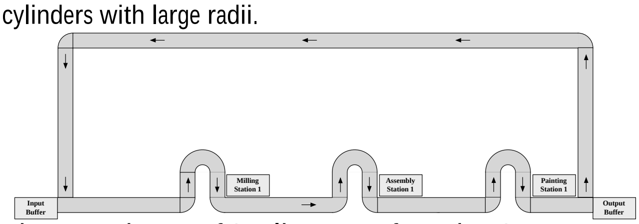

Figure 6. Phase I of Starling Manufacturing System

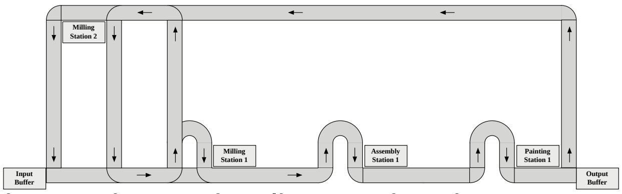

Figure 7. Phase II of Starling Manufacturing System

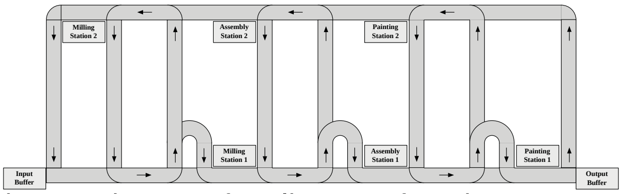

Figure 8. Phase III of Starling Manufacturing System

These wooden cylinders are turned for slots and tabs, milled, assembled and painted. Two shuttles transport them between value adding resources and the two independent buffers. Figure 6 shows the initial configuration, Figure 7 adds a second machining station, and Figure 8 makes all three value-adding resources redundant.

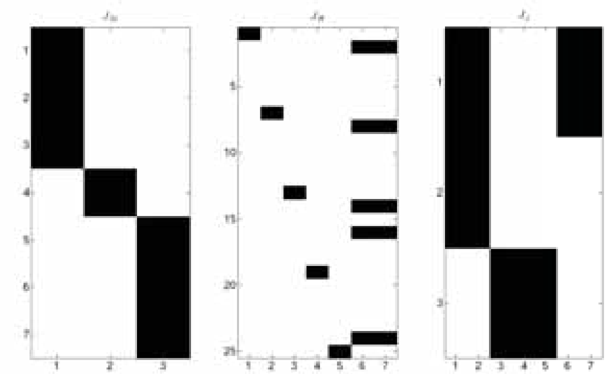
Figure 9.Starling Manufacturing System Knowledge Base

Next, the following sets of processes and resources are identified. In Phase I, M={Turning Station 1, Assembly Station 1, Painting Station 1}. B={Input Buffer, Output Buffer}. H={Shuttle A, Shuttle B}. P_μ={Lathe Tab, Lathe Slot, Mill Hole, Assemble, Paint Red, Paint Yellow, Paint Green}. P_η ={m_im_j, m_ib_k, b_km_i, b_kb_l} ∀ i,j=1,2,3, k,l=1,2. P_γ={Small Radial, Big Radial, Axial}. The production processes and resources for the other system configurations may be determined analogously. Figure 9 presents the transformation, transportation, and holding knowledge bases for the Starling Manufacturing System in Phase I as monochrome images. The scleronomic constraints matrices are initially set to zero. The rheonomic constraints matrix has the minimal constraints previously identified. The knowledge bases, constraints matrices, and product feasibility matrices for the other production system configurations and product variants can be readily formed by analogy. This example is fully worked in [Farid 2007; Farid & McFarlane 2008].

The production design structure matrix for Stage I is taken as given from the worked example in [Farid 2008] and is shown graphically in Figure 7.

On this foundation, the numerical results for reconfigurability and its key characteristics are summarized in Table 1. Absolute measurements are shown plainly. Figures in parentheses are normalized to a comparable but ideal system with no scleronomic constraints, the minimal rheonomic constraints, and no coupling on the off-block diagonal of the production design structure matrix.

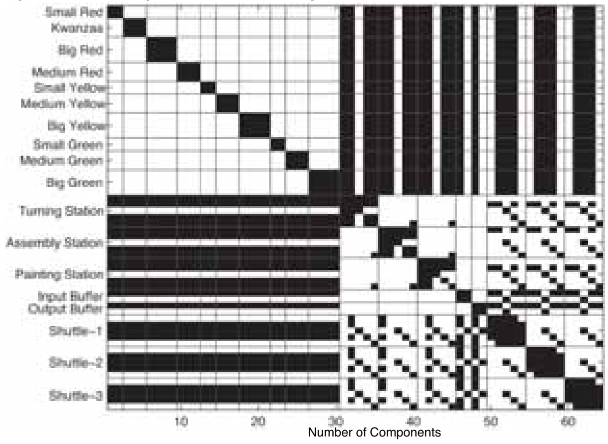

Figure 10. Starling Manufacturing System Production Design Structure Matrix

The values found in Table 1 shed some interesting insights into the Starling manufacturing system in both relative and absolute terms. Relatively speaking, the system is highly integrable. About 7/8 of the available rheonomic production degrees of freedom are achieved. The modest loss can be attributed to the required integration effort between material handlers and other resources. Rheonomic constraints are not part of the normalized figure because the normalization used the norm of a minimally constrained system. The convertibility values are substantially lower at approximately 1/5 and 2/5's respectively. This is to be expected because products and resources are typically much more coupled than resources are with each other. Finally, the system is fully customized because the product line makes use of all of the available production processes. These relative values are fairly constant over the three stages of the system's life. This result is also expected as the average number of integration interfaces per pair of subsystems is relatively constant over time. One would expect these values to vary if there were a massive refactoring of the system's overall structure.

Table 1. Reconfigurability & its Key Characteristics for Starling Manufacturing System

	Stage I	Stage II	Stage III
Integrability	134.92 (0.8705)	348.72 (0.8675)	2475 (0.8980)
Transformation Convertibility	10.4 (0.20)	16.4 (0.20)	20.8 (0.20)
Transportation Convertibility	76 (0.38)	150 (0.3846)	538 (0.3927)
Customization	1	1	1
Reconfigurability	221.32 (0.5438)	515.12 (0.5894)	3033.8 (0.7172)

From an absolute measurement perspective, the most interesting trend is the relative sizes of the integrability and convertibility measures. Over the three stages, a number of resources were added and the associated rheonomic degrees of freedom grew substantially. At the same time, the size of the product line was held constant. As a result, the reconfigurability values became increasingly dominated by the integrability term rather than the convertibility terms. These results are consistent with the intuitive descriptions and are insightful. They encourage the use of the suite of measures rather than relying on the reconfigurability measure alone. Large relative reconfigurability measures could be caused by an exceptionally large number of loosely coupled capabilities, a well-leveraged and easily configured product line or both.

The demonstration of the key characteristic measures serves two fundamental purposes. First, as a group, they give a multi-faceted picture of the reconfigurability of a manufacturing system. The facility of adding products and resources is addressed and the degree to which the system is utilizing its capabilities is also represented. These measures also demonstrate the fundamental reliance on manufacturing modularity and degrees of freedom. The combination of manufacturing modularity with manufacturing degrees of freedom is also objective and consistent. Highly integrable and convertible systems should ideally have high numbers of degrees of freedom. These degrees of freedom should also be easily integrated into the remainder of the manufacturing system. In this way, one may conceive a number of practical questions for which the integrability and convertibility measures have direct application:

- How much more easily would a new resource be integrated into one plant versus another? (integrability)
- Which of two new resources would be more easily integrated into a single plant? (integrability)
- How much more easily would a new product be integrated into one plant versus another? (convertibility)
- How much more easily would a new resource allow the production of the existing production line? (convertibility)?

In such a way, production degrees of freedom and modularity make a convincing sufficiency case towards reconfigurability measurement.

From the perspective of practical application, the reconfigurability and key characteristic measures provided in this work are very much data intensive. Nevertheless, their underling axiomatic design for large flexible systems' knowledge base and the production design structure matrix are entirely compatible with model based systems engineering (MBSE) and their associated software tools. Therefore, it is very likely that these measures can be practically incorporated into such software tools as MBSE becomes the norm in production system design and control and automation system integration.

5 CONCLUSION

This work has built upon the recently developed reconfigurability measurement produce measures of reconfigurability and its key characteristics of modularity, integrability, convertibility, and customization as applied to reconfigurable manufacturing systems. To that end it used the axiomatic design for large flexible systems' knowledge base to address reconfiguration potential and the production design structure matrix to address reconfiguration ease. These measures represent the completion of the reconfigurability measurement process and have been applied on illustrative example consistent with previous work. In the future, the authors envision that these measures will be integrated into model based systems engineering tools that system integrators can use in the engineering design of production systems.

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A REVIEW ON INFORMATION IN DESIGN

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ABSTRACT

Independence of design, information and complexity are the basic concepts of Axiomatic Design. These basic concepts have proven to be generic; axiomatic design was successfully applied in many markets and on a broad range of products and services. Information, or entropy, plays a central role in Axiomatic Design. In this paper an attempt is made to organise the different kinds of information, understand them, and evaluate the consequences of the ways they can be applied. A number of six kinds of information are reduced to two most determining kinds of information for the design. Unorganised information is about choosing the right and independent design relations. Axiomatic information is about further optimisation of these design relations. This paper leads to the confirmation that axiom 1 & 2 are in fact corollaries of the complexity axiom that is constituted of the two kinds of information. Though this revises the foundation of Axiomatic Design, the operation and practical application are not much affected for a number of reasons. One of them is that a higher axiom does not alter the basic ideas behind Axiomatic Design; it remains axiomatic.

Keywords: Axiomatic Design, Information, Complexity, Independence, Entropy

1 INTRODUCTION

Independence of design, information and complexity are the basic concepts of Axiomatic Design (AD) as developed by Nam P. Suh and his team at the Massachusetts Institute of Technology (MIT). The basic concepts have proven to be generic: Having its origin in manufacturing, AD was successfully applied in many markets and on a broad range of products and services.

AD declares 'Axioms' that cannot be proven nor derived from physical phenomena. A number of seven conceptual axioms were defined back in 1978 when the first paper about AD was presented [Suh et al, 1978]. Only two of those seven axioms stood the test of time, now known as the 'Independence Axiom' and the 'Information Axiom'. In 1999 a third axiom was added, the 'Complexity Axiom', addressing four different types of complexity in design processes [Suh, 1999]. The general guideline of AD is that Functional Requirements (FRs) are satisfied by a sensible selection of Design Parameters (DPs), and the probability of this happening is a measure of success for the system design. The probability is a central theme around which the axioms are carefully wrapped.

The probability of DPs satisfying FRs, if not ideal ($P<1$), is a measure for information. Information or 'Entropy' is a state of chaos and, in good accordance with the nature of the specific axioms, it should be reduced. Depending on the kind of information, one of the three axioms and their underlying methods are applied to address the information as appropriate as possible. In this paper an attempt is made to organise the different kinds of information, understand them, and evaluate the consequences of their application. The relation between information and complexity is investigated.

This paper is organised as follows: In section 2 an evaluation is made of the current status of information and earlier investigations about the information as a function of the design matrix. Section 3 is inventories information within and just outside the framework of AD. Information is decomposed and visualised to show the relations between the different kinds. Section 4 discusses the findings and summarises conclusions.

2 INFORMATION AS A BASIS OF ALL AXIOMS

Information is mostly interpreted as transferred knowledge concerning a particular state or circumstance. Information in engineering is mostly related to the notion of complexity. If a system is complex, a lot of information is required to describe the system.

2.1 INFORMATION IN AXIOMATIC DESIGN

Information in Axiomatic Design is derived from the information technology using a logarithmic measure of entropy according to Hartley [Hartley, 1928] and Shannon & Weaver [Shannon & Weaver, 1949]. According to this theory, information is inversely related to the probability of success of a DP causing a FR to be within tolerances. The information axiom dictates that information content should be minimised, and thus maximising the probability of FRs to be satisfied. Suh describes two main types of information, 'Useful' and 'Superfluous' information. Useful information is information that affects FRs. Superfluous information does not affect the relation between DPs and FRs. Therefore, superfluous information is no information from the axiomatic perspective.

2.2 INVESTIGATIONS FOR THE INDEPENDENT BEHAVIOUR OF THE AXIOMS

The dependency of the Axioms has been investigated a number of times. The first book about AD [Suh, 1990:67] includes a paragraph about the relationship between axioms 1 and 2. Suh addresses the misunderstanding that the independence axiom is a 'consequence of the information axiom', by explaining that a coupled design could have lower information content than an uncoupled design. Without the independence axiom it is not possible to choose an uncoupled design, which, from the design perspective, is more preferred than a coupled design. A preferred sequence is proposed: 'first realise an independent design, before optimising it by reduction of the information content of that design'. The second book [Suh, 2001:175] contains some mathematical proof of the independence, based on the Bolzmann entropy of the FR array as was published by [El-Haik & Yang, 1999]. If the design matrix is square and non-singular with constant entries, and DPs are normally distributed random variables, the entropy h of the FRs is given by

$$h(f\{FR\}_m) = h(f_{DP}\{DP\}_n) + |lnA| \tag{1}$$

where |A| is the determinant of the design matrix [A]m.n. Investigation of the determinant |A| leads to the understanding that a coupled matrix can indeed have a lower information content than an uncoupled matrix. Not specifically mentioned, but logically coming forth from the result, is the fact that uncoupled and decoupled matrices with the same diagonal elements have the same entropy and therefore have equal amounts of information. So a coupled matrix could lead to lower information than a decoupled or uncoupled matrix, which was reflected by the substantiation of corollary 7. The book of [El-Haik, 2005] confirms equation (1). Based on analysis of the design matrix, a coupled design could have lower information content and thus appear to be a better option. This is overruled by the independence axiom. Therefore, both axioms serve a particular goal and should be maintained.

2.3 INFORMATION AS BASIS FOR REAL COMPLEXITY

Complexity is defined as 'A measure of uncertainty in achieving the specified FRs' [Suh, 2005:4,58,65]. The Complexity Axiom advises to 'Reduce the complexity of a system'. The theory defines two kinds of complexity, time-independent and time-dependent. This paper is limited to time-independent complexity, which does not change with time. Time-independent complexity consists of two components: 'Real' and 'Imaginary' time-independent complexity, further to be referred to as real and imaginary complexity (C_R and C_{Im}).

Real complexity is inversely related to the probability of success that the associated FRs are satisfied according to one of the following relations

$$C_R = -\sum_{i=1}^{m} log_b P_i \tag{2}$$

$$C_R = -\sum_{i=1}^{m} log_b P_{i|\{j\}} \tag{3}$$

depending if the system is uncoupled (2) or decoupled (3). Relation (2) is under the reservation that the total probability P_i is the 'joint probability of processes that are statistically independent'. Relation (3), for decoupled systems, is modified to correct for dependencies in the probabilistic function [Suh 2005:57]. 'b' Is in both cases the base of the logarithm, usually in bits of nats according to the definition by [Hartley, 1928].
Given (2) and (3), real complexity can be related to the information content, which was defined in terms of the probability of success of achieving the desired set of FRs [Suh 1990:59], as

$$I = C_R \tag{4}$$

2.4 INFORMATION AS BASIS FOR IMAGINARY COMPLEXITY

As explained in 2.3, information content I_i is defined in terms of the probability P_i of satisfying FR_i. In a system with more FRs, the joint probability of satisfying all FRs is applied. The question rises what is the relation between information and entropy to imaginary complexity.

2.4.1 CURRENT DEFINITION OF IMAGINARY COMPLEXITY

Imaginary complexity is defined as complexity that exists due to 'a lack of understanding about the system design, system architecture or system behaviour' [Suh, 1999:120]. It is caused by the absence of essential knowledge of the system. The designer cannot solve the problems in a structured manner and therefore is forced to apply trial-and-error. Imaginary complexity exists until understanding of the problem is acquired; it instantly and permanently disappears when the knowledge becomes present. Though the source of imaginary complexity, a trial-and-error process, can be stochastic, Suh never relates trial-and-error probabilities to information of any kind. Imaginary complexity is by definition not related to information in AD and trial-and-error probabilities will not increase the information content of a design. The motive for this choice was not found in Suh's work; it is basically a matter of definition.

2.4.2 BOLZMANN ENTROPY AS BASIS FOR IMAGINARY COMPLEXITY

As imaginary complexity does not lead to information as defined in the axiomatic context, a broader perspective could be applied. This perspective is based on two observations. First, the information theory of Shannon and Weaver, based on the Bolzmann entropy, is 'related to the number of alternatives that remain possible to a physical system' [Shannon & Weaver 1949:1]. It does not relate to what the design 'is' as much as what the design 'could be', being an amount of freedom of choice [Shannon & Weaver 1949:8,9]. In this case it points to the number of design outcomes as function of the stochastic variability in the design (design being the relation between FRs and DPs). The result of this observation is that, if the trial-and-error probabilities have a

stochastic nature, it increases the Bolzmann entropy. Secondly, the quality of a design never exceeds that of the designer. A 'good design' in the hands of an ignorant designer will not be recognised as such. Optimisations in the perception of the designer will lead to reinvention of the wheel; they might lead to a different good design, but could also degrade the level of the design. This observation leads to the belief that a design is only as good as the understanding of its designer. It cannot be assumed that an ignorant designer will produce a good design and the lack of knowledge, as a result, will cause an increase of the entropy in the design.
Based on these observations, trial-and-error probabilities should be considered to contribute to the entropy in the design.

The increase of entropy is analogue to an increase of the information content in the design. Note that this information is a different kind of information, not the same as defined for the information axiom in AD. Consequently, a new definition is needed to differentiate these two kinds of information. The entropy related to trial-and-error processes, provided that they are stochastic and independent, is analogue to real information defined conforming the method of Hartley and Shannon as

$$I_{UnOrg} = -\sum_{j=1}^{n} log_b\, P_j \qquad (5)$$

where P_j is the joint probability caused by trial-and-error events taking place in the design process.

The information caused by trial-and-error processes is called 'Unorganised Information'. Unorganised information only exists if the design matrix has not been organised yet. When the design matrix is organised, by decoupling FRs and DPs, this kind of information will have disappeared completely. Unorganised information does influence the relation between FRs and DPs but has no impact on the common range of the system. As such, unorganised information is structurally independent from information as defined by the information axiom (further to be referred to as 'Axiomatic Information').

Though imaginary complexity was never defined specifically in terms of Hartley's logarithmic function, it was applied as such in [Suh, 1999:121] and [Suh, 2005:66]. By formalising this, imaginary complexity equals unorganised information as

$$I_{UnOrg} = C_{Im} \qquad (6)$$

2.5 MAGNITUDE OF AXIOMATIC INFORMATION AND UNORGANISED INFORMATION

The information content of real- and imaginary complexity are of a different magnitude [Suh, 2005:71]. A simple calculation example indicates what order of magnitude may be expected. If a system, with a uncoupled or decoupled design matrix has five FRs that are satisfied 95% of the time, the probability of satisfying all FRs and the axiomatic information content could be calculated with (2)

$$I_{Ax} = -\sum_{i=1}^{m} log_b P_i = -\sum_{i=1}^{m} I_{FRi}$$

$$I_{FRi} = -log_2(0.950) = 7.40 \cdot 10^{-2}$$

$$I_{Ax} = -5 \cdot 7.40 \cdot 10^{-2} = 0.370$$

where the outcome is given in bits. If the same system is coupled, unorganised information can be calculated by completing (5)

$$I_{UnOrg} = -\sum_{j=1}^{n} log_b\, P_j = -log_2 \prod_{j=1}^{n} P_{5FRs(t\&e)}$$

$$P_{5FRs(t\&e)} = \frac{1}{n!} = \frac{1}{5!} = 0.833 \cdot 10^{-2}$$

$$I_{UnOrg} = -log_2(0.833 \cdot 10^{-2}) = 6.91$$

and unorganised information is again in bits and may be compared to the axiomatic information of the first calculation. In this situation, axiomatic information cannot be calculated because in an unorganised design it is unclear which DPs are used to satisfy the FRs.

This case with 5 FRs already shows the unorganised information to be significantly larger than the unorganised information (0.370 vs. 6.91). This ratio seems typical in the comparison of axiomatic and axiomatic information. The ratio will precipitately increase with the number of FRs. Analogue to information, the same can be concluded for complexity; imaginary complexity is by nature of a larger scale than real complexity.

3 THE COMPONENTS OF INFORMATION

3.1 DOING THE RIGHT THINGS RIGHT

A recommended way, to address design problems, was described by [Suh, 1990:67] and addresses axiom 1 first and subsequently axiom 2. In the broader domain of information, as entropy of the design, this means that unorganised information should be addressed first followed by the reduction of axiomatic information. It is not advised, as a common procedure for concurrent engineering, to address the two kinds of information simultaneously. This is because the efforts of addressing unorganised information has a fundamental effect on the design; it selects the design relations and, by doing so, it sets challenges for successful optimisation of system ranges and design ranges later on in the design process. These optimisations might be lost if the design relations are changed in a later stadium which leads to a loss of efforts. Therefore it is important that the design relations are well chosen, selecting an independent way to address FRs and preferably envisioning on the optimisation of the design ranges. This is referred to by 'doing the right things'; focussing on the right relations for the design. After this, matching the system- and the design ranges optimises the relations. This is referred to as 'doing things right'. When the two processes have competed, the system will comprise the right design relations with the right probability density functions.

From this perspective the more general concept arises that unorganised information is about doing the right things and axiomatic information is about doing things right (though these statements are not meant to be inexhaustible, they well contribute to general understanding).

3.2 RELEVANCY OF INFORMATION TO THE SYSTEM DESIGN

So far, a lack of understanding of the system design was considered to be the source of unorganised information; missing knowledge hinders the designer to make the right choices for the essential relations in the design and FRs are not satisfied by DPs. But what if a designer believes that a DP indeed does relate to an FR while in reality this is not the case. This situation again comes forth from a lack of understanding of the design; the designer does not have the knowledge that the parameter is not relevant. So what will be the effect on the information content of the design by this otiose DP? Earlier was put that the level of a design never exceeds the knowledge of the designer. However, in some cases it is possible that unorganised information is eliminated from the design and becomes superfluous. If otiose information is present in a design it could disappear. Since many system designs are redundant in some way, there is typically more than a single DP that can be optimised to meet a certain FR. According to good AD practice, the designer will decide to use the process of fixing some of the DPs [El-Haik, 2005:69]. The variable will be converted to a constant by defining its value and maintaining this situation as steady as possible. The process of fixing is continued until the design matrix is square with an equal number of DPs and FRs. The process of fixing may lead to two possible occurrences; 1) the otiose DP was maintained in the square matrix or, 2) the otiose DP was fixed.

Ad1) if an otiose DP is maintained in a non-redundant design matrix, it means that at least one of the FRs cannot be satisfied. The design matrix is not understood which leads to an increase of unorganised information;

Ad2) if the process of fixing eliminates an otiose DP from a non-redundant design matrix, all FRs can be satisfied. The DP will not influence the functionality of the system, but due to its redundancy it will increase the cost of the system. There is no impact on complexity since the uncertainty of achieving the FRs is not affected. This analysis indicates that otiose DPs that are fixed, though caused by ignorance, do not contribute to unorganised or axiomatic information. Fixing the DP has removed it from the design matrix and the FRs are no longer affected by this DP; the otiose information has become superfluous.

3.3 INFORMATION OVERVIEW

An inventory of the different kinds of information as discussed in this paper:

- Total information; the total information content of the design (full entropy of the design);
- Useful information; the part of total information that affects the relation between FRs and DPs;
- Superfluous information; information that does not affect the relation between FRs and DPs;
- Otiose information; a specific kind of superfluous information that is believed to affect the relation between FRs and DPs but in reality it does not. Otiose information is based on ignorance and therefore might increase the unorganised information content of a design;
- Axiomatic information; useful information due to a discrepancy in design ranges and system ranges;
- Unorganised information; useful information that is not recognised as such due to ignorance of the designer.

The tree of figure 1 explains the relations between these kinds of information. Note that superfluous information and unorganised information are no information according to the definition of axiom 2. Useful, axiomatic and unorganised information do affect the relation between FRs and DPs; they all lead to complexity. Otiose information only affects this relation if an otiose DP remains in the design matrix; only then it contributes to information within the definition of AD.

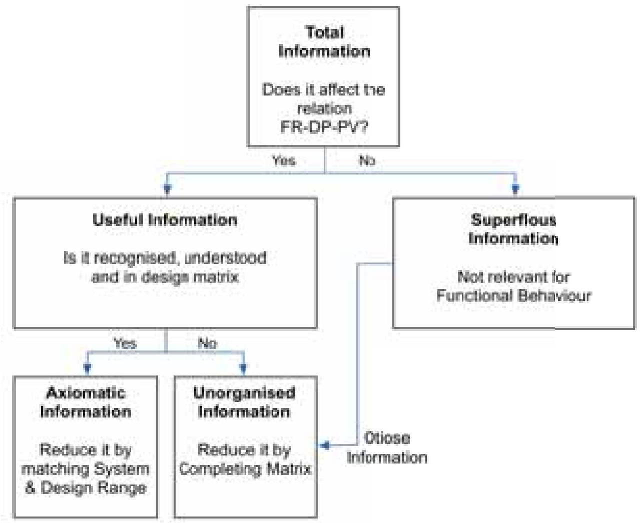

Figure 1: Overview with types of information and their relations

The kind of information can be determined by a number of two parameters: 1) is the presence of the information content recognised in the design, and 2) does it affect the FRs of the system. This is shown by figure 2.

	Relations Recognised	Relations Not Recognised
Does Affect FRs	Axiomatic Information	Unorganised Information
Does Not Affect FRs	Superfluous Information	

Figure 2: Axiomatic, unorganised and superfluous information can be determined with two parameters

3.4 VISUALISATION OF THE AXIOMS IN A TWO DIMENSIONAL INFORMATION SPACE

Information may be visualised in a two dimensional space. As axiomatic and unorganised information are different kinds of information, with structurally different origins making them independent of each other, their vectors will be perpendicular. According to (4), axiomatic information leads to real complexity. According to (6), unorganised information leads to imaginary complexity. Therefore this representation is analogue to Suh's complexity diagram [Suh, 2005:71].

If axiom 1, 'Maintain the independence of the functional requirements, is plotted it will guide a progressing design in the downward vertical direction as shown in figure 3. The reason for this is that axiom 1 solely addresses unorganised information: 1) the imaginary component of complexity in an uncoupled design is equal to zero which by definition eliminates the existence of unorganised information [Suh, 2005:71], 2) the process of trial-and-error does not affect the overlap of design- and system-ranges leaving unorganised information in the system untouched. This is in harmony with (4) & (6), where the outcome of (4) is constant and the outcome of (6) is decreasing.

Axiom 2, 'Minimise the information content of the design', affects by definition only axiomatic information. The component of axiomatic information is affected by matching the design range and system range but not by trial-and-error, the outcome of (4) is changes but the outcome of (6) remains constant.

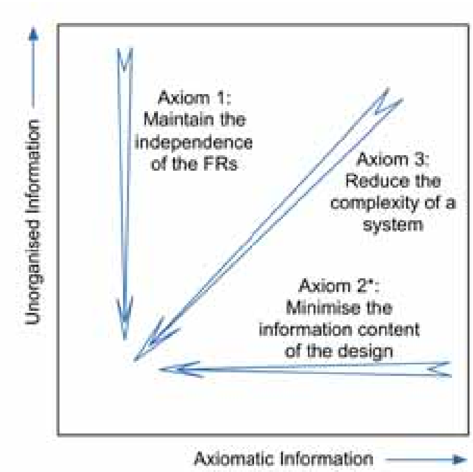

Figure 3: According to Axiom 1, a progressing design moves downward in vertical direction. Axiomatic information is not affected

If axiom 3 is plotted, complexity is maximal at the right upper corner and is zero in the lower left corner. Figure 3 shows the direction of a progressing design that satisfies the complexity axiom. The effect of the information axiom and the complexity axiom are in this case exactly the same; the outcome of (4) and (6) are decreasing.

4 DISCUSSION & CONCLUSIONS

A number of six kinds of information have been reviewed in this paper. Not all these kinds of information are considered to be information by the definition of information axiom.

4.1 UNORGANISED INFORMATION VS COMPLEXITY

Axiomatic information differs from unorganised information, which is mainly to be addressed before organisation of the design matrix. Unorganised information is very comparable to imaginary complexity though two considerations should be made before defining them as one and the same: 1) The inability of a design to satisfy the independence axiom should be considered to be information according to the definition by Shannon and Weaver and, 2) Hartley's logarithmic measure for imaginary complexity should be used as a measure. If these conditions are adopted, imaginary complexity and unorganised information are equivalent.

4.2 AXIOM 1 AND AXIOM 2 AS COROLLARIES OF USEFUL INFORMATION

Useful information, as defined by Suh, is information that adversely influences satisfaction of the FRs; information content in the design will lead to a reduced satisfaction of the FRs for that design. Useful information is the aggregate of both axiomatic- and unorganised information. Therefore, it can logically be decomposed into information relating to axiom 1 and axiom 2, making the axioms fully independent. Since useful information is the basis of complexity, the same could be done with the complexity axiom. Axiom 1 & 2 are in fact corollaries of the objective to reduce the useful information content, or complexity, of a design. Though this might be considered as a disruptive determination, the operation and practical application of AD are not much affected by this for at least three reasons. First, the possibility to develop axiom 1 & 2 from the complexity axiom has already been reported by [Suh, 2005: 83]. He mentions the complexity axiom being less explicit than particularly the independence axiom and advises to apply the axioms as they are. Secondly, axiom 3 will maintain its axiomatic character in AD and will still be axiomatic in a sense that it cannot be derived from a higher truth. Third, axiom 3 is not easily applied in the design process. It does not structure the order in which the information content of the design should be addressed. Axiom 1 and axiom 2 are best maintained as starting points of the design process, and should be addressed in that particular order. This basically leaves the AD methodology intact as is.

4.3 OTIOSE INFORMATION

Fixing otiose DPs eliminates these DPs from the design matrix. There is no further impact on information since the fixed DP no longer affects the uncertainty of achieving the FRs. However, the designer's ignorance has not disappeared. Otiose information is always either a part of superfluous- or unorganised information.

4.4 DOING THE RIGHT THINGS AS GAME CHANGER

Unorganised information will equal zero for a design in which independent FR-DP relations were chosen because satisfaction of the FRs is no longer a matter of trial-and-error. A multitude of independent designs can be found for a typical design. However, depending on the chosen solution, the collection of processes that need matching of design- and system-ranges will differ per situation, greatly determining the remaining amount of work for optimisation. Therefore it is important to reduce unorganised information before axiomatic information which is referred to as 'doing the right things' before 'doing the right things'. In this statement 'things' are referring to design relations.

4.5 CONCLUSIONS

At least a number of six different kinds of information, according to the definition of Shannon and Weaver are playing a role in the design process. In the ultimate design, all information should have disappeared.

Axiomatic information, as defined within AD, has been defined considerable narrower and is limited to the matching of the design- and system-ranges of the design.

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CONCEPTUAL DESIGN EVALUATION OF DIFFERENT FRICTION DEVICES THROUGH THE USE OF AXIOMATIC DESIGN

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ABSTRACT

Defining the best design solutions is a current issue for a lot of design teams. This issue is becoming more and more important due to the high standard requested to new products and to the need of meeting customer satisfaction with the lowest cost. Defining critical functions of a product by meeting customer satisfaction and reaching the goals of a new project is a critical activity in order to provide the success of the company and the business efficacy. The identification of the best design, according to the two axioms, permits companies to minimize the high costs related to trial and error approach, avoiding mistakes and designing goods systematically. In this paper Axiomatic Design principles are used to evaluate the agreement level to the best design of some concepts concerning a friction device of a mechanism. The proposed friction devices work to avoid overloads on the mechanism used to release the spare wheel of a vehicle. This approach consists of drawing the design matrix for each concept to compare them with the triangular or diagonal matrix. Such kinds of matrices are typical of a functional independence among critical functions, according with the theory of Axiomatic Design. Each concept will be evaluated also in terms of the information content according to the second axiom, in order to identify the design solution which maximizes the probability to verify the design requirements.

Keywords: Concept synthesis and evaluation, Concepts Choosing Process, Axioms agreement assessment.

1 INTRODUCTION

Choosing the best design, according to the axiomatic design theory, is increasingly important in modern engineering activities to reach maximum performance and customer satisfaction with economical convenience.

Choosing the wrong design could lead to product failures and high costs to investigate how to fix them. On the other hand, the many compromises needed during product design are often responsible for a non-optimal design and for a reduction in the design process efficiency (delays or cost rising). Several attempts have been made in order to develop the nearest design to the best one, like MADM or QFD approaches (e.g. in [Cavallini *et al.*, 2013], [Cavallini *et al.*,2013], [Jahan *et al.*, 2010], [Ulrich and Eppinger, 2011]). A non-optimal design could not be also effective to meet the customer requirements. Because of this, it is very important to set the main functional requirement (FR) at the higher level, i.e. what the device, or the concept, should do. According with the axiomatic theory several main FRs could be found by drawing a QFD matrix or executing customer interviews.

The aim of this paper is to drive towards a skimming selection of several concepts through the agreement evaluation of each concept to the best design condition.

2 SCOPE AND USED APPROACH

In this paper the authors are going to select a concept from a pool of possible solutions, evaluating the agreement level to the best design conditions described in the axiomatic design theory. These concepts are about a friction device used in the automotive industry to avoid overloads when the spare wheel of a vehicle is lowered or raised.

The friction device works when it is operated by the user who wants to raise or lower the spare wheel of his vehicle. The user has to apply a torque to a lever in order to unlock the wheel and lower it, or raise it until its lock. If the torque is excessive, the friction device will permit sliding between the parts which lead the input and the output of the motion.

The complete architecture of the friction device can be defined by decomposing the highest level FR and DP, creating hierarchies of FRs, DPs and PVs. This is done through zigzag mapping among these domains, according with what has been stated by Thompson [2013].

This case deals with one FR design since the main FR is “To transmit the torque without overloads” and it is common for all solutions. A way to achieve this main FR is a system able to maintain a selective contact between two surfaces (DP1 is common for all concepts). Such system shall permit to perform the selection between the no sliding condition and the sliding one depending on the amount of transmitted torque.

The main FR is further split into three different FRs at the second layer of zigzagging. These common FRs for all concepts are FR1.1 “To realize selection between sliding condition and no sliding one”, FR1.2 “To make adherent shapes and non-adherent ones” and FR1.3 ”To hold component parts linked”.

As previously stated, this friction device has the aim to avoid overloads in the mechanism, so it works linearly until the applied torque reach 50 Nm, than large sliding occur and the given torque fall down to values next to 0 Nm. Within the limit value of 50 Nm the behaviour of the device is almost linear and the ratio between the applied torque and the given one is 1. In Figure 1the curve which relates the applied torque and the given one is shown.

Several concepts are diversified by how they achieve these functions and in the following layers of zigzagging.

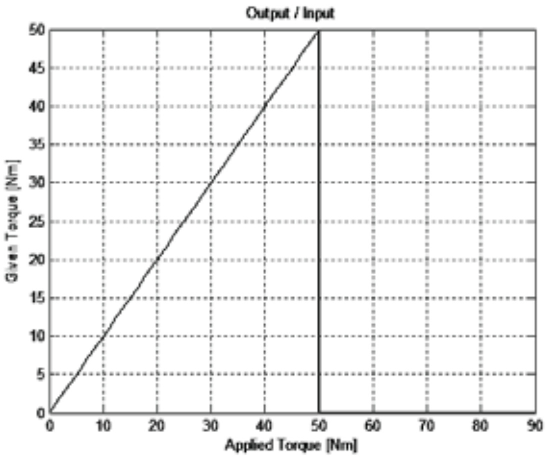

Figure 1 Relation between the applied torque and the given one to avoid overloads.

2.1 CONCEPT ONE: BELLEVILLE SPRINGS

The first concept is characterized by the Belleville springs to achieve the selection between the condition of torque transmission when the two surfaces are adherent without sliding, and the condition of no torque transmission with an amount of sliding between the two surfaces in contact.

In Figure 3, a section of this concept is shown and the component parts can be seen. Torque enters in the device through the cap. It is transmitted by the cap to the plates and gets out through the lower cogwheel, while the shaft is fixed. The first plate is coupled with the cap, so it can rotate with it,while it is kept in contact with the second plate by the springs pack at the upper side. The second plate has several pads on the upper surface that fill some grooves on the lower surface of the first one and its axial position along the shaft is fixed at the bottom side by a screwed support of the lower cogwheel. The coupling between the grooves and pads is shown in Figure 2.

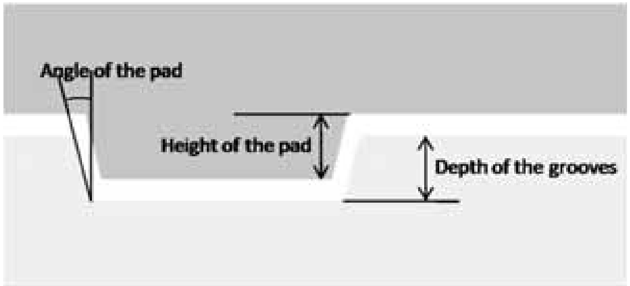

Figure 2 Coupling between grooves and pads.

The shaft presses the Belleville springs pack against the second plate, which stays in contact with the pads on the opposite surfaces of the first one. When the torque increases over the given limit of resistant torque, sliding occurs and a shift between the two surfaces, which are no longer adherent, takes place. When the torque increases over the given limit of resistant torque, sliding occur and a shift between the two surfaces, which are adherent no more, takes place. Sliding works in reducing the amount of transmitted torque until the adherence between pads and grooves is restored.

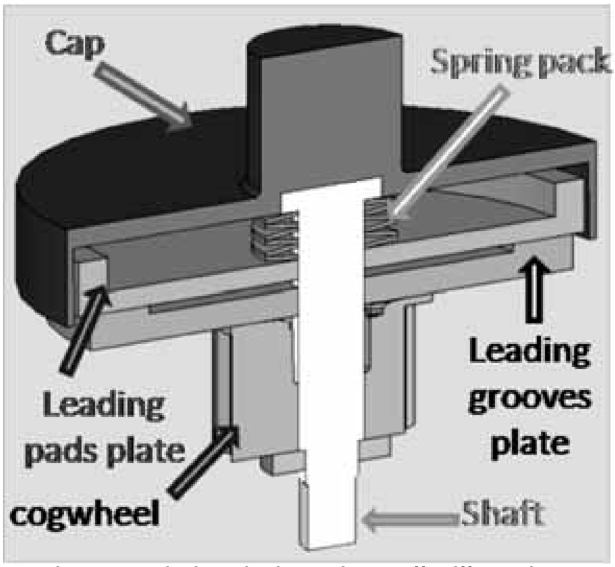

Figure 3 Friction device using Belleville springs.

Using the zigzagging method, the authors have mapped the functional and physical domains identifying some correlations among FRs and PDs. This has led to drawing the design matrix for the concept. The FRs of this mechanism further common ones are defined as follow:

FR1.1.1 To control the position of the pads
FR1.2.1 To turn the actuation torque in compression force above the spring
FR1.2.2 To apply the preload of the spring
FR1.2.3 To transmit the torque to the pads

The characteristic DPs further DP1 are defined as follow:

DP1.1 Belleville spring(s)
DP1.2 Grooves / pads system
DP1.3 Case
DP1.1.1 Spring stiffness
DP1.1.2 Spring free height
DP1.1.3 Number of springs

DP1.2.1 Height of the pads
DP1.2.2 Angle of the pads
DP1.2.3 Depth of the grooves
DP1.3.1 Height of the internal vane

In Table 1 the design matrix which relates the FRs and DPs vectors is reported.

	DP1	DP1.1	DP1.2	DP1.3	DP1.1.1	DP 1.1.2	DP 1.1.3	DP 1.2.1	DP1.2.2	DP1.2.3	DP 1.3.1
FR1	X										
FR1.1		X									
FR1.2			X								
FR1.3				X							
FR1.1.1					X			X	X	X	
FR1.2.1								X	X		
FR1.2.2						X	X			X	X
FR1.2.3										X	X

Table 1 Belleville Springs Design Matrix

2.2 CONCEPT TWO: HELICAL SPRINGS

The second concept is characterized by some helical springs. The motion enters through the shaped shaft and it is transmitted to the case (output) via springs. A cap (that is semi-transparent in the picture) has some linear guides to make the springs move only along the radial direction. The springs lead shaped blocks to fill some grooves in the internal side wall of the case. The springs keep these blocks pressed against the grooves of the case allowing the torque transmission. If the torque overcomes the given limit the helical springs will be compressed and the shaped blocks will get out the grooves reducing the amount of torque since it is transmitted no more. In Figure 4 a view of the device is shown with shaped blocks and helical springs.

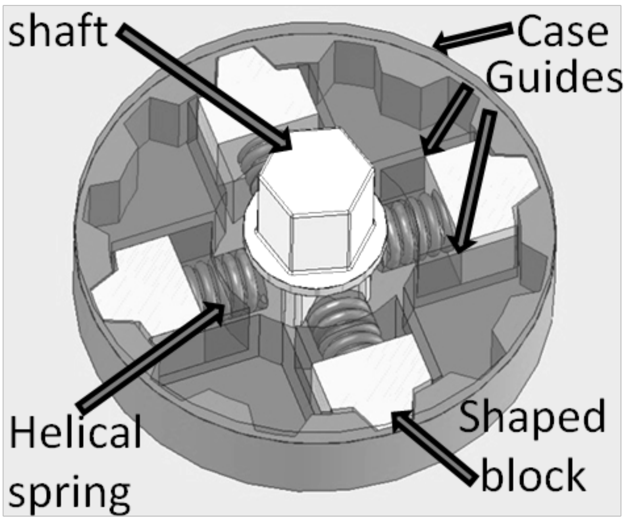

Figure 4 Friction device using helical springs.

The design of this solution is defined through the zigzagging method which can set a hierarchy among several layers of FRs and DPs. The DP1, FR1, FR1.1, FR1.2 and FR1.3 are the higher level which is common for all concepts.
The lower FRs of this mechanism are defined as follow:

FR1.1.1 To control the position of the blocks
FR1.1.2 To drive the springs
FR1.2.1 To turn the actuation force into a compression force on the spring
FR1.2.2 To apply the preload to the spring
FR1.2.3 To transmit the torque to the case

The characteristic DPs further DP1 are defined as follow:

DP1.1 Helical spring(s) and Cap
DP1.2 Shaped blocks
DP1.3 Containment casing
DP1.1.1 Spring(s) stiffness
DP1.1.2 Spring free height
DP1.1.3 Springs number
DP1.3.1 Height of the teeth
DP1.3.2 Angle of the teeth
DP1.3.3 Case diameter
DP1.4.1 Guides on the cap

In Table 2 are shown the correlations which link functional requirements and the adopted design solutions.

	DP1	DP1.1	DP1.2	DP1.3	DP1.1.1	DP 1.1.2	DP1.1.3	DP 1.3.1	DP1.3.2	DP1.3.3	DP 1.4.1
FR1	X										
FR1.1		X									
FR1.2			X	X							
FR1.3			X	X							
FR1.1.1					X		X	X	X	X	X
FR1.2.1								X	X		
FR1.2.2					X	X				X	
FR1.2.3								X	X		
FR1.1.2											X

Table 2 Helical Spring Concept Design Matrix.

2.3 CONCEPT THREE: FLAT SPRING

The third concept has a flat spring to achieve the selection between the sliding condition and the non sliding one. In this case the spring is a single shaped steel piece whose leading edges fill the grooves on the side wall of the case.
A shaped cap holds the stopping spring in its position. When torque raises over given limit, the spring elongation is such to make the leading edges overcome the grooves, losing the contact and decreasing transmitted torque until it will reach lower values. In Figure 5 the device is shown.
The design of this solution is defined through the zigzagging method which can set a hierarchy among several layers of FRs and DPs. The DP1, FR1, FR1.1, FR1.2 and FR1.3 are the higher level which is common for all concepts.
The lower FRs of this mechanism are defined as follow:

FR1.1.1 To control the spring edges position
FR1.1.2 To transmit the torque to the case
FR1.1.3 To constrain the spring
FR1.2.1 To turn the torque into a load over the spring
FR1.2.2 To apply a preload to the spring

The characteristic DPs further DP1 are defined as follow:

DP1.1 Flat spring
DP1.2 Containment casing
DP1.3 Cap
DP1.1.1 Spring stiffness
DP1.1.2 Spring free height
DP1.1.3 Spring number
DP1.2.1 Grooves depth
DP1.2.2 Angle of the grooves
DP1.2.3 Case diameter

DP1.3.1 Guides on the cap

In Table 3 are shown the adopted design solutions and their corresponding functional requirements.

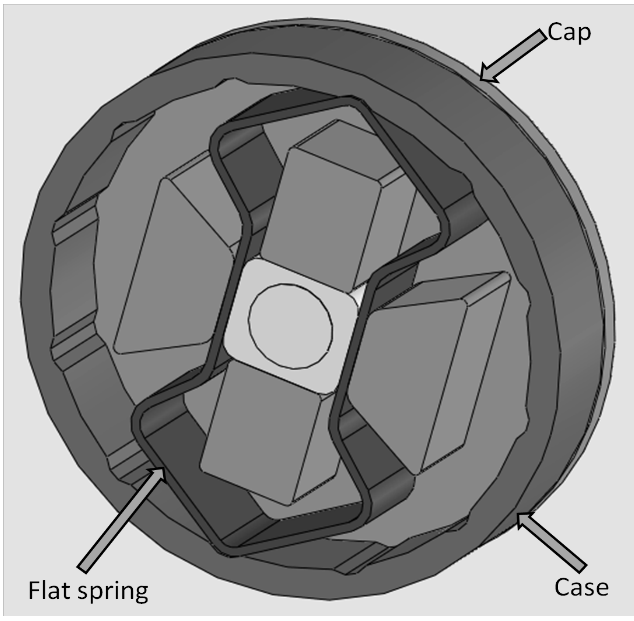

Figure 5 Friction device using flat spring.

	DP1	DP1.1	DP1.2	DP1.3	DP1.1.1	DP 1.1.2	DP1.1.3	DP 1.2.1	DP 1.2.2	DP1.2.3	DP 1.3.1
FR1	X										
FR1.1		X									
FR1.2		X	X	X							
FR1.3			X								
FR1.1.1					X		X	X	X	X	
FR1.1.2								X	X		X
FR1.1.3											X
FR1.2.1								X	X		X
FR1.2.2					X	X				X	

Table 3Flat Spring Concept Design Matrix

2.4 EVALUATION OF THE INFORMATION CONTENT PER EACH CONCEPT

Each concept has been compared through second axiom, evaluating its fitting with the accepted range of the given torque. The accepted torque is 50±5Nm,deriving from structural computations.

Different devices employ different technologies and need several working processes in order to be manufactured. The concept which mounts some Belleville springs needs different processes to manufacture the pads joint despite the requested processes for the one that mounts the flat spring. Various machining processes and sequences of these lead different tolerances, dimensional errors, specific features for each kind of manufacturing sequence. It derives these three concepts are intrinsically different and characterized by a different tolerances accuracy. A very important tolerance is the error of critical dimensions because it may influence the values for given torque which may be different than the expected ones. The critical dimension of the flat and helical spring concepts is the radius dimension while the critical dimension of Belleville spring concept is the axial dimension.

Authors will evaluate the matching between the expected range and the response of the system in terms of actuating torque.

The dimensional error has been introduced by machining operations for each concept and it is as known as the characteristic curve which relates that and the torque. The dimensional error is estimated as 0,4mm (i.e. ±2mm) for the critical dimension of the different concepts.

As stated previously, the expected range of torque values depends on dimensional errors which are given by different working processes. The relation which links them is a characteristic curve for each system. In Figure 6 this relation between the given torque and the dimensional error for the flat spring and the helical springs can be seen. The given torque is lower than 50 Nm when the dimensional error tends to increase its value. Positive values are quite acceptable for this application in order to avoid the components overload, so they may not be considered.

In Figure 6 it can be seen how the given torque exponentially increases itself with lower errors when flat springs are used. In such case small variations in error may lead to wide variations in the given torque.

The concept with helical and Belleville springs present a smaller variation of the torque in respect to dimensional error and torque values near the target.

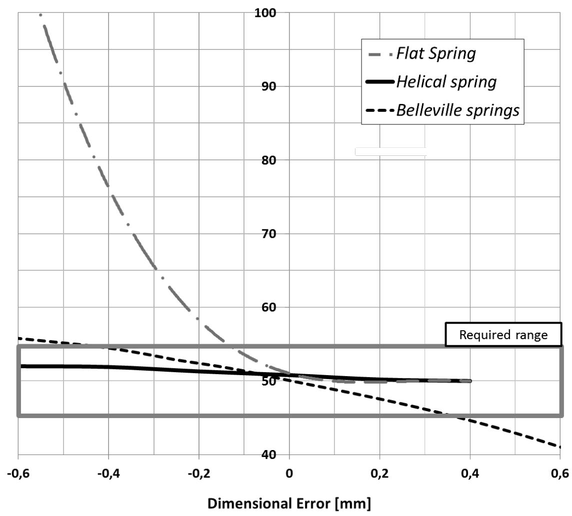

Figure 6 Given torque respect to dimensional error.

The range of dimensional error and its distribution depend on the adopted machining process and their features, which are well known and present in technical datasheets.

The points within dimensional error range are characterized by a probability density function, i.e. a curve giving the specific frequency for each value of them. This curve may be typically a Gaussian but in this paper it has been simplified using a trapezium shaped fuzzy function which is easier to compute.

It is easy to achieve the limits of the range within the given torque falls because of it is dependant by the error through the known relation in Figure 6. The torque frequency values are found in the same way, using those referred to some errors as inputs. In Figure 7 this state is shown concerning the Flat spring concept.

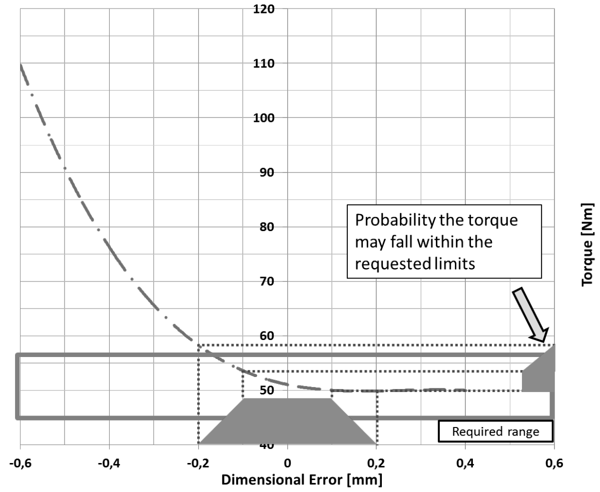

Figure 7 Flat spring response in terms of probability of success.

In Figure 7 the given torque is shown and it falls partially out of expected limits. The information content, i.e. the probability not to satisfy the requested limits, is represented as the area under these curves. In Figure 8 and in Figure 9 the torque distribution in case of helical and Belleville springs is displayed.

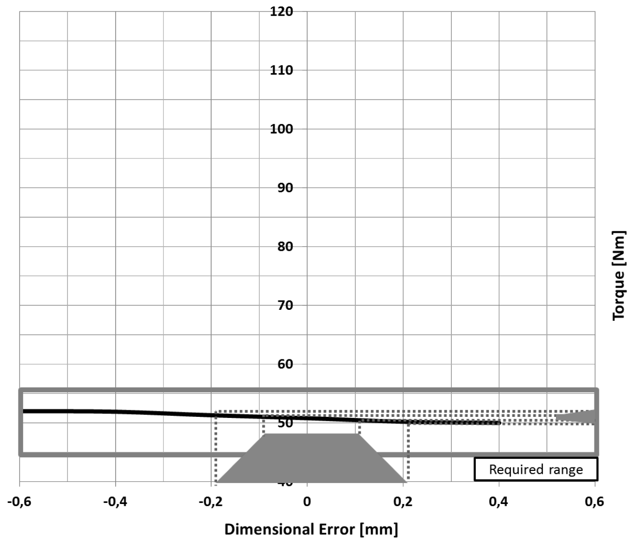

Figure 8 Helical springs response in terms of probability of success.

In Figure 7, 8 and 9 the information content of each of three concepts is shown. It is represented by the area under the torque curve which falls outside the expected limits for torque. In this Helical and Belleville cases this area is collapsed in a narrow strip just inside the expected limits for the torque, so the information content is zero. This achievement is quite foreseeable since the characteristic curve of these springs is very smooth and almost constant, so variations in dimensional error lead to minimal variations for the given torque.

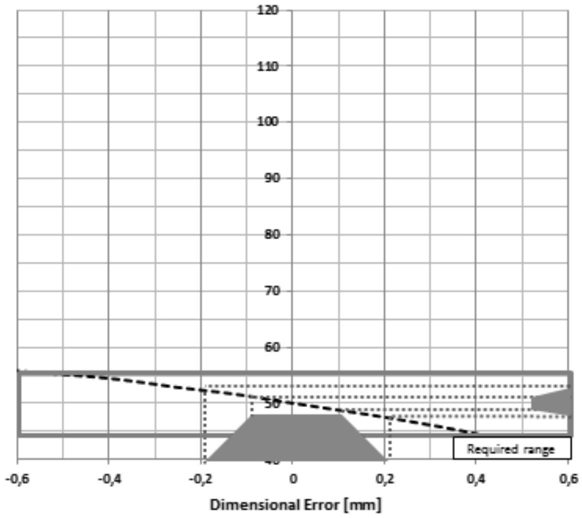

Figure 9 Belleville springs response in terms of probability of success.

3 CONCLUSIONS

In this paper an example of selection among several concepts using axiomatic design is proposed. Three different solutions to achieve the main FR have been presented, so the authors have tried to draw out the design matrix and compare the information content of several concepts in order to select them, according to the two axioms. At first the design matrix for each concept has been drawn. The design matrix of the Belleville Spring concept is the most similar to the ideal one, described in Axiomatic Design Theory. From the point of view of the second axiom, the Belleville spring concept has the lowest information content since the torque distribution falls within the design range. The helical springs concept is the worse from the point of view of matrices comparison but it is characterized by a low information content. The flat spring concepts is not the worse in reproducing the ideal matrix condition, but it has the highest information content since its torque distribution partially falls out of the design range. This leads to identify the best design allowing to dismiss the flat and helical spring concepts.

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AN INTEGRATED QFD AND AXIOMATIC DESIGN METHODOLOGY FOR THE SATISFACTION OF TEMPORARY HOUSING STAKEHOLDERS

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ABSTRACT

Modern construction projects must meet the requirements of a diverse range of stakeholders, each of whom have their own unique needs and constraints. Ideally these needs would be identified early in the design process when the designers have the largest impact on cost and functionality of the project. Unfortunately, this stage is typically approached in an informal and non-homogenous manner. Designers often do not use formal and systematic tools until later in the design process. This study proposes a new systematic approach to the conceptual design of construction projects -specifically temporary housing- by combining Quality Function Deployment (QFD) and Axiomatic Design (AD). This combined methodology helps ensure that the design meets customer's needs, as well as satisfies the design objectives in a logical sequence. More precisely, the QFD-AD method proposed innovatively combines two prevalent design methodologies in a way that allows a seamless translation of diverse customer needs into a formal and methodical design approach. The design of a refugee housing unit is presented as an illustrative case study of temporary housing.

Keywords: Quality Function Deployment (QFD); Axiomatic Design (AD); QFD-AD; refugee housing; civil engineering design.

1 INTRODUCTION

The success or failure of a construction project is highly dependent on ensuring stakeholder satisfaction. In modern construction project, designers must to fulfill the requirements of a large and diverse range of stakeholders, as well as achieve an ever expanding list of life-cycle properties. Today, constructability, durability, life-cycle maintenance, energy efficiency, the cost of maintenance, environmental impact, and social-economic impact have been added to the more traditional concerns in building design like aesthetics, structural integrity and initial cost [Albano and Suh, 1992]. According to Marchesi et al. [2013], the intricacy of modern architectural design demands a more rational approach to the design phase when decisions with fundamental and extensive effects on appearance, performance, and costs are made. This is perhaps even truer in the case of Temporary Housing (TH in the reminder of this text), which faces the broader challenges of a typical construction project as well as the need to satisfy a diverse range of stakeholders. To handle the growing complexity and find a more rational approach to design, many designers are looking outside of their traditional domain for solutions, particularly during the early design phase [Albano and Suh, 1992, Armacost, et al., 1994, Delgado-Hernandez, et al., 2007, Dikmen, et al., 2005, Gargione, 1999, Pheng and Yeap, 2001, Yang, et al., 2003]

Throughout a construction project timeline, the decisions impact decreases as the project progresses such that earlier decisions have greater importance. However, "rigorous analytical methods and optimization systems are used for decisions that impact project costs by plus or minus 7% (detailed design phase), while decisions that impact project costs plus or minus 30% (conceptual design phase) are internalized"[Albano and Suh, 1992]. Civil engineering and architectural work typically begins with a broad conceptual design performed by experienced experts who have received input from key stakeholders. However, the mounting intricacy of the conceptual design phase makes it difficult for even the most experienced engineer to effectively capture and understand the diverse range of customer demands, much less ensure all of their needs are met during preliminary design phase. Temporary housing, a field awash with different stakeholders, is even more liable to have trouble capturing the customer demands. Design of temporary housing is equally, if not more, complex as a traditional construction project, particularly given the diverse contexts, environments, and stakeholders they are subject to. Therefore, it is critical to have robust, rigorous, and methodical approaches to early conceptual design for said TH projects.

Traditional design methods typically include building to code, formal/informal discussions with the clients and/or iterative design stages; however, some find these methods lacking in their ability to capture client needs and requirements and so other methods not typically applied in construction design may be useful. "In the construction industry, usually the client needs and requirements are not treated systematically. Even if they are collected before the design phase, they tend to be disregarded and finally vanish as the construction phase goes on" [Dikmen, et al., 2005]. This has forced the construction industry to turn to other fields for direction. Newer fields, like manufacturing engineering, have developed a number of methods to improve product design and development projects based on customer requirements. Literature has demonstrated that manufacturing new product development (NPD) and construction share a number of similarities [Formoso, et al., 2002]. Due to this similarity, methods used in NPD are easily adaptable to the construction industry. Two popular NPD methodologies are Quality Function Deployment (QFD) and Axiomatic Design (AD), both of which are used in this study.

AD was developed by Nam P. Suh in the 1980's and has quickly grown in popularity because of its ability to improve the conceptual design stage of a variety of different products. It has been used to develop products as complex as an autobus or refrigerator, to simple products like an efficiently designed soda can or bottle opener [Suh, 1995, Suh, 2001]. AD works by creating a systematic approach to decomposing the design in a series of steps that takes it from a high-level view to a low-level view, while simultaneously encouraging adaptability. While AD is a strong design methodology, currently it assumes that the designer has identified the users Functional Requirements "well" before beginning. In earlier works, AD was used specifically for Temporary Housing conceptual design [Gilbert III, et al., 2013, Gilbert III, et al., 2013].

The QFD methodology was developed in Japan in the 1960's by Mitsubishi Heavy Industries to improve the design of ships in the Kobe shipyards. It was adopted by Toyota in the 1970's and since has been used by car manufacturers worldwide to increase customer satisfaction [Delgado-Hernandez, et al., 2007]. Over the past forty years, QFD has continued to grow in popularity and use in other industries as a means to systemically assure that customer needs and wants are clearly specified and drive the product design and production process [Cohen, 1995]. QFD translates the difficult to understand customer requirements into measurable technical characteristics through a cascading series of relationship matrixes. The relationship matrix ensures that every customer need is addressed by at least one element in the design, and further helps designers better understand the most important design elements.

In light of the QFD's ability to capture the Voice of Customer (VoC) and map it into requirements, and the AD's ability to guide the design process from high-level requirements into a conceptual design, combining the two processes seems a beneficial match. The idea of integrating QFD and AD has been explored in by Suh [2001], Taglia and Campatelli [2006] and El-Haik and Said [2005]. In his work, Suh states that he chose not to integrate the QFD process because it could impede the creative process of generating a new design by compromising the designer's ability to work in a "solution neutral environment." Taglia and Campatelli and El-Haik and Said both found the linked QFD-AD process could be potentially useful, but did not strongly demonstrate how to use the two methods simultaneously.

This paper seeks to address the conceptual design of TH using a QFD-AD methodology where the two have been seamlessly connected through a modification of the QFD process using the taxonomy of AD as proposed by Thompson [2013]. This combined method will work well with temporary housing because the design process of TH is more integrative than creative in application; therefor Suh's concern of QFD compromising the ability to create a solution neutral environment is of less concern. The fundamental needs are relatively well known; however, the relative importance of each need and how needs are integrated together is not known. QFD and AD will answer these questions in sequential order.

Refugee housing has many stakeholders that need a formal approach to address their needs. Since no formal methodologies exist in the construction industry to both assess customer requirements and systematically approach the conceptual design of a construction project, this combined methodology is well-suited to fill this gap and to improve the design of complex projects. The methodology is applied to a TH illustrated example but it has potential to find other construction project applications, or may possibly be utilized in entirely different fields.

The remainder of this paper will proceed as follows. Section 2 introduces the QFD and the AD inner workings, and explains how the use of QFD at the start of AD is beneficial to the conceptual design process. Section 3 presents a case study to demonstrate the application of this theory to the conceptual design of a temporary housing unit. Ultimately, Section 4 provides a discussion of the results and a conclusion.

2 A QFD-AD METHODOLOGY

Quality Function Deployment (QFD) is a well-known methodology for mapping customer needs into technical requirements and determining the most important features to ensure customer satisfaction with a product. Section 2.1 provides a brief introduction into the theory and literature on QFD. Axiomatic Design (AD) is proposed as a methodology to develop a conceptual design for a civil engineering project. Section 2.2 briefly introduces the fundamental axioms that govern AD.

2.1 EXISTING QUALITY FUNCTION DEPLOYMENT (QFD) TO ENSURE CUSTOMER NEEDS DRIVE DESIGN

QFD is composed of a series of "quality tables" that move a design from the Voice of Customer (VoC) down to the detailed operations level. The House of Quality (HoQ) is the first phase and arguably the most important phase of the QFD process. In fact, most QFD studies focus almost exclusively on the HoQ phase of design [Chan and Wu, 2005]. The HoQ displays the VoC and translates them into Technical Requirements (TRs), using the importance of different customer needs values to help determine the most important TRs to ensure customer satisfaction with the product. Typically, QFD is used in product development, quality management, or customer needs analysis; however, in recent years it has been expanded into other fields of study like engineering, management, teamwork, planning, design, costing, timing and decision making [Chan and Wu, 2002].

The advantages of using the QFD process in the construction industry have been strongly presented in literature. Some researchers have discovered additional benefits beyond "creating a more enhanced customer orientation", "more effective product development", and "improved communications and teamwork" that are typically discussed in QFD literature [Chan and Wu, 2002, Chan and Wu, 2005]. Kamera et al. [2005], and Griffin and Hauser [2002] both found QFD to be extremely beneficial in improving communication in project teams, and subsequently the success or failure of a project. One company found the use of QFD has resulted in 30-50% reduction in engineering changes, 30-50% shorter design cycles, 20-60% lower start-up costs, and 20-50% fewer warranty claims [Zakarian and Kusiak, 1999]. Although the benefits of QFD are highly proven in the construction industry, with dozens of papers written on the matter, the methodology has still not gained hold in the field [Armacost, et al., 1994, Delgado-Hernandez, et al., 2007, Dikmen, et al., 2005, Gargione, 1999, Pheng and Yeap, 2001, Yang, et al., 2003]. However, the trend is slowly changing.

In order to seamlessly integrate the QFD and AD design process, adjustments need to be made to the QFD matrix. The new process works by first filling in an adjusted house of quality like the one in Figure 1 below. The key difference between this QFD and a traditional QFD is the TRs and the roof of the house (boxes 4-12 in Figure 1). The Technical Requirements are split into Constraints (Cs), non-Functional Requirements (nFRs) and Functional Requirements (FRs), three of five essential elements of AD decomposition as highlighted by Thompson [Thompson, 2013]. In this paper, Optimization Criteria (OCs) and Selection Criteria (SCs) are considered to be parts of constraints for simplicity. Projects that are more complicated may find it worthwhile to include these two items in addition to Cs, nFRs and FRs. The Functional Requirements should come from the second level decomposition. The roof of the house is done identically to a typical QFD by specifying the direction and strength of the relationship between the different TRs. However, the information provided in the roof will be used to guide the AD process. The roof provides the designer a compact and rapid view of the different Cs and nFRs that will affect the decomposition of the FRs in the AD zigzag design process. The QFD will provide the designers with important information, such as the most important FRs to ensure clients' satisfaction, and which Cs are most likely to hinder the realization of the project. From this information, designers can determine the most important areas to invest resources. When the QFD is completed, the designer moves to AD to complete the design.

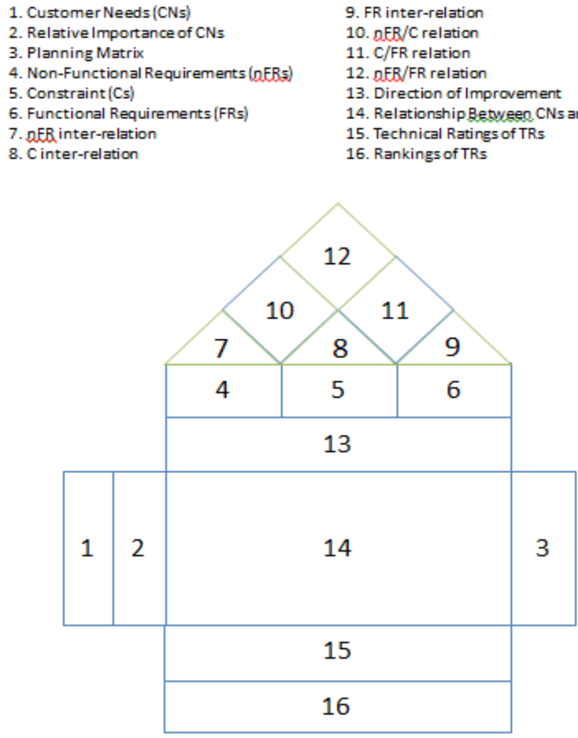

Figure 1 Modified QFD

2.2 Fundamental Concept of Axiomatic Design

Within this combined methodology, AD is used to translate/relate/link the Functional Requirements (FRs) to Design Parameters (DPs). While Axiomatic Design typically considers the customer needs; it does not yet have a methodical process of translating the customer needs into FRs.

The heart of AD is the two fundamental axioms upon which it is built, the independence axiom and the information axiom, where an axiom is a "truth that cannot be derived for which there are no counter examples or exceptions" [Suh, 2001]. These are formally stated by Suh [Suh, 2001]:

Axiom 1: The Independence axiom. Maintain the independence of the functional requirements.

Axiom 2: The information axiom. Minimize the information content of the design.

For additional information regarding either axiom, the reader should refer to [Albano and Suh, 1992, Suh, 1995, Suh, 2001].

AD is a rigorous design tool and has been applied in many areas. In its relatively short history, AD has been used in fields ranging from industrial design to aerospace engineering. It has even been used in the construction industry. It helps designers start with the statement of "what we want to achieve" and ends with a clear idea of "how we want to achieve it" AD was established to create a systematic, scientifically based process that would make "human designers more creative, reduce random search process, minimize iterative trial-and–error processes, and select the best designs among those proposed" [Suh, 2001].

Axiomatic Design has been applied in architecture by Pastor and Benavidas [2011], structural engineering by Albano and Suh [Albano and Suh, 1992], and transportation engineering by Baca and Farid [2013]. In earlier works, it was also applied to the design of a modular temporary housing unit, where it was found to be beneficial in making the design process more systematic and flexible to changes in requirements or resources [Gilbert III, et al., 2013, Gilbert III, et al., 2013].

In this integrated methodology, very few changes were made to the AD process. The key difference was that QFD was used to capture the customer needs and transform them into functional requirements, nonfunctional requirements, and constraints per Thompsons [2013] taxonomy. These FRs, nFRs and Cs can then be used in the AD zigzag process, where the Cs and nFRs from the QFD guide the decomposition of the FRs and DPs.

3 CASE STUDY: DESIGN OF A REFUGEE HOUSE

In the following section, a case study is used to demonstrate the application of the combined QFD-AD methodology to the design of a refugee temporary housing unit. A brief introduction into refugee housing is provided in Section 3.1. While Section 3.2 demonstrates how the QFD can be used to capture customer needs and convert them into ranked FR's. Section 3.3 takes the TR's from section 3.2, and converts them into DPs using AD. Section 3.4 concludes the case study by demonstrating how the use of the AD information axiom helps assess and select the most appropriate solutions (DPs) to the given FR's. The case study focuses on one branch of the AD decomposition, a broader scope has been done in an earlier paper [Gilbert III, et al., 2013].

3.1 CASE STUDY BRIEF

It is easy to contend that a safely built infrastructure and adequate housing conditions are among the most elemental human needs. Yet still a large proportion of refugees live in terrible and inhumane conditions [Brifcani, et al., 2012]. The camps are often overcrowded, and housing within the camps filled beyond capacity [De Felice and Petrillo, 2011]. Not only are the housing units overcrowded, they are poorly designed with little thought in mind for meeting the occupants needs. In a study of Sri Lankan Refugee camps, typical housing was found to be poorly ventilated, overcrowded, with no chimney to vent smoke from cooking with wood [Armacost, et al., 1994]. In another study of housing in the Palestinian refugee camp, Jalazonee, dampness was present in 72.5% of the houses, while 50.5% had mold, 37% had leaks, and only 41.5% were exposed to the sun [De Felice and Petrillo, 2011]. In addition to the above problems, residents of many of these shelters have to deal with the constant threat of contagious diseases, especially Malaria.

Many organizations provide temporary housing for these refugees; however, the limited funds shift the focus to speed and quantity over quality and functionality. This typically results in the distribution of tents. In fact, currently more than 3.5 million people worldwide live in tents provided by agencies like UNHCR. The tents are compact, easy and cheap to manufacture, store, and ship. However, the technology behind the tents has not changed in years, and they provide little security and perform poorly in hot and cold conditions. Their inadequacy demonstrates a strong need for better designed housing options for refugees. Realizing this, the Ikea foundation and UNHCR recently joined in a collaborative project to design a new type of refuge shelter. The new design is built to have a lifetime of several years (compared to the current tent lifetime of 6 months), better thermal resistance, more privacy, and access to solar power for lighting. It is also designed to be compact for easy storage and transportation, and inexpensive to manufacture (expected cost of $1000 per unit). They are not alone, and a range of other groups have been founded to address this growing problem.

While the work done by Ikea foundation is a step towards improving the housing situation faced by refugees, there are still millions of refugees in need of better housing. Currently temporary housing camps are unsafe, thus it is essential to provide safe homes that are free of physical hazards. In a number of studies on the effect of poor housing on health conditions has found that crowded-cramped conditions in conjuncture with inadequate housing can lead to anxiety stress, high-blood pressure, acute respiratory infections, and poor mental health among children [Brifcani, et al., 2012, De Felice and Petrillo, 2011]. If dampness and mold is present, these problems may expand to include aches and pains, digestive disorders, and respiratory tract infections [Ho, et al., 1999]. The crowded conditions of the camps also encourage the spread of communicable and contagious diseases such as tuberculosis. New housing needs to address the health and safety issues of the refugees while simultaneously meeting the shipping, storage, manufacturing and cost requirements of agencies providing the structures. What is more, since the refugee's status is fundamentally temporary, their housing needs a temporary solution. However, it is clear that do to the tremendous heterogeneity and diversity of voices of stakeholders, an integrated one size fit all approach will not work.

3.2 ASSESSING CUSTOMER NEEDS

The first step of creating a QFD is obtaining the Voice of Customer (VoC). This information can be obtained from a range of sources including, but not limited to surveys, interviews, focus groups, and observation. Often customers are ambiguous with their description of needs, and may confuse a physical object for functional requirement. For example, a customer may specify they need an A/C unit (an object), however, what they mean is a way to regulate the internal temperature (a functional requirement). Customers may also provide vague (subjective) specifications, or provide very general ideas. Affinity trees and diagrams can help clarify and assist in the completion of the list of needs.

In this study, the Customer Needs (CNs) are determined from the open literature published on the subject. Table 1 shows the CNs found based on the work of Gilbert et al. [2013], Arnold [2009] and Ballerino [2002]. This was determined by first specifying the higher level CNs, and then determining the components that compose said high level needs. The importance of each low-level element to the user was determined and averaged to find the importance of the high-level elements to the customer. Note that the table gathers CNs from multiple stakeholders.

Table 1 Customer Needs and Level of Importance

Who it matters to	Customer Needs (High-Level)	Importance High-level (1-9)
End User	Be Climatically Comfortable	7
	Support Health and Safety	7.25
	Support User Activity	5.6
	Be Aesthetically Pleasing	4.67
End User/ Provider	Function and Performance	8.25
	Be Easy to Assemble	6.33
Provider	Be Easy to Manufacture	5.67
	Match Site	5.67
	Be Sustainable	6
	Minimize Cost	8
	Be Easy to Transport and Store	8.5

Similar to the CNs, the TRs are determined from the literature, designer experience, and an extensive review of the attributes highlighted by temporary housing like that proposed on habitat.com, morethanshelters.org and the Ikea foundation home. Like with the customer needs, the higher-level TRs where further decomposed into the Cs, nFRs, FRs. Each of these three is then further decomposed into high-level TRs for the QFD, and low-level TRS to capture a more complete view. The high level TRs are shown in Table 2 below.

Table 2 High-Level Constraints (Cs), non-Functional Requirements (nFRs) and Functional Requirements (FRs)

Constraints
Environmental Impact
Volume During Transportation/storage
Number of Components
Number of Materials
Design/ Volume When Built
Complexity of Assembly
Complexity of manufacturing
Modularity
Material Physical Properties
Non-Functional Requirements
Durable
Inexpensive
Lightweight
Aesthetically pleasing
Functional Requirements
Protect and Maintain Internal Environment
Maintain Structural Integrity
Support User Activity

The QFD in this case study is created around the VoC of the people who will purchase and provide the temporary structure (groups like UNHCR or the Red Cross and Red Crescent), not just the end users (IDPs and Refugees). This is different from a typical product designed using QFD. This is not to say the end users requirements are not taken into account, but rather, they are taken into account alongside the other tradeoffs made by the purchaser/owner. For example, the end user does not care about the amount of energy required to ship, store, and manufacture the shelter. However, they do care about the internal temperature of the shelter during the peak of summer. As can be seen in the list of CNs, both of these factors are acknowledged. This is due to the fact that from the provider's point of view, the end users comfort and the embodied energy of the structure are both important.

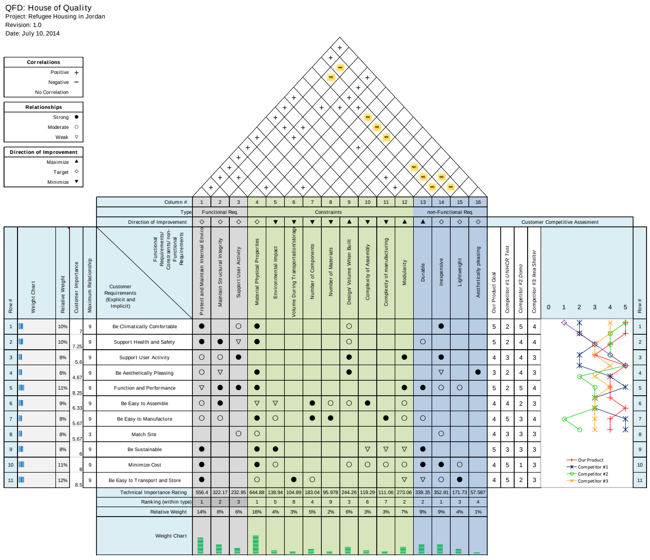

Figure 2 QFD for a temporary house

The displayed QFD in Figure 2 provides a benchmark analysis of 3 different existing and proposed temporary housing solutions. Specific information was not available for all aspects of the units, so ratings are based on literature about each unit. *UNHCR tents* are the units typically used for refugee housing today. As can be seen in the benchmark, they are inexpensive to produce, store and ship, however they are not very effective at addressing the comfort or activity needs of the users. UNHCR is looking at addressing this issues in the near future [Lolachi, 2010]. The second unit, *Domo*, was designed by a German group called More Than Shelter. It is a conceptual design that has been proposed to improve the quality of life of people living in refugee housing and slums by creating spaces to empower people. These units will be more expensive than a UNHCR tent, but are much more adept at meeting the user needs [morethanshelters]. The final solution, the *IKEA shelter*, was unveiled in 2013, and is considered a promising solution to improve the quality of housing for refugees and IDPs [Zimmer]. Ikea seems to be a more middle of the road solution between the UNHCR tent and the Domo, providing less versatility then the Domo, but better at meeting user needs then the UNHCR tent. Using these different units as benchmarks helps to recognize where opportunities exist, and can help designers to better understand how other designers address, or don't address, the VoC.

3.3 Decomposition of a Refugee Shelter

After the customer needs were used to highlight the high-level FR's, nFRs and Cs of the system, the design of the temporary housing system was done using the AD zigzag methodology.

As can be seen in the QFD, the high-level FRs are:

- FR1= Protect and Maintain Internal Environment
- FR2= Maintain Structural Integrity (against static and dynamic loading)
- FR3= Support User Activities (for up to 5±2 people)

Which are constrained by:

- C1= Environmental Impact
- C2= Volume During Transportation/Storage
- C3= Number of Components
- C4= Design/Volume When Built
- C5= Complexity of Assembly
- C6= Complexity of Manufacturing
- C7= Modularity
- C8= Material Physical Properties

Using the nFRs and Cs from the QFD, the design parameters (DPs) selected to fulfill each of these FRs are:

- DP1= Passive Building Envelope System
- DP2= Active Mechanical System (i.e. fan ventilation)
- DP3= Structural System
- DP4= Building Interior and Layout

The DPs that are selected to fulfill the high-level FRs provide insights about the form of the shelter. The selected DPs may also change depending on designer's point of view and previous experiences. For example, designers more comfortable working with Structural Insulated Panels (SIPs) may have chosen to combine the Structural and Envelope System into a single DP. In short, the decomposition of the same system by two different designers will nearly always be different. This is considered an advantage, because it highlights that the methodology does not impede creativity in the design process.

During the AD design process, the conceptual design should start to take form in the designers mind. Each continuous step of the zigzag process and expansion of the Design Matrix (DM) will further develop the shelter form. A design matrix, like the one displayed in equation (1) below, needs to be formulated for each level of the decomposition to avoid violating the Independence Axiom. In this case, the choice of a building envelope system will have an effect on the structural system. For example, if the building envelope is designed to be load bearing, it will be part of the structural system. The DPs "Building Envelope" and the "Mechanical System" are created to form a redundant design which gives designer the option to add in an active cooling/heating element to improve buildings thermal performance.

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{Bmatrix} = \begin{bmatrix} X & X & 0 & 0 \\ X & 0 & X & 0 \\ 0 & 0 & 0 & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \\ DP_4 \end{Bmatrix} \quad (1)$$

Design Matrix (1) shows that the design is both designed to be redundant and is decoupled at the highest level (hence, the independence axiom is not violated). Next, each of the FRs will be further decomposed. For brevity, only FR1s decomposition will be shown, however the other FRs will follow a similar decomposition format. FR1 was chosen because it provides the primary function a refugee house needs to afford based on the Maslow hierarchy of needs [Simons, et al., 1987]. The other three FRs all provide secondary, albeit important, functions for the users.

The building envelop system is perhaps the most important part in ensuring the good health and safety of its occupants. It is responsible for a number of very important functions related to the internal climate of the structure. While the mechanical system may play an important role in this function in a typical building, most refugees have limited or no access to electricity or driving power that allow most mechanical systems to function. This means that majority of the control of the internal climate will be done passively with the external envelope. The envelope of the structure must maintain a reasonable internal temperature throughout the entire day, and should resist fluctuations in external temperature from the summer to winter seasons or from day to night. The envelope should also prevent excessive moisture and water ingress. Condensation due to excess moisture is one of the leading problems of health issues in the refugee camps. Safety of the occupants and their belongings is also an essential FR. Crime is often a major problem in large camps. It is essential that refugees' security is maximized, and they can help protect the few belongings they have left. Protection from mosquitos is also important since malaria is a rampant problem in refugee camps.

FR1s decomposition is shown below:

FR1.1= Allow Controllable Interaction with External Environment

FR1.2= Passively Control Indoor Climate

FR1.3= Prevent Entrance of Insects and Pest

Which are solved using the following DPs:

DP1.1= Fenestration (Door/ window)

DP1.2= Curtain Wall and Floor

DP1.3= Insect Resistant Features

Again this can be mapped into a Design Matrix to ensure the first axiom is not violated. The Design Matrix (2) below shows that the decisions regarding the Curtain Wall and Floor as well as the Fenestration both affect the ability of the structure to "Passively Control Indoor Climate." This intuitively makes sense since the Door and Window will be important in passively cooling the building in hot weather, and will be one of the main sources of heat leakage from the structure in cold weather. Likewise, choices of door and window will affect the buildings ability to prevent the entrance of insects (in addition to other insect resistant features).

$$\begin{Bmatrix} FR_{1.1} \\ FR_{1.2} \\ FR_{1.3} \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ X & X & 0 \\ 0 & X & X \end{bmatrix} \begin{Bmatrix} DP_{1.1} \\ DP_{1.2} \\ DP_{1.3} \end{Bmatrix} \quad (2)$$

Since the independence axiom is not violated, the third level of decomposition can be created by following the Zigzag process. First FR1.1 is decomposed into:

FR1.1.1= Allow Controllable Entrance to Structure
FR1.1.2= Allow Entrance of Natural Light into Structure
FR1.1.4= Remove smoke from cooking/heat fires

DP1.1.1= Door
DP1.1.2= Window
DP1.1.4= Closable Cooking Vent

$$\begin{Bmatrix} FR_{1.1.1} \\ FR_{1.1.2.} \\ FR_{1.1.3} \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ X & X & 0 \\ X & X & X \end{bmatrix} \begin{Bmatrix} DP_{1.1.1} \\ DP_{1.1.2} \\ DP_{1.1.3} \end{Bmatrix} \quad (3)$$

Next, FR1.2 is broken down into:

FR1.2.1= Regulate Air Flow/Quality
FR1.2.2= Regulate Moisture in Air and Prevent Accumulation of Free Standing Water within Unit
FR1.2.3= Maintain Internal Temperature of 23 ± 6 Degree C

DP1.2.1= Natural Ventilation
DP1.2.2= Water Resistant Barrier
DP1.2.3= Passive Cooling and Heating techniques

$$\begin{Bmatrix} FR_{1.2.1} \\ FR_{1.2.2.} \\ FR_{1.2.3} \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ 0 & X & 0 \\ X & 0 & X \end{bmatrix} \begin{Bmatrix} DP_{1.2.1} \\ DP_{1.2.2} \\ DP_{1.2,3} \end{Bmatrix} \quad (4)$$

In the last step of the level 2 zigzag decomposition, FR1.3 is broken into the following:

FR1.3.1= Prevent Entrance of Insects from Openings
FR1.3.2= Prevent Entrance of Bugs and Pests from Under Structure

DP1.3.1= Screen on All Openings with Mesh Size <1mm
DP1.3.2= Impenetrable Base

$$\begin{Bmatrix} FR_{1.3.1} \\ FR_{1.3.2} \end{Bmatrix} = \begin{bmatrix} X & 0 \\ 0 & X \end{bmatrix} \begin{Bmatrix} DP_{1.3.1} \\ DP_{1.3.2} \end{Bmatrix} \quad (5).$$

4 CONCLUSION AND FUTURE WORK

The same tents have been utilized for most natural disaster and refugee camps for the past twenty years. While many design ideas for refugee shelters have been proposed, none have been able to completely replace the tent. This is because they are unable to adequately meet the stakeholder requirements, either from a design or cost point of view. Recently, many designers, including the IKEA foundation, have attempted to address this problem; however, only time will tell if a successful design will emerge from their work. This paper proposes a method designers can use to improve the likelihood that better design is created.

To our knowledge, this paper is the first demonstration of a seamless and integrated application of QFD and AD for a particular application, and is used to systematically guide the process of creating a temporary house conceptual design based on stakeholder needs. QFD has already proven its use to construction projects in literature, and AD has developed wide acceptance due to its ability to improve creativity, minimize the iterative process, and quickly optimize for the best solution [Suh, 2001, Zakarian and Kusiak, 1999]. The seamless integration of the two methods uses the strengths of each approach. After introducing the changes made to the QFD and AD process, a case study was provided to demonstrate the use of the process in the design of a temporary housing shelter. Although the case study does not present the complete design, it does demonstrate the combined methodology's ability to capture the VoC in a systematic design process.

The case study found that the combination QFD-AD method streamlined the design process, and helped to ensure that the VoC directed the entire conceptual design creation. This new approach to combining the QFD-AD methodologies may be applicable in other industries as well. Future work may include developing a more efficient way of combining the process to maximize the impact of the VoC on the design process, and perhaps expanding the QFD to include other design variables beyond nFRs, FRs and constraints. This includes Selection Criteria (SCs) and Optimization Criteria (OCs). Material selection using the AD information axiom also proved less efficient than desired.

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AN AXIOMATIC DESIGN STANDPOINT OF SOCIO-POLITICAL MODELS FOR SUSTAINABLE GOVERNANCE

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ABSTRACT

The most widely accepted definition of sustainability is the one of the World Commission on Environment and Development (WCED), a. k. a. the Brundtland Commission, which states that the "sustainable development is the development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs". Accordingly, sustainable development takes into account the population, the economic and the environmental dimensions. Axiomatic Design (AD) allows expressing the many interactions between the aforementioned three concerns that yield to coupled design equations, which may have a higher or a lower degree of complexity depending on the number and on the nature of the requirements. Using the first two dimensions, *i.e.*, the population and the economic ones, we can accomplish design equations that reflect the traditional socio-political shape of the Western civilization. Thereafter, one introduces the third dimension, the environmental one, expanding the design equation by adding the so-called eco-requirements and the related parameters. Doing so, it expresses, or will to express, the shifting from the former socio-political ideas about the role of engineering design to the new concept of sustainable design, giving rise to the discussion about different models for the future development of the mankind. One of the objectives of the application of AD to the sustainability problem is to help choosing design solutions with as low complexity as possible. In order to achieve it, one could change the design range of the extant requirements or try different sets of design parameters, as well as freeze some specific elements of the design equation or try redundant design solutions. Different solutions for sustainability may reflect diverse socio-political models of governance, which are also briefly discussed in the paper.

Keywords: sustainable design, axiomatic design, governance, socio-political models.

1 INTRODUCTION

During the last decades of the 20th century, the international community became increasingly aware of the need to act over the continuous aggression that is being done to the natural conditions of the Earth.

The formal international discussion about sustainability may have been launched in Stockholm, Sweden, during the United Nations Conference on Human Environment, in 1972. This conference issued a 26-principle declaration on the relationship between the human activities and the environment [*Declaration of the United Nations Conference on the Human Environment*]. Principle five is particularly important and states, "the non-renewable resources of the earth must be employed in such a way as to guard against the danger of their future exhaustion and to ensure that benefits from such employment are shared by all mankind". The conference also initiated an "action plan for the human environment" involving education, exchange of information, social and cultural issues, and human settlements. It has not explicitly mentioned the role of the economy, although it made important references about the role of financial help to the developing economies.

About one decade later, in 1983, Secretary-General Pérez de Cuéllar appointed the former Norwegian prime minister Gro Harlem Brundtland to chair the World Commission on Environment and Development under the aegis of the United Nations. This commission, latter known as the Brundtland Commission, first introduced the notion of sustainable development through the well known statement: "Sustainable development is the development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [*Report of the World Commission on Environment and Development - Our Common Future*]. Some have criticized this definition, as "meeting the needs of future generations" does not explicitly comprise the future human requests, as well as the future technologies.

Furthermore, the commission declared that "areas of population, food security, the loss of species and genetic resources, energy, industry, and human settlements" are all interconnected, giving the basis for the rising of the United Nations Conference on Environment and Development in Rio de Janeiro, 1992, also known as the Earth Summit or the Rio Conference.

The main results of the Rio Conference are summarized in the 27 principles of the Rio Declaration on Environment and Development, the Agenda 21 and the Forest Principles. It is especially meaningful the fourth principle of the Rio Declaration, which states that "in order to achieve sustainable development, environmental protection shall constitute an integral part of the development process chain and cannot be considered in isolation from it" [*Rio Declaration on Environment and Development*]. New developments of the Rio Declaration came in 1997, 2002 and 2012 and the main milestone that came after Rio was most likely the 1997's Kyoto Protocol. This protocol supported by the United Nations Framework Convention on Climate Change (UNFCCC), aims at reducing the emissions of anthropogenic greenhouse gases (GHG), namely CO_2, in order to stabilize it "at a level that would stop dangerous anthropogenic interference with the climate system."

During the 1990s, it became clear that one should slow down the consumption of the finite natural resources and minimise the pollution generated by the human activity as a means to achieve sustainability. It was also acknowledged that the current generations should ensure the future fittingness to life of Earth, as well as the welfare of the next generations. This awareness is transversal to all the human activities, including engineering design, which must therefore concern with society, environment and economy along the whole life cycle of the design objects, in a simple scheme usually abbreviated through the PPP acronym, which means people, planet and profit, as shown in Figure 1.

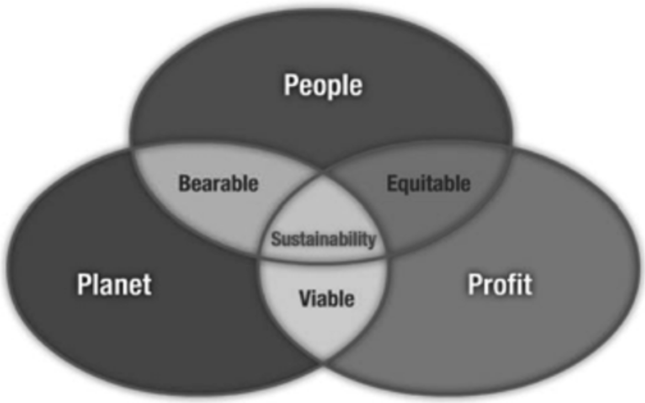

Figure 1. The triple bottom line of sustainability [Chiu and Chu, 2012]

Hence, sustainable design refers to the development of socially acceptable products that carry out their functions and generate profit to the stakeholders, while using minimum material and power resources, as well as generating minimum scrap.

The success of sustainable design depends on decisions that are usually made in a circumstance of scarce knowledge and sizeable uncertainty.

2 MODELS OF SUSTAINABILITY

Any book of economy describes the basic economic model as a permanent cycle between the enterprises, or production organizations, and the households, or more generally the population, as shown in Figure 2. The enterprises pay wages to the population that provide the working force to the enterprises; on the other hand, households buy products for which they pay to the enterprises and these ones provide the households the required goods or services.

It is out of the context of this paper to discuss the role of the families and the individuals in the society and we will use the term "population" to aggregate the concepts of individual and household. Among other meanings, the term "society" may express the different relationships between the population and the public and private production entities, which will be here jointly designated as "enterprises". Some anthropologists define "society" as a group of individuals with common aspirations, possibly forming a whole country. Others, however, say that countries have populations and not societies. Lady Thatcher, a renowned follower of this current of opinion, once said about the obligations of the government to the people, "there is no such thing as society. There are individual men and women, and there are families."

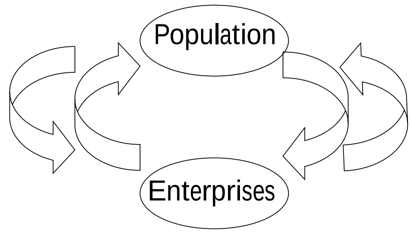

Figure 2. Economic cycles between population and enterprises.

The basic social interactions depicted by arrows in Figure 2 are difficult to address, as there are multiple feedback loops that tend to increase in number with the advancement of the economy. Models of equilibrium between production and consumption started in the 19th century with Jean-Baptiste Say. Keynes published in 1936, in the end of the Great Depression, The General Theory of Employment, Interest and Money, which although assuming states of equilibrium in the economy, argued about the need of government interventions in periods of recession. Processes in economy are in reality dynamic, making it possible to define feedbacks along the time between the major entities of an industry [Forrester, 1961-2013]. The dynamics of the US economy was well explained by Forrester using the System Dynamics National Model, and since the 60s there has been a continuous effort to simulate the dynamic behaviour of the society. As a result, it is now possible to address the activities of organizations and enterprises, clusters, and even the human behaviour and decision-making, taking into account instability and oscillations [Sterman, 2000].

Alongside with the known growing mechanisms of enterprises and population, there are loops of energy and materials that affect the economy in the long term. The increase in the productivity of the enterprises allows lowering the unit price of the goods they produce while increasing the wages of their workforce. This stimulates the population to invest and to spend more money in goods, yielding to a positive result to the enterprises. Yet, this cycle is depleting the reserves of raw materials as well as changing the climate.

This model, which has been considered sound since the industrial revolution, gives a negligible importance to the environment as it takes the geosphere as an infinite source of materials and energy, as well as an infinite sink for the waste that results from their use. The model is no longer acceptable, as the environment is proving to have a decisive role in the current and in the future economy.

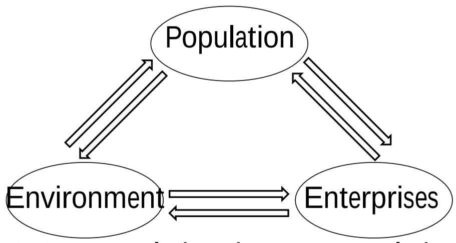

Figure 3. Current relations between population, enterprises and environment

Figure 3 depicts the present day relations between the population, the enterprises and the environment, showing the cycles between any pair of entities by pairs of arrows. Most models of sustainability aim at solving important but specific problems, focussing on one of the aforesaid relations. The most common ones centre their attention on the relation between environment and population, or in a corporate viewpoint, between enterprises and environment.

Other approaches to sustainability than the triple bottom-line are the natural step, the ecological footprint and the 50 years time scale of Graedel and Klee. All these methods focus on the scarcity of natural resources, including energy, as the present rate of consumption is impossible to sustain in a large timescale or at a global geographical scale.

Assuming a human centred approach, the hierarchy of values that should be used to choose the actions leading to sustainability depends firstly on the consequences they cause to the mankind and secondly on their impact on the environment. Thereafter, the highest level that require immediate action is the one "that, if continued at the current or forecasted rate, endanger the survival of humans" [Marshall and Toffel, 2005]. Human actions depend, or will depend, on the limits that the original functions of the ecosystem diverge from an acceptable range when subjected to a disturbance, as well as according to the extent the ecosystem is able to regain the original functionality in an acceptable time frame.

Some well-known methodologies, such as the EIA (environmental impact assessment) and the SEA (strategic environmental assessment), are used to solve problems of people in areas affected by environmental strains. EIA applies to the context of individual projects or events and aims at identifying environmental problems that should be mitigated by appropriate decisions and the corresponding implementation processes. On the other hand, SEA seeks the integration of community plans to the related geographical context *i.e.*, local, regional, national or international.

Moreover, enterprises are paying attention to the decisions related to the environment, due the economic impact they may have. Several studies carried out in the context of enterprises have shown that internal environmental programs impact the social and the economic areas. However, when sustainability programs are focussed on social issues, usually there is an impact in the environmental conscience of the populations, but with small financial benefits [Gimenez et al., 2012].

As expected, any sustainable program should have in mind the sustainability issue from the early stages of the design process. When one considers different alternatives, it is important to take into account the total amount of energy and raw materials that should be employed in the whole life cycle of the design object. It is also necessary to check and take into account the resulting economic and environmental impacts of our decisions [Eddy et al., 2013].

With larger productions, one could standardize and specialize labour and production, so that producing the same amount of goods would require less people and capital. In order to foster this cycle, enterprises use several marketing and innovation techniques, so that they can reach more customers at increasingly lower prices. As a result, the economy trend is to dematerialize through continuous renovation and remanufacturing, reusing and recycling, consuming less raw materials while focussing on final services [Ayres and Bergh, 2005].

The strategies for sustainability of the energy-intensive industries also have a strong economic impact, as their most common behaviours are the increasing utilization of scrap and the recovery of energy. Currently, industries are searching for alternative fuels and raw materials, due to the increasing price and scarcity of the traditional ones. Most likely, industry will soon develop symbiotic actions between different companies and between companies and customers in order to reduce waste and cost.

More and more there is a claim for global models leading to new economic and social models that require a smaller contribution from the environment.

During the 70s, it became very clear the detrimental consequences that a damaged environment could cause to people. In the 90s the society set new regulations about the environment. As it is more and more evident, the economy impacts the society and the environmental preservation impacts the economy [Schönsleben et al., 2010].

A recent global model proposed by Tim Jackson [Jackson, p. 228, 2009] includes a picture similar to the one of Figure 3, and argues that it is possible to achieve sustainability increasing the eco-entrepreneurship. Accordingly, some eco-enterprises will focus on social activities while others will try to increase the productivity of raw materials. In such relations, the participation of persons in the eco-enterprises will raise the human abilities. Hence, any high level action towards sustainability should have in mind that sustainable development leads to coupled designs with various economic and environmental loops that affect the population.

3 SOME NOTES ON AXIOMATIC DESIGN

Axiomatic Design (AD) aims at finding the best design solution for a certain set of functional requirements (FR) by using the most appropriate design parameters (DP). According to AD, every design solution can be represented by a design equation of the type $\{FR\}=[A]\{DP\}$, where $[A]$ is the design matrix. The shape of the design matrix allows perceiving "good" and "poor" design solutions. Ideally, design solutions might be uncoupled, or at least decoupled. Therefore, the main goal of AD is to help choosing the best design from a set of alternative solutions.

Anyway, sometimes it is not possible to change the design solution due to intrinsic relations, as it occurs when addressing the problem of sustainability.

Therefore, a new line of research is to establish from the set of corollaries and theorems of AD [Suh, 1990] the way to handle with coupled designs. The following list of guidelines, derived from the stated corollaries and theorems, summarizes the actions to employ in order to help solving a coupled design.

G1: Try to change the design in order to get a decoupled or an uncoupled design (from Corollary 1 of AD);

G2: Try to use the largest possible acceptable range for the FRs, so that the cross interference of DPs is as low as possible (from Corollary 6 of AD);

G3: Try freezing some DPs by assuming acceptable values for them [Fradinho, 2013];

G4: If the extant coupling depends on some interactions between DPs and FRs, try to store or deliver the result of such interaction into sinks or sources (from Theorem 24 of AD);

G5: Use a redundant solution in order to get rid of the extant couplings (from Theorem R1 of Coelho et al.) [Coelho et al., 2012]

In the following sections, Guidelines 4 and 5 will be used to solve the coupled designs that characterize the sustainable solutions.

4 THE PEOPLE AND PRODUCTION MODEL

From more than a century ago, the damages that were caused by the industry to the environment did not take part on the general development equation. The main requirements of those times were to ensure the production of agricultural and industrial goods in order to satisfy the needs of the population.

The Western paradigm of the 20th century has been to provide welfare to the population, based on the creation of a strong public service, and on development warranted by public and private enterprises. During all the 20th century century the paradigm remained the same, even though the increasing needs of the population and the overwhelming evolution of the means of production.

In a AD point of view, one may define consistently the FRs and DPs [Thompson, 2013] as follows:

FR_1: Provide welfare to the population;

FR_2: Produce/provide goods and services;:

DP_1: Public service;

DP_2: Enterprises.

Public service is a set of facilities provided by the government through the public sector or through non-governmental entities financed by the government. Beside security, military and law administration, the Western public services also provide free healthcare and education to a large extent. Moreover, the public services may include facilities that depend on the city council, as for example gas, electricity or water supply and a myriad of other commodities. Some of those commodities are enterprises directly dependent of the public services, other are private organizations that report to regulators.

Enterprises are typically business economic bodies, aiming at producing tradable goods and services, in order to get a profit. Furthermore, enterprises produce wealth to the country or community providing welfare to the population, by paying wages, taxes or providing other direct means of welfare.

The aforementioned relationships may have an AD translation in the following design equation:

$$\begin{Bmatrix} FR_1 \\ FR_2 \end{Bmatrix} = \begin{bmatrix} X & X \\ X & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \end{Bmatrix} \tag{1}$$

The design matrix of Equation 1 shows that at the highest design level the design equation for the society is a coupled design. One may imagine how difficult it may be to tune such a coupled design at the lower levels of the design decomposition! Moreover, tuning all the elements of such an equation with all the cycles and feedbacks defined trough governmental policies would give rise to dictatorships.

The solution implemented in the Western countries, at least since the World War II, is to alternate the government action along the time changing the relative importance of the enterprises and of the public services. Therefore, according to AD, this is a way of solving the coupling by changing the design model into an uncoupled or a decoupled design, depending on the social conditions.

As a consequence, it is important to notice that:

- The following design equations show a governance attitude, and not the existent relational flows that model the behaviour of the society;
- The DPs vary according to the approach. In other words, DP_1 and DP_2 are formed by different sets of entities depending on the approach.

Moreover, the range of each FR, especially in what concerns to the welfare of the populations, may vary along the time, making an acceptable range to be unacceptable years later. Especially in periods of austerity, persons may accept a wider range of variation of the FRs, recovering latter to the initial state, a feature that is called “resiliency”.

If the initial situation is attainable anymore, persons may adjust to the new situation in a process called “adaptability”.

In what concerns to naming the approaches, we will call a rightist approach to the one that focus on the role of the enterprises to produce goods and services and a leftist approach to the one that gives a more important role to the public services. Thus, under the rightist trend, most of the economic bodies responsible for the services and other commodities are enterprises.

In this system, the role of the public services is providing welfare to the population without interfering on wages and other benefits that enterprises may give to their employees. Even though, different rightist approaches may locate health care, education and even housing under the public services. Anyway, one can believe that the market establishes the relations between welfare and enterprises, with small government interference. On the other hand, the public services have a small direct impact on the production, although may influence it deeply through contracted work with enterprises.

Equation 2 shows the design equation for such a kind of governance denotes an uncoupled design.

As for a better readability, one uses a blank element in the matrix instead of a small x to express low dependency between DPs and FRs. Thus, all blank elements in the following equation, as well as in all further equations, express in reality week governance attitudes.

$$\begin{Bmatrix} FR_1 \\ FR_2 \end{Bmatrix} = \begin{bmatrix} X & \\ & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \end{Bmatrix} \tag{2}$$

If the system cannot fulfil FR_1, one or more buffers may be added in order to provide the necessary welfare to the population, as expressed in Equation 3.

$$\begin{Bmatrix} FR_1 \\ FR_2 \end{Bmatrix} = \begin{bmatrix} X & & X \\ & X & \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ B \end{Bmatrix} \tag{3}$$

These buffers may be inter-social help, usage of domestic savings, loans from the banks, or increasing the deficit at the country size. These solutions allow keeping a resilient FR_1, avoiding the need for variation of its range to some extent.

Notice that using the buffer turned the design into a redundant one, which remains uncoupled.

On the other hand, the leftist approach gives a larger role to the public services, which include sectors with a production objective. As such, DP_1 may now include most of the commodities and other state owned enterprises, which give a stronger help in the fulfilment of FR_1.

In this system, after defining the public sector, the enterprises play the role of tuning the system in order to achieve the production objective.

Equation 4 represents a decoupled design, indicating that DP_1, the public services, might be the first to set followed by the setting of the enterprises (DP_2).

$$\begin{Bmatrix} FR_1 \\ FR_2 \end{Bmatrix} = \begin{bmatrix} X & \\ X & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \end{Bmatrix} \tag{4}$$

Some approaches to this societal model may force the enterprises to play an important social role, causing the system to turn into a coupled design.

It is possible to help fulfilling FR1 by using buffer systems similar to the ones described in Equation 3, as shown in Equation 5.

$$\begin{Bmatrix} FR_1 \\ FR_2 \end{Bmatrix} = \begin{bmatrix} X & & X \\ X & X & \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ B \end{Bmatrix} \tag{5}$$

The buffer in Equation 5 may be any one of the aforementioned, but historically the public deficit is the most typical in the European Union (EU) zone. This has been a very successful policy that allowed the system to be resilient, until the deficit turned out to be a problem for most countries.

In reality, after the World War II, Europe felt a great development being able to provide a progressive welfare to their populations. This welfare allowed the populations to easily adapt to better conditions of living. Since the 90s, the need to maintain the welfare regarding the smaller increase of production, made the EU to solve Equation 1 by introducing borrowed money as a buffer in the equation. This new DP, DP_D, helps solving Equation 1 turning the design into a decoupled redundant design, as shown in Equation 6.

$$\begin{Bmatrix} FR_1 \\ FR_2 \end{Bmatrix} = \begin{bmatrix} X & X & X \\ X & X & \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_D \end{Bmatrix} \tag{6}$$

Whatever will be the performance of the public services and enterprises, it is possible to fulfil the requirement of providing welfare to the population. This new design had as side effect to allow smoothing the differences between rightist or leftist approaches to the society. However, it had the cost of increasing the public deficit to more than 90% of the GDP of the EU-18 countries [Eurostat Compact Guides]. Because of this, a new era is now coming to the Euro zone that makes the governments to ask the populations to adapt to lower levels of welfare.

Making the argument of a rightist or leftist policy dependent of the social and economic context maybe is not the best solution for Equation 1. The governments need to balance between Equation 2 and Equation 4, or most probably between Equation 3 and 5, changing from one to the other whenever the corresponding buffers are no longer able to fulfil the expected FR_1.

5 THE ENVIRONMENT REQUIREMENT

A new requirement is arising nowadays, FR_3, because one needs to limit the impact of the human activities in the environment. The need of this new FR in the design equation of the society is becoming increasingly recognized by the population and governments.

The impact of the environment on the living of individuals and on the economy is no longer an academic hypothesis claimed by scientists, but turns into reality. Katrina hurricane (2005) in Louisiana, USA; the 2009 bushfires in Victoria, Australia; or the floods in Rio Grande do Sul, Brazil, in 2013, all are examples of how the nature may have a decisive importance in the welfare of populations and on the production needs.

Another example, the Fukushima disaster, illustrates very well the various dependencies between people, economy and the environment: starting with and earthquake, the nuclear power plant of Fukushima had electrical and mechanical interactions that caused the leakage of radioactive material [Nakao et al., 2013]. Next, this leakage caused a new environment problem that affected a large city area where it is no longer possible to live. In the end, the Fukushima power station was forced to close.

From the aforesaid, societies realized that the need of living in a healthy environment became a key asset of the modern life. Therefore, the new FR_3 might state as:

"reduce the environmental impact of human activities";

and the corresponding DP_3 as:

"environment-friendly technologies."

In the 70s, people start acquiring an environment consciousness that forced governments to issue regulations on the polluting activities of the economy. Usually, these regulations epitomize restrictions on enterprises or people activities, in order to allow maintaining the general society Equation 1. Examples of the former are the imposition of reductions on the usage of old cars in certain areas of a city; incentives for changing from a more polluting fuel, such as coal, to a less polluting one, such as natural gas; or stressing for use a more efficient equipment corresponding to the desired level of emissions.

Assuming that there is a solution for Equation 1 apart from the environmental restrictions, setting a solution inside the boundaries imposed by the environment may be possible by adding a new DP, DP_R. The goal of DP_R is to remove the pollutants that are emitted above a prescribed level that the existent systems needed to produce in order to fulfil the production of the goods and services. Therefore, the design turns into a decoupled redundant design (Equation 7).

$$\begin{Bmatrix} FR_1 \\ FR_2 \end{Bmatrix} = \begin{bmatrix} X & X & \\ X & X & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_R \end{Bmatrix} \qquad (7)$$

Examples of DP_R at a global scale could be the carbon sequestration in saline caves or in aging oil fields, the bio-energy with carbon capture and storage, and the technologies for carbon dioxide removal. At a smaller scale, the smoke filters installed at the thermoelectric power plants, the systems for industrial water treatment and the automobile catalytic converters are examples of systems that allow reducing the impact on the environment without changing the exiting producing systems.

The nowadays challenge is to change from a driven system with environmental restrictions to a new society that incorporates the environmental as a new functional requirement.

5.1 THE NEW DESIGN EQUATION

The society challenge of the present and of the next generations is to achieve a solution for the coupled design shown in Equation 8.

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{Bmatrix} = \begin{bmatrix} X & X & X \\ X & X & X \\ X & X & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{Bmatrix} \qquad (8)$$

The reader might be aware of how difficult it has been to govern a country which design equation at the highest level is a (2x2) as stated by Equation 1. Now, imagine how hard it will be the governance expressed by the new equation!

Notice that according to the AD's Theorem 5, adding a new FR to the design equation does not mean that solving the problem is just a matter of adding an extra DP. In fact, it is necessary to look for a complete new design and check in what extent the new added DP interfere with the existent FRs.

As it was shown at the introduction to this paper, the fourth principle of the Rio's declaration expresses a similar idea as the one of Theorem 5, making the introduction of the environment requirement a huge task.

Many simplifications of Equation 8 are possible according to the policy followed by the governments, which will depend on the extent of the environment degradation, the production volume and the expected welfare of the populations. Anyway, Equation 8 generally represents a more complex design than Equation 1.

The next sections of the paper will focus on some possible approaches to this problem, without having the leaning to decide what is the right solution.

5.2 A PROSPERITY PARADIGM

To help solving Equation 8, one may assume that at a Western working mode of the new economy, and out of any catastrophic situation, the relation between the environment-friendly technologies, DP_3, and the welfare of the population, FR_1, has a weak relation.

On the other hand, the "public services", DP_1, have a greater or lesser influence on the reduction of the environmental impact of the human activities, FR_3, depending on the economic bodies it includes.

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{Bmatrix} = \begin{bmatrix} X & X & \\ X & X & X \\ X & X & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{Bmatrix} \qquad (9)$$

Equation 9 shows that the system is a coupled design. However, Equation 10 better expresses the situation of Equation 9, because it includes the benefits of the environmental buffer, B_E.

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{Bmatrix} = \begin{bmatrix} X & X & & \\ X & X & X & \\ X & X & X & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \\ B_E \end{Bmatrix} \qquad (10)$$

Equation 10 represents a decoupled redundant design, which makes a less attentive reader to presume that it has an easy solution. Nonetheless, the environmental buffer (B_E) just gives some time to help solving the real problem.

To solve Equation 9, a government might choose to reinforce some interactions, while decreasing the importance of others. The choosing of the interactions to decrease is a policy decision depending on ideology, the society situation and the economic resources.

Thus, a government might choose a greater or a lesser influence of the enterprises in providing the welfare to the population and to choose the role of the environmental-friendly technologies (eco-tech).

Now, let us suppose that the choice is a rightist policy focused on the role of enterprises, which pay a special attention to the eco-technologies. In this instance, the welfare of the populations depends on the public services, while the enterprises aim at producing the necessary tradable goods. Moreover, one may suppose that the economic bodies of the public services have a weak interference in the environment. Additionally, the eco-techs may have an important role in the production of goods and services.

Equation 11 expresses the picture of this societal approach, which the authors call a rightist-eco-tech policy for sustainability.

This equation shows a decoupled design, and allows choosing an appropriate sequence to tune the equation in order to fulfil the FRs. In this design, the eco-tech (DP_3) is the first DP to adjust. Moreover, the eco-DP also has a role to play in the production of goods and services. Subsequently, the government will choose independently the other two parameters, DP_2 and DP_1, respectively the enterprises and the public services.

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{Bmatrix} = \begin{bmatrix} X & & \\ & X & X \\ & & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{Bmatrix} \qquad (11)$$

One can read Equation 11 in two different ways, a theoretical and a pragmatic one. In the former the eco-technologies need to be developed to solve the environmental problem and foster for eco solutions in the production field; in the latter one uses directly the existent technologies trying to have a similar approach.

Equation 12 shows a rightist-enterprise driven solution. The sequence for tuning the DPs begins with choosing the enterprises, and afterwards the public services or the eco-technologies.

In this approach, the government gives priority to the role of the enterprises, because DP_2 have not only a production role but also an environmental one. After choosing DP_2, the public service and the eco-technologies are mutually independent.

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{Bmatrix} = \begin{bmatrix} X & & \\ & X & \\ & X & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{Bmatrix} \qquad (12)$$

Coming back to the leftist approach already shown on Equation 4, two alike but different approaches emerge, a leftist-eco-tech economy and a leftist enterprise-driven one. In both the leftist solutions, there is an important role of the economic bodies of the public services over the environment.

Equation 13 shows the leftist-eco-tech solution, which is a decoupled design.

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{Bmatrix} = \begin{bmatrix} X & & \\ X & X & X \\ X & & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{Bmatrix} \qquad (13)$$

In this approach, a government should first tune the public services, noticing the interference they have on the environment and on the production. Next, depending on the impact on the environment, it chooses the usage of the eco-technologies, which play the role of fostering the production requirement. At last, the role of the enterprises is to tune the remaining production of tradable goods in order to achieve the prescribed FR_2.

Finally, Equation 14 shows the leftist-enterprise driven approach, which is again a decoupled design. The setting sequence of the DPs in this system starts by fulfilling the needs of the population, followed by tuning the role of the enterprises and ends by choosing the eco-technologies.

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{Bmatrix} = \begin{bmatrix} X & & \\ X & X & \\ X & X & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{Bmatrix} \qquad (14)$$

Although it is difficult to give detailed examples of societies where Equations 11 to 14 hold, it is nevertheless possible to identify examples of enterprise-driven and eco-technological approaches to the environment.

LEED (Leadership in Energy and Environmental Design) is an example of the former, for it may give to the buildings owners an endorsement if they are environmental responsible and use resources efficiently. This program is enterprise-driven, but not compulsory, and aims at quantifying the design, construction, operation, and maintenance quality of a building all along its life cycle. It uses a system of ratings from the very early stage of the design, allowing different ways for attaining the qualification.

ISO 14001 is another enterprise-driven approach to sustainability. It helps creating an environmental management system that integrates the processes and the procedures of the enterprises to protect the environment. As a result, one could stress the high efficiency in energy and material usage that the large chemical and automotive enterprises have experienced in the last decades.

On the other hand, the eco-technology approaches to sustainability largely interfere in the society, and are usually developed or applied by governments or related institutions. As for example, the focus of the Portuguese government in the wind energy made it possible to install in the last decade wind turbines with a total power of about 4,500 MW. This currently represents about 20% of the installed electric power, and about 50% of the used renewable sources.

In this example, the choice was well known technology, so that it was just necessary to develop the application. Other potential approach could be to develop the technology from the very beginning, as it happened with the OLEV (Online Electrical Vehicle). OLEV was a brainchild of Professor Suh during his leadership of KAIST, and can significantly reduce the energy costs of public transportation.

Currently, EU is making an important effort in the development new renewable technologies from the outset, by making a huge investment in research and development until 2020.

5.3 OTHER PROSPERITY PARADIGMS

Other prosperity paradigms may arise from Equation 9, or from any of the derived societal descriptions, by introducing new DPs to turn them into redundant designs. Equation 15 shows the introduction of DP_D, the public deficit, and environmental buffer B_E.

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{Bmatrix} = \begin{bmatrix} X & X & & & \\ X & X & X & & \\ X & X & X & X & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \\ DP_D \\ B_E \end{Bmatrix} \qquad (15)$$

The public deficit invested on the accomplishment of the environment requirement, along with the natural ecologic buffer may give the society a smooth transition to a cleaner economy. In order to do it, it is necessary a strong investment in new technologies, changing the buildings and the design of the cities, as well as advancing in the research and development of new procedures and technologies.

6 DISCUSSION AND CONCLUSIONS

This paper briefly describes some current models of governance and points out some possible solutions to help solving the new sustainability problem. The big challenge for the present and future generations is the integration of environmental requirements in the societal equation.

The current models of governance need to fulfil two FRs, namely to “provide welfare to the population” and to “produce/provide goods and services”. This may lead to a greater or a lesser interference of the government.

In the case of a lesser interference, the design is uncoupled and we called it a rightist approach; in the leftist approach, there are more relations defined by the government, making it a decoupled design.

Adding the environmental FR, "to reduce the environmental impact of the human activities", one forces the governments to look for a complete new design for the society. According to AD, the main conclusion is that the sustainable society will be more complex than the current one.

Both the rightist and the leftist models may focus on enterprises or on the eco-technologies, giving rise to the four possible environmental models that are discussed in this paper. All these models are decoupled, so that the tuning of the DPs must follow a definite sequence.

Therefore, as a second conclusion, the governments might be aware that there is an appropriate sequence to tune the DPs in the sustainable design equation.

Moreover, to change the society to a more environmental focussed one, it will be necessary huge investments to introduce new technologies that start at a domestic scale and end at least at a country scale.

The current deficit of EU might make hard to address these kinds of investments. Anyway, EU is making a big effort toward the search and implementation of new environmental technologies through the Horizon 2020 Program.

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ADAPTIVE TOLERANCE ALLOCATION TO ADJUST THE SIGMA LEVEL THROUGH MINIMIZATION OF THE INFORMATION CONTENT

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ABSTRACT

Nowadays, mass production companies usually employ the sigma level as the preferred metric to control their activities with the purpose of operational optimization. Six-sigma is usually taken as the minimum level to achieve the excellence of the organization. To increment the global sigma level of assembly operations it is necessary to assure a suitable level for the capability index, C_{pk}, in the manufacture of each one of the assembly components. C_{pk} depends on the design tolerances and on the characteristics of the manufacturing process and is usually attained by adjusting the manufacturing variables according to the data acquired through quality control. If these data were sent to the design department, then it would be possible to attain some prescribed sigma level at the assembling operation by selective adaptation of the tolerance allocation, without any intervention on the manufacturing processes. The tolerance values of the complete mechanical system are mutually dependent according to the adopted model of analysis, but they must assure the functionality of the assembled sets. However, the manufacturing of each component is independent from the others.

The knowledge about the manufacturing capability indices allows computing the information content, the best situation being to achieve the highest sigma level so that one could have the lowest information content for the overall manufacturing process. This paper presents a method that allows an adaptive tolerance allocation that leads to the required sigma level. The method is adaptive, for it can consider changes of the manufacturing system.

Keywords: process capability, information content, tolerance allocation, six-sigma.

1 INTRODUCTION

The lack of knowledge of the actual capabilities of manufacturing processes, associated to required tight tolerances, may yield to great difficulties to make products with the specifications required by design.

Manufacturing processes are exposed to several disturbances that may cause dimensional and geometrical variations of the manufactured part. These variations should be kept within the specified design tolerances, which accomplishment is translated into quality of the manufacturing process. If the product is an assembly of several components, the situation becomes more complex, since the variation of the quality characteristic of the assembly depends on the contributions of the components' variations.

The use of quality control methods, such as Statistical Process Control (SPC) is a industry standard, particularly in the automotive supply chain, where it is used for monitoring and controlling the processes with the aim of ensuring that they operate at their full potential [Dietrich & Schulze, 1998]. Statistical methods like SPC usually generates large amounts of data that accurately characterize the processes, which allow achieving the values for the capability indices of the manufacturing tasks.

Nowadays, mass production companies usually employ the sigma level as the preferred metric to control their actions. Their purpose is the operational optimization, specifically when the product is an assembly, which overall quality level depends on the quality of each component. Six-sigma is usually taken as the minimum overall quality level to achieve excellence in every production company.

Six-sigma is a set of practices for process improvement that seeks to improve the quality of the processes' outputs. In terms of the Axiomatic Design (AD) theory, the conceptual frameworks of six-sigma implementation do not take into account the potential contribution of the design parameters (*DP*s) to the whole solution [El-Haik, 2005]. In some cases, this leads to neglect the need for design changes when the candidate solution for manufacturing in not satisfactory or is not the most rational one. As a result, the traditional approach of just readjusting the process variables (*PV*s) may not be enough to solve a specific problem, or may be a more costly solution.

The adjustment of the nominal values to new targets within the specified tolerances, or changing the tolerance ranges keeping the nominal values, or both, are considered soft changes. A change is considered hard when it involves the elimination or the addition of *DP*s or *PV*s in the relevant mapping [El-Haik, 2005].

All the potential improvements should be considered when a six-sigma solution must be accomplished. In the second member of Equation 1, the first term represents a design change, that is, changing the functional requirements (*FR*s), while the second relates to a process change. Therefore, an efficient axiomatic quality strategy should be characterized by the use of both terms [El-Haik, 2005].

$$\frac{\partial FR_i}{\partial PV_k} = \frac{\partial FR_i}{\partial DP_j}\frac{\partial DP_j}{\partial PV_k} \tag{1}$$

In the industry, particularly in manufacturing plants, it is usual to readjust the *PV*s to find better values when the capability indices are below the targets. This is accomplished using statistical data acquired by the quality control, namely, the capability index, C_{pk}, which depends on the design tolerances and on the characteristics of the manufacturing process.

The lack of communication between those responsible for the design and for the production, in advanced stages of manufacturing, leads to missing the opportunity of matching the design to the actual process capabilities. In the case of mechanical tolerances, there are other reasons that usually lead to a process change, instead of a design change, basically when: i) the quality of the manufacturing operation of each component of an assembly set is independent of what happens with others; ii) the tolerances of the components, which once assembled confers the set´s functionality, are not independent, for they must satisfy an analytical model (worst case or statistical). This implies that any adjustment of the first term of Equation 1 can only be made if is possible to act coherently on other components according to the required functionality of the system as whole. Therefore, if the design team have data of quality control from all manufacturing operations, then it is able to change the tolerance allocations for each component, in strict accordance with the required functionality of the mechanical system. Minimizing the information content makes this change, given that the tolerance allocation of each component yields to a better capability index for its manufacture. Thus, one can attain a better sigma level to the assembly, which means a better resilience for the overall process through adaptive tolerance allocation. This approach seems to be appropriate to effectively upgrade the product specifications in accordance with the evolution of the actual capabilities of the production, or to the cases where the manufacturing systems are subjected to substantial variations.

2 TOLERANCE ALLOCATION AND CAPABILITY INDICES

A right allocation of mechanical tolerances must ponder the following issues: a) the variation of each dimension of a mechanical assembly´s component must guarantee the functionality of the set; b) the (low) manufacturing cost of each component; c) the ease of the assembling operations; d) the ease of the metrological control operations.

The allocation of tolerances must be made using synthesis methods according to an analytical model [Chase & Greenwood, 1988; Wu *et al*., 1988; Zhang, 1997]. As for the analytical model, there are basically two: the worst-case model and the statistical model. The first one takes into account the whole range of tolerance for each dimension, so that its application is appropriate to the cases of small production runs. As for the second, it is more appropriate for mass production. In the latter, the stacking method is based on the fact that the manufacturing processes are characterized by variability, and on the low probability of assembling two sets of components with the same extreme deviations. According to Spotts [1973], in a model with a normal distribution, the overall tolerance, t, of a stacked assembly with n components, relates to the tolerances of the components, t_i, i=1.. n, through

$$t = \sqrt{\sum_{i=1}^{n} t_i^2}\ . \tag{2}$$

The process capability is a measurable property that can be expressed as a ratio between the tolerance range and the process variability, and it is often represented by the process capability index, C_{pk} [Montgomery & Runger, 2014]. C_{pk} is used to deal with biased distributions. Letting the lower and the upper specification limits be LSL and USL, respectively, then the capability index of process i is given by

$$\left(C_{pk}\right)_i = \min\left\{\frac{USL_i-\mu_i}{3\sigma_i}, \frac{\mu_i-LSL_i}{3\sigma_i}\right\}, \tag{3}$$

where μ_i and σ_i are the process mean value and the standard deviation.

For the same process i, the probability of not occurring X is the sum of the lateral nonconforming probabilities given by

$$\left(p_f\right)_i = P\left(X < LSL_i\right) + P\left(X > USL_i\right). \tag{4}$$

The nonconforming probability of the process can also be computed through

$$\left(p_f\right)_i = \int_{-\infty}^{LSL_i} f_i(x)dx + \int_{USL_i}^{+\infty} f_i(x)dx, \tag{5}$$

where x is a normal random variable which probability density is given by

$$f_i(x) = \frac{1}{\sigma_i\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu_i}{\sigma_i}\right)^2}. \tag{6}$$

Equation 5 can only be solved numerically but a standard normal distribution table (Z table) allows computing the value of the nonconforming probability through the equation

$$\left(p_f\right)_i = P\left(Z < \frac{LSL_i-\mu_i}{\sigma_i}\right) + P\left(Z > \frac{USL_i-\mu_i}{\sigma_i}\right) \tag{7}$$

The total probability of functional nonconformity is the probability of an assembly not satisfying its specification, which can be computed through

$$\left(p_f\right)_{Total} = 1 - \prod_{i=1}^{n}\left(1-\left(p_f\right)_i\right). \qquad \neg \tag{8}$$

The number of defects per million opportunities (*DPMO*) is obtained from the probability of occurrence of a nonconforming assembly, and is given by

$$DPMO = \left(p_f\right)_{Total} \times 10^6 \tag{9}$$

The output of industrial processes can vary over time and their sigma level can be computed through

$$SigmaLevel = \Phi^{-1}\left(1-\frac{DPMO}{10^6}\right)+1.5, \qquad (10)$$

where Φ^{-1} is the normal inverse distribution function [Evans & Lindsay, 2008]. The 1.5 offset in the equation allows for the aforesaid variation.

Due to the independence of the manufacturing process of each component, the determination of the sigma level of the whole process allows monitoring the behaviour of the long-term process performance. Usually, the goal of the industrial processes is based on six-sigma for the long-term performance analysis, which means a *DPMO* lower than 3.4.

3 THE PROPOSED METHOD

In order to increment the global sigma level of an assembly operation, it is necessary to ensure an appropriate capability index to each one of the manufacturing operations (*i.e.,* of each one of the assembly´s components). The flowchart of the proposed method is outlined in Figure 1.

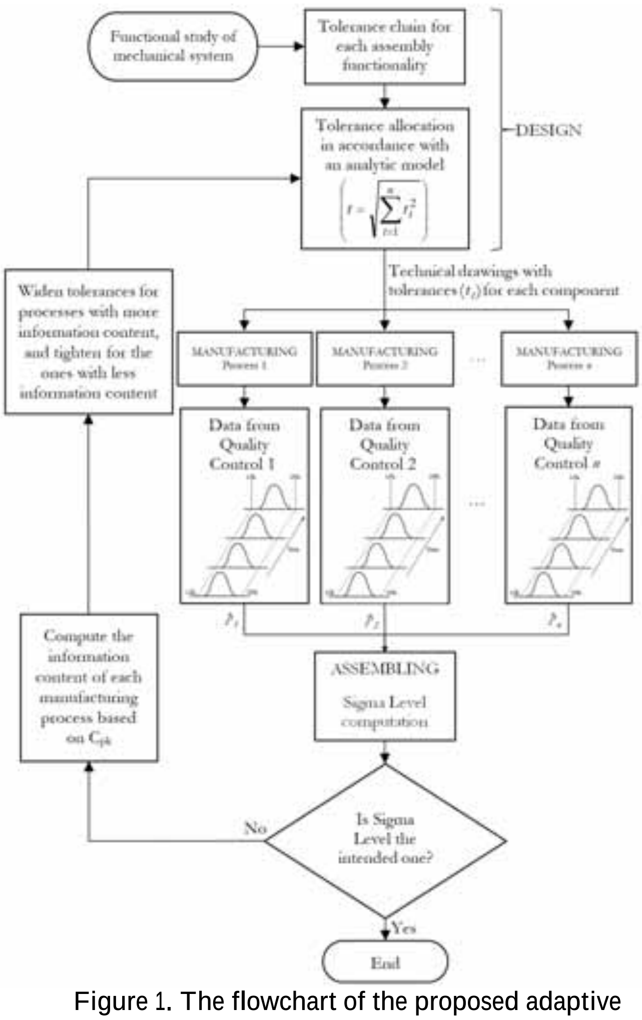

Figure 1. The flowchart of the proposed adaptive tolerance allocation to adjust the sigma level

The appropriate value for C_{pk} is usually attained by adjusting the manufacturing process by taking into account the data acquired through quality control.

If these data were sent to the design department, then it would be possible to attain a suitable value for the sigma level for the assembling operation through selective adaptation of the tolerance allocation to the different components, without any intervention on the manufacturing processes.

The method fosters the communication between design and quality throughout the production phase. As in many other sectors, real time communication is essential within any organization, because it allows a better perception of the difficulties and the capabilities of each department, as well as timely and more effective corrective actions.

The advantage of this method is that it allows achieving a higher sigma level in the overall process without any change in the processes. This increase is achieved by adapting the design specifications to the actual capabilities of the manufacturing processes, therefore not following the usual approaches of reducing the process variation to increase the overall quality of the manufacturing process.

Business groups consisting of several production units that are responsible for large productions should pay great attention to the data exchange between the design and the quality control departments of the involved production units.

The proposed method is appropriate for the cases where the production of distinct components is committed to different factories. However, it cannot be regarded as a means to avoid the optimization of manufacturing processes of low capability.

4 AN APPLICATION OF THE METHOD

An organization is responsible for the design and production of a specific product. This one is a mechanical assembly with three components that must be mass-produced, which nominal dimensions are depicted in Figure 2. The manufacturing of the components is committed to three independent plants, each of them being responsible for the production of a different component of the assembly.

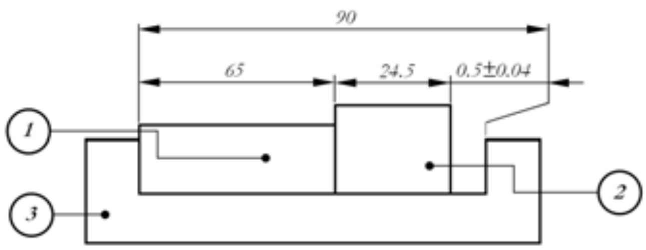

Figure 2. The mechanical assembly under study (dimensions in mm)

The top-level functional requirement of the mechanical assembly is the clearance of 0.5 mm ± 0.04 mm that is shown in the figure. By design, the existing three design parameters (*i.e.* the tolerances to the nominal dimensions of the three components) cannot be unified. Therefore, we have a redundant design with one *FR* and three *DP*s.

The manufacturing plants are not known at the phase of product development, so that the industrialization phase of the design is based on general data.

4.1 THE 1ST TOLERANCE ALLOCATION

It was assumed that the allocation of tolerances should be initially based on industry standards, as well as on the uniformity of quality condition. It was also assumed that the tolerance bands are symmetrical for all the components of the dimension chain.

Therefore, tolerance values of the ISO 286 IT8 grade were allocated to all the components, in order to ensure that the level of precision would be the same for all the dimensions of the tolerance chain.

The relevant nominal dimensions of the three components and of their initial tolerances are presented in Table 1.

Table 1. The first tolerance allocation

Component number	Nominal Dimension [mm]	Tolerance (IT8) [mm]
1	65	0.046
2	24.5	0.033
3	90	0.054

The tolerance of the assembly is 0.078 mm, as computed through Equation 2. Thus, the computed tolerance band is narrower than the specified value of 0.08 mm (*i.e.* ± 0.04 mm).

If the three manufacturing plants are independent, then it is easy to presume that the three processes have different capability indices.

According to the aforementioned records of quality control, the plant to which was committed the manufacture of component 1 has the lowest capability index and the fabricator of component 3 exhibits the highest C_{pk}.

The simulation of the manufacturing processes was carried out through Equation 8 using the quality control data and assuming the normal distribution condition. The results of the simulation are shown in Table 2.

Table 2. Values of the capability study relative to the first tolerance allocation

Process (dimension)	C_{pk}	Percentage outside specs	DPMO	Sigma Level
1 (65 mm)	1.38	3.44e-05	34.4	
2 (24.5 mm)	1.68	2.17e-07	0.22	
3 (90 mm)	1.91	9.05e-09	0.0091	
Overall		3.46e-05	34.6	5.48

Table 2 shows that the sigma level of the whole process is high, although lower than 6; nevertheless, the capability indices of the processes are irregular. The difficulties experienced by process 1 to produce within specifications, led to a high percentage of nonconforming parts. Thus, any process improvement of processes 2 and 3 to increase the overall sigma level will be limited by the comparative lower capability of process 1.

If the manufacturing plants try to do their best, than any capability improvement implies increased costs, specifically with the acquisition of equipment with a higher performance. However, this approach would not take into consideration the manufacture as a whole, each plant acting individually.

In an overall outlook, the approach should ponder the possibility of adjusting the design specifications of all the manufacturing operations.

The proposed model considers that the quality control data collected at each factory can be used by the design team to reallocate tolerances, taking into account the actual capabilities of all the involved manufacturing processes. This implies opening additional data flows from all the manufacturing plants to the design department.

In this condition, the design team can adjust the tolerance values, without any change in the manufacturing processes and preserving the relationship between them through the analytical model of Equation 2. The proposed criterion is based on the following assumptions: a) the best tolerance allocation is one that leads to the lowest information content of the system as whole; b) the manufacturing processes are independent; c) the minimization of the information content is achieved through the improvement of the process with the worst capability index, which is made possible through the levelling of the C_{pk} values of the different manufacturing processes.

4.2 THE RESULTS

The application of the proposed method is made iteratively, in accordance with the analytical model of Equation 2. The goal is upgrading the worst C_{pk} while levelling all the others concurrently. Indeed, this computing process is coupled, but the result can be applied independently.

Table 3 contains the result of the computing process, which satisfies the tolerance of the clearance that was imposed by design, since the new computed t is 0.08 mm.

Table 3. Tolerances resulting from adaptive allocation

Component number	Nominal Dimension [mm]	Tolerance [mm]
1	65	0.055
2	24.5	0.033
3	90	0.048

For these new specifications, a new simulation of the production of components 1, 2 and 3 was performed. This simulation was carried out with the same process variance, because it was assumed that process did not change. Table 4 shows the values that were obtained.

Table 4 - Values of the capability study with adaptive tolerance allocation

Process (dimension)	C_{pk}	Percentage outside specs	DPMO	Sigma Level
1 (65 mm)	1.67	5.80e-07	0.58	
2 (24.5 mm)	1.66	3.44e-07	0.34	
3 (90 mm)	1.72	2.60e-07	0.26	
Overall		1.18e-06	1.18	6.22

Now one can see that fine-tuning the design tolerances of the components 1 and 3 allowed increasing the C_{pk} of process 1. Actually, levelling the capability indices led to a better sigma level in the overall productive process, 6.22 instead of 5.48, which means an increase of 13.5%.

The raise of the sigma level of the entire production process represents an increase in the overall quality of the product, and it is worth stressing that this was achieved without rising costs, because no changes were made in the manufacturing processes.

4.3 VALIDATION THROUGH INFORMATION CONTENT

The independence of the manufacturing processes allows writing down the design equation 11 to represent the accomplishment of the design tolerances specified to each component.

$$\begin{Bmatrix} Tol.\ 1 \\ Tol.\ 2 \\ Tol.\ 3 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ 0 & X & 0 \\ 0 & 0 & X \end{bmatrix} \begin{Bmatrix} Manufacturing\ Process\ 1 \\ Manufacturing\ Process\ 2 \\ Manufacturing\ Process\ 3 \end{Bmatrix} \quad (11)$$

As one can see, this is an uncoupled design, for which the total information content, I_t, can be computed through the equation

$$I_t = \sum_1^3 -\log_2 p_i \quad (12)$$

where p_i is the probability of each design tolerance being satisfied by the manufacturing process, which is given by

$$p_i = 1 - \left(p_f\right)_i \quad (13)$$

where p_f is the nonconforming probability that can be computed through Equation 7.

The information axiom states that the best design is the one with the smallest information content [Suh, 1990]. Therefore, let us compare the levelled solution that we have found with the one that was initially considered.

Using Equation 12, we can find the information content for the initial situation:

$$\left(I_t\right)_I = 4.99x10^{-5}\ bit \quad (14)$$

After the tolerance reallocation is made, and using again the same equation, the information content becomes:

$$\left(I_t\right)_F = 1.71x10^{-6}\ bit \quad (15)$$

Because

$$\left(I_t\right)_F < \left(I_t\right)_I, \quad (16)$$

one can conclude that the tolerance reallocation yielded to a better design solution.

5 CONCLUSION

This paper presents a method that allows adaptive tolerance allocation using data previously acquired by quality control departments, and shows how this data can be used to adapt design specifications to the industrial reality.

The knowledge about the capability index of manufacturing operations allows computing the corresponding information content, and high sigma levels in the manufacturing of assemblies correspond to low information content.

The method makes it possible to increase the efficiency of manufacturing systems, even if their overall capability was already attained by the corresponding production systems.

As an overall conclusion, the presented case study describes an efficient axiomatic quality strategy through design change, as represented by the first term of Equation 1.

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BUSINESS INTEROPERABILITY: DYADIC SUPPLY CHAIN PROCESS DECOMPOSITION USING AXIOMATIC DESIGN

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ABSTRACT

In today's competitive environment, companies must strive to cooperate in order to survive. Supply chain cooperation has become a strong asset relying on large integration and coordination of its well-structured processes. However, supply chain operations are conditioned by interoperability, for which until now is missing a tool that helps managers to identify and solve its problems. This article presents the supply chain process redesign supported by the Axiomatic Design Theory.

Keywords: business interoperability, axiomatic design, supply chain management, process interoperability.

1 INTRODUCTION

The fierce competition between companies requires networked cooperation such as supply chains (SC), in order to face the current market situation. In this context, business interoperability is an enabler that makes it possible to execute SC operations such as planning, sourcing, delivering, producing and returning, in a seamless fashion, permitting a suitable process alignment and information flow and guaranteeing high performance and competitiveness [Huhns *et al.*, 2002]. However, the lack of interoperability is an emerging issue in information technology (IT) based cooperation.

In this work we present a method to decompose the processes between two supply chain actors. The paper is structured as follows: section two makes a brief review on the key topics (business interoperability and supply chain operations); section three describes the methodology for analysing and re-designing the supply chain dyadic cooperation; section four presents an example of the process decomposition between two SC actors supported by Axiomatic Design Theory (AD); and, section five presents the conclusions.

2 BUSINESS INTEROPERABILITY

2.1 BUSINESS INTEROPERABILITY DECOMPOSITION

Legner & Wende [2006] defined business interoperability as "an organizational and operational ability of an enterprise to cooperate with its business partners and to efficiently establish, conduct and develop IT-supported business with the objective to create value". Since the original concept introduced by IEEE [1990], interoperability has grown into a wider subject, integrating several organizational, operational and technological areas, currently becoming a complex subject [Rezaei *et al.*, 2013]. IDEAS [IDEAS, 2003], INTEROP Framework [Chen *et al.*, 2008; Chen, 2006], ATHENA Interoperability Framework (AIF) [ATHENA, 2007], ATHENA Business Interoperability Framework (BIF) [ATHENA, 2007] and European Interoperability Framework (EIF) [IDABC, 2010; Vernadat, 2010] are examples of frameworks and researches that present different perspectives, which reflect the issues that one must tackle to achieve higher levels of interoperability, that is, to get close to the concept of "optimal interoperability" [Legner & Lebreton, 2007]. Accordingly, and based on the definition of Legner & Wende [2006], we propose the Business Interoperability Components as depicted in Figure 1.

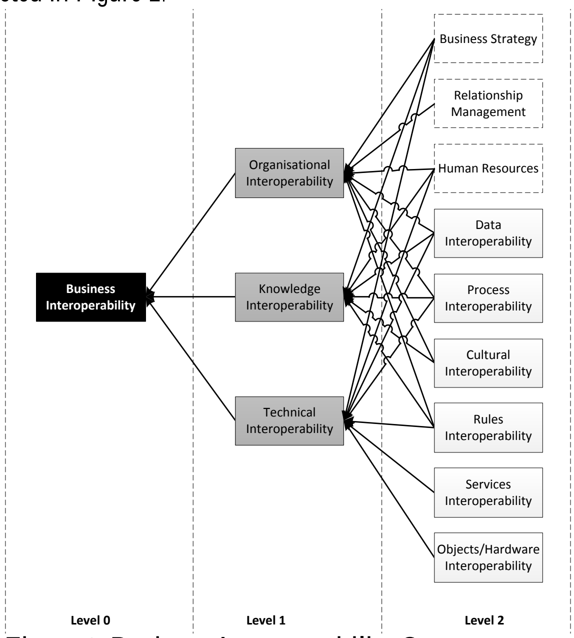

Figure 1. Business Interoperability Components.

These components portray individual perspectives of interoperability that, in each way, contribute to the concept of

Business Interoperability. This approach to the decomposition of business interoperability aims at systematizing the design of dyadic relationships using AD. This approach allows looking at the interoperability components to see how they guarantee an interoperable dyadic relationship.

2.2 PROCESS MODELLING AND THE SUPPLY CHAIN OPERATIONS

Modelling supply chain processes stems in the concept of process integration and coordination [Vernadat, 1996]. The supply chain operations reference model (SCOR), as introduced by [Supply Chain Council, 2010], provides a cross-industry standard in the definition and configuration of supply chain management processes. However, the SCOR model does not show how to proceed to achieve interoperability.

According to Chen [2006], process interoperability (PI) refers to the way internal processes from different companies interact with each other. The identification [ATHENA, 2005], sequencing [Chen, 2006; Chen *et al.*, 2008] and alignment [ATHENA, 2007; Tolk, 2003] of these processes are critical issues when designing the SC operations between two or more firms. Those authors stress the relevance of coordinating the internal processes into an interface or public process.

3 THE METHODOLOGY TO ANALYSE AND RE-DESIGN DYADIC COOPERATION

Figure 2 presents the method that is proposed to deal with the analysis and re-design of supply chain dyads.

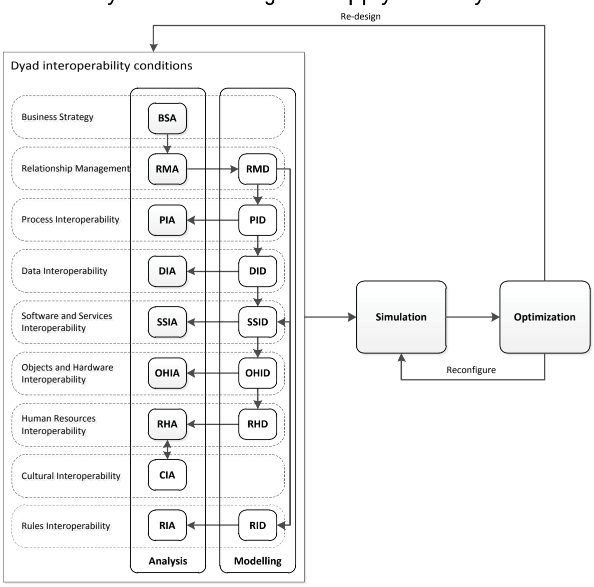

Figure 2. Methodology to analyse and re-design dyadic cooperation.

In this method, the first step is to analyse and model the dyad interoperability conditions in terms of the business interoperability components that represent the "as-is" situation. Next, one simulates the "as-is" model and one identifies the various scenarios that may lead to a more interoperable situation. At last, in the optimization stage, one finds which one of those scenarios has the best performance in terms of interoperability and in terms of supply chain performance.

3.1 STAGES OF ANALYSIS AND DECOMPOSITION

As mentioned in the previous section, the first step of the method is to determine the dyad interoperability conditions. This is achieved by interleaving the interoperability and the performance analyses, and modelling the interoperability components in a process that we call analysis and decomposition stages (A+D stages) (see Figure 2). The sequence of these stages has to do with the relationship between the business interoperability components. On the top of the method are the managerial and governance aspects, such as the business strategy and the management of the relationships that impact subsequent components. For instance, in business strategy analysis (BSA), the cooperation objectives are addressed and the dyad is analysed to verify if these ones are clear-cut to both companies and if the individual aspects are aligned into a cooperation business strategy. Managerial and governance aspects have impact in operations. Process interoperability decomposition (PID) and process interoperability analysis (PIA) are ruled by the prior aspects of interoperability, thus constituting the focus of this method. All the following stages are associated to the operations taken place in the dyad. For instance, data interoperability decomposition (DID) and data interoperability analysis (DIA) concerns to exchange of data between the firms that perform the processes. Issues like semantic alignment, communication paths and data quality are addressed in this stage in order to ensure that the data is properly interpreted, that there are sufficient contact points to exchange data, and that data is usable.

In terms of interoperability, the process resources are the information technology assets (software and systems interoperability, as well as objects and hardware interoperability) and the human resources. These resources enable processes and data exchange. As in the case of data interoperability, these resources are connected to the process interoperability.

3.2 PROCESS INTEROPERABILITY DECOMPOSITION (PID) AND ANALYSIS (PIA)

As stated before, process interoperability is the core of the method. Governance and management impact interoperability and two main elements rule the interaction between enablers and resources: the modelling and the analysis of the processes. The first element is the so-called process interoperability decomposition (PID), where individual and interface process identification, sequencing, and monitoring are addressed by using Design Structure Matrix (DSM) [Eppinger & Browning, 2012], Business Process Modelling Notation (BPMN) [Fettke, 2008] and supply chain practices implementation, in order to find which are the aspects that drive cooperation towards better effectiveness and efficiency. Figure 3 describes the method for decomposing a process in a dyad. For each actor in the SC dyad, we propose the characterization of each process (PI_1), the sequencing (PI_2) and the identification of the monitoring resources (PI_3). Next, the processes are aligned with the organisational structure of the company (PI_6). At last, after representing the company's internal processes, the interface process is created by aligning individual processes into a collaborative process (PI_5).

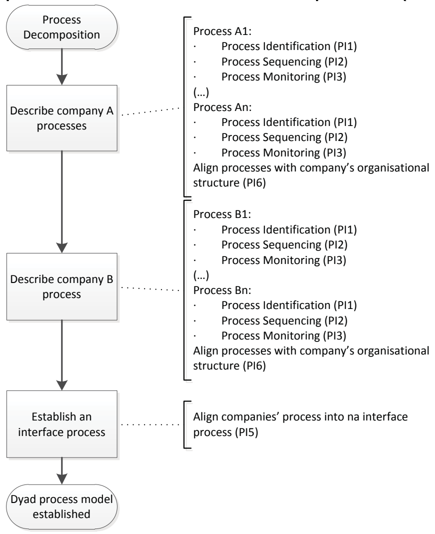

Figure 3. Process interoperability decomposition (PID) method.

Process interoperability analysis (PIA) is done after decomposing the process, and we suggest assessing the alignment and the visibility, as well as the appropriateness of the organisational structures to the processes. Both the process and the organisational alignment are addressed in qualitative and modelling standpoints. On the one hand, one makes a qualitative evaluation of the actors of the dyad; on the other hand, one verifies these two factors for better workflow arrangement and distribution through the companies' sections by using the DSM approach with optimization algorithms.

4 EXAMPLE: AUTOMOTIVE SUPPLY CHAIN DYAD

As an example, a 2nd tier raw material supplier (company A) and a 1st tier supplier (company B) constitute the dyad under analysis. On the AD perspective, the costumer in this case is the dyad. Hence, the top-level costumer need (CN) is to ensure high level of interoperability that should be achieved by the design of the sourcing and the delivery operations.

The interoperability conditions in terms of business strategy and process interoperability are specified in the design of Table 1.

Table 1. The dyad business strategy and process interoperability conditions.

FR_0: Ensure interoperability on sourcing and delivery operations.	DP_0: Systematic design of the dyad.
FR_1: Establish the cooperation goals and conditions for the dyad.	DP_1: The negotiation of a contract.
$FR_{1.1}$: Establish purchasing requirements.	$DP_{1.1}$: The company B's purchasing model.
$FR_{1.1.1}$: Settle an agreement for lead-time.	$DP_{1.1.1}$: The standard lead-time is one week.
$FR_{1.1.2}$: Define the deadline to reject orders.	$DP_{1.1.2}$: The supplier (company A) has five days to reject an order.
$FR_{1.1.3}$: Establish the payment conditions.	$DP_{1.1.3}$: The payment is authorized only after receiving the invoice and the materials.
FR_2: Manage internal and interface processes of the cooperation.	DP_2: The role assignment, the process design and the coordination of the sourcing and delivery activities.
$FR_{2.1}$: Define the company B processes.	$DP_{2.1}$: Company B is the buyer and performs the purchasing and reception operations.
$FR_{2.1.1}$: Define the purchasing process.	$DP_{2.1.1}$: The features of the purchasing process.
$FR_{2.1.1.1}$: Define the inventory policy.	$DP_{2.1.1.1}$: The inventory level is defined every week by the materials resource plan (MRP).
$FR_{2.1.1.2}$: Define the procedure to place an order.	$DP_{2.1.1.2}$: The purchasing is performed by sending the order schedule and waiting for order fulfilment.
$FR_{2.1.1.3}$: Define the order validation method.	$DP_{2.1.1.3}$: The orders are considered accepted except in case of delays and rejection.
$FR_{2.1.2}$: Define the payment procedure.	$DP_{2.1.2}$: The payment is made after receiving the invoice and the products physically.
$FR_{2.1.3}$: Sequence company B's individual tasks.	$DP_{2.1.3}$: The design of the process, material and information flows on purchasing process (see "Figure 4.").
$FR_{2.2}$: Define the company A processes.	$DP_{2.2}$: Company A is the supplier and is responsible for receiving orders and deliver materials to company B according to the pre-established lead-time.
$FR_{2.2.1}$: Define order reception procedure.	$DP_{2.2.1}$: Company A receives an order schedule and checks the inventory level to fulfil orders.
$FR_{2.2.2}$: Define the order validation procedure.	$DP_{2.2.2}$: Order validation performed by checking stored materials and production availability.
$FR_{2.2.3}$: Sequence company A's individual tasks.	$DP_{2.2.3}$: The design of the process, material and information flows on delivery process (see "Figure 5.").
$FR_{2.3}$: Align companies' internal processes.	$DP_{2.3}$: Interface process.

The corresponding design matrix is depicted in Table 2. The dependency between FRs and DPs, which comes from the chosen DPs, conditions the design of the processes. For instance, the establishment of a deadline to cancel orders ($DP_{1.1.1}$) has direct influence in the definition of the method to validate orders on the purchasing process ($FR_{2.1.1.3}$).

PID method is applied to FR_2. Process identification (PI_1) is portrayed by $FR_{2.1}$, $FR_{2.1.1}$, $FR_{2.12}$, $FR_{2.2}$, $FR_{2.2.1}$ and $FR_{2.2.2}$. Process sequencing (PI_2) is applied to $FR_{2.1.3}$ and $FR_{2.2.3}$. Finally, the companies' internal processes alignment (PI_5) is applied to $FR_{2.3}$.

Table 2. Design matrix for the supply chain dyad.

	DP1	DP2	DP1.1	DP2.1	DP2.2	DP2.3	DP1.1.1	DP1.1.2	DP1.1.3	DP2.1.1	DP2.1.2	DP2.1.3	DP2.2.1	DP2.2.2	DP2.2.3	DP2.1.1.1	DP2.1.1.2	DP2.1.1.3
FR1	X																	
FR2	X	X																
FR1.1			X															
FR2.1			X	X														
FR2.2					X													
FR2.3				X	X	X												
FR1.1.1							X											
FR1.1.2							X	X										
FR1.1.3							X		X									
FR2.1.1							X			X								
FR2.1.2							X				X							
FR2.1.3										X	X	X						
FR2.2.1													X					
FR2.2.2														X				
FR2.2.3													X	X	X			
FR2.1.1.1																X		
FR2.1.1.2																X	X	
FR2.1.1.3								X										X

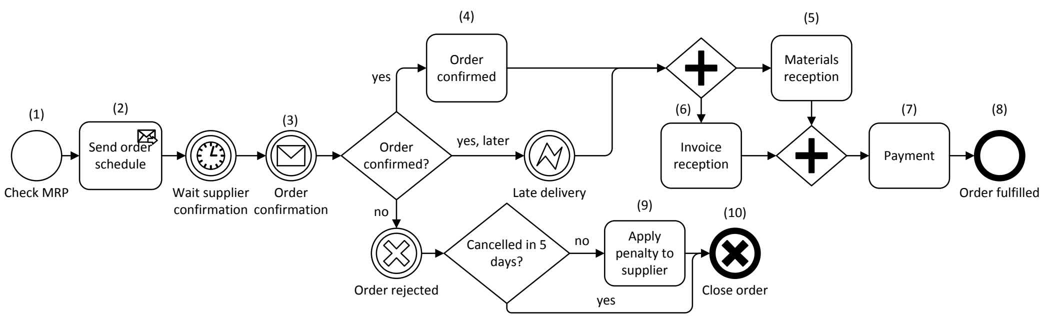

Figure 4. Company B's purchasing business process model ($DP_{2.1.3}$).

As for FR_2, stating the main operations and the procedures that must be used to achieve the sourcing and delivery goals specifies the process considerations. $FR_{2.1.3}$ corresponds to the alignment of the tasks of company B with the business process flow. The existing conditions of company B are presented in Figure 4. The process sequence is a direct consequence of the FR and DP decomposition. For instance, purchasing condition $DP_{1.1.3}$, establishes that the payment activity is preceded by a set of parallel activities: invoicing and reception of materials, which are requirements for making payments. Delays in any one of those activities will delay the payment to company A. Also, the condition $DP_{1.1.2}$ results in an additional process (see (9) in "Figure 4.") that, in case of order rejection delay, will result in negotiation of penalties.

In turn, the process of company A is presented in Figure 5, which portrays the sequence of the business procedures that should be performed to receive ($FR_{2.2.1}$) and validate orders ($FR_{2.2.2}$).

The next step in the proposed method is to align these processes with the company's organisational structure. In this example we are dealing only with one company section. Hence, the next step is to design the interface processes. Here, data, material and currency flows are mapped to interconnect the business processes. The result for the existing conditions is presented in Figure 6.

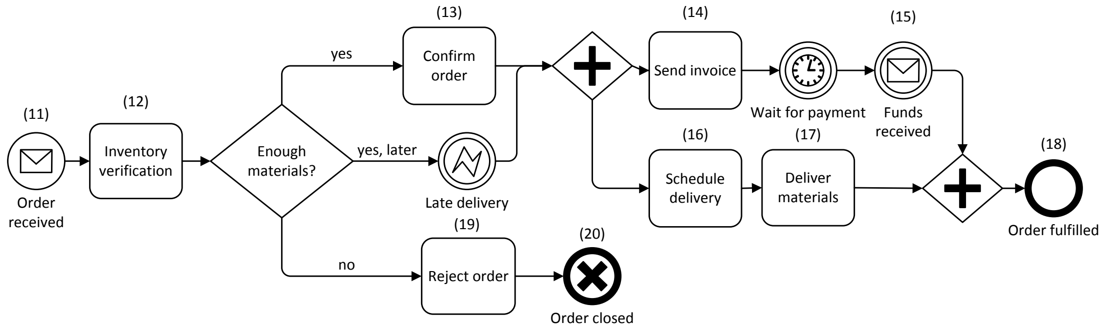

Figure 5. Company A's business process model ($DP_{2.2.3}$).

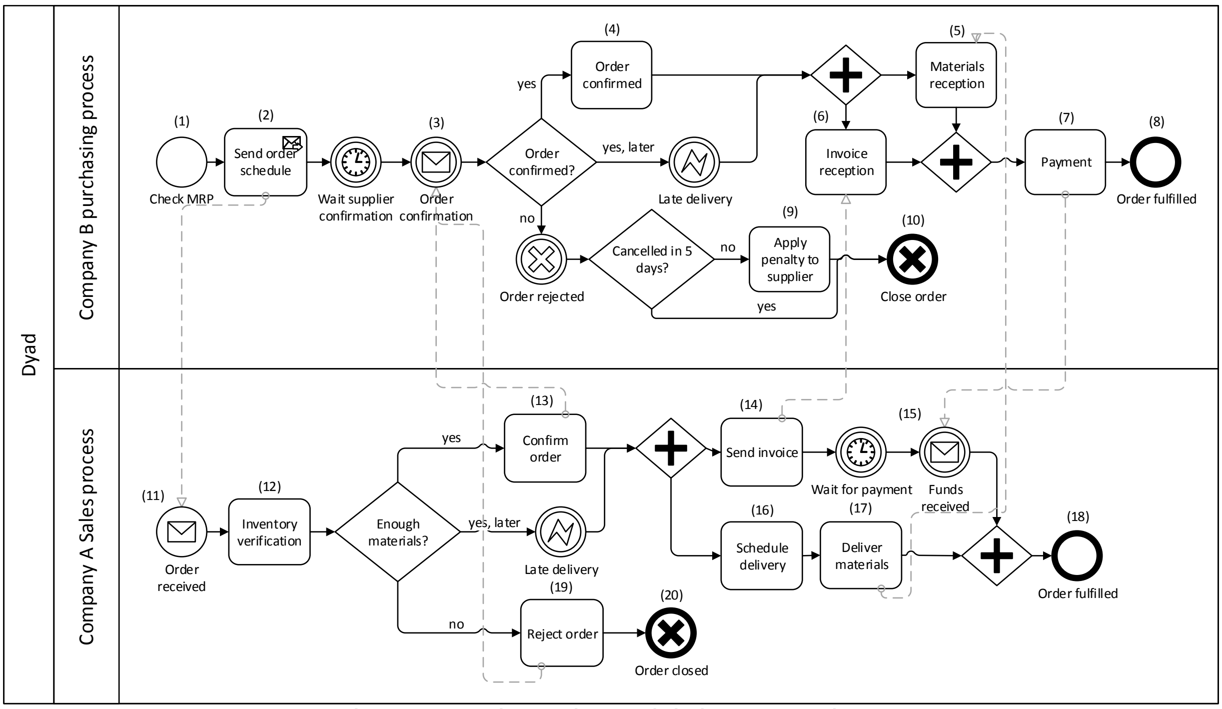

Figure 6. Dyad sourcing and delivery operations.

Representing the internal and the interface activities in a DSM (see Figure 7) allows visualizing the interactions between processes. The numbered activities of Figure 7 correspond to the numbers shown in Figure 6.

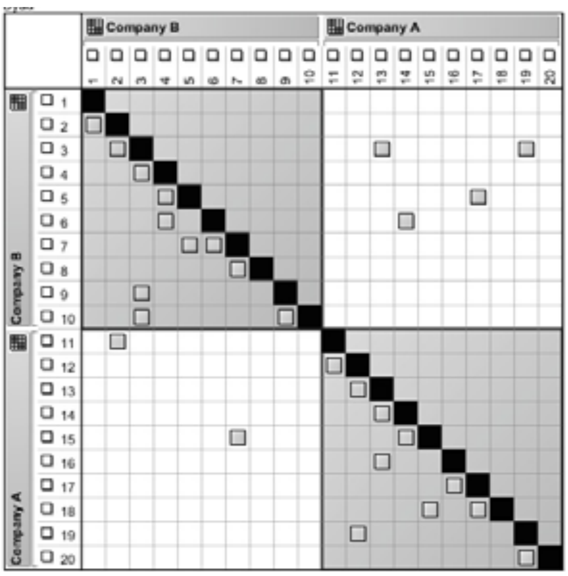

Figure 7. A DSM representation of the dyad (DSM made using the software "Cambridge Advanced Modeller" developed by Wynn *et al.* [2010]).

One should notice that there are six interactions in the interface of the two companies. We must act on those ones in order to identify and solve the interoperability problem. For example, both BPMN and DSM representations show a strong dependency between the purchasing and the sales processes. Checking the MRP and placing an order initiate the purchasing process. After placing the order, the procedure stops until company B confirms or rejects it. In the perspective of company B, the order placement is what triggers the sales process. The process is almost fully executed and, if the order is confirmed, it stops again waiting for the payment of company A. However, company A only makes the payment when the invoice and the materials are received. The activities in both companies depend on each other in the interactions (14)-(6), (17)-(5) and (7)-(15) (see Figure 7). This complex operation deserves great attention in modelling and in applying the subsequent A+D stages. The effectiveness of the process depends on the features of each one of the interactions and on the available resources. The effectiveness is studied through simulation as a means to check if the procedures generate delays on each other. The result of this study may require the re-configuration of the dyad in terms of information systems that enable the interactions (2)-(11), (13)-(3), (19)-(3), (14)-(6) and (7)-(15); or the material flow on (17)-(5).

5 CONCLUSION

The present research contributes to developing an integrated tool to assess and re-design IT-supported cooperation, using a systematic approach to identify interoperability problems, as well as to select optimisation tools to eliminate or to mitigate them.

The method presented in section 3 allows guiding the axiomatic design application by interleaving the analysis and the decomposition stages, while keeping the integrity of the business interoperability issues that are related to the industry sector under analysis.

The proposed method for process decomposition allows linking the governance and managerial issues to the operational reality of business. This is useful in dyad analysis and design because it allows keeping track of previously defined aspects when advancing the design. The presented example demonstrates that the cooperation objectives are very relevant in the process design, such as in the case of order cancelling deadline that influences the order validation process in both companies.

The Business Process Model Notation (BPMN) and the Design Structure Matrix (DSM) have particular relevance in modelling processes. BPMN allows easy forms of representing process, material, information, and currency flows and provides suitable symbols to represent information technology assets, users, communication, etc. As for the DSM approach, it allows to go deeper in the interaction between processes. As illustrated by Figure 7, the interactions that occur in the interface between the two companies become evident and it is possible to check where a process begins and ends. On more complex processes (*e.g.*, representing all the supply chain operations, such as production, planning, sourcing, delivery and returning) it is possible to allocate processes to organisational sectors (as proposed in section 3.2), and to verify the process alignment and distribution through clustering algorithms.

Future work will concentrate on applying the next stages of the proposed methodology. For example, after defining the process interfaces, data exchange will be modelled and analysed in order to identify information barriers, such as semantics faults, or database heterogeneity. At last, using simulation tools it will be possible to study various scenarios without interfering with the actual system, thus providing the solution that results in less cost and time.

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AXIOMATIC DESIGN MODEL TO ASSESS INFLUENCES AFFECTING PEDAGOGIC-LEARNING IN THE COURSES ENGINEERING MATERIALS I AND FLUID MECHANICS I (PART 1)

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ABSTRACT

This paper explores to set an axiomatic design model in the Assessment of Influences Affecting Pedagogic-Learning in order to succeed in finding core factors affecting student's performance for the courses Engineering Materials I (CE 221) and Fluid Mechanics I (CE 211-F). These subjects are the building blocks of engineering knowledge, thus require that the student should grasp the knowledge before he/she moves to the next level. The survey aims to understand what student influential factor best relate to teacher goals. The questions asked to get the perception of what influences students' about pedagogic-learning on the two subjects were taken from a inventory of teaching goals by Angelo and Cross (1993). On the course Engineering Materials I (CE 221), there are 92 second-year students from Mineral Processing, Mining and Civil Engineering. On the other hand, there are 42 second-year students from Civil Engineering for the course Engineering Fluid Mechanics I (CE 211-F). The study uses the axiomatic design (AD) principles in finding success on the assessment of the influential factors that affects student pedagogic-learning. The study found that by using AD, the analysis of the assessment is simplified and the factors that influence the students in each subject are best identified. The result of the assessment helps the author identifying the gap of teaching and learning and to find ways to bridge that gap using a new framework to address the challenges of culture-rich and educational-poor factors of influence in pedagogic learning. This document is composed by two parts.

Keywords: Pedagogic-learning, assessment, framework, influences, model.

1 INTRODUCTION

Papua New Guinea (PNG) has an abundance of natural resources, with mineral deposits like copper, gold and oil accounting about 72% of export earnings or nearly two-thirds of PNG's export revenues. PNG has embraced an economy boom in the last ten years particularly in the sector of resources, but the human development (2013) is only 0.466% of average Human Development index in the Asia Pacific region as of 2013, according to the Human Development Report of the United Nations, while the international average Human Development index was 0.694% and the Asia Pacific region recorded 0.68%. Former Lae MP Bart Philemon (Human Development, 2013) pointed out that 2-3 million (the 7-21-years old, as per the 2011-2012 National Population Census report) Papua New Guineans, out of a population of more than seven million, are illiterate and describe the country as an island of gold floating on oil, which means "our country is richly blessed with many natural resources that is the envy of many other countries". But despite these blessings, PNG is ranked 153 out of 187 countries and noted as the 34th poorest ranking nation in the world in terms of human development as measured by United Nations. The Asian Development Bank (2003) forecasted that neither economic nor social change is likely to occur without a literate and healthy population, education is a major determinant of development everywhere in Asia and the Pacific.

For engineering courses, failure rates are as high as 35% (Karim, 2011) because students have real problems in understanding some fundamental concepts and principles if they are abstract in nature. The author's experience in teaching reveals students' difficulty in the courses of Engineering Materials I (CE 221) and Fluid Mechanics I (CE 211-F). The CE 211-F is combined with Engineering Solid Mechanics, making it a 8-hour coursework. With a large number of students in a class setting for CE 221, it is likely that those circumstances may influence the students' performance.

Ravinder (2011) found that today's educational struggle in PNG is a struggle for pedagogy, more specifically, PNG pedagogy that is responsive to the PNG condition today. Pedagogy is based on a premise that the purpose of education is to transmit knowledge and skills (Knowles, 1980). As defined by Wikipedia, Knowledge (2013) is a familiarity with someone or something, which can include facts, information, descriptions, or skills acquired through experience or education and can refer to either theoretical or practical understanding of a subject. It can be implicit (as with practical skills or expertise) or explicit (as with the theoretical understanding of a subject); it can be more or less formal or systematic. Malcolm Knowles (1980), who popularized the pedagogical concept in the United States in the 1970's, define pedagogy as the art and science of teaching children, as derived from the Greek words *paid*, meaning "child" and *agogus* meaning "leader of". This concept is not limited to children but is adaptive to adult learners too. In his article Pedagogy & Technology, Webb (2014) defines pedagogy as teaching for learning through activities that impart knowledge, which are illustrated as:

Technology -> activities -> tasks -> (products + experiences -> learning) -> outcomes
Teaching = scaffolding learning activities + mediation of learning experiences
Learning = (activities ->) experiences + programmed knowledge + questioning insight

Learning outcomes must be measured so that whatever deficiency in learning can be alleviated by the teaching strategies on the next time the same subject is thought. Teacher matters (2014) says that many factors contribute to the student's academic performance, including individual characteristics and family and neighborhood experiences. But research suggests that, among the school-related factors, teachers matter the most. When it comes to student performance, the teacher is estimated to have two to three times the impact of any other school factor, including services, facilities, and even leadership. Rachal (1983) stressed that the lecturer direct approach, or the pedagogical approach, would still require the lecturer to follow a free exchange of ideas and to allow students to pursue personal interests (through papers, projects, or presentations) as long as they go along with the course objectives. The lecturer must also provide leadership and take primary responsibility for evaluation to determine that the expected result is obtained.

Teaching is a complex activity that is strongly affected by external decisions about curriculum and assessment. The teacher plays a crucial role in the implementation of curriculum and assessment, as well as in the student achievement. Research has identified some teaching effectiveness factors, such as teacher expectations of their students, teacher knowledge of the subject, and other learning approaches which contribute to the feedback associated with formative assessment strategies. The author believes that the use of evaluation helps to reduce high failure rates, as they are costly to all stakeholders since the throughput of the University is reduced. This increases the cost of training graduates, as well as reducing admission opportunities for high school students seeking a University education. For a country like Papua New Guinea, where there is only one technological university, as well as for the rest of the Pacific Islands, with an intake of fifty students a year per discipline, low pass rates impose a huge cost in terms of low number of students graduating and reduced intake of potential students due to the shortage of space caused by the low throughput of the university.

It is in this premise that the study is conducted in order to determine the student personal philosophies that influence their learning as directed by the teacher (pedagogic) in the courses Engineering Materials I (CE 221) and Engineering Fluid Mechanics I (CE 211-F).

1.1 TEACHING STRATEGIES AND ASSESSMENT IN THE COURSES CE 221 & CE 211-F

The teaching strategies that the researcher used in the courses are lectures, tutorials, and experiments. The outlying concepts and principles in the courses are given in lectures and are reinforced during tutorial sessions. The hands-on of some outlying concepts and principles are conducted by laboratory experiments. Because of a large group of students attending the experiments and the limited number of laboratorial setups, the laboratory experiments are just exhibited by the technical personnel that support the courses. The assessments used to measure student's achievements are: assignments (A), quizzes (Q), laboratory experiment reports (L), and written final examination as shown in Table 2.

Table 1. Arrangement of the teaching strategies for CE 221 & CE 211-F

	Method	Contact hours		number of AQL		Grading % weight	
		CE 221	CE 211-F	CE 221	CE 211-F	CE 221	CE 211-F
Teaching Strategies	Lectures	1	3				
	Tutorials	1	1				
	Experiments	1					
Assessment	Assignments, A			6	3	12	15
	Quizzes, Q			6	3	16	15
	Lab Reports, L			3	3	8	5
	Attendance	Every meeting		Every meeting		4	5
	Final Examination	At the end of each semester		At the end of each semester		60	50

Student consultation is already incorporated in the tutorial sessions, in which the reinforcement on the contents is made to increase student's content grasp of the subject matter and is believed to help them increasing their internal marks or continuous assessments.

1.2 SAMPLE USED IN THE COURSES CE 221 & CE 211-F

There is a total number of 118 second-year students from Mineral Processing (BEMP-2), Mining (BEMN-2) and Civil Engineering (BECV-2) enrolled in the first semester of calendar year 2013 for the course Engineering Materials I (CE 221), and 47 second-year students from Civil Engineering for the course Engineering Fluid Mechanics I (CE 211-F) who responded a questionnaire. The questionnaire was given to the students on a reward scheme of additional two (2) marks added to their internal marks or continuous assessments in order to get a majority of responses and encourage them to fill up the questionnaire with diligence. However, only 92 complete turnouts of 107 returned questionnaires were considered in this study, out of 118 distributed questionnaires for CE 221 and 47 for CE 211-F with 44 returned questionnaires and 42 complete turnouts. Sampling criteria below as applied results to an appropriate sampling for both courses on study.

The sampling criterion is based on the Slovin's formula:

$$n = \frac{N}{1+Ne^2} \qquad (1)$$

where:

n = sample size
N = population size
e = margin of error

1.3 SURVEY TOOLS USED IN THE ASSESSMENT OF COURSES CE 221 & CE 211-F

The survey tools used in the analysis of influences are items of questions from the teaching goals inventory list of Angelo and Cross (1993), which the author believes that embodies the desired teaching goals in the learners' point of view. There are fifty closed-type questions to find what best influences the student (according to a five-point Likert scale) with the following descriptors:
(1) *Not applicable*, an influence that student never want to have;
(2) *Unimportant*, an influence that student rarely want to have;
(3) *Important*, an influence that student sometimes want to have;
(4) *Very Important*, an influence that student often want to have;
(5) *Essential*, an influence that student always/nearly want to have.

Table 2. Set of Influences Questions in the Survey of Student's Perception

Item	Description of Influence
1	Influences that develop ability to apply principles and generalizations already learned to new problems and situations.
2	Influences that develop analytical skills.
3	Influences that develop problem-solving skills.
4	Influences that develop ability to draw reasonable inferences from observations.
5	Influences that develop ability to synthesize and Integrate information and ideas.
6	Influences that develop ability to think holistically: to see the whole as well as the parts.
7	Influences to develop ability to think creatively.
8	Influences that develop ability to distinguish between fact and opinion.
9	Influences that improve skill at paying attention.
10	Influences that develop ability to concentrate.
11	Influences that help improve memory skills.
12	Influences that help improve listening skills.
13	Influences that help improve speaking skills.
14	Influences that help improve reading skills.
15	Influences that help improve writing skills.
16	Influences that help develop appropriate study skills, strategies, and habits.
17	Influences that help study skills, strategies, and improve mathematical skills.
18	Influences that help learn terms and facts of this course.
19	Influences that help learn concepts and theories in this course.
20	Influences that develop skill in using materials, tools, and/or technology central to this course.
21	Influences that help learn to understand perspectives and values of this course.
22	Influences that help learn techniques and methods used to gain new knowledge in this course.
23	Influences that help learn to evaluate methods and materials in this course.
24	Influences that help learn to appreciate important contributions to this course.
25	Influences that help develop openness to new ideas.
26	Influences that help develop an informed concern about contemporary social issues.
27	Influences that help develop a commitment to exercise the rights and responsibilities of citizenship.
28	Influences that help develop a lifelong love of learning.
29	Influences that develop aesthetic appreciations.
30	Influences that develop an informed historical perspective.
31	Influences that develop an informed understanding of the role of science and technology.
32	Influences that develop an informed appreciation of other cultures.
33	Influences that develop capacity to make informed ethical choices.
34	Influences that develop ability to work productively with others.
35	Influences that develop management skills.
36	Influences that develop leadership skills.
37	Influences that develop a commitment to accurate work.
38	Influences that improve ability to follow directions, instructions, and plans.
39	Influences that improve ability to organize and use time effectively.
40	Influences that develop a commitment to personal achievement.
41	Influences that develop ability to perform skillfully.
42	Influences that cultivate a sense of responsibility for one's own behavior.
43	Influences that improve self-esteem/self-confidence.
44	Influences that develop a commitment to one's own values.
45	Influences that develop respect for others.
46	Influences that cultivate emotional health and well-being.
47	Influences that cultivate physical health and well-being.
48	Influences that cultivate an active commitment to honesty.
49	Influences that develop capacity to think for oneself.
50	Influences that develop capacity to make wise decisions.

1.3 DEMOGRAPHIC AND SOCIAL PROFILE

The demographic and social profile where not included in the analysis for factoring and regression as the author consider it irrelevant because lectures and other activities in the classroom are conducted for both genders or wherever they come from and their other preferences. These information are equally useful to help the researcher established an information base which may have interest from whatever the result of the assessment of influences affecting pedagogic learning earlier presented. The data is presented in table 3.

Table 3. Demographic and Social Profile for CE 221 & CE 211-F Respondents

Description	CE 221		CE 211-F	
	f	%	f	%
1. Self-motivation to study the course				
Lecturer's instruction	1	2.38	6	6.52
Grade	6	14.29	4	4.35
Develop higher order thinking skills	4	9.52	23	25.00
Prepare for job/careers	26	61.9	50	54.35
Foster development and personal growth	2	4.76	3	3.26
Develop basic learning skills	3	7.15	6	6.52
2.Method of submission course undertaking				
Student server	7	16.67	27	30.43
Hard copy	33	78.57	55	59.78
Soft copy (via email)	11	4.76	9	9.78
3. Strategies and Assessment				
Lecture	11	26.19	28	30.43
Laboratory/Test	15	35.71	19	20.65
Assignment	11	26.19	35	38.04
Quiz	5	16.67	10	10.87
4. Information Collection				
Internet	32	76.19	67	72.83
Books at the library	3	7.15	2	2.17
Books own	2	4.76	3	3.26
Lecture notes	5	11.90	20	21.74
5.Peer Impact				
Yes	30	71.43	44	47.83
No	12	28.57	48	52.17
6. Gender				
Male	39	92.86	75	81.52
Female	3	7.15	17	18.48
7. Living in Dormitories				
Yes	41	97.62	83	90.22
No	1	2.38	9	9.78
8. Lae, Morobe resident				
Yes	0	0	2	2.17
No	42	100	90	97.83
9. Scholar				
Yes	37	88.10	71	77.17
No	5	11.90	21	22.83
10. Course Selection				
Yes	25	59.52	51	55.43
No	17	40.48	41	44.57
11. Finances				
Yes	21	50	49	53.26
No	21	50	43	46.74
12. Information Gathering				
Free will to use search engine	36	85.71	73	79.35
Directed to a link	6	14.29	19	20.65
13. Background in Mathematics				
Good	37	88.10	NA	NA
Not	5	11.90	NA	NA
14. Critical thinking				
Exercise by self	38	90.48	NA	NA
Exercise as directed	4	9.52	NA	NA
15. Understanding in real life				
Yes	41	97.62	NA	NA
No	1	2.38	NA	NA

where f is the frequency of the responses.

The students are as diverse as the country's population with more than 800 languages and a culture that is many-sided and complex. It is estimated that more than 7000 different cultural groups exist in Papua New Guinea, and most groups have their own language. Because of this diversity, which is a matter of pride, many different styles of cultural expression have emerged; each group has created its own expressive forms in art, dance, weaponry, costumes, singing, music, architecture and much more. In addition, the presence of international students from other Pacific Island countries like the Solomon Islands makes it even more diverse. The Papua New Guinea University of Technology is the only technological university in the country and in the Pacific (except Australia and New Zealand).

2 AXIOMATIC DESIGN MODEL (ADM)

Axiomatic design (2014) is defined as a systems design methodology using matrix methods to systematically analyze the transformation of customer needs into functional requirements, design parameters, and process variables. Nam Suh (2001) defines Axiomatic Design, as the creation of synthesized solutions in the form of products, processes or systems that satisfy perceived needs through a mapping between Customers Needs (CNs), Functional Requirements (FRs) Design Parameters (DPs), and Process Variables (PVs) that consists on the mapping of "what we want to achieve" and "how we want to achieve it", as shown in figure 1.

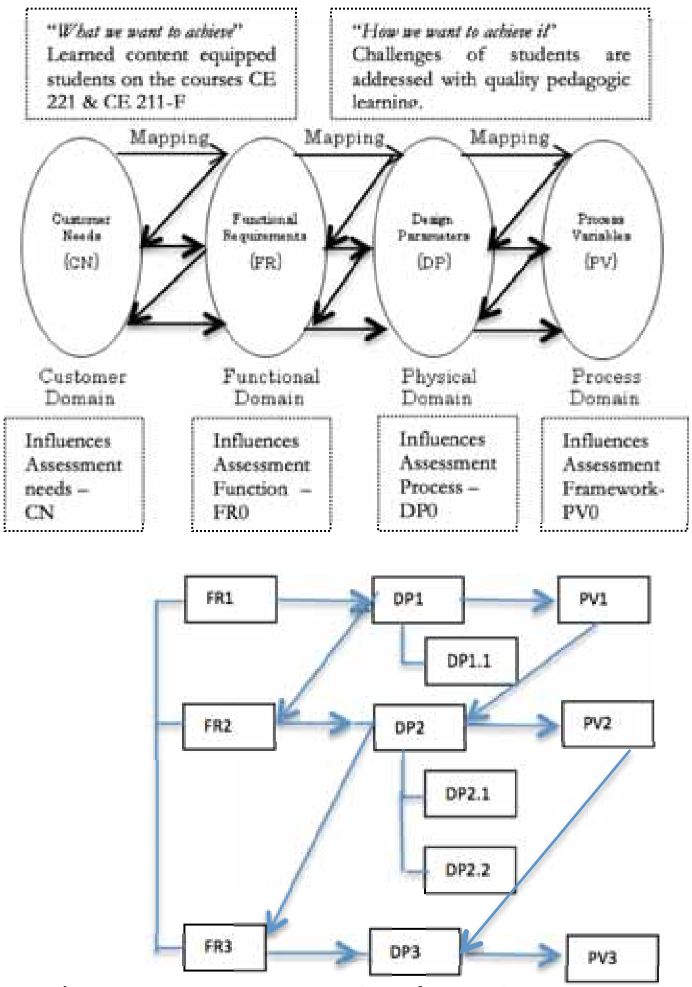

Figure 1. ADM Decomposition of FR's, DP's & PV's

The interpretation of what is the Customer Domain-Customer Needs (CNs), Functional Domain-Functional Requirements (FRs), Physical Domain-Design Parameters

(DPs), and Process Domain-Process Variables (PV)s is given in table 4.

Table 4. Definition of ADM Parameters

What we want to achieve?	
CN	Assess effectively CE 221 & CE 211-F students pedagogic learning
FR	FR0 –Realize effective assessment of CE 221 & CE 211-F pedagogic learning: FR1 – Provide feedback through Assessment (survey conducted to identify influences on pedagogic learning) FR2 – Provide a mechanism that incorporates influential factors to student pedagogic learning FR3 – Provide a support tools to implement the intervention framework on identified factors influencing pedagogic-learning
How we want to achieve it?	
DP	DP0 – Effective Assessment of Influences on Pedagogic Learning of CE 221 & CE 211-F DP1 – Analysis of student's responses (Quantitative Analysis) DP1.1 – Mean, Factor Analysis & Regression DP2 – Analysis of influential factors to student pedagogic learning DP2.1 4 – Model of Productive Pedagogy DP2.2 – Uncoupled Design Matrix DP3 – Student support tools necessary to achieve the intervention framework on identified factors influencing pedagogic-learning
PV	PV – Create an intervention framework supporting gap on identified factors affecting pedagogic learning on CE 221 & CE 211-F PV1 – Intervention Concept formulation PV2 – Paradigm Shift Framework PV3 – Lecturer's modification on lecture plans, lecture notes, student activities, and assessments

In order to define when the design solution is acceptable, Thomson (2013) stressed that the input constraints set a hard limit on the values of a quality or metrics.

A key aspect of axiomatic design is the separation between *what a system has to achieve* (functional requirements) and the design choices involved in *how to achieve it* (design parameters).

The analysis of assessing pedagogic learning using AD is presented on the Axiomatic Design Model (ADM) as illustrated in the diagram of figure 1. The ADM diagram shows the decomposition for the analysis of the question "how we want to accomplish", which is mapped to "what we want to accomplish".

2.1 APPLICATION OF DP'S

SPSS software was used for assessment. Factor analysis was used because there are a large number of related variables. The analysis is useful in reducing a large number of related variables to a smaller, more manageable, number of dimensions or components.

2.1.1 Results of DP's - Mean of Responses Analysis on Productive Pedagogies Model

The questions on influences were crafted into Productive Pedagogies (Hill, 2010; Gore, 2013) according to the weighted mean and are organized around a model of four groups of questions:

1) *Recognition of Difference*, understanding multiple forms of knowledge (i.e. cultural knowledge, inclusivity, narrative, active citizenship, and group identity);
2) *Connectedness*, linking learning to a wider world (i.e. connections to the world, problem-based curriculum, background knowledge, knowledge integration);
3) *Intellectual Quality*, making the learner experience more intellectual demands (ie. higher order thinking, meta-language, deep knowledge, deep understanding, substantive conversations, knowledge seen as problematic); and
4) *Supportive Classroom Environment*, expecting students to be responsible for their own learning and expecting high standards (i.e. student control, student support, engagement, explicit criteria or quality performance, self-regulation).

The weighted mean of each cluster was calculated establish the scale of influence illustrated below:

4.5 – 5.0 – Essential, an influence that student always, nearly want to have
3.5 – 4.49 – Very important, an influence student often want to have
2.5 – 3.49 – Important, an influence that student sometime want to have
1.5 – 2.49 – Unimportant, an influence student rarely wants to have
1 – 1.49 – Not applicable, an influence that student never want to have

The use of clusters is an attempt to find the relevance of the descriptors, in which the responses of the students are evaluated by the weighted mean in accordance with the productive pedagogy model presented in table 5.

The result shows that for 1) For Recognition of Difference, students perceived that both CE 221 and 211-F *are Very Important*, 2) For Connectedness, CE 221 is perceived to be *Very Important* while CE 211-F is said to be *Essential*, 3) For Intellectual Quality, CE 221 is perceived to be *Very Important* while CE 211-F is said to be *Essential*, and 4) Supportive Classroom Environment is perceived to be *Very Important* for both subjects.

The mapping in this design addresses the influences under the 4-category model of productive pedagogy, which results are assessed as *very important* or *essential*. As we toss the processes to the functions, we find that there is a need to make an analysis without bias or pre conception and find a new relation to understand student preferences in the right way. The above idea still circled to teacher preferences, so a multivariate statistics using SPSS software was used in the analysis because it considers more than one dependent variables at a time and controls type-1 errors by considering a set of dependent variables in a multidimensional space, while accounting the dependent variables as well as the relationships between individual variables and dependent variables.

Table 5. Pedagogical Framework Influences for CE 221 & CE 211-F parallel to Productive Pedagogies

1. *Recognition of Difference*

Item	Influences Description	Influence scale	
		CE 221	CE 211-F
18	Help learn terms and facts in this course	4.69	4.3
19	Help learn concepts and theories in this course	4.67	4.37
20	Develop skill in using materials, tools and/or technology central to this course	4.62	4.36
21	Help learn to understand perspective	4.45	4.15
22	Help learn techniques and method used to gain new knowledge in this course	4.55	4.52
23	Help learn to evaluate methods and materials in this course	4.48	4.17
24	Help learn to appreciate important contributions to this course	4.29	4.03
25	Help develop openness to new ideas	4.45	4.1
26	Help develop an informed concern about contemporary social issues	4.05	3.37
27	Help develop a commitment to exercise the rights and responsibilities of citizenship	4.48	3.74
28	Help develop a life-long love of learning	4.62	4.09
29	Develop aesthetic appreciations	4.21	3.51
30	Develop an informed historical perspective	4.17	3.39
	Over all rating	4.44, Very Important	4.01, Very Important

2. *Connectedness*

Item	Influences Description	Influence scale	
		CE 221	CE 211-F
31	Develop an informed understanding of the role of science and technology	4.62	4.30
32	Develop an informed appreciation of other cultures	3.93	3.53
33	Develop capacity to make informed ethical choices	4.29	3.79
34	Develop ability to work productively with others	4.52	4.29
35	Develop management skills	4.67	4.43
36	Develop leadership skills	4.48	4.29
37	Develop a commitment to accurate work	4.69	4.7
38	Improve ability to follow directions, instructions and plans	4.64	4.41
39	Improve ability to organize and use time effectively	4.6	4.64
40	Develop a commitment personal achievement	4.57	4.4
41	Develop ability to perform skillfully	4.45	4.45
	Overall rating	4.5, Very Important	4.3, Essential

Intellectual Quality

Item	Influences Description	Influence scale	
		CE 221	CE 211-F
1	Develop ability to apply principles and generalizations already learned to new problem situations	4.69	4.53
2	Develop analytical skills	4.81	4.41
3	Develop problem-solving skills	4.69	4.52
4	Develop ability to draw reasonable inferences from observations	4.43	4.49
5	Develop ability to synthesize and integrate information and ideas	4.5	4.4
6	Develop ability to think holistically, to see the whole as well as the parts	4.48	4.17
7	Develop ability to think creatively	4.74	4.65
8	Develop ability to distinguish between fact and opinion	4.36	3.97
9	Improve skill at paying attention	4.57	4.12
10	Develop ability to concentrate	4.62	4.21
11	Help improve memory skills	4.36	4.12
12	Help improve listening skills	4.31	4.15
13	Help improve speaking skills	4.38	4.12
14	Help improve reading skills	4.17	4.2
15	Help improve writing skills	4.05	3.96
16	Help develop appropriate study skills, strategies and habits	4.69	4.4
17	Help study skills, strategies and improve mathematical skill	4.81	4.5
	Overall rating	4.51, Very Important	4.29 Essential

3. *Supportive Classroom Environment*

Item	Influences Description	Influence scale	
		CE 221	CE 211 F
42	Cultivate a sense of responsibility for one's own behavior	4.31	4.03
43	Improve self-esteem/self-confidence	4.38	4.26
44	Develop commitment to one's own values	4.17	4.13
45	Develop respect for others	4.38	4.25
46	Cultivate emotional health and well being	4.36	4.02
47	Cultivate physical health and well being	4.31	4.0
48	Cultivate an active commitment to honesty	4.48	4.4
49	Develop capacity to think for oneself	4.31	3.6
50	Develop capacity to make wise decisions	4.69	4.65
	Overall rating	4.04, Very Important	4.14, Very Important

The specific analysis used is the exploratory factor analysis to identify the variables apparently resembles to principal component analysis, but has some important distinctions. Methods of factor analysis are used when an underlying factor structure is presumed to exist but cannot be easily represented by a single value. The result is tossed again or mapped to FR's to further refine and understand the challenges that the students are facing so that an appropriate intervention or solution could be adopted.

The results of the analysis and the conclusion, as well as the bibliographic references, are presented in the Part 2 of this document.

AXIOMATIC DESIGN MODEL TO ASSESS INFLUENCES AFFECTING PEDAGOGIC-LEARNING IN THE COURSES ENGINEERING MATERIALS I AND FLUID MECHANICS I (PART 2)

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2.1.2 CE 221 Results of Factor Analysis & Multiple Regression Analysis (DP1's)

The factor analysis used Principal Component Analysis with Rotation and Varimax with Kaiser Normalization. The Rotation converged in 5 iterations, and the component value is rejected below 0.30. Kaiser-Meyer Measure of Sampling Adequacy is 0.936, Bartlett's Test of sphericity has approx. Chi square of 13047.557. The result of factor analysis for CE 221 by using SPSS is presented in Figures 2 (a, b).

Rotated Component Matrixa

	Component		
	1	2	3
Q26	.873	.373	
Q30	.844	.416	
Q25	.803	.352	.419
Q46	.791	.334	.434
Q42	.788	.342	.467
Q32	.782	.546	
Q14	.780	.481	
Q24	.779	.333	.458
Q23	.776	.482	.321
Q08	.773	.320	.472
Q21	.767	.480	.331
Q13	.756	.461	.376
Q15	.741	.360	.511
Q06	.731	.494	.380
Q49	.718	.574	.300
Q27	.718	.554	
Q28	.715	.455	.460
Q29	.697	.611	
Q47	.684	.453	.526
Q44	.678	.504	.454
Q45	.665	.629	
Q09	.662	.593	.354
Q10	.653	.616	.343
Q33	.651	.520	.443
Q12	.620	.617	.403
Q40	.447	.791	.378
Q38	.435	.790	.387

Extraction Method: Principal Component Analysis.
Rotation Method: Varimax with Kaiser Normalization.

a. Rotation converged in 5 iterations.

Figure 2a. Rotated Component Matrix – CE 221

Rotated Component

	Component		
	1	2	3
Q02	.493	.779	.318
Q05	.401	.778	.428
Q41	.453	.773	.368
Q48	.367	.767	.454
Q16	.451	.763	.413
Q35	.462	.761	.385
Q20	.541	.752	.308
Q04	.449	.750	.383
Q11	.365	.742	.504
Q19	.584	.723	
Q34	.581	.709	
Q43	.562	.706	.330
Q31	.628	.691	
Q01	.410	.689	.510
Q17	.372	.684	.567
Q18	.609	.682	.311
Q03	.381	.668	.588
Q36	.552	.664	.423
Q22	.418	.656	.535
Q07	.418	.471	.749
Q39	.403	.486	.742
Q37	.403	.479	.708
Q50	.383	.526	.683

Extraction Method: Principal Component Analysis.
Rotation Method: Varimax with Kaiser Normalization.

a. Rotation converged in 5 iterations.

Figure 2b. Rotated Component Matrix – CE 221

Figure 2 (a & b) shows the rotated component matrix for CE 221, in which three components comes of relevance on the Pearson R correlation. Interestingly, before the application of the rotation, the most striking behavior found in the study was that student's concentration is in disturbed mode. "Help improve listening skills" and "ability to concentrate" are the first two with the highest R. This shows that a big classroom with 118 students in lecturing mode is pretty good of a challenge to enhance learning without a microphone.

Total Variance Explained

Component	Rotation Sums of Squared Loadings	
	% of Variance	Cumulative %
1	38.467	38.467
2	36.183	74.650
3	18.356	93.006
4		
5		
6		
7		
8		
9		
10		
11		
12		
13		
14		
15		
16		
17		
18		
19		
20		
21		

Extraction Method: Principal Component Analysis.

Figure 3. Total Variance Explained on Rotation sums of squared loadings – CE 221

Figure 3 shows the percent of variance of the three (3) components as explained.

Total Variance Explained

Component	Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total
1	43.364	86.729	86.729	43.364	86.729	86.729	19.234
2	2.036	4.072	90.801	2.036	4.072	90.801	18.091
3	1.102	2.205	93.006	1.102	2.205	93.006	9.178
4	.682	1.364	94.370				
5	.392	.783	95.153				
6	.298	.596	95.749				
7	.289	.577	96.326				
8	.237	.474	96.800				
9	.188	.377	97.177				
10	.183	.365	97.542				
11	.155	.310	97.852				
12	.133	.265	98.118				
13	.106	.213	98.330				
14	.101	.202	98.532				
15	.096	.192	98.725				
16	.072	.144	98.869				
17	.063	.126	98.995				
18	.053	.105	99.100				
19	.047	.095	99.195				
20	.041	.081	99.276				
21	.035	.070	99.346				

Extraction Method: Principal Component Analysis.

Figure 4. Total Variance Explained – CE 221

Figure 4 shows the total variance of the the 3 components in which component 1 and 2 are closely related. By assessing the influences, it was found a distinct behavior in which cultural values matters most to students followed by the educational values. With a diverse community, so rich in cultural values, the challenges now posed to the researcher is how cultural aspects are addressed and preserved while the educationl values are enhanced so as quality of learning is to achieve. The rest of the figures give visual reprepresentations of the behavior of the predictors.

Component Transformation Matrix

Co...	1	2	3
1	.645	.628	.435
2	.761	-.577	-.297
3	-.064	-.522	.850

Extraction Method: Principal Component Analysis.
Rotation Method: Varimax with Kaiser Normalization.

Figure 5. Component Transformation Matrix- CE 221

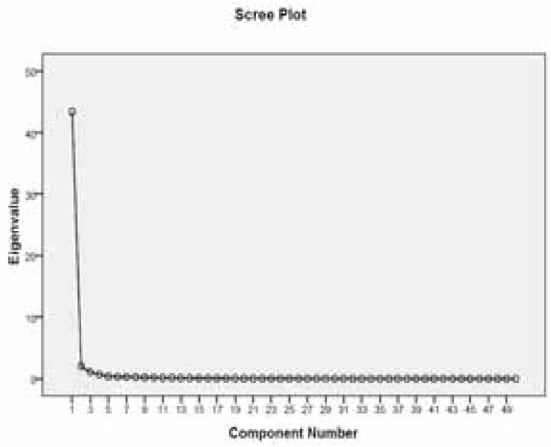

Figure 6. Scree Plot on Factor Analysis – CE 221

Figure 6 shows the scree plot of the influential patterns in linearity in which two (2) components prevail, as illustrated by the Eigenvalue of each component number of predictors.

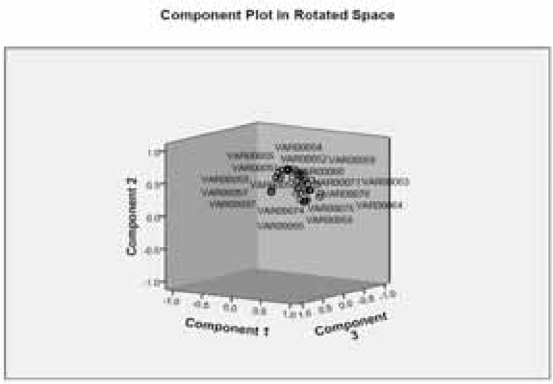

Figure 7. Component Plot on Factor Analysis

The 3D component plot in rotated space is shown in figure 7, where x represents component 1 – the cultural aspect, y depicts component 2 – the educational aspects, and z is component 3. The plot in of figure 8 shows that only a component, the cultural aspect, is strong.

Figures 9 and 10 give a better insight in the problem under analysis.

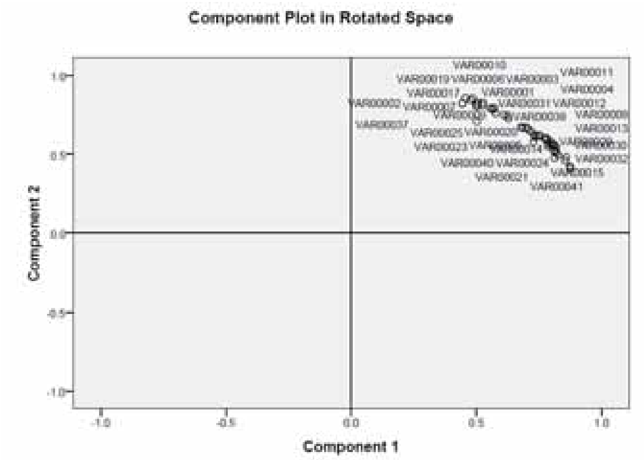

Figure 8. Component Plot on Factor Analysis – CE 221

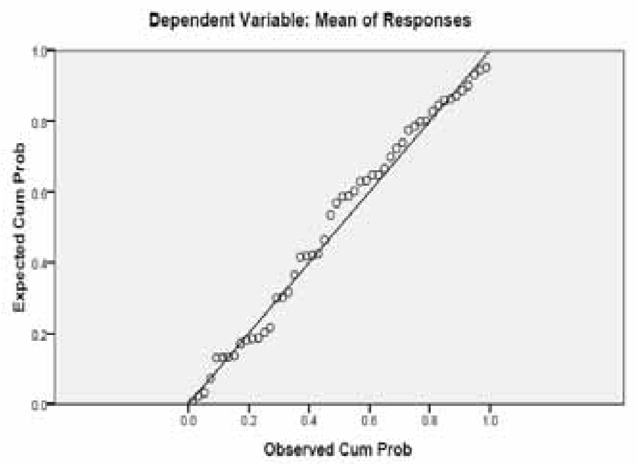

Figure 9. Normal P-P Plot of Regression Standardized Residual – CE 221

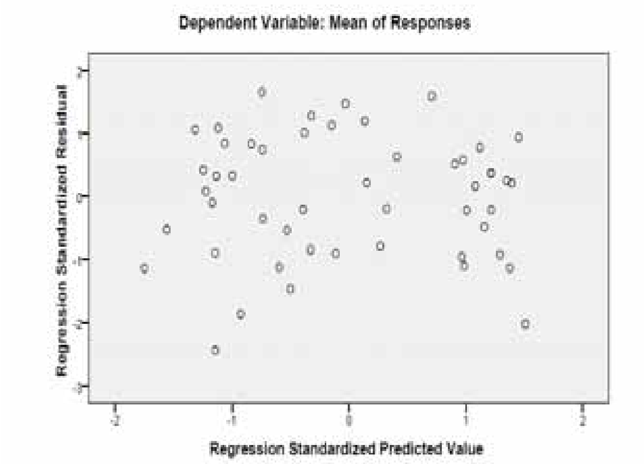

Figure 10. Regression Scatter plot – CE 221

Multi regression analysis was made to find out the relationship of the weighted means of each response with the rotated matrix of R values. The results are shown in figures 11 to 14.

Descriptive Statistics

	Mean	Std. Deviation	N
Mean of Responses	4.4648	.20463	50
Influence Factor 1	.6007	.15621	50
Influence Factor 2	.5854	.14591	50

Figure 11. Regression Descriptive Statistics – CE 221

Correlations

		Mean of Responses	Influence Factor 1	Influence Factor 2
Pearson Correlation	Mean of Responses	1.000	-.671	.492
	Influence Factor 1	-.671	1.000	-.718
	Influence Factor 2	.492	-.718	1.000
Sig. (1-tailed)	Mean of Responses	.	.000	.000
	Influence Factor 1	.000	.	.000
	Influence Factor 2	.000	.000	.
N	Mean of Responses	50	50	50
	Influence Factor 1	50	50	50
	Influence Factor 2	50	50	50

Figure 12. Regression Correlation – CE 221

Variables Entered/Removed[b]

Model	Variables Entered	Variables Removed	Method
1	Influence Factor 2, Influence Factor 1[a]	.	Enter

a. All requested variables entered.

b. Dependent Variable: Mean of Responses

Figure 13. Retained Variable – CE 221

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	.925	2	.462	19.280	.000[a]
	Residual	1.127	47	.024		
	Total	2.052	49			

a. Predictors: (Constant), Influence Factor 2, Influence Factor 1

b. Dependent Variable: Mean of Responses

Figure 14. ANOVA – CE 221

Figures 13 and 14 show that the variable is a statistically significant *unique* contribution to the equation. This is very dependent on which variables are included, and how much overlap there is among the independent variables. The criterion is that if the Sig. value is less than .05, then the variable gives a significant unique contribution to the prediction of the dependent variable. Thus, if Sig. is greater than .05, then one can conclude the corresponding variable do not give a significant unique contribution and should be rejected. In this case, two components are retained and none is rejected.

2.1.3 CE 211-F Results of Factor Analysis & Multiple Regression Analysis (DP1's)

The factor analysis uses Principal Component Analysis as extraction method, while rotation method uses Varimax with Kaiser normalization. The rotation converged after 5 iterations. Kaiser-Meyer measures rotation above 0.30, the rest are rejected. The result of factor analysis for CE 211-F is presented below.

Total Variance Explained

Component	Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total
1	44.807	89.614	89.614	44.807	89.614	89.614	24.264
2	1.657	3.314	92.928	1.657	3.314	92.928	22.200
3	.693	1.386	94.314				
4	.567	1.133	95.447				
5	.525	1.051	96.498				

Extraction Method: Principal Component Analysis.

Figure 15. Total Variance Explained – CE 211-F

Rotated Component Matrix[a]

	Component 1	Component 2
Q47	.874	.421
Q43	.874	.410
Q32	.858	.480
Q15	.855	.459
Q21	.826	.492
Q48	.819	.507
Q44	.818	.546
Q29	.817	.525
Q41	.811	.476
Q30	.811	.557
Q24	.809	.521
Q49	.805	.558
Q26	.800	.574
Q45	.798	.559
Q46	.786	.587
Q42	.786	.564
Q40	.785	.550
Q14	.779	.600
Q12	.772	.598
Q13	.772	.598
Q08	.753	.619
Q33	.745	.617
Q22	.733	.610
Q34	.732	.625
Q27	.727	.576
Q23	.717	.643
Q36	.717	.643

Extraction Method: Principal Component Analysis.
Rotation Method: Varimax with Kaiser Normalization.

a. Rotation converged in 3 iterations.

Figure 16. Rotated Component Matrix – CE 211-F

Rotated Component Matri

	Component 1	Component 2
Q05	.705	.660
Q11	.696	.670
Q20	.683	.668
Q39	.678	.670
Q19	.456	.857
Q10	.485	.856
Q28	.476	.842
Q07	.504	.827
Q06	.525	.827
Q17	.443	.822
Q02	.443	.822
Q18	.502	.814
Q03	.524	.813
Q50	.501	.802
Q09	.571	.794
Q16	.556	.791
Q01	.556	.791
Q35	.566	.784
Q31	.577	.759
Q25	.610	.748
Q04	.625	.744
Q38	.627	.726
Q37	.502	.708

Extraction Method: Principal Component Analysis.
Rotation Method: Varimax with Kaiser Normalization.

a. Rotation converged in 3 iterations.

Figure 17. Rotated Component Matrix – CE 211-F

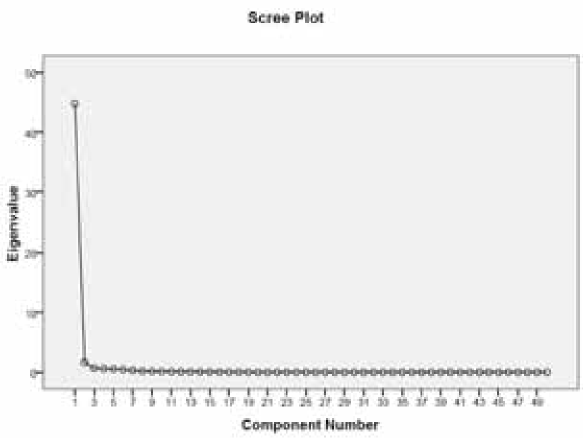

Figure 18. Scree Plot on Factor Analysis – CE 211-F

Figures 15, 16 and 17 shows the total variance of the two components in which components 1 and 2 are closely related. By assessing the influences, it was found a distinct behavior where cultural values matters the most to students, followed by the educational values. Similar results were found for CE 221.

With a diverse community, in which the country is so rich in cultural values, the challenges now posed are how cultural aspects are addressed and preserved while educationl values are enhanced so as quality of learning is to achieve. The rest of the figures give visual reprepresentations of the behavior of the predictors.

What was so intriguing in the data of the correlation matrix before they were rotated was the rejection of a predictor that requires the application of outlying principles and concepts in Engineering Fluid Mechanics. The strongest components show that the relevance of cultural aspects is greater than that of the educational aspects. However, when rotation is applied, the said predictor is included but with a reduced value for R. It is thus imperative that teaching Engineering Mechanics & Engineering Materials to a diverse group in which no one comes from Lae City, where the University is located, requires a strategy that best suit their particular preferences to motivate participation. Interestingly, it was found that the respondents do not like to be instructed by the lecturer because only 2.38 percent responded. Many of them said they wanted to prepare for their career as Civil Engineers, but they wanted to do it their own way, according to their own cultural beliefs. Indeed, teaching these groups of students is so challenging.

Figure 18 shows the scree plot of the influential patterns where two (2) components prevail, as illustrated by the Eigenvalue of each component number of predictors.

Descriptive Statistics

	Mean	Std. Deviation	N
Mean of Responses	4.1918	.32252	50
Factor Comp 1	.6840	.13422	50
Factor Comp 2	.6542	.12804	50

Figure 19. Descriptive Statistics for Regression model – CE 211-F

Figures 19 and 20 show the descriptive statistics of the predictors for CE 211-F.

Correlations

		Mean of Responses	Factor Comp 1	Factor Comp 2
Pearson Correlation	Mean of Responses	1.000	-.547	.484
	Factor Comp 1	-.547	1.000	-.968
	Factor Comp 2	.484	-.968	1.000
Sig. (1-tailed)	Mean of Responses	.	.000	.000
	Factor Comp 1	.000	.	.000
	Factor Comp 2	.000	.000	.
N	Mean of Responses	50	50	50
	Factor Comp 1	50	50	50
	Factor Comp 2	50	50	50

Figure 20. Regression Correlation – CE 211-F

Multi regression analysis was performed to find out the relationship of the weighted means of each response with the rotated component matrix R values. The results are shown in figures 21 to 29.

Variables Entered/Removed[a]

Model	Variables Entered	Variables Removed	Method
1	Factor Comp 1	.	Stepwise (Criteria: Probability-of-F-to-enter <= .050, Probability-of-F-to-remove >= .100).

a. Dependent Variable: Mean of Responses

Figure 21. Retained Variable – CE 211-F

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	1.527	1	1.527	20.529	.000[a]
	Residual	3.570	48	.074		
	Total	5.097	49			

a. Predictors: (Constant), Factor Comp 1
b. Dependent Variable: Mean of Responses

Figure 22. ANOVA – CE 211-F

Coefficients[a]

Model		Unstandardized Coefficients B	Std. Error	Standardized Coefficients Beta	t	Sig.	Correlations Zero-order	Partial
1	(Constant)	5.091	.202		25.173	.000		
	Factor Comp 1	-1.315	.290	-.547	-4.531	.000	-.547	-.547

a. Dependent Variable: Mean of Responses

Figure 23. Correlation Coefficients – CE 211-F

Looking at figures 21 to 23, one can see that the variables included in the model contributed to the prediction of the dependent variable. We find this information in the output box labeled **Coefficients**, in the column labeled **Beta** under **Standardized Coefficients**. The *standardized* coefficients are used to compare the different variables, not the *unstandardized* ones. 'Standardized' means that these values for the different variables have been converted to the same scale so that one can compare them. If there is a need for constructing a regression equation, unstandardized coefficient values, which are labeled as B, should be used. In this case, the researcher is interested in *comparing* the contribution of each independent variable; therefore, we will use the beta values, in which the Beta column has the largest beta values (ignoring any negative signs). The largest beta coefficient is -.547, which is related to Component 1. This means that this variable makes the strongest unique contribution to explain the dependent variable when the variance explained by all other variables in the model is controlled.

Coefficients[a]

Model		Correlations Part	Collinearity Statistics Tolerance	VIF
1	(Constant)			
	Factor Comp 1	-.547	1.000	1.000

a. Dependent Variable: Mean of Responses

Figure 24. Collinearity Coefficients – CE 211-F

Figure 24 shows the collinearity of the coefficients of the predictors for CE 211-F, along with factor component 1, while figure 25 relates to the excluded variable.

Excluded Variables[b]

Model		Beta In	t	Sig.	Partial Correlation	Collinearity Statistics Tolerance	VIF	Minimum Tolerance
1	Factor Comp 2	-.710[a]	-1.506	.139	-.214	.064	15.653	.064

a. Predictors in the Model: (Constant), Factor Comp 1
b. Dependent Variable: Mean of Responses

Figure 25. Excluded Variable – CE 211-F

Collinearity Diagnostics[a]

Model	Dimension	Eigenvalue	Condition Index	Variance Proportions (Constant)	Factor Comp 1
1	1	1.982	1.000	.01	.01
	2	.018	10.392	.99	.99

a. Dependent Variable: Mean of Responses

Figure 26. Collinearity Diagnostics – CE 211-F

Figure 26 shows the collinearity diagnostics for CE 211-F for the regression.

Figure 27 shows a statistically non-significant *unique* contribution to the equation. The criterion is if the Sig. value is less than .05 (.01, .0001, etc.), then the variable is a significant unique contribution for the prediction of the dependent variable. The criterion is if Sig. is greater than .05 (in this case Sig is 0.139), then one can conclude that that variable is not making any significant unique contribution and is rejected. In this case, one component is retained and one is rejected.

Residuals Statistics[a]

	Minimum	Maximum	Mean	Std. Deviation	N
Predicted Value	3.9419	4.5088	4.1918	.17652	50
Std. Predicted Value	-1.416	1.796	.000	1.000	50
Standard Error of Predicted Value	.039	.080	.053	.011	50
Adjusted Predicted Value	3.9213	4.5180	4.1925	.17772	50
Residual	-.66924	.44031	.00000	.26992	50
Std. Residual	-2.454	1.615	.000	.990	50
Stud. Residual	-2.498	1.631	-.001	1.009	50
Deleted Residual	-.69369	.44931	-.00073	.28079	50
Stud. Deleted Residual	-2.651	1.661	-.008	1.031	50
Mahal. Distance	.000	3.224	.980	.855	50
Cook's Distance	.000	.114	.020	.028	50
Centered Leverage Value	.000	.066	.020	.017	50

a. Dependent Variable: Mean of Responses

Figure 27. Residual Statistics – CE 211-F

To check whether an unexpected case has any undue influence on the results for our model as a whole, we can check the value of the Cook's Distance, which can be found close to the bottom of the Residuals Statistics table of figure 27. According to Tabachnick & Fidell (2001), cases with values larger than 1 are a potentially problematic. In our case, the maximum value for the Cook's Distance is 0.114, which suggests no major problems.

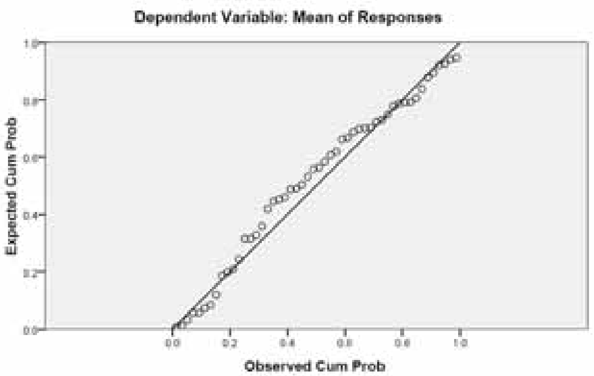

Figure 28. Normal P-P Plot of Regression Standardized Residual – CE 211-F

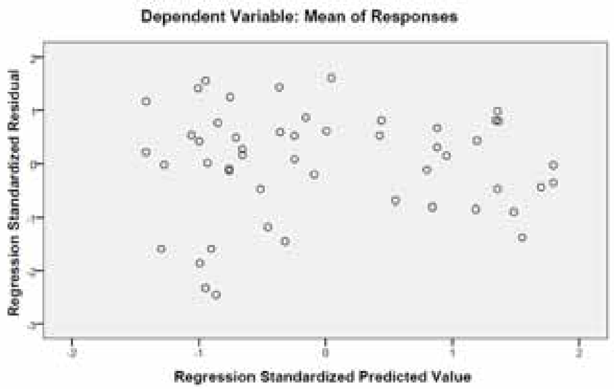

Figure 29. Regression Scatter – CE 211-F

Figures 28 and 29 give a better insight to the problem under analysis.

2.1.4 DP3 - Student Support Tools

From the results of factor analysis, two striking relationships of the students' influences were found for both courses: 1) **cultural aspects** (self-concept and self-efficacy belief) and 2) **educational aspects** (academic behavior and attitude). A support mechanism is needed to address these issues, taking into account that PNG students usually favor the cultural aspects rather than educational values.

As a background to understand the preferred support tools, a review on the Papua New Guinea people's daily lives is useful and can be found at Culture of Papua New Guinea (2014).

Briefly, PNG people lives vary enormously because their great majority of the population lives in diverse rural landscapes in villages or hamlets. Rituals to ensure success and prosperity accompany many of their activities. The clan forms the major unit of social organization. Almost all Melanesian societies are patrilineal, and even matrilineal societies remain patriarchal, i.e., male-dominated. In some areas, lineage and land rights can be claimed through either parent, so people can belong to both their parents' clans. Large tribes are not usual, but when they exist, they have a certain degree of political unity and they can be viewed as federations of clans. They may share origin myths, and in such cases clans can be seen as being like "brothers," sons of a founding father. These social structures form the lines of conflicts expressed in the inter-clan warfare that persists in the Highland provinces, and in those areas they often form the lines of political competition in contemporary elections.

When people migrate from rural villages to urban areas or to rural resettlement areas, they carry their languages and traditions with them and re-create their original social structures. Social bonds and obligations form the so-called *wantok* system, which can provide support for struggling in their new locations and create heavy demands to the more wealthy people who feel obliged to support their kin. The demands of *wantok* are often considered as root cause of corruption. Intergenerational tensions reflect the stresses of rapid social change in rural and urban contexts. In both villages and cities, music and dance celebrations often mark important life-cycle events such as birth, death, initiation, menarche, economic transactions (even the opening of a roadway), peacemaking, and religious observances. It is in this context that mapping the PV's from the DP's is essential as it addresses relevant facts that support the students' effective pedagogic learning. How the PV's are applied will be shown in the following discussion.

2.2 APPLICATION OF PV'S

The intervention applied during the study time is the merit system or extra marks scheme to support the students' needs of escalating self-efficacy. The results are shown in figure 30 and were used as means to increase the percentage of passing without the content wise of the coursework. Thus, applications of the best strategy or solution to the challenges revealed by this study inspired on the Axiomatic Design approach.

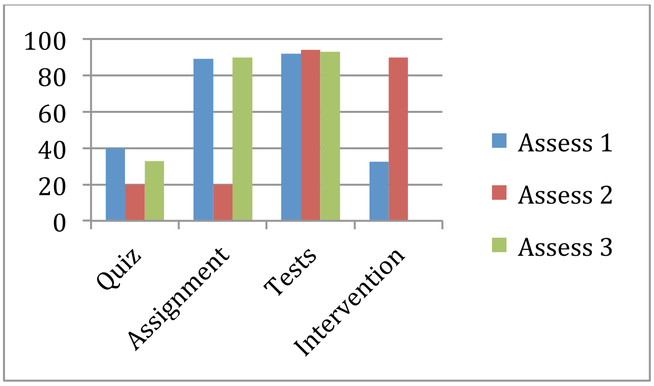

Figure 30. CE 211-F Assessment

The figure shows the students' difficulty in understanding the course is relevant. To raise the students' performance, an intervention was incorporated in the assessment process, as shown in figure 31.

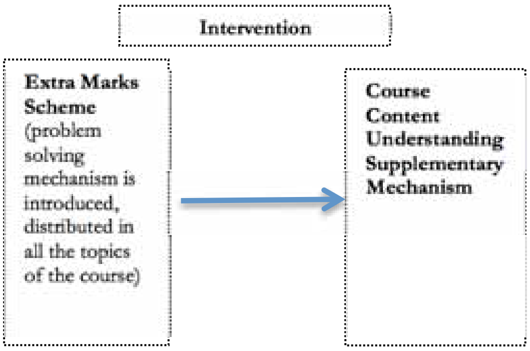

Figure 31. Intervention Mechanism

Section 2.2.1 below shows the result of the intervention.

2.2.1 The students' performance

2.2.1.1 CE 221 – Engineering Materials

The results of student performance in the Engineering Materials class are presented in figure 32.

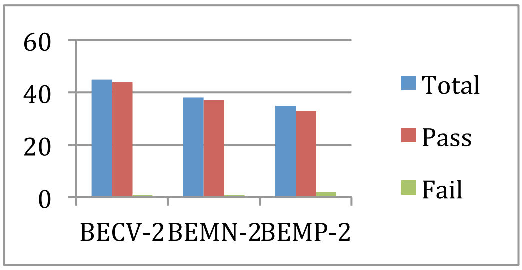

Figure 32. Engineering Materials (CE 221) Student Performance

The graph of figure 33 shows the achievements (A's, B's, C's, D's, E's and F's grades). The result is pretty good, but the researcher finds that it is not content rich, thus another intervention should be sought.

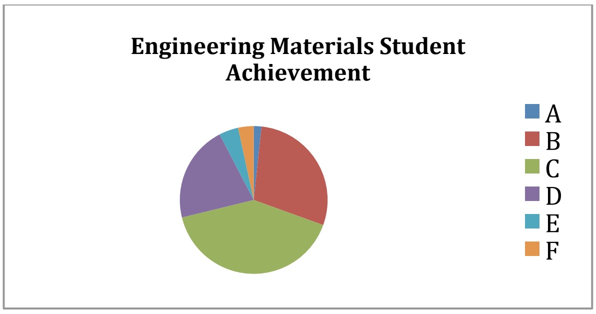

Figure 33. Engineering Materials (CE 221) Student Achievement

2.2.1.2 CE 211-F – Fluid Mechanics

The Engineering Fluid Mechanics (CE 211-F) class achievement result is shown in figure 34.

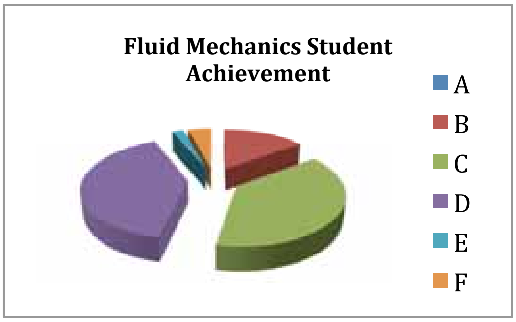

Figure 34. Fluid Mechanics (CE 211-F) Student Achievement

2.2.2 Course Content Bridging Framework

Figure 34 depicts the conceptual framework of the challenge posed by the assessment of the students' pedagogic learning using the AD Model. In this case, the PV's are part of the AD Model. The conceptual framework has the shape of a funnel that induces the learner to achieve the maximum pedagogic learning in content-wise courses such as Engineering Materials and Engineering Fluid Mechanics, in culture-friendly environments, without sacrificing the quality of the required educational wealth that usually results from the use of the inductive technique.

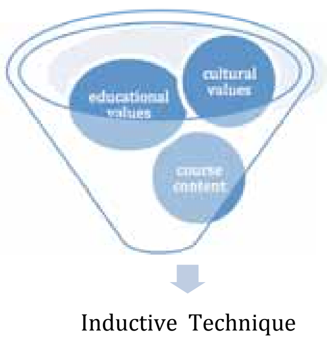

Figure 34. Culture-Educational Paradigm Shift Framework

The cultural value of the figure is over the course content and above the educational values. This illustration describes the findings of the study. Students want an experience where their self-concept and self-efficacy is maintained, and where behaviors are supported by cultural values, and the academic behavior and attitude is embodied in the educational values. The researcher will call this phenomenon as culture-educational paradigm shift since it best describes the figure.

Two very distinct and opposing instructional approaches are the inductive and the deductive ones (Inductive and Deductive Instruction, 2014). Both approaches can offer certain advantages, but the biggest difference is the role of the teacher. In a deductive classroom, the teacher conducts the lessons by introducing and explaining concepts to the students (this is the instructional method used by the researcher, of which most of the students responses are opposing), and then expecting students to complete tasks to practice the concepts; this approach is very teacher-centered. Conversely, inductive instruction is a much more student-centered approach and makes use of a strategy known as 'noticing'. Instead of explaining a given concept and following this explanation with examples, the teacher presents students with many examples showing how the concept is used. The intent is that the students "notice", by way of examples, how the concept works.

3 CONCLUSION

The conclusion is that the pedagogical framework should include four groups: *Recognition of Difference* and *Social support* were rated 'very important' influencing factors to students both in CE 221 and CE 211-F. In addition, *Connectedness* and *Intellectual quality* were rated 'very important' and 'essential' for CE 221 and CE 211-F respectively. Because of the diversity of the population, the students who are enrolled in the above mentioned courses perform differently. However, when a multivariate analysis was applied, the pedagogical framework earlier posed was changed to address the challenge of the culture-rich and educational-poor values. In addressing these challenges, a new concept is realized and come up with a Culture-Education Paradigm Shift Framework by adopting the Inductive Instructional Methodology.

It is hereby recommended that the next delivery of the courses should be conducted in a Culture-Educational Paradigm Shift framework to address the challenges that were found by using the Axiomatic Design Model in the assessment of the pedagogic-learning results of Engineering Materials (CE 221) and Engineering Fluid Mechanics I (CE 211-F).

4 ACKNOWLEDGEMENT

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A THEORY OF MATURITY

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ABSTRACT

The 'Axiomatic Design Methodology' uses 'Axioms' that cannot be proven nor derived from physical phenomena. The axioms serve as guidelines for the design process of products and systems. The latest contribution was the addition of the 'Complexity Axiom' in 1999. However, the underlying theory of complexity did not get much traction by designers and their managers yet. It emphasises difficulties in the design, not primarily focussing on solutions. The 'Theory of Complexity' is converted to a 'Theory of Maturity' in this paper. It is supported with a graphical way to plot maturity as it develops. It visualises the results in a way that can be understood by all entities in a company, engineers, managers, and executives. Understanding the maturity of a system enables selection of the right measures to control it. Visualisation enables communication between the interacting parties. If successful development trajectories are understood, eventually from earlier experience, even better corrective actions can be applied. The method appears an affirmative way to graphically represent progression in design, thus presenting advances in a positive context. Though positively presented, it is not the case that the method hides problems; presumed and legitimate project progression can be quite different, which challenges the designer to understand the process. In this way, the method sends out a continuous warning to stay critical on design choices made.

Keywords: Axiomatic Design, Information, Complexity, Independence, Maturity

1 INTRODUCTION

'On an Axiomatic Approach to Manufacturing and Manufacturing Systems' [Suh, 1978] was the first scientific paper to introduce the Axiomatic Design (AD) methodology. AD declares axioms that cannot be proven nor derived from physical phenomena. In that first paper, a number of seven axioms were defined. Only two of those seven axioms are still maintained over 35 years later, now known as the 'Independence-' and the 'Information Axiom'. The other axioms have been changed into corollaries or theorems, because they were incidentally proved or could be deduced from the remaining two Axioms. In 1999 a third Axiom was added, the 'Complexity Axiom', addressing different kinds of complexity that can reside in product- or system designs.

The activities to decompose axioms into corollaries and theorems have led to a substantial framework of design guidelines. Just under fifty have been defined in total, which tends to make the AD theory complex to novice users. The addition of the complexity axiom further extends AD, as well in opportunities as in multiplicity of AD itself. It is another reason that AD didn't get extensive traction yet.

In addition, a theory of complexity is not happily accepted by designers and their managers. It emphasises the difficulties in the design, not primarily focussing on solutions and the other positive aspects of a well functioning design. Therefore the 'Theory of Complexity' is converted in this paper to a 'Theory of Maturity'. It is supported with a graphical way to plot maturity of a progressing design and visualise the results in a way that it can be understood by all entities in a company. It combines the strengths of AD with a simple and clear way of communication: About 'doing the right things' followed by 'doing things right' [Puik, 2014].

This paper is organised as follows: In section 2, maturity is defined and explained in an axiomatic context. Section 3 explains the relation of maturity with the axioms. Section 4 introduces an axiomatic method to visualise maturity, by plotting presumed and legitimate maturity in a two dimensional space. Section 5 discusses the findings and summarises conclusions.

2 MATURITY OF A PRODUCT DESIGN

Maturity is defined as: 'The quality of reaching full development' [Oxford, 2014]. Products or systems that are fully developed, and thus mature, may be expected to function according to the user's expectations. It may be seen as a Utopian image that is difficult to attain but it would lead to an exceptional quality of products.

2.1 MATURITY TRACKING

Understanding the maturity of a system enables awareness how the system will behave under circumstances within or without the specified operational range. But it is even more important to monitor maturity as it evolves during the design process:

- It enables the possibility to follow the system- or product-design during the design stages to estimate progression;
- It increases understanding of errors made during the design process and how they were addressed in order to avoid them in the future;
- It helps selection of the right measures to control product

development, like the use of appropriate methods for 'Systems Engineering' (or 'Engineering Design' as it is more commonly referred to in the US).

2.2 ABSOLUTE AND RELATIVE MATURITY

It is a legitimate question if it is possible to reach the state of full maturity. A product design can always be optimised further, which means that the future product will have a higher state of development and thus will be more mature. On the other hand, a product that completely fulfils the wishes of the customer, may be considered fully mature. Maturity has an absolute, as well as a relative characteristic. The on-going development of a car could be considered as an example: Good cars were produced already twenty-five years ago. E.g. Japanese cars in the late eighties already were generally reliable and well engineered. They might be considered mature. Cars today are not necessarily engineered to a higher level, but do have more options for passive and active safety. From this perspective, a modern car may be considered more mature than a late eighties car. This perspective recognises two kinds of maturity, 'Absolute Maturity' and 'Relative Maturity':

- Relative maturity indicates how well a design is engineered;
- Absolute maturity indicates to what extent a design is optimised, i.e., its design status compared to comparable products or systems in the past.

This paper focusses on relative maturity, how it can be decomposed, characterised and measured.

2.3 AXIOMATIC MATURITY

The AD methodology can be applied to characterise relative maturity. AD focusses on Functional Requirements (FRs) and how they are satisfied by Design Parameters (DPs) [Suh, 1990]. From this perspective, a mature design is capable of satisfying all FRs. Therefore Axiomatic Maturity (AM) is here defined as *'the quality of satisfying all FRs of a system'*. This makes AM inversely related to Axiomatic Complexity, which is defined as 'A measure of uncertainty in achieving specified FRs' [Suh, 2005]. However, complexity is in practice expressed in entropy, or information, according to the definition of Shannon for information technology [Shannon, 1948]. AM will be expressed as the vector sum of the joint probabilities of independence and robustness as

$$\overrightarrow{AM} = \vec{P}_j + \vec{P}_i \tag{1}$$

where P_j is the probability coming forth from dependencies in the design or system, P_i is the probability due to limitations in robustness, and b is the base of the logarithm, usually in bits or nats according to the complexity definition by Shannon.

3 RELATION OF MATURITY AND THE AXIOMS

As AD uses axioms to advise on the actions to apply during the design of products and systems, it is a question how AM relates to the axioms. All axioms are information axioms according to the Shannon theory [Puik, 2014], so all axioms are associated in some manner to AM. Axiom 1, the independence axiom, is related to 'Unorganised Information', which is information that is present in a system that has not been organised yet and still has an incomplete or a coupled design matrix. Axiom 2, the information axiom, is related to 'Axiomatic Information', which may be present in a system, with a well-organised design matrix that is at least decoupled but can also be uncoupled. Axiom 3, the complexity axiom, is represented by both the information of axiom 1 and axiom 2 [Puik, 2014]. Since the two kinds of information are of a different kind, again the vector sum is taken. The complexity in the system, when the axioms have not been satisfied yet is given by

$$\vec{C}_{Total} = \vec{I}_{Ax} + \vec{I}_{UnOrg} \tag{2}$$

$$I_{Ax} = C_{Re} = -log_b P_i \tag{3}$$

$$I_{UnOrg} = C_{Im} = -log_b P_j \tag{4}$$

where I_{Ax} and I_{UnOrg} respectively are the axiomatic and unorganised information and b is the again the base of the logarithm. The AM can be found by substitution of (3) and (4) into (1)

$$\overrightarrow{AM} = \vec{b}^{-I_{Ax}} + \vec{b}^{-I_{UnOrg}} \tag{5}$$

$$\overrightarrow{AM} = \vec{b}^{-C_{Real}} + \vec{b}^{-C_{Im}} \tag{6}$$

Two things should be noted when applying equation (5) or (6) to determine AM:

1) The equations are of a value that is constantly changing due to the evolving design and only become stable when the design matrix is known and at least decoupled. In this situation I_{UnOrg} (C_{Im} in (6)) becomes zero, the latter term will become one and will have no further effect. The reason for this is that the design matrix is a game changer to organised information. Changes of the matrix lead to the exclusion of existing DPs and include new DPs in the design, which implicitly means that the match of system range and design range becomes obsolete and needs to be reconsidered.

2) The latter term is of a much larger magnitude than the former. The reason is that the probability of unorganised information is caused by trial-and-error [Suh, 2005], for organised information it is the overlap of system and design range. The procedure of trial-and-error will cause considerably larger information content and therefore significantly smaller probabilities than the probability due to axiomatic information [Puik, 2014].

4 VISUALISATION OF MATURITY IN AN AXIOMATIC MATURITY DIAGRAM

Visualisation of the design process enables the product or system design to be graphically tracked as it develops. If ideal development trajectories are understood, and the graphical position can be determined, then corrective actions can be planned to bend the development in the most optimal direction for the specific situation, e.g.:

- Most efficient development path in terms of investment (SMEs);
- Optimised development path for project lead time (semiconductor industry);
- Lowest chance for development errors (safety systems, medical);
- Etc.

4.1 The Axiomatic Maturity Diagram

The Axiomatic Maturity Diagram (AMD) is based on the independence- and the information axioms. The diagram uses two axes, one for each axiom, plotting the joint probability that the axiom is fully satisfied. This is carried out applying the first and second term of (1). The vectors for P_j and P_i are perpendicular. P_j is the measure for independence on the horizontal axis. P_i is the measure for information on the vertical axis. The horizontal axis is the 'axis of ignorance' starting at full ignorance and ending with 'proof of concept'. This indicates that there is no ignorance left in the system. The vertical axis represents 'robustness of the DPs satisfying the FRs' from not- to fully robust. Robustness is applied according to Suh's real-complexity definition [Suh, 2005]. In this definition, the information axiom addresses only the axiomatic component of information and not the unorganised part, which is addressed by the independence axiom.

The lower left corner indicates a high level of ignorance. The designer has little knowledge how to satisfy FRs with his DPs and therefore the AM is low. The upper right corner shows low information content and maximum probability of FRs being satisfied. This is the area of high AM. The direction for development of products and systems is from the lower left to the upper right. Products are fully mature when they reach the upper right corner of the AMD, as marked with a dot. The AMD is plotted in figure 1.

Figure 1: The AMD. The horizontal axis plots the independence axiom, the vertical Axis plots the information axiom. The development path is arbitrary

It might be noticed that the axes of the AMD are swapped compared to the real and imaginary axes in Suh's complexity diagram [Suh, 2005:71]. This is correct. There are two reasons to deviate from that definition; 1) axioms 1 and 2 are simply plotted in that order, and 2) the level of independence, as set by axiom 1, never moves backwards (as long as no knowledge of the designer is lost, it will typically increase). This is not the case for the information axiom (optimisation of the design matrix can lead to different FR-DP relations and the satisfaction of the information axiom might initially decrease). By choosing this way of plotting, the maturity development path takes the form of a mathematical function. This makes reading the AMD more natural.

4.2 Presumed and Legitimate Position in the AMD

As a product design moves through the AMD, during the development process, its position as presumed by the designer may not be the same as the legitimate position of the design in the AMD. This difference is caused by a lack of knowledge to the designer. If the design error is discovered, a correction on the discrepancy can be carried through. If not, the discrepancy will be corrected at some point in the remaining part of the development process. The correction, in that case, will come as a surprise.

4.3 Determining the Legitimate Position

Since discrepancies between presumed and legitimate positions in the AMD are caused by a lack of knowledge to the designer, acquisition of the knowledge would lead to an instant disappearance of the discrepancies. Obviously, there is no method that comprehensively enables this; every design would indeed be a 'Good' design if such a method would exist. What can be done is to apply methodologies that objectively determine the position of a design in the AMD as it progresses. This forces the presumed position to be based on facts instead of gut feeling. It will contribute to a higher degree of realism of the designer. A few of such methods have been described in literature. To track the independence axiom, Suh has reported a sequence of steps to follow [Suh, 2004]. More recent work was done by Puik et al [2013-1]. It defines a framework of seven steps to follow the independence axiom during design progression, starting with decomposition of the design, finding the DPs, decoupling the matrix and, testing the system to make sure that all DPs really have been found. Following the information axiom is more straightforward as it does not blur the perception of the designer as much as the independence axiom (no further discrepancies). FMEA [Suh, 2004], [Puik, 2013-2] or qualitative analysis [Puik, 2013-3] could be applied to objectively monitor progression of the information axiom. By performing checks, based on these methods, on a regular basis, discrepancies between presumed and legitimate positions can be corrected before they grow to unwanted proportions. Heavy corrective actions may be prevented.

4.4 Ideal Development Path Through the AMD

Product development, as indicated above, will start somewhere at the lower left and will move diagonally upwards. The starting point will depend on the complexity of the project definition. A high-tech project that is new to the world might start with high amount of ignorance compared to a project that aims to develop according to the first-time-right philosophy.

The development will rarely follow a straight line. In the axiomatic literature [Suh, 1990], [Suh, 2001], [Suh, 2005], [El-Haik, 2005], it is found that axiom 1 and 2 are typically satisfied in that order. This is done by completion and decoupling of the design matrix before matching the system- and the design ranges of FRs and DPs. The result is 'doing the right things' first, followed by 'doing things right'. This leads to a preferred path that first moves to the right and then angles upwards. It is plotted in figure 2.

Figure 2: A preferred development path through the AMD, as indicated in literature, first moves to the right to satisfy Axiom 1. After this, Axiom 2 is satisfied in an upward direction

In practice, it is rarely the case that the ideal path is followed. It would mean that not any design flaws are made.

4.5 Consequences of Typical Errors

Design errors that occur can be plotted in the AMD. It will lead to a discrepancy of the presumed and legitimate position in the diagram. If a design error is found, by executing one of the methods as described in §4.4, the discrepancy decreases. If all errors in the design are known the presumed and legitimate positions will be the same. This does not necessarily mean that all knowledge is present but the designer does fully understand the status of the project.

Wrong DP

A wrongly chosen DP leads to the situation that the DP not or insufficiently satisfies the related FR. It will seem to the designer that the design matrix for this DP is known and decoupled, but in fact this is not the case. Time and effort are spent to match the system and design ranges of this DP, but since the DP has no or very little effect these efforts are spent in vain. Discovery of the error increases independence of the design but typically reduces organised information with less robustness as effect. The reason is that the design matrix will need corrections as a result to the faulty DP. A new DP will need to be installed to address the related FR. Discovery of the error leads to a loss of design efforts. The impact of the error will increase in proportion to the discovery time, as the negative effects tend to accumulate. Hence, early detection of errors leads to lesser loss of efforts and should be pursued. Figure 3 plots the discontinuity when discovering a faulty DP in the design matrix.

No decoupling

No decoupling means that all DPs are known but the design matrix is coupled. The design can be optimised by matching the system- and design ranges. However, unorganised information remains in the system. An example is the combination lock as described by Suh [2004].

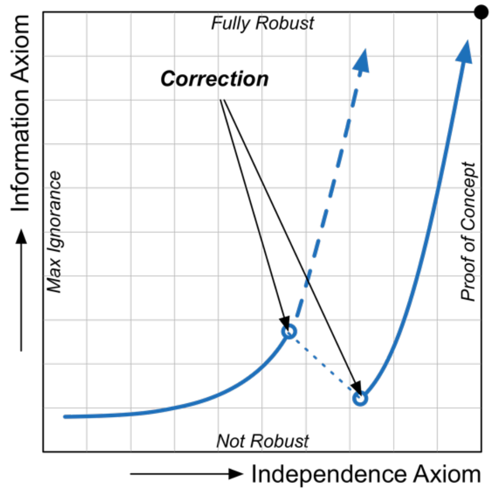

Figure 3: Discovery of a wrong DP leads to better independence but sets the Information Axiom back. The dotted line shows the development if the error would not have been discovered

If a combination lock is to be opened without knowing the code it is a matter of trial-and-error to open it. Even if the instruction manual is available it is not possible to open it without further knowledge (being the code). All organised information is removed from the system and axiom 2 is fully satisfied, but the independence axiom is not. The result, when the error is discovered, is dependent on the number of DPs that have to be replaced. The result of replacing DPs will lead to a fallback in satisfaction of axiom 2. If no DPs have to be changed, like the combination-lock example, the effects are minimal and the design will get rid of remaining dependencies. A fully mature state would instantly be the result. Both options are shown in figure 4.

Figure 4: A coupled design matrix does not prevent satisfaction of axiom 2. However, if decoupling of the matrix needs replacement of DPs, axiom 2 is not automatically satisfied for the new DPs and a lot of efforts may be lost (option a). Option b shows a luckier situation that the DPs can be maintained. In this case the impact on the design is minimal

Non matching system- and design ranges

A non-matching system and design range for one or more of the relations between FRs and DPs leads to the situation that the information axiom cannot be fully satisfied. Note that axiomatic information according to (3) is defined as joint probability (quantified product of all probabilities). Therefore the mature state is only reached if all system- and design-ranges are matched (figure 5).

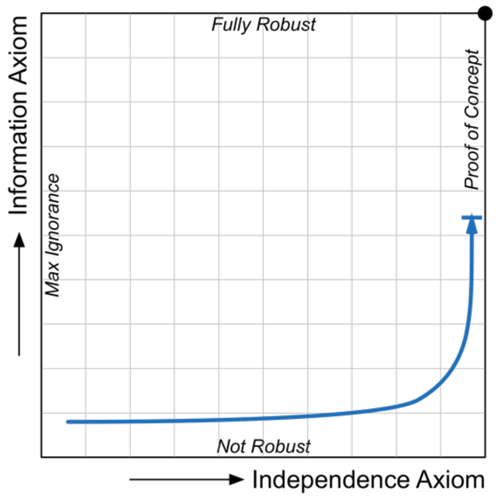

Figure 5: A non-matching system- and design range prevents the mature state from being reached. The design will not become robust

In this case, the discrepancy between presumed and legitimate positions in the AMD has disappeared. The discrepancy is only present until the design becomes independent. Remaining organised information does not change it. Only unorganised information will lead to a discrepancy of presumed and legitimate position.

5 DISCUSSION AND CONCLUSIONS

The AMD is an unbiased way to graphically represent progression in design. It shows progression, and not a reduction of complexity, thus presenting advances in a positive context. However, it is not the case that the AMD shies away from problems in the design; by showing that the presumed and legitimate positions in the diagram can be quite different, it sends out a continuous warning to stay critical on design choices made and the related presumed status.

5.1 Ideal Development Path Through the AMD

Product and system design is about taking controlled risks. A certain amount of trial-and-error in finding a well functioning set of FRs and DPs is acceptable if not inevitable. The ideal path through the AMD, as indicated in literature, prioritises reduction of independence before reduction of axiomatic information. Though this seems a solid way to go, it might be acceptable in some cases to choose a different way e.g., a way that involves more risk but accelerates the design process at a cost of resources. It is not clear yet what the characteristics of such a path are and how it can be plotted through the AMD. It remains part of future research.

5.2 Discrepancies in the AMD

Studying the discrepancies between the presumed and the legitimate positions in the AMD is a good thing, but this does not help future design projects. The problem is that the discrepancies are caused by a lack of knowledge and, if the designers were aware of this, they would take care of the problem instantly. In the execution of design projects it is never completely clear if discrepancies are latent. Till now, the AMD cannot change this.

A positive contribution of the AMD is that faulty scenarios, eventually from the past, can be analysed and characterised. Causes and consequences become clear lessons for future design projects. In learning organisations, including universities, the AMD can serve as an effective tool to explain the origin of errors made in student-projects. It will significantly contribute to the learning experience.

Only unorganised information leads to discrepancies in the AMD. Axiomatic information does not contribute to it because errors in overlap of system and design range come to the surface automatically and will be instantly recognised by the designers.

Discovery of discrepancies in the AMD can reveal ineffective engineering efforts but this is depending on the kind of error that is made. Some errors have been described in this paper, many more scenarios could occur. Charting other scenarios is work for future research.

5.3 AMD as Means for Communication Between Management and Engineers

The AMD may elevate the level of communication in the organisation because the impact of errors that are found and the correction related discrepancies can be graphically communicated. It widens the scope of personnel to be addressed and being capable of understanding what went wrong, for engineers, managers and executives.

5.4 Further Remarks

The AMD could benefit from better methods to detect the discrepancies. However, this is not simple. These methods should be capable of detecting the ignorance of the designer. The current methods use benchmarks that could be organised in a balanced scorecard. No evaluation has been made yet to study how existing tools for systems engineering can contribute.

5.5 Conclusions

The Axiomatic Maturity Diagram is a way to plot the progression of a developing product or system design. There is a preferred path that a product could run through, coming forth from the AD literature that advised to first satisfy the independence axiom followed by satisfaction of the information axiom.

Any product has, in an arbitrary development stage, a legitimate position in the AMD, but that position may be different of the position as presumed by the designer. The discrepancy between these positions is a measure for the ignorance of the designer. It will probably lead to efforts being spent in vain.

The Axiomatic Maturity Diagram is especially suitable for a learning environment, because the feedback of development actions can be analysed afterwards to provide valuable feedback.

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SIX SIGMA ROADMAPS AND THE DEGREES OF INNOVATION – AN EXPLANATION BASED ON THE AXIOMATIC DESIGN THEORY

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ABSTRACT

Six Sigma is a customer-focused, data-driven, and project-based approach that makes use of structured methodologies to drive business success through improving the functional performance of existing products, services and processes, or by creating new design solutions. All Six Sigma methodologies rely on a certain roadmap with well-defined stages, where for each one clear goals, deliverables, and outcomes are set. There are many Six Sigma roadmaps available. Knowing this, an important question arises: which Six Sigma roadmap to use in a certain continual improvement or design project? The answer depends on the project scope, namely in the degree of innovation inherent to such project. In this paper, we do show how Axiomatic Design Theory can provide a useful reasoning to help project team leaders to determine which Six Sigma roadmap should be employed in each situation, attending to the innovation degree inherent to the project.

Keywords: Design for Six Sigma (DFSS), innovation degree, Six Sigma.

1 INTRODUCTION

The majority of the implementations of Six Sigma employ the five-phase DMAIC (Define, Measure, Analyze, Improve, Control) roadmap for the execution and completion of continual improvement projects [Montgomery and Woodall, 2008]. However, DMAIC is not suitable for design or redesign projects; for such cases, the use of a Design for Six Sigma (DFSS) methodology is more appropriate.

Throughout the years, a wide variety of DFSS roadmaps have been proposed. The different roadmaps were identified, described and compiled in research work carried out by Shahin [2008] and Watson and DeYong [2010]. More recently, Marques [2013] studied the published literature on the subject, compared the different existing roadmaps, and, among other conclusions, demonstrated that the DMADV (Define, Measure, Analyze, Design, Validate) and the IDOV (Identify, Design, Optimize, Validate) roadmaps are the most often mentioned in scientific papers, as well as the most often used in practice.

On the other hand, the selection of the most suitable roadmap strongly depends on the degree [Shahabuddin, 2008] and type [Hambleton, 2008] of innovation involved in a Six Sigma project. Since the choice of the most appropriate Six Sigma roadmap must attend to the degree of conceptual changes to be introduced in the technical system, Marques *et al*. [2014] developed a Six Sigma Life Cycle model that distinguishes four degrees of innovation and relates these with the main Six Sigma roadmaps. In this paper, the reasoning behind this model is explained by making use of the Axiomatic Design concepts. The role of Axiomatic Design within these roadmaps is also discussed.

The paper is organized in four sections. Section 2 provides a literature review on how Axiomatic Design Theory has been used a Six Sigma context or applied during the development of a Six Sigma project. In section 3, the four different degrees of innovation that may be present in a Six Sigma project and their corresponding roadmap are explained from the viewpoint of Axiomatic Design. Finally, the main conclusions that can be drawn from this research are described in section 4.

2 LITERATURE REVIEW

The advantages of applying Axiomatic Design during a Design for Six Sigma (DFSS) project have been pointed out by many authors. Arcidiacono [2002] discussed the benefits in using Axiomatic Design principles during the stages that compound the DMADV roadmap; the authors called their approach as Axiomatic Design for Six Sigma (ADFSS). In their well-known book, Yang and El-Haik [2003] were probably the first to describe in great detail the benefits of making use of Axiomatic Design theory a DFSS project and how it can contribute to enhance the conceptual robustness of a design solution being developed; the authors adopt a version of the four-phase IDOV roadmap for the DFSS methodology. Jugulum and Samuel [2008] also suggest an extensive use of the Axiomatic Design Theory during a DFSS project, but they prefer to follow the DMADV roadmap. Dickinson [2006], by applying Axiomatic Design in the context of other roadmap (IDDOV – Identify, Define, Develop, Optimize, Verify) showed that the integration of Axiomatic Design in a DFSS context can actually be used accomplished in any roadmap.

Regardless the chosen roadmap, the usefulness of applying Axiomatic Design in a DFSS projects is justified by the following:

- To ensure that the flow-down of the critical to quality characteristics (CTQCs) of a given technical system is properly and coherently done [He *et al*., 2009].
- To create an architecture that completely captures the construction of a technical system functions [Jugulum and Samuel, 2008].
- To minimize the chance of conceiving and developing a product, service or process with design vulnerabilities, which might undermine its operational performance [Khalaf and Yang, 2006].
- To facilitate the functional optimization stage of the design process [Yang and El-Haik, 2003].

The employment of Axiomatic Design in a DFSS project is mainly done at the following three phases of the design process [El-Haik, 2005]:

1) Concept development, where alternative conceptual solutions for the high-level design are generated and evaluated, thus arising a winning design concept.
2) Preliminary design, where design decomposition tasks are carried out, thus detailing the functional and physical structures until the technical system can be implemented.
3) Optimization, where Axiomatic Design, by capturing the cause-and-effect relationships among FRs and DPs, can be helpful to develop transfer functions so operational optimization strategies, such as parameter and tolerance design, can then be put in place. In addition, the independence and information axioms can be used to maximize the conceptual robustness of the design before the operational optimization.

The “concept development” and “preliminary design” phases occur during the Design stage of both IDOV and DMADV, which are the most often adopted DFSS roadmaps. The “optimization” phase take place at the Optimize stage of IDOV and the Design stage of DMADV. Hu and Pieprzak [2005] demonstrated that the attainable level of operational robustness is much reliant on the chosen conceptual solution for the technical system, proving Axiomatic Design a rational structure basis for evaluation of proposed design alternatives and the subsequent selection of the best alternative. In a DFSS project, the high-level design often needs to be further detailed by decomposing the initial set of functional requirements (FRs) and design parameters (DPs); this can be effectively accomplished by employing the principles of Axiomatic Design [Mader, 2005].

Many of the DFSS approaches, especially for product design contexts, suggest the adoption of the Taguchi Robust Design strategy, which comprises three steps: 1) conceptual design; 2) parameter design; 3) tolerance design. As underlined by Yang and Pieprzak [2005], conceptual optimization must precede operational optimization, so Axiomatic Design should be employed before parameter design, since conceptual vulnerabilities usually cause operational robustness problems by introducing complexity/information into the design solution (axiom 2) that increase noise factors and increase variation in the functional response of the product or process. The relationships among Axiomatic Design and Taguchi Robust Design are explored by Kar [2000] and El-Haik [2005].

Axiomatic Design is rarely employed during the DMAIC roadmap since the design concept is not altered, but it is very useful for creating new design solutions, as well as for diagnosing and improving existing designs [Truscott, 2003]. Generally, DMADV is more suitable for redesign projects, while IDOV is more appropriate when a new design needs to be created [Shahabudin, 2008]. Jugulum and Samuel [2008] explicitly refer that the conduction of a Six Sigma project should attend to the type and degree of innovation inherent to such project.

The design hierarchy, which results from the top-down process of decomposition where design decisions are defined in an increasing level of detail, can be related to the degree of innovation associated to a Six Sigma project. When just small or incremental conceptual modifications are introduced in a technical system, only design changes the lower levels of the decomposition tree are likely to be affected. On the contrary, as Crawley *et al*. [2004] state, when a major/disruptive break occurs, it is necessary to undo choices at increasingly higher levels of the decomposition tree, so as technologies mature, the active design choices are pushed lower and lower, ultimately to the component level.

El-Haik [2005] distinguishes incremental design from creative design, as the former can be further divided into soft changes and hard changes. The author explains that, in the context of Axiomatic Design, a creative design case implies the definition of a completely new set of FRs and DPs to be further decomposed; in an incremental design case with the introduction of hard changes, the initial set of FRs are not changed but alterations in the DPs array are required; for incremental design soft changes, neither the FRs nor the DPs arrays are changed, but usually involve adjustments in the specification(s) in one or more FRs and/or in the values of some of the DPs within the permitted tolerances.

3 DFSS ROADMAPS AND THE DEGREES OF INNOVATION – AN EXPLANATION BASED ON AXIOMATIC DESIGN

Marques *et al*. [2014] recognized that the methodological approach (i.e. the roadmap) to be followed by a Six Sigma project, strongly depends on the conceptual maturity of the technical system targeted by the project, that is to say, on the degree/level of innovation inherent to the Six Sigma project. They developed a Six Sigma Life Cycle framework, comprising a Technical System Life Cycle model that suggests four levels or degrees of innovation and their corresponding Six Sigma project roadmap. This reasoning is exhibited in figure 1.

In this section, the relationship among the different Six Sigma methodological approaches and their corresponding degree of innovation will be explained from an Axiomatic Design theory perspective.

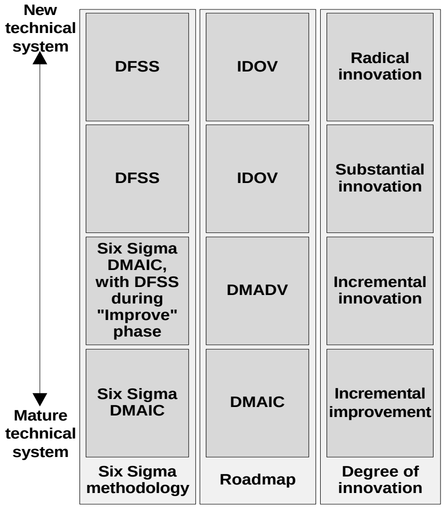

Figure 1. Relationship among the Six Sigma roadmaps and the degrees of innovation (adapted from Marques *et al.*, 2014).

In Six Sigma, a critical to quality characteristic (CTQC) represents the translation of a relevant customer requirement into a metric that is accompanied by an operational definition, which represents a clear, unambiguous, and observable standard of acceptance. When a CTQC is formulated in a functional mode, it corresponds to an FR. For this reason, CTQCs considered in a Six Sigma project can be regarded as being part of the functional domain [Yang and El-Haik].

In the following four subsections, the influence that each degree of innovation mentioned in figure 1 has in a Six Sigma project is explained using the Axiomatic Design theory.

3.1 INCREMENTAL IMPROVEMENT – DMAIC ROADMAP

Continual improvement projects are performed according to the DMAIC roadmap. This kind of projects usually consists in the optimization of one or few CTQCs, which is achieved by adjusting some of the key process input variables (KPIVs) in the process domain. Since redesign is not an option in DMAIC Six Sigma projects, the physical domain containing the DPs is generally ignored. This reasoning is illustrated in figure 2. Note that the decomposition tree is not shown because most of the time it is not necessary to develop this kind of detail in the process domain [Brown, 2006].

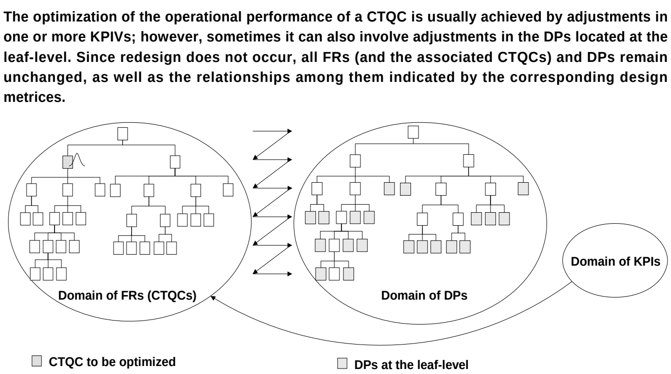

Figure 2. Scope of a Six Sigma DMAIC type of project explained by making use of the Axiomatic Design theory.

Sometimes the physical domain is considered; when this is the case, only adjustments in the values of the DPs, located at the leaf-level, within the permitted tolerances

3.2 INCREMENTAL INNOVATION – DMADV ROADMAP

Figure 3 depicts the reasoning behind redesign projects using the DMADV roadmap often utilized in DFSS. Similarly to DMAIC projects, it is intended to optimize the operational performance of a product, service or process regarding one or few of its CTQCs. However, in the DMADV case, the domain containing the DPs is always considered.

Because the degree of innovation is only incremental, no substantial or dramatic changes are introduced in the design concept. In the functional domain, the specifications associated to the FRs can be adjusted to reflect the intended enhancement in the operational performance of the system. The KPIVs in the process domain can also be adjusted, like in the incremental improvement case, but in the DMADV roadmap case, where redesign activities takes place, there are DPs located at the leaf-level within the decomposition tree that can be changed.

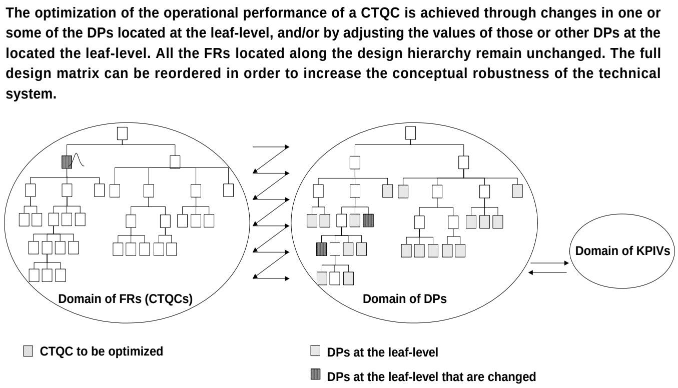

Figure 3. Scope of a Six Sigma DMADV type of project explained by making use of the Axiomatic Design theory.

3.3 SUBSTANTIAL INNOVATION – IDOV ROADMAP

The IDOV roadmap can be adopted in a DFSS project for either substantial or radical innovation. Substantial innovation involves redesign efforts and is characterized by the fact that the basic functions performed by the technical system remain unchanged. In this class of DFSS projects, at least one design concept that can effectively satisfy the set of top-level FRs is available to serve as reference.

This type of DFSS projects is often launched when substantial enhancements in the operational performance of the technical system, regarding some of its CTQCs, are required. This usually implies greater redesign efforts than simply introducing soft changes as described for the incremental innovation case. Substantial innovation is achieved by altering, adding and/or removing DPs somewhere in the design hierarchy, not limited to the leaf-level. Such changes in a given DP has consequences on the levels immediately below [Lindholm *et al.*, 1999], belonging to the same branch of the decomposition tree; actually, it implies the need of redefining the sets of sub-FRs, of their corresponding sub-DPs, and of the design matrices relating them.

The reasoning behind this type of DFSS projects, from an Axiomatic Design perspective, is illustrated in figure 4.

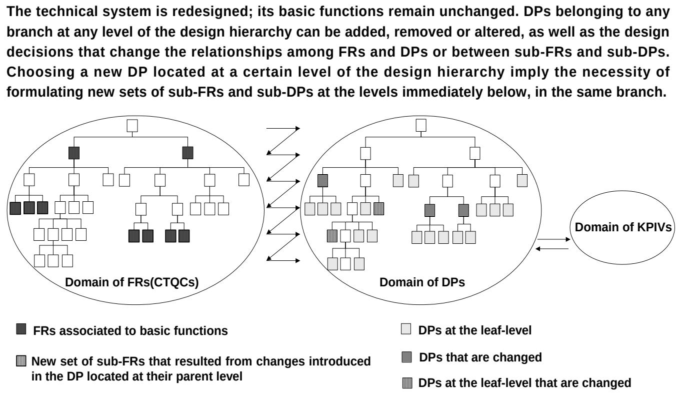

Figure 4. Scope of a DFSS project using the IDOV roadmap when substantial innovation is involved, explained by making use of the Axiomatic Design theory.

3.4 RADICAL INNOVATION – IDOV ROADMAP

This situation means that a complete new design is to be conceived and developed during the IDOV roadmap. In this type of DFSS projects, no design concept effectively meeting the FRs associated to the basic functions of the technical system is known. It means that a new set of top-level DPs needs to be defined, as well as the relationships among FRs and DPs at the highest level of the design hierarchy, provided by the design matrix. The whole decomposition, in a radical innovation situation, needs to be performed until the design can be implemented. This reasoning is exhibited in figure 5.

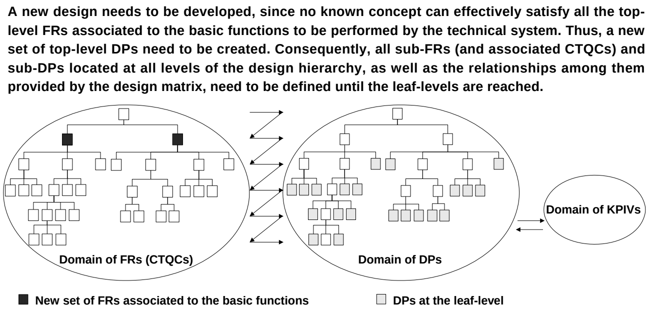

Figure 5. Scope of a DFSS project using the IDOV roadmap when substantial innovation is involved, explained by making use of the Axiomatic Design theory.

4 EXAMPLES

Table 1 depicts examples of real Six Sigma projects that were developed, the roadmap that was used and the degree of innovation inherent to them. These examples illustrate the reasoning behind the theoretical formulation described in section 3.

5 CONCLUSIONS

This paper discussed the role and applicability of Axiomatic Design in the context of different degrees of innovations inherent to a Six Sigma project. It was concluded that in traditional Six Sigma DMAIC projects, adopted for continuous improvement contexts, no DPs are changed, introduced or removed. For DFSS redesign projects carried out through DMADV, it was showed that in incremental innovation contexts changes in the DPs only occur at the leaf-level, while in substantial innovation situations, when the IDOV roadmap is used, changes in the DPs arrays can occur at any level of the design hierarchy, but usually not at the top-level. Finally, for radical innovation, which also adopts the IDOV roadmap, it was demonstrated that in the absent of a design concept that can effectively satisfy all the top-level FRs linked to a basic function, a new set o top-level DPs needs to be developed, which means the whole decomposition process needs to be carried out.

Table 1. Examples of Six Sigma projects, corresponding roadmaps used and the degree of inherent to each of them.

Six Sigma project scope	Roadmap	Degree of innovation
Quality improvement of a die casted product through the reduction of the likelihood of pores to occur. This was done by varying different levels of the controllable key process input variables in order to determine the optimal combination of these variables that minimizes the chances of pores to occur. The design decisions for the product were not altered.	DMAIC	Incremental improvement
A project was initiated with the objective of improving a casement window product model in terms of minimization of the heat transfer across its profiles. The minimization of the heat transfer is a requirement that is associated to a basic function of this product. To achieve that goal, small conceptual changes in the product's configuration and in some of its components needed to be introduced.	DMADV	Incremental innovation
A new transportation service targeting a new and specific market was designed. The highest-level basic functions of this service are identical to other transportation services, so this is not a radical innovation case. Only the design solutions/parameters needed to be tailored to the mentioned market, giving origin to specific sub-FRs formulated during the decomposition process.	IDOV	Substantial innovation

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METHODOLOGICAL CONTRADICTIONS SOLVED BY THE LINEARITY THEOREM: THE VACUUM CLEANER AS A CASE STUDY

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ABSTRACT

This paper is the continuation of a previous one where the vacuum cleaner was used as an academic example for teaching Conceptual Design. In this paper the example is extended by including the use of the Linearity Theorem as a screening tool that allows the student to select the best configuration. The paper shows several contradictions that arise when students have to face design problems with the use of Axiomatic Design in a qualitative way. In particular, ambiguities derived from the individual or sequential application of the Axioms are described. The Linearity Theorem is proposed as a powerful tool for applying both Axioms at the same time and hence for overcoming the difficulties associated to the aforementioned contradictions.

Keywords: Axiomatic Design, Education, Design Matrix, Linearity Theorem.

1 INTRODUCTION / STATE OF THE ART

Independence Axiom (A1), "maintain the independence of the functional requirements (FRs)" [Suh, 1990], leads to formulate the design matrices (DM) as the main tool for assessing designs, and hence, for guiding the decision-making process during the conceptual design.

Information Axiom (A2), "minimize information content" [Suh, 1990], leads to formulate the probability of success as the main guide for refining the search of solutions.

In the classical methodology proposed by Suh there exists an asymmetry between both axioms. The asymmetry is born because priority is given to the Independence Axiom. Indeed, the Information Axiom is used for selecting the best design among all the designs that fulfill the Independence Axiom [Suh, 1990, 2001]. Benavides [2012] also shows that it is wise to force firstly the accomplishment of A1 and secondly the accomplishment of A2 because this way facilitates the calculation of the probability of success. Therefore, the asymmetry consists in preferring a sequential application of the axioms in detriment of a parallel application of them. The preference of the sequential approach is clearly stated in this alternate statement of A2 "The best design is a functionally uncoupled design that has the minimum information content" [Suh, 1990].

In addition, during the conceptual design phase it is difficult to calculate the probability of success and thus, A2 must be applied in a qualitative way; Suh [2001] or Benavides [2012] present theorems that help the designer in this task. But in several cases, the fact of having a pure qualitative description makes the result of a sequential application of the axioms different from the result of a parallel application of the axioms. From a formal point of view, this fact resembles a contradiction in the Axiomatic Design Theory. The contradiction is born because the definition of the Best Design as the one that has a Diagonal Design Matrix, requires the application of both axioms at the same time [Suh, 1990, Benavides, 2012], but it does not include all the restrictions imposed by the second Axiom. In other words, the classical methodology for qualitatively selecting the Design Parameters (DPs) only seeks to achieve a diagonal matrix without using any other additional knowledge derived from the Information Axiom. The main reason is the difficulty to derive qualitative guidelines from the quantitative formulation of the information content.

In this paper we use the same lecture structure that was given by Rodriguez and Benavides [2013] for the resolution of a pedagogical case study. The main concern of that work was to help students and practitioners in the comprehension of Axiomatic Design principles and methodology as postulated by Suh [1990, 2001]. Hence, the lecture structure was focused on the resolution of a challenge that must join at the same time 1) enough simplicity for allowing its resolution in two or three hours, and 2) enough difficulty for letting the difficulties of applying the methodology arise. This challenge was enunciated as "obtain the best design for a vacuum cleaner". In this work we will extend the same example with the purpose of showing how a decision-making process based on qualitative arguments leads to contradictions that are sometimes detected by the students, creating in them a feeling of lack of rigor.

Fully understanding of the implications derived from a qualitative application of the A2 obligates the educator to face the aforementioned contradictions, and also obligates him to give a solution to that concern. To achieve this objective, this paper starts with the cyclone system, which was the one selected by Rodriguez and Benavides [2013] as the best design for the vacuum-cleaner challenge, and deeps in its qualitative resolution showing how the contradiction of applying a sequential approach appears. Then, a solution based on the use of a very restrictive theorem is proposed. In this case, the theorem selected is the Linearity Theorem, which was mathematically proved by Benavides [2012]. Linearity Theorem is a necessary consequence of both Axioms at the same time; thus, if the Linearity Theorem is not satisfied, at least one of the Axioms is not satisfied (normally, for uncoupled designs, it will be the Information Axiom). Therefore, what we say to our students is that it is wise to use the Linearity Theorem because in other case the fulfillment of the Axioms is in serious jeopardize, even more when only qualitative arguments are used in the design process. Paper shows how this qualitative argumentation is delivered to the students and how the contradictions appear. Finally the paper shows how the aforementioned contradictions are removed because the theorem forces a stronger use of both axioms during the qualitative argumentation, solving the contradiction and producing a unique response to the proposed challenge.

2 PROPOSED STRUCTURE

The steps for conducting pedagogical lectures are [Rodriguez and Benavides, 2013]:

1. **Quantitative formulation of the design problem.**
   a. Challenge definition.
   b. Selection of the minimum number of independent FR in a neutral solution environment.
   c. Establishment of constraints.
   d. Definition of FRs in terms of measurable variables
2. **Description of the solution through its main DPs.**
   e. Writing of the design equations (physical laws).
   f. Identification of DPs.
   g. Establishment of new constraints derived from the DPs.
3. **Writing of the design matrix.**
4. **Analysis with the use of the Independence Axiom.**
5. **Analysis with the use of the Information Axiom.**
6. **Analysis with the use of the Linearity Theorem. Selection of DPs (this may imply to create new DPs and a new physical solution).**
   h. Forcing the fulfillment of the Linearity Theorem.
   i. Establishment of future improvements.
   j. Outline new challenges.

This lecture structure is the same described by Rodriguez and Benavides [2013], and it is in turn based on the methodological steps described by Suh [1990, 2001]. However in this paper, the sixth step is completed with the Linearity Theorem.

Linearity Theorem (statement 1): Linear designs are better than non-linear designs.

The proof of this theorem requires both Axioms [Benavides, 2012] and is out of the scope of the pedagogical lecture presented in this paper. For practical uses, mainly in the 6th point of the lecture, two alternative statements of the Linearity Theorem are explained to the students:

Linearity Theorem (statement 2): The ideal design matrix is uncoupled and constant.

Linearity Theorem (statement 3): When two different DPs can be used for satisfying one FRs, the best DP (the DP that must be chosen by the designer) is the most linear one.

Since the proof of the Linearity Theorem uses the Axioms, the fact of forcing its accomplishment during the conceptual design is a necessary condition (but not sufficient) for the accomplishment of the Axioms. The difference between using the theorem or not appears because the Linearity Theorem forces a stronger definition of the ideal design: The best design must have (a null information content and) a diagonal design matrix and a constant design matrix. This definition imposes that all the elements in the design matrix of the ideal design must be constant, what is a direct consequence of the Linearity Theorem [Benavides, 2012]. Note that, in general, the qualitative formulation of the probability of success avoids checking if the information content is null (this fact is even more patent when students are involved because a teaching lecture tends to be more qualitative than quantitative); i.e. in a scenario where the information content cannot be calculated because there are only qualitative argumentations, the information content is not a practical part of the ideal design definition, and for that reason we put that part in brackets in the classical definition: The best design must have (a null information content and) a diagonal design matrix; which is a version of the alternate statement of A2 given by Suh: "the best design is functionally uncoupled and contains minimum information content". (Note that it's an alternate statement and not a definition.) Note also that the new definition of the ideal design, given by the statement 3 in this paper, comes from both Axioms at the same time and, for that reason, makes a more intensive use of A2 than the classical one. To have a more exigent definition of the ideal design helps to remove or solve some of the contradictions that appears due to not calculate the information content and use qualitative argumentations instead. This problem is more severe at preliminary stages of conceptual design, and hence, it is where it is worthier to use the Linearity Theorem.

2.1 QUANTITATIVE FORMULATION OF THE DESIGN PROBLEM

2.1.1 CHALLENGE DEFINITION

Since the challenge "Analyze two different technologies (porous filter and centrifugal separation) for filtering dust particles when vacuum cleaning. Identify their main dependences and select the best solution according to Axiomatic Design." was solved in a previous work [Rodriguez and Benavides, 2013], the students know that the best solution is the one based on the cyclone physics. For that reason, the new challenge for the new lecture is: "Analyze a vacuum cleaner that uses the technique of centrifugal separation for filtering dust particles. Identify their main dependences and improve the solution according to Axiomatic Design."

2.1.2 SELECTION OF THE MINIMUM NUMBER OF INDEPENDENT FRS IN A NEUTRAL SOLUTION ENVIRONMENT

FR1: Clean-up dust particles.
FR2: Retain dust particles.
FR3: Operate during a fixed period of time.

The concept of direct independence [Benavides, 2012] is used to realize that the needs stated in FR1, FR2 and FR3 are functional requirements because they represent, in a neutral solution environment, independent concepts.

2.1.3 ESTABLISHMENT OF CONSTRAINTS

The main set of constraints that usually appear are: minimum cost, maximum energetic efficiency, easily of use. But also the number of particles collected by unit of time. For the purpose of this lecture they are not relevant.

2.1.4 DEFINITION OF FRS IN TERMS OF MEASUREABLE VARIABLES

FR1: Clean-up dust particles: u_1

FR1 represents the functionality of cleaning-up particles, which might be represented by the speed of the air that must remove the dust particles from the floor. Let u_1 be this speed.

FR2: Retain dust particles: $d_{\min}$

FR2 represents the functionality of separating all the particles that have a size bigger than $d_{\min}$.

FR3: Operate during a fixed period of time: $t_{\max}$

FR3 represent the maximum period of time that the customer expects to operate the device.

2.2 DESCRIPTION OF THE SOLUTION THROUGH ITS MAIN DPS

We will construct the design matrix using directly the physical model that relates the FRs to the DPs for the centrifugal based solution. This physical model is based on the one described by Rodriguez and Benavides [2013]. For the sake of clarity, we will repeat here the main laws that lead to relate the final value of the FRs to a given set of values of the DPs.

2.2.1 WRITING OF THE DESIGN EQUATION (PHYSICAL LAWS)

We will assume that the air can be modelled as an incompressible fluid. Under this assumption, the mass flow rate $\dot{m}$ through the system can be modeled as

$$\dot{m} = \rho_0 A_1 u_1 \tag{1}$$

where ρ_0 is the air density at room conditions, and A_1 is the cross sectional area of the inlet pipe (see Fig. 1).

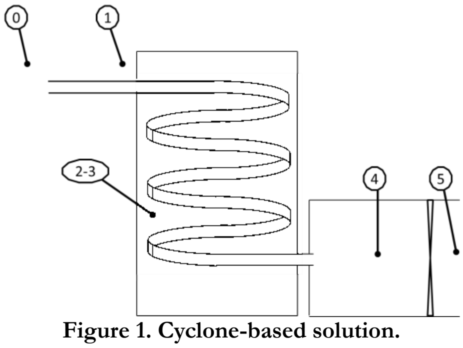

Figure 1. Cyclone-based solution.

The second physical law considers that there is an electrical motor that converts electrical energy into kinetic energy. If we assume that the available power after the conversion is $\dot{W}$, the mechanical energy injected into the air is given by:

$$\dot{W} = \dot{m}\frac{u_1^2}{2} \tag{2}$$

The combination of Eqs. (1) and (2) lead to the physical law for FR1:

$$u_1 = \frac{\dot{m}}{\rho_0 A_1} = \sqrt[3]{\frac{2\dot{W}}{\rho_0 A_1}} \tag{3}$$

The next physical law to take into account is the one that describes the centrifugal force in the cyclone. The cyclone comprises a stream tube which follows a helical stream line with a characteristic radius R and N_c turns. The differential equation that describes the radial displacement of a dust particle inside the cyclone is:

$$\frac{4}{3}\pi\left(\frac{d_d}{2}\right)^3 \rho_d \ddot{x} = \frac{4}{3}\pi\left(\frac{d_d}{2}\right)^3 \rho_d \frac{u_1^2}{R} - \frac{1}{2}\rho_0 \dot{x}^2 c_d \left(\frac{\pi d_d^2}{4}\right) \tag{4}$$

For large particles or for low radial speeds the following inequality holds:

$$\frac{\frac{1}{2}\rho_0 \dot{x}^2 c_d \frac{\pi d_d^2}{4}}{\frac{4}{3}\pi\left(\frac{d_d}{2}\right)^3 \rho_d \frac{u_1^2}{R}} << 1 \tag{5}$$

Under this condition Eq. (4) yields to:

$$\ddot{x} = \frac{u_1^2}{R} \tag{6}$$

This equation can be integrated to obtain:

$$\dot{x} = \frac{u_1^2}{R} t \tag{7}$$

$$x = \frac{1}{2}\frac{u_1^2}{R} t^2 \tag{8}$$

The time spent by the particle inside the cyclone is:

$$t = \frac{2\pi R N_c}{u_1} \tag{9}$$

Taking into account Eqs. (5) to (9), we can write the condition for neglecting the aerodynamic forces:

$$d_p >> 3\pi^2 N_c^2 c_d \frac{\rho_0}{\rho_d} R \tag{10}$$

A particle will escape from the cyclone towards the container when $x \geq d_1$, where d_1 represents the diameter of the tube (note that $A_1 = \pi d_1^2 / 4$). Thus a particle will reach the container if the following inequality is satisfied:

$$N_c \geq \frac{1}{\pi}\sqrt{\frac{d_1}{2R}} \tag{11}$$

Since $d_1 << R$ and $N_c > 1$, the previous inequality is always satisfied. Thus, all the particles that have a large size (defined by Eq. (10)) are always retained with independence of the value of the rest of the DPs. As a consequence, only if $d_{\min}$ is less than the value $3\pi^2 N_c^2 c_d R \rho_0 / \rho_d$, FR2 is not satisfied. Hence, it is convenient to simplify the Eq. (4) for the case of having particles with a diameter much lower than that. In that situation, the aerodynamic force becomes dominant and the radial velocity becomes constant as stated by:

$$\dot{x} = \sqrt{\frac{3}{4c_d}\frac{\rho_d}{\rho_d} d_d \frac{R}{u_1^2}} \tag{12}$$

This equation can be integrated to obtain:

$$x = \sqrt{\frac{3}{4c_d}\frac{\rho_d}{\rho_d} d_d \frac{R}{u_1^2}} t \tag{13}$$

Taking into account Eq. (9), the minimum size of the dust particles retained into the container is obtained from the condition $x(t) = d_1$, which yields to the design equation for FR2:

$$d_{\min} = \frac{3c_d}{4\pi^3}\frac{\rho_0}{\rho_d}\frac{A_1}{RN_c^2} \tag{14}$$

The last physical law relates the volume of dust collected during a period of time to the available volume in the chamber 2-3. Obviously, this time will depend on the density of dust particles per unit of volume n. The operational time is calculated when the whole dust container, whose volume is V_{23}, is full:

$$t_{\max} = \frac{\dfrac{V_{23}}{\dfrac{4}{3}\pi\left(\dfrac{d_d}{2}\right)^3}}{n\dfrac{\dot{m}}{\rho_0}} = \frac{3V_{23}}{2\pi d_d^3 n \sqrt[3]{2\dot{W}A_1^2}} \tag{15}$$

2.2.2 IDENTIFICATION OF DPS

The DPs derived from design equations Eqs. (3), (14) and (15) are A_1, V_{23}, N_c, R, and $\dot{W}$. (At this point, students are advised of having a redundant design with three FRs and five DPs). Which three DPs are the best ones?

2.2.3 ESTABLISHMENT OF NEW CONSTRAINTS DERIVED FROM THE DPS.

One option for selecting only three DPs is to collect several of them just in the same term. For example, we could use $\dot{W}$ or A_1 for assuring FR1 because both appear, combined as the main parameter $\dot{W}/A_1$, in Eq. (3). When only the main DPs are used to describe the solution, the physical formulation can be expressed in a qualitative DM as follows:

$$\begin{pmatrix}\text{Clean-up dust particles}\\ \text{Retain dust particles}\\ \text{Operate a long time}\end{pmatrix} = \begin{pmatrix}X & 0 & 0\\ X & X & 0\\ X & x & X\end{pmatrix}\begin{pmatrix}\text{Vacuum } (\dot{W}/A_1)\\ \text{Cyclone } (RN_c^2)\\ \text{Container capacity}(V_{23})\end{pmatrix} \tag{16}$$

The lower case x in the matrix reminds that there is a weak dependency in that term: the less the minimum size of the collected dust is, the larger the number of dust particles per unit of volume collected in the reservoir. However since this variation affects to the particles with minimum volume, we will neglect this effect, i.e. we will consider $\partial n/\partial(RN_c^2) \approx 0$.

At this point, we explain that the DM in Eq. (16) is not linear due to the dependence of FR2 and FR3 with A_1. In addition, we remark in class that the groups of DPs made in Eq. (16) are not unique, and hence there exist some degree of arbitrariness in that Design Matrix. In matrix (16), DP1 was chosen as the specific power installed in the system because it is a quite engineering parameter that measures the amount of power per unit of system size, and hence, it allows the engineer to compare systems of different sizes. It affects to FR2 because if DP1 changes due to a variation of A_1 Eq. (14) shows that FR2 varies too. However, if the inlet area is removed from DP1 because it is not considered a main DP any more, the physical formulation also responds to the following DM:

$$\begin{pmatrix}\text{Clean-up dust particles}\\ \text{Retain dust particles}\\ \text{Operate a long time}\end{pmatrix} = \begin{pmatrix}X & 0 & 0\\ 0 & X & 0\\ X & 0 & X\end{pmatrix}\begin{pmatrix}\text{Vacuum } (\dot{W})\\ \text{Cyclone } (RN_c^2)\\ \text{Container capacity}(V_{23})\end{pmatrix} \tag{17}$$

Both matrices show that the design is uncoupled for FR1 and FR2. However, because the former has a less number of off-diagonal elements, the second one is closer to the ideal design. This difference comes from reducing the number of DPs to the number of FRs such as the ideal design requires. This reduction is, in fact, made by imposing design constraints in the DPs not selected [Suh, 1990]. Therefore, depending on how the designer defines the constraints that affect the DPs, several design matrix are obtained. This resembles an inconsistency in the qualitative application of the Axiomatic Theory because the first design matrix induces us to think that using the specific power as a design parameter is worse than using just the power for a frozen value of the area, but engineers have well-founded arguments for preferring the specific power. This incoherence is quite important from the academic point of view because it produces a negative impact in the students that realize that question. They perceive the existence of different DMs for the same problem as an arbitrariness in the decision making process, and hence, they tend to reject the Axiomatic Design Theory for not considering it a scientific or well-founded methodology when a tool to select the most accurate DPs. In our lectures we solve this problem saying that all the variables that can be controlled by the designer are DPs, but that only a few number of them are the best ones.

2.3 WRITING OF THE DESIGN MATRIX

Our approach for removing the flaw addressed before is to accept that all the physical variables are susceptible of being DPs and hence, all of them must be considered main parameters. Thus, according to the design equations written before, the resultant design matrix can be written as follows:

$$\frac{\partial u_1}{\partial \dot{W}} \neq 0; \frac{\partial u_1}{\partial A_1} \neq 0; \frac{\partial u_1}{\partial R} = \frac{\partial u_1}{\partial N_c} = \frac{\partial u_1}{\partial V_{23}} = 0 \tag{18}$$

$$\frac{\partial d_{\min}}{\partial \dot{W}} = \frac{\partial d_{\min}}{\partial A_1} = \frac{\partial d_{\min}}{\partial V_{23}} = 0; \frac{\partial d_{\min}}{\partial R} \neq 0; \frac{\partial d_{\min}}{\partial N_c} \neq 0 \tag{19}$$

$$\frac{\partial t_{max}}{\partial \dot{W}} \neq 0; \frac{\partial t_{max}}{\partial A_1} \neq 0; \frac{\partial t_{max}}{\partial V_{23}} \neq 0; \frac{\partial t_{max}}{\partial R} = \frac{\partial t_{max}}{\partial N_c} = 0 \tag{20}$$

Resulting in the following design matrix:

$$\begin{pmatrix} \Delta u_1 \\ \Delta d_{min} \\ \Delta t_{max} \end{pmatrix} = \begin{pmatrix} \frac{\partial u_1}{\partial \dot{W}} & \frac{\partial u_1}{\partial A_1} & 0 & 0 & 0 \\ 0 & \frac{\partial d_{min}}{\partial A_1} & \frac{\partial d_{min}}{\partial R} & \frac{\partial d_{min}}{\partial N_c} & 0 \\ \frac{\partial t_{max}}{\partial \dot{W}} & \frac{\partial t_{max}}{\partial A_1} & 0 & 0 & \frac{\partial t_{max}}{\partial V_{23}} \end{pmatrix} \begin{pmatrix} \Delta \dot{W} \\ \Delta A_1 \\ \Delta R \\ \Delta N_c \\ \Delta V_{23} \end{pmatrix} \tag{21}$$

At this point, with the full formulation of the DM, the student realizes that 1) the design is coupled because A_1 affects to all the FRs, and 2) the design is redundant because there are more DPs than FRs. Both are unexpected events for a concerned student because it strongly contrasts with the classical formulation given by the DM in Eq. (17). Now the contradiction is even more apparent because the new DM (with the full set of available DPs) separates even more the design matrix from the ideal one. Thus, the previous inconsistency, far from disappearing, becomes stronger, which transmits again the impression of methodological weakness when identifying the most adequate DPs.

2.4 ANALYSIS WITH THE USE OF THE INDEPENDENCE AXIOM

The classical approach to solve this ambiguity consists on freezing the variable that does not satisfy the Independence Axiom the most and select the DPs from the rest of variables [Suh, 1990]. Therefore, the straightforward selection derived from the application of the Independence Axiom is, for example, the following one (which resembles the structure of the DM in Eq. 17)

$$\begin{pmatrix} \Delta u_1 \\ \Delta d_{min} \\ \Delta t_{max} \end{pmatrix} = \begin{pmatrix} \frac{\partial u_1}{\partial \dot{W}} & 0 & 0 \\ 0 & \frac{\partial d_{min}}{\partial R} & 0 \\ \frac{\partial t_{max}}{\partial \dot{W}} & 0 & \frac{\partial t_{max}}{\partial V_{23}} \end{pmatrix} \begin{pmatrix} \Delta \dot{W} \\ \Delta R \\ \Delta V_{23} \end{pmatrix} \tag{22}$$

However, this approximation has the problem of applying exclusively the Independence Axiom, giving to the Information Axiom a secondary role.

2.5 ANALYSIS WITH THE USE OF THE INFORMATION AXIOM

According to the Axiomatic Design Theory the Information Axiom is applied after the Independence Axiom for selecting the best design among all the ones that fulfill the Independence Axiom. In this case, there is another possibility that could be best than the previous one. It is the following,

$$\begin{pmatrix} \Delta u_1 \\ \Delta d_{min} \\ \Delta t_{max} \end{pmatrix} = \begin{pmatrix} \frac{\partial u_1}{\partial \dot{W}} & 0 & 0 \\ 0 & \frac{\partial d_{min}}{\partial N_c} & 0 \\ \frac{\partial t_{max}}{\partial \dot{W}} & 0 & \frac{\partial t_{max}}{\partial V_{23}} \end{pmatrix} \begin{pmatrix} \Delta \dot{W} \\ \Delta N_c \\ \Delta V_{23} \end{pmatrix} \tag{23}$$

However, in a qualitative formulation where the information content cannot be obtained, any selection between (22) and (23) appears again as an arbitrariness.

Since the Axiomatic Design postulates an objective definition of the best design, any arbitrariness in the method for obtaining it appears as a contradiction of the theory. We propose to fix this problem with the use of the Linearity Theorem.

2.6 ANALYSIS WITH THE USE OF THE LINEARITY THEOREM

The quantitative description plus the Linearity Theorem allow us to focus the students on selecting DPs or on creating new ones, if the available DPs do not fulfil the Linearity Theorem.

We think that making the design decisions on applying both Axioms at the same time is more powerful than apply them individually or sequentially. For that reason, our approach lies on explaining that it gives more value to force the solution to satisfy a theorem that comes from both axioms at the same time than to apply only one axiom (or to apply a reduced definition of the best design); in general, we assume that it gives more value to use a stronger definition of the ideal design: If it is not linear, it is not the best design.

Since the Linearity Theorem leads to a stronger definition of the best design, we encourage our students to use it for selecting the best set of DPs. In the case of the FR2, Eq. (14) tell us that FR2 has the most linear dependency with variable A_1, neither with R nor N_c. For that reason, A_1 should be chosen as the DP2; however this decision produces a contradiction with the theory itself because it leads to a coupled design that does not satisfy the Independence Axiom (and because its relation with FR1 is not linear). The removal of this contradiction is presented to the students as a new challenge. At this point we induce students to think of how this solution could be improved. More specifically, they are asked about how the dependency between u_1 and d_{min} due to A_1 could be removed: students are able to focus A_1 for the design improvement by using Linearity Theorem.

2.6.1 PROPOSING UNCOUPLED SOLUTIONS AND OUTLINE NEW CHALLENGES

The previous challenge exposes students to a creative problem with the following hints: 1) due to the Linearity Theorem, they know that *area* is an important DP, and 2) due to the Independence Axiom, they know that A_1 is a bad DP. One solution to this innovative/creative challenge is to add more *areas* as DPs: one possibility that can be explored is adding the inlet diameter A_0 as a new design parameter. This addition changes the design in Fig. 1, by adding the inlet diameter as a new design parameter, into the new solution presented in Fig. 2, where the cyclone diameter is different from the inlet diameter.

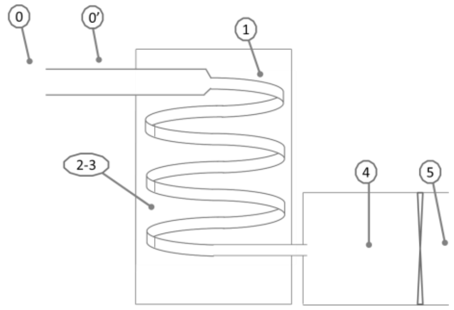

Figure 2. Cyclone-based solution with decoupled air speeds.

In this new solution a new DP has been added to the system in order to decouple the inlet speed from the cyclone speed. The new equations are

$$u_{0'} = \frac{\dot{m}}{\rho_0 A_{0'}} = \sqrt[3]{\frac{2\dot{W}}{\rho_0 A_{0'}}} \tag{24}$$

$$d_{\min} = \frac{3c_d}{16\pi^2}\frac{\rho_0}{\rho_d}\frac{A_1}{RN_c^2} \tag{25}$$

$$t_{\max} = \frac{3V_{23}}{2\pi d_d^3 n \sqrt[3]{2\dot{W}A_{0'}^2}} \tag{26}$$

And the DM derived from them is

$$\begin{pmatrix} \Delta u_{0'} \\ \Delta d_{\min} \\ \Delta t_{\max} \end{pmatrix} = \begin{pmatrix} \frac{\partial u_{0'}}{\partial \dot{W}} & \frac{\partial u_{0'}}{\partial A_{0'}} & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{\partial d_{\min}}{\partial A_1} & \frac{\partial d_{\min}}{\partial R} & \frac{\partial d_{\min}}{\partial N_c} & 0 \\ \frac{\partial t_{\max}}{\partial \dot{W}} & \frac{\partial t_{\max}}{\partial A_{0'}} & 0 & 0 & 0 & \frac{\partial t_{\max}}{\partial V_{23}} \end{pmatrix} \begin{pmatrix} \Delta \dot{W} \\ \Delta A_{0'} \\ \Delta A_1 \\ \Delta R \\ \Delta N_c \\ \Delta V_{23} \end{pmatrix} \tag{27}$$

This allows us to write the following design matrix

$$\begin{pmatrix} \text{Clean-up dust particles} \\ \text{Retain dust particles} \\ \text{Operate a long time} \end{pmatrix} = \begin{pmatrix} X & 0 & 0 \\ 0 & X & 0 \\ X & 0 & X \end{pmatrix} \begin{pmatrix} \text{Vacuum } (\dot{W}/A_{0'}) \\ \text{Cyclone } (A_1/RN_c^2) \\ \text{Container capacity}(V_{23}) \end{pmatrix} \tag{28}$$

This shows that although DM in Eq. (17) is formally similar to the DM in Eq. (28), the physical solutions are not. Therefore, the contradictions coming from the arbitrariness were due to forget to implement a new design parameter. This is quite interesting because in this problem the number of DPs was already larger than the number of FRs. However, this possibility still can use A_1 as DP2 and $\dot{W}$ as DP1, while still keeping the design matrix for FR1 and FR2 diagonal.

3 CONCLUSION

This paper explores some contradictions and arbitrariness that can appear when Axiomatic Design is used in a qualitative way, particularly, when qualitative examples are used for teaching it to students and the ideal design is exclusively based on the functional independence. It is proposed that using a definition of the best design as strong as possible mitigate these problems. In this paper, the stronger definition is "the best design is the one that has a constant and diagonal Design Matrix" which arises from the Linearity Theorem. In particular, it has been shown that this definition of the Best Design fixes that problem for the case study of the cyclone vacuum cleaner, and it has been shown that the solution requires increasing the number of physical variables.

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AXIOMATIC DESIGN AS A CONSULTANCY TOOL IN PRODUCT DESIGN

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ABSTRACT

The practice of innovation and technological advising demands from consultancy companies the ability to propose consistent solutions to their customers' challenges. This paper explores the use of Axiomatic Design as a consultancy tool by Altran group, and how the unequivocal definition of optimal design given by the axioms constitutes a high-value for strategic decisions. More specifically, from the methodological research carried on in collaboration with the School of Aeronautics of Universidad Politécnica de Madrid, this work presents how Axiomatic Design has been used to advise Altran clients in innovation and improvement challenges, focusing on the lessons learnt by applying it to product design. Additionally, the discussion presents the main difficulties and benefits found on the aforementioned applications.

Keywords: Axiomatic Design, consultancy, decision making, product design.

1 INTRODUCTION

Practicing consultancy requires from advising firms not only the analytical description of customers' challenges, but the appropriate rationale that justifies the decision making. According to each consultancy scenario -strategic, operational, innovative, technological etc.- customers' challenges are formulated in specific terms that are natural to each of the aforementioned contexts, and that more adequately represent customers' challenge definition.

When speaking about strategic consultancy in the framework of technological problems, (this paper considers technological problems the ones in which the application of practical science to obtain a specific product is required) the comprehension of the physical laws governing the problem definition results critical, even when the challenge drive is to answer to strategic considerations, for instance, the design and development of a new product. In technological environments (field where Altran Consulting Group is focused on), according to the authors' opinion, the strategic management analysis should not be decoupled and separately understood from the technical analysis: strategic, technical and users' insights should be considered in the challenge definition.

When combining technological and strategic advising, most of the activities are oriented to respond to one of the main concerns of companies: "how can we gain competitive advantage?" Although innovation is used as a common answer to it, the real challenge surfaces when the world of innovation has to be translated and implemented into the operational world. Unfortunately, very often both worlds are developed separately in many companies. As a consequence, when companies try to bring to their operational world some of the disruptive ideas that are generated thanks to the efforts put into creative activities, they realize that the constraints and own rules of operations severely condition or even avoid such implementation.

Furthermore, the word innovation is sometimes misunderstood and applied to any activity pertaining to engineering or to the high tech domain, independently from the nature of the activity. Consequently, many of the so-called innovation activities do not have any innovative motivation, but they correspond to general engineering developments.

As depicted by the iterative process presented by Suh [Suh, 1990], Figure 1 shows how analysis is used as a guarantee to achieve a valid solution to the design problem. As it is exposed, to gain competitive advantage in such step of the design process is difficult. Indeed, the more the number of iterations required to achieve a valid solution, the less the possibility to synthetize disruptive ideas to revolutionary products. When the efforts are put exclusively in analysis, the design problems become optimization problems rather than innovation ones.

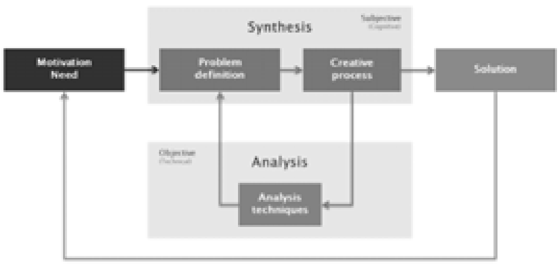

Figure 1 The design process as a feedback system, based on Suh [Suh, 1990].

In such context, the innovation success passes through the ability to synthesize and analytically select only the good ideas during the preliminary stages of design [Suh, 1990]. However, one of the most common misunderstandings in the industry is that analytical techniques should be used to validate products, prototypes etc., but for validating neither ideas nor concepts. In addition, in most companies, the following question surfaces: how to promote innovation by diminishing the technological risk? If the key milestones to achieve disruptive innovation and to gain competitive advantage are the preliminary synthesis steps of design, where the product is still not defined… how can we analyze the idea rather that the product? At this point the selection of a design process that adequately merges different technological approaches results critical [Benavides, 2012].

In this sense, the ideas in this paper were born due to the Axiomatic Design theory. The methodology used in the practical cases solved by the company is based on Suh's Axiomatic Design [Suh 1990 and Suh 2001], and has been adapted to Altran's particular context through the experience and through the collaboration with the School of Aeronautics (ETSIA) at the Universidad Politécnica de Madrid (UPM), where it was studied how to convert the Axiomatic Design framework into a systematic procedure that could be implemented with other design theories in technological advising. In any case, the experience gained by Altran answering to these questions will be presented trying to keep as much as possible the perspective of the use of Axiomatic Design in different fields of application. Additionally, it will be presented how the definition of a theoretical optimum design helps clients to position their products in front of their competitors, while understanding the inner constraints or requirements that condition the achievement of the optimal design.

This paper is structured as follows: in the next section a justification of why Axiomatic Design was considered by Altran the optimal tool to answer to the aforementioned questions is presented. Further, a set of lessons learnt in product design will be exposed. Finally, important ideas and difficulties are discussed, previous to collect the main conclusions.

2 THE CHOICE FOR AXIOMATIC DESIGN

The early stages of design (particularly in innovation problems) are generally characterized by a lack of precise information. Key questions have to be answered in these phases: What are the main needs that should condition the first levels of the design hierarchy? What are going to be the main critical points of the solution? Which one is the best solution to the design problem? How costs can be surfaced from the very early decisions? How can the same methodological approach guide the whole product lifecycle? Figure 2 collects some of the questions around the product definition during the preliminary design.

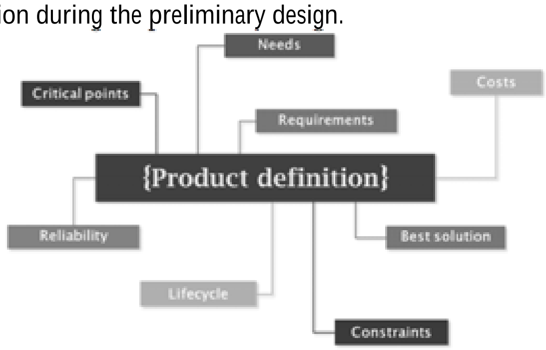

Figure 2 Context in the early stages of design.

Generally, the relations between FRs, DPs and constraints that achieve the optimal design are answered thanks to analytical tools. Nonetheless, as Figure 3 illustrates, even if the number of available tools and the knowledge about design increases, the impact of the design decisions taken during the analysis, prototyping or redesign phase is significantly restricted by the design decisions that have been adopted during the conceptual phase. According to Suh mapping and zigzagging processes [Suh, 1990] "what used to be design parameters at a higher level of the design parameter hierarchy may become constraints at a lower level of the design parameter hierarchy", the number of degrees of freedom decreases as the design process advances. Actually, the main decisions affecting cost and freedom to achieve disruptive products have been already taken during the early stages: analysis, by itself, may not guarantee innovation. For that reason, one of the most challenging questions for engineers is to get a rationale that justifies the "physical" design decisions while the amount of quantitative information is still marginal.

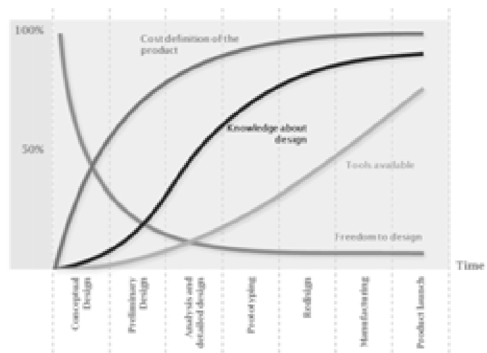

Figure 3 Trends in the design process

In this context, Axiomatic Design is extremely valuable because it permits to establish the optimal relations between FRs, DPs and constraints, even if the amount of available information is still vague or not precisely defined.

As a consultancy tool, it is very important to notice that one of the most important steps of Suh's methodology [Suh, 1990] is the appropriate definition of the design problem. Once the design problem has been appropriately stated, Axiomatic Design identifies the best design solution to the challenge.

Thanks to the establishment of design hierarchy levels throughout zigzagging in four domains (Customer, Functional, Physical and Process), [Suh, 1990, 2001], Axiomatic Design gives understanding of the whole conceptual product lifecycle until the product is ready to be launched (including brand positioning and value proposal). One of the key assets in this aspect is that Axiomatic Design establishes a common vocabulary for the four design domains. This represents a key point that tremendously facilitates concurrent engineering which in general is difficult to accomplish when the collaboration between different departments is strongly conditioned by different decision making criteria and design principles. Furthermore, the formulation of the design problem and of the characteristic intervals for FRs, DPs and PVs from a multi-domain perspective permits to guide the whole design process, and to establish the main relations that are critical to understand the customer challenge from a global perspective [for further information on the implementation of acceptance interval in Axiomatic Design, please, refer to Benavides, 2012]. Actually, the knowledge of these relations, even if the design process turns over a detailed optimization where Axiomatic Design may not be applied, is crucial to orientate it and to support understanding of some results that cannot be understood only from a detailed perspective. The zigzagging combined with mapping process achieves simultaneously the functional and the physical design, which is one of the key points to understand the solutions to the customer challenge.

Another main reason for choosing Axiomatic Design is that the unique and unambiguous definition of the best design (thanks to the two axioms) complements other methodologies. Indeed, even if the design process is not strictly guided by the mapping or zigzagging processes but by other methodologies such as functional analysis, Lean, TRIZ, Model Based System Engineering, Pugh Total Design, Decision Multi-criteria Matrices, reliability-based design, etc., the axioms constitute an excellent tool to validate the design decisions that are taking throughout the process, indicating if the configurations achieved with the use of any other design methodologies violate the axioms, and consequently, generate poor designs.

Table 1 collects some of the Axiomatic Design characteristics and relates them to main value drivers that a consultant company takes into account.

Table 1 Decalogue Axiomatic Design - Value

AXIOMATIC DESIGN	VALUE
Universal methodology	Multi-sectorial applicability
Design over the need	Sustainability
Robust Design	Quality
High standard theory	Talent
Product and manufacturing design	Concurrent engineering: counselling in all the design steps
Relatively new theory	Innovation leadership
Unambiguous definition of best design	Complement for other methodologies
The best solution is described because of the relations between FRs, DPs and constraints	Robust methodology for gaining competitive advantage from the very early stages of the design process[1]
Identifies the best solution in the conceptual design	Competitive advantage from the early stages
Permits innovation, and improvement	Widespread approach
Optimizes the design process FRs – DPs	Efficiency added to efficacy: development
identifying critical points	costs reduction

[1] Nakao [Nakao, 2011] reviews how appropriate strategies in the selection of FRs and DPs definition guides to superb products.

3 LESSONS LEARNT IN PRODUCT DESIGN

The following section depicts some of the lessons learnt when applying Axiomatic Design as a consultancy tool in the field of product design. It is divided into three subsections compiling the experiences gained in the analysis and improvement of existing products and in the development of new ones. Each subsection will treat some methodological aspects, some of the main difficulties found, and finally, some of the main benefits obtained.

3.1 IMPROVEMENT OF AN EXISTING PRODUCT

From the methodological perspective, Suh [Suh 1990, and Suh 2001] presents how the same methodological approach can be used for the analysis of existing products and for the development of new ones. In the first case, the design equation is built from the description of the existing product by means of the relations between FRs and DPs; whereas in the second case, the design equation is built thanks to the creative process that identifies the appropriate DPs that satisfy the minimum set of FRs. In this sense, the translation of the functions of the product in terms of FRs is not the consequence of the creative process mapping from the Customer Domain into the Functional Domain. In general, as a first approach, the first set of functions and solutions to them are established by the product owner who depicts the different functions and constraints, while describing the physical parts satisfying them. From the rigorous perspective of the theory, this design equation may not be axiomatic, and this is one of the key aspects to begin the improvement.

Unfortunately the reformulation of the design problem is very often forgotten. However, its reformulation with rigor can conduct to extremely valuable improvements. Some of the following questions can be useful for the practitioner in order to reformulate the design problem and identify potential improvements:

- Is the design challenge unambiguously stated and the existing solution an adequate answer to it?
- Is the set of functionalities given by the client minimum and independent?
- Are the system and input constraints clearly identified as separate entities than FRs?
- Are acceptance intervals for FRs and variation intervals for DPs clearly stated?
- Can the set of functionalities be reformulated into design levels with a clear correspondence to the physical domain?
- Even if a FR seems unnecessary… which is its importance related to the final client satisfaction?

In general, the value proportioned to the final solution coming exclusively from the reformulation of the design problem is tremendous and in general unexpected from the client. Although it seems a minor activity, it may suggest deep changes in the way that customers face their challenges. A methodological approach can be found in [Rodriguez, 2013].

Once the design problem is reformulated from the Axiomatic Design perspective (i.e. the problem definition is clearly stated), the set of FRs is independent, hierarchical and minimum in each design level, the acceptance and variation intervals are well identified and the constraints formulated. Starting at this point, the procedure turns into the study of the design equation [Suh, 1990] by means of the compliance with the two axioms. Once the design problem is properly reformulated and the design equation written, the elimination of off-diagonal dependencies and the minimization of the information content will detect the potential list of improvements [Suh, 1990 and Suh 2001].

3.1.1 MAJOR DIFFICULTIES

Further are presented some of the major difficulties that have been found in the analysis of existent solutions:

To identify the real design challenge: even if it appears as a simple task, to identify the real design challenge requires in general some iterations with the product owner. In the analysis of existing products, two challenges have to be considered. The first one corresponds to define the main customer's need to which the product answers. The second one describes the kind of improvement the design problem has to face, and consequently, establishes the framework that delimitates the degrees of freedom for the improvement analysis.

Number of FRs: very often, because the product is already existent and defined in detail, the number of functionalities given by the product owner is high. This aspect makes considerably difficult the initial steps of the analysis. In one hand the solution may be perfectly described. On the other hand, most of the functional requirements pertain to low levels of the design hierarchy, and very often, they are not the most relevant for the conceptual improvement of the existing solution.

Hierarchy levels: if the product owner has not clearly established design levels during the design of the product, grasping the functional requirements into design hierarchies may result into a difficult task. This is particularly critical because, according to Axiomatic Design, the next level of the hierarchy level cannot be defined until the DPs of the previous level have been defined [Suh, 1990], which behave as constraints to the next level. Depending on the number of FRs and DPs, the obtaining of the hierarchy levels for an existing solution may result difficult. It is important to notice, that as design decisions behave as restrictions to the next design levels, dependencies pertaining to the first levels of hierarchies are the most critical and in general, the root of the main deficiencies of the product. So the ability to identify the minimum set of FRs of the first design levels in existing products is crucial to succeed in their improvement.

Make FRs independent: when the solution exists and the FRs have not been defined by the designer as the minimum set of independent functions per design level, to find the minimum number of independent FRs can surface the existence of inadequate or "useless" FRs. This assumption can imply a completely new perspective on the product, which in a redesign for improvement may not be possible.

Client reaction to very simple but straightforward questions: when technological counselling, very simple questions may require the answer from the most experienced engineer. Asking about which are the dependencies between the different DPs and FRs, and their weight as terms of the design matrix, is very often a question that the customer has not thought about. The counsellor applying Axiomatic Design must understand that this question, even if for him is simple, requires a deep understanding of the product analysed, and commonly, not only from the technical perspective but from the strategic one too. Additionally, the consultant must be aware of the fact that this way of thinking could be completely new for the customer and not necessary easy for him.

Identification of the laws of physics: in many design problems, the transfer function (as a generalization of the design equation [Benavides, 2012]) is obtained from the formulation of the laws of physics. However, very often the aforementioned laws are not fully known by the designer (they are based on experience; can be implemented in a simulation software that uses them implicitly; some products imitate proved existing solutions, etc.). Because of the effort and resources consumed in analytical tools and optimization, this is not always critical. Nonetheless, from the Axiomatic Design perspective, the knowledge of these laws may result in the knowledge of the available DPs and their importance.

To give an appropriate consideration to the constraints: constraints are not always properly formulated (misunderstood as FRs, of less importance, lately introduced in the conceptual process, incomplete…). When analysing an existing solution, the constraints to the design problem are difficult to detect, particularly, when the analysis is done much later that the design was done. The constraints study is critical not only from the design problem formulation, but also to understand the potential margin of improvement the solution has. Very often, acceptance and variation intervals, DPs and FRs are frozen because of constraints that cannot be removed even if they are conditioning the achievement of the optimal design. Benavides [2012] gives a practical definition of constraints and the way of differentiating them from FRs.

3.1.2 MAIN BENEFITS

Some of the main benefits obtained are:

Drastic reduction of the time required for product redesign: thanks to the reformulation of the design problem and the analysis of the compliance of the two axioms, the potential improvements are immediately identified without the consumption of a huge amount of iterative analytical tools or models.

Justification of the key improvements detected: Axiomatic Design adds not only efficiency in the identification of critical points. Moreover, based on its rationale, it permits a clear justification of the decisions that have to be taken, which is absolutely necessary in a technological advising context.

Understanding of the main constraints that limit the improvement: in many cases, some constraints cannot be easily eliminated (for example, constraints coming from strategic positioning of a corporation, contract with providers…). In this context, it is critical to identify them in order to comprehend why a certain improvement cannot be adopted.

Easier understanding of Information Axiom: Information content is in general difficult to calculate. Very often, the quantitative formulation of Axiom 2 makes difficult its application during qualitative solving, particularly, when the available information is still vague. However, in improvement design, Axiom 2 is easier understood as "maximize the probability of success of satisfying a FR" [Suh, 1990] because the functionality of the solution can be check-out. Indeed, during improvement analysis design teams immediately perceive how complex design decisions decrease the probability of success.

Deeper knowledge on the solution: it is astonishing how product owners increase their knowledge on their products after applying Axiomatic Design in a redesign process. Suddenly, a huge amount of relations between functions, constraints and design parameters are surfaced and justified, and the product is understood from a global perspective. In this context they are able to take better decisions through the whole life cycle of the product.

Positive impact in the four domains: even if the improvement analysis is carried out only on two domains, for instance between FRs and DPs, the obligatory mapping process surfaces important relations between CNs and PVs, particularly, when the redefinition of the acceptance and variation intervals of FRs and DPs.

A valuable complement to other methodologies: here it is important to notice that the nature of the information given by Axiomatic Design is substantially different to the one furnished for example by optimization. Whereas numerical analysis or multipurpose optimizations give accurate results for defined variables, Axiomatic Design gives understanding of the relations between the main variables of the design problem. Consequently, it introduces a criterion to properly define the detailed analytical problem, once the best improvements have been selected: with the use of Axiomatic Design, the number of tentative improvements diminishes.

3.2 NEW PRODUCT DEVELOPMENT

Methodologically speaking, Suh [Suh 1990 and Suh 2001] establishes the basic steps to conduct the design process through the four domains. One of the main and most important differences with the situation described in improvement design is that in the development of new products, the designer defines the set of FRs when mapping from the Customer Domain. His creativity is not only put in the search of design solutions, but it is first of all oriented to fully understand the Voice of Customer and to properly formulate the design problem. The definition of the design challenge is again critical and very often requires several iterations with the design team. An adequate challenge definition should deeply contain the main user insights detected during the exploration of the Customer Domain, and consequently, must orientate the design effort to the satisfaction of the main expectations of the product customers without containing any preconceived solution. Once the challenge definition is properly settled, the translation of CNs into FRs and constraints for the first level of hierarchy can be easily achieved. Once the set of minimal independent FRs and constraints are settled, and the acceptance intervals defined, the designer has to identify the most accurate DPs that satisfy the set of FRs. According to the nature of the design problem, the DPs can derive from various fields, for instance, from the laws of physics if the transfer function is known, or from the best practices in the context of Lean and operational excellence context etc. Once the list of DPs is surfaced, the most appropriate in terms of compliance with the two axioms have to be selected. Suh [Suh, 1990] and Benavides [Benavides, 2012] expose techniques to properly select the DPs.

The following sentences may help the practitioner to succeed in this step:

- Is the definition of the design challenge implicitly defining a preconceived solution?
- In order to find the first level of the design hierarchy… which of the CNs is essential to answer to the design challenge?
- From all the CNs detected, which of them reveal the same concept?
- Several needs can be translated into a single function with an appropriate acceptance interval?
- Some of the constraints identified can be included into a FR in terms of its acceptance interval?
- Which of the CNs is essential for the functionality of the product and which pertain to aesthetics or other perceptive attributes?
- Once the essential CNs are detected… which is the minimum set of FRs satisfying them?
- From the set of DPs identified… which of them make the design problem more linear?
- Some of the constraints identified can be included into a DP in terms of its variation interval?

3.2.1 MAJOR DIFFICULTIES

Some of the main difficulties found in applying Axiomatic Design to the obtaining of new products are listed below:

Communicate the importance of the challenge definition: the critical nature of this step (as exposed in the improvement design) is not always well understood. However it is essential, even more, in innovative challenges. From the authors' experience, it is worth to iterate with the design teams until a real innovation challenge is formulated, even if they consider it useless in the beginning. Otherwise, the whole design process can turned into the description of a preconceived or existing solution.

Give importance to acceptance and variation intervals: as Axiomatic Design is very often used from a qualitative point of view, the design intervals are frequently forgotten. However, their definition is crucial to trace throughout the domains of the design process how the FRs and DPs must vary in order to satisfy CNs and FRs respectively. (Acceptance and variation intervals are implicitly involved in the Second Axiom by Suh [1990, 2001]; and they are explicitly included in the First Axiom by Benavides [2012]). The definition of those intervals can elucidate the probability to succeed in the optimal solution to the design challenge.

Give importance to constraints and differentiate them from FRs: the basic product specifications not always distinguish between requirements and constraints. Consequently, it is important to communicate to the design team how, from Axiomatic Design perspective, constraints do not have the same value as FRs, and hence, how to differentiate both concepts.

Difficulty to understand Information Axiom as a guide for designing: most commonly, Axiom 1 is well understood by design teams as a design guideline to encompass the creative process in the ideation of new products. However, Axiom 2 it is not. As presented by Suh [Suh, 1990], Axiom 2 permits to select between two uncoupled designs. However, very often the information required to be able to apply it is available during the early stages of design, nor the distribution of the probability function associated to the different FRs. Additionally, design teams are not always familiar with the appropriate definition of system range and design range [Suh, 1990]. In this context, it is important to incorporate qualitative conclusions derived from the Information Axiom that can accompany the creative design process, as physical integration, wide tolerances or the use of symmetries [Suh, 1990 and 2001] and Benavides [Benavides, 2012].

New concept of FRs: in Axiomatic Design the rigor in the definition of FRs is critical to succeed in the whole design process. Thomson [Thomson, 2013] collects some of the major errors in the definition of FRs. From the counselling perspective, the design process should not go on until the whole design team has interiorized the concepts of direct independency between FRs [Benavides, 2012] and neutral solution environment [Suh, 1990]. The rigor and the importance of it is not always easy to communicate, particularly, when the design team has to reformulate the basic specifications of the design product, and moreover, change the way they have been approaching requirements definition.

Zigzag mapping: in Axiomatic Design the appropriate definition of each design level is critical because it contains the minimum set of FRs and DPs that freeze a conceptual solution in each step of the design process. Consequently, the design team has to simultaneously do the functional design and the architectural design. One cannot be understood without the other, and the design axioms could not be applied. This way of proceeding is very often new for the design teams; not necessarily the mapping and the search for a solution to each function (QFD already presented it), but the rigor needed to properly apply Axiomatic Design and obtain the maximum benefit of it.

Applying it to systems engineering: a typical characteristic of system engineering is the amount of FRs it deals with. Although the use of Axiomatic Design in this context is presented and systematized by Suh [Suh, 2001], according to the authors' experience its application still remains difficult from the practical perspective. In one hand, traditionally in systems engineering all the requirements are first postulated, and subsequently, the architecture is built up. On the other hand, the application of the Independence Axiom requires the set of requirements were related to the systems' architecture. Consequently, in order to apply Axiomatic Design in this context, systems engineers must deeply change their ways of designing. First of all, defining exclusively functions in a neutral environment which means to formulate requirements with a design perspective and not only from a validation and verification point of view. Later, selecting the minimum number of FRs per design level and identify the adequate modules of the architecture. Therefore, even if the use of Axiomatic Design in systems engineering adds value and keeps complexity at minimum levels [Lu, 2009], its practical application requires a deep transformation in the way engineers design systems, which is not always achievable or desired.

3.2.2 MAIN BENEFITS

As a continuation of the difficulties encountered, some of the most relevant benefits of the application of Axiomatic Design to the design of new products are described:

Functional and physical designs are achieved simultaneously: although it is an imperative from the methodological perspective, it constitutes an extremely valuable approach for the design of new products. Because the set of FRs cannot be defined until the previous level of DPs is frozen, the number of useless FRs is minimum. Consequently, the complexity generated by a big amount of FRs can be controlled and maintained at its minimum level. Moreover, this way of guiding the obtaining of the final solution, permits to clearly trace the set of CNs, FRs, constraints and DPs throughout the whole process. This aspect is of a high importance when changes have to be done and demand going back to higher levels of the design hierarchy.

Trade-offs are minimized: selecting the best design configuration with the use of the design axioms minimizes the use of pondered matrices and other subjective techniques. Once the design problem is conveniently formulated, the design principles unequivocally identify the best solution. Trade-offs between pros and cons are not necessary (or marginal), and consequently, the number of subjective and not rationalized design decisions is minimal.

Strategic and technical positioning: from the strategic point of view, the design axioms identify the best solution to a particular design problem. As the context may be similar for different competitors, Axiomatic Design points the optimal solution. Consequently, when solving any design challenge in a competitive environment, the theory permits to identify how far are competitors from the optimal solution, how far is the proposed solution from that optimal, and in case the optimal could not be reached, which are the main restrictions that impede its consecution. Axiomatic products are strategically better positioned because technically speaking they approach the best conceptual solution.

Identification of technological limits and strategic R&D lines: because Axiomatic Design identifies the most critical dependencies, it naturally identifies which are the technological limits of the conceived solutions. To surpass these limits, strategic R&D lines have to be defined. The solving of a critical dependency or of a technological limit results in gaining competitive advantage.

A common vocabulary for concurrent engineering: one of the main difficulties to implement concurrent engineering in corporations is the lack of a common semantic that facilitates the communication between the multidisciplinary design teams. Axiomatic Design principles establish a common vocabulary and common criteria that are valid for all the domains of the design process. To have an unambiguous definition of the best design with a common vocabulary is a key milestone to be able to implement concurrent or multidisciplinary engineering.

Achievement of innovation with minimum technological risk: the systematic use of the design axioms conceptually validates the potential design solutions. The compliance with the design principles from the very early stages of the design process facilitates the selection of the best ideas in each level of the design hierarchy. Solutions are consequently validated before investing resources in their development, and innovation is guaranteed minimizing the technological risk generated by the development of inadequate designs.

A natural complement for other methodologies: as it has been stated in improvement design, the axiomatic design principles are a natural complement to other design methodologies or industry practices. In the context of new product development, it is particularly interesting the combination of Axiomatic Design with theories dealing with the product value proposition. For instance Suh [Suh, 1990] explains the combination with QFD as an excellent tool to translate CNs into FRs and consequently, identifying the critical functionalities of the product in order to maximize customers satisfaction. Another interesting combination is the use of Axiomatic Design for enriching classical benchmarking. In such cases, the design principles permit to plainly identify the reasons that make the different industry actors be more competitive from a conceptual design perspective. Identifying these reasons is of high value for defining corporate strategies. Related to benchmarking, it has to be noticed how powerful is the synergy between Axiomatic Design and business model generators, such as Business Model Canvas [Osterwalder, 2010]. In this context, Axiomatic Design helps to define and explain the value proposition of products, the reasons of their competitive advantage, and moreover, the relation with customer needs. Finally, it is important to comment an additional connection with methodologies oriented to motivate creativity, such as Synectics. In general, these methodologies are excellent to potentiate inventive and to generate disruptive innovations. However, they define a role in the creative process (sometimes called the owner of the design challenge) who selects among all the ideas generated the ones he or she considers the best to solve the challenge. Combining Axiomatic Design with creative methodologies results in an excellent design tool for synthetizing and selecting the best disruptive innovations.

4 CONLCUSIONS

In this article, a basic review of the lessons learnt applying Axiomatic Design as a consultancy tool has been presented. First of all, it has been justified why Axiomatic Design constitutes an excellent methodology for technological advising. Afterwards, some of the key points that surface when facing improvement and innovative designs were presented. As a result, Axiomatic Design, thanks to the unequivocal definition of the best design according to Suh principles, permits to select exclusively the best design configurations for the early stages of design. Furthermore, it justifies the decision making, it simultaneously achieves strategic and technological product placement, it permits to face different challenges with a single methodology, it facilitates multidisciplinary engineering while incorporating a common vocabulary, it promotes innovations with the minimal technological risk, and it surfaces the critical points that may reduce the value of the conceived or improved solutions.

As a result, Axiomatic Design as postulated by Suh is an optimal tool for counselling, in order to gain competitive advantage from the very early stages of product definition or improvement.

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AN AXIOMATIC DESIGN BASED APPROACH ON ANALYSIS OF ALTERNATIVE ROUTE(S) TO THE CONGESTED MENDANA HIGHWAY OF SOLOMON ISLANDS

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ABSTRACT

The Solomon Islands road network consists of three major highways, Kukum, Tandai and Mendana. The Kukum highway has major and minor un-signalized junction, overhead pass, and a dual carriageway. Tandai Highway has light traffic, minor junction and a single carriage way. The Mendana Highway has major & minor un-signaled junction, roundabout, underpass, and dual carriageway. Of the three highways, Mendana undergoes the most traffic congestion at Honoria section because of the high demand of the road use to access the basic services whilst vehicle increases and uses on a fewer road availability competing with the pedestrian users. The paper discusses on how to find alternative route to ease the traffic congestion of existing highway by axiomatic design (AD) approach contributing to the over-all analysis of process to determine which alternative route is the best viable. Selection of alternative route is a complex process and the application of AD is found to simplify the overall analysis.

Keywords: Cost Benefit Analysis, Axiomatic Design, Benefit cost analysis, Traffic Congestion, Net Present Worth

1 INTRODUCTION

Traffic congestion is a condition on road networks that occurs as use increases, as demand approaches the capacity of a road or of the intersections along the road. Traffic congestion occurs when a volume of traffic or modal split generates demand for space greater than the available road capacity. Traffic congestion negative impacts are: wasting time of motorists and passengers or opportunity cost, non-productive activity for most people, reduces regional economic health, delays (which may result in late arrival for employment, meetings, and education) resulting in lost business, disciplinary action or other personal losses, inability to forecast travel time accurately leading to drivers allocating more time to travel (just in case) and less time on productive activities, wasted fuel increasing air pollution and carbon dioxide emissions owing to increased idling, acceleration and braking, wear and tear on vehicles as a result of idling in traffic and frequent acceleration and braking leading to more frequent repairs and replacements, and stressed and frustrated motorists that leads to road rage and reduced health of motorists and higher chances of collisions due to tight spacing and constant stopping-and-going.

Urban traffic congestion is a serious and growing problem in many large and small cities around the world. Solomon Islands is also among these countries around the world that suffers urban traffic congestion. Its capital city Honiara (2013), a springboard for tourism activities is located on the northwestern coast of the island of Guadalcanal (Guadalcanal Campaign in World War II) with population of 64,609 people as of 2009, but as of 2012 record the population reached 549,598 according to World Bank (2014) data. Referring to an increase in population of 8.51%, the demands of road services is not enough to support it causing much congestion of the highway leading to major government services, schools and Honiara International Airport (former known as Henderson Field). The traffic concentration according to Gupta (2002) is eighty percent at Honiara City and the remaining is spread throughout the two populous provinces. The roads in Honiara were built decades ago (during the world war II) with little maintenance and expansions. The article titled Why Honaria Has A “Failed Transport Service” (2014) unveils the issues of poor road management and infrastructure that causes traffic jam on the roads as drivers tend to take shorter routes to avoid getting stuck and not getting enough income at the end of the day. Moreover, because more buses are running on a fewer roads resulting in a competition for space on the roads and passengers directing drivers in short routes to get ahead of other buses.

Table 1. Analysis of Existing Transport Infrastructure Feature

			Major junction		Minor Junction			Carriage-way				Contribution to the City									
		Bottleneck	Signal	Unsignal	Signal	Unsignal	Over-pass	Single	Dual	roundabout	Under-pass	Commercial area	Historical area	Residential	Accident Prone	Most desired	Short distance to most services	Attraction	Access to airport	Access to major gov't service	Schools
1	Kukum Highway	x		x		x	x		x					x							
2	Tandai Highway			x		x		x						x							
3	Mendana Highway	x		x		x			x	x	X-closed	x	x	x	x	x	x	x	x	x	x
4	Metaniko	x														x			x	x	x
5	Roundabout	x								x		x	x		x	x	x	x	x	x	x

The table 1 above is established to get the scenario of the traffic condition of Honiara. Even the two way lane bridge (new bridge) at the Mataniko River cause a bottle neck before and after the bridge as it holds traffic that flows to and from the four way lanes. The merging lane is unsmooth and does not continue to the end of the lane at a speed that matches to the other lane in which racing to the other end infuriates other drivers, finding a short bus route. Short bus route is a new behavioral concept currently practiced by public bus owners causing inconvenience for Honiara population today. It is in this context that the study is conducted to ease the traffic congestion of Honiara City that leads the researchers to consider axiomatic design concept to simplify the best design approach in the analysis.

2 METHOD: AXIOMATIC DESIGN AS A DESIGN TOOL

Congestion is a lot more complex than simply "too many vehicles trying to use the road at the same time," although that is certainly a major part of the problem. Congestion results from the interaction of many different factors — or sources of congestion. Congestion has several root causes that can be broken down into two main categories: 1) Too much traffic for the available physical capacity to handle, and 2) Traffic-influencing events. And congestion levels have risen in cities indicating that the transit routes are not able to keep pace with rising demand.

Identifying the complexity of which highway to be considered a new route as to ease traffic congestion is complex for Honiara City whose financial resources are limited. However, there is a simple design process popularized by Suh (1990) called axiomatic theory of design, which presents the independence and the information axioms, a theory that can explain or prescribe the design process. The axiomatic design (AD) approach provides a rational and systematic framework to help designers during the development of products, systems, and processes. AD is applied in many different fields that foresee design activities, such as this case study, modelled after Suh and shown in figure 1.

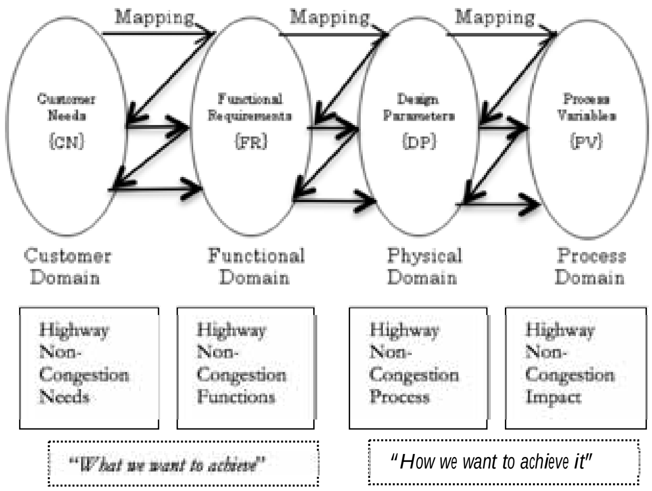

Figure 1. Axiomatic Design Study Model

Suh (1990) stressed that a good design should satisfy the independence and the information axioms. These axioms can identify a solution that fulfils the perceived needs through a mapping process between functional requirements (FRs) and design parameters (DP's). To resolve the design problem a FR-DP relations are mapped as follows: FRs-*DPs* (that describes the real condition of the system): congested-*bottleneck*, no traffic signal-*minor/major junction*, carriageway-*single/dual*, quick turnaround-*roundabout*, pedestrian-*overpass/underpass*, access to business-*commercial area*, access to historical area-*tourism*, occurrence of accident-*accident prone*, preferred/desired-*convenient*, less time travelled-*short distance to most services*, attraction-*beautiful site*, easy access to airport-*airport*, access to government agencies/school-*government services*, and access to residential-*residential blocks*.

The FRs-DPs are mapped for each highway as presented in section 2.1 of problem identification. The mapping leads to the preparation of an axiomatic design matrix for the study. According to Suh (2001), AD drives the designer through the different domains by mapping CA's, FR's, DPs and PVs, in which this process of mapping gets from a domain to the other. The CA's are first defined, then the minimum set of independent FRs are provided in line with the design goals, then DPs are mapped to satisfy the predefined FRs, and finally the PV or the plan for the product production is mapped. Each domain is decomposed into a hierarchy until the design is sufficiently detailed as shown in the figure 2.

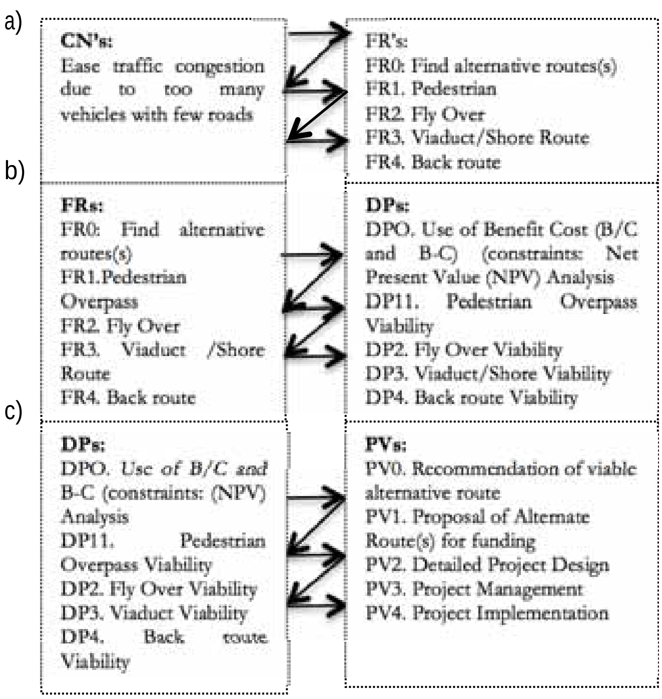

Figure 2. AD Decomposition Framework

Decomposition is a method to address the complexity of the design problem by dividing a problem into simpler sub-problems. In AD decomposition, the design decisions are made in an explicit way in order to solve the problem using the design axioms, eliminating bad ideas as early as possible to concentrate on promising ideas. The use of the independence axiom and the information axiom follows the concept of mapping and a design matrix is represented to display the relationships between FRs and DPs, as shown in figure 3. Mapping from FRs to DPs, are presented as cases to this study.

	DP1	DP2	DP3
FR1	X	O	O
FR2	X	X	O
FR3	X	O	X

Figure 3. FR-DP design matrix

2.1 Problem Identification

Case 1. Kukum Highway

Kukum Highway / FR	DP	bottleneck	minor junction	major junction	dual	roundabout	underpass	commercial area	tourism	Accident prone	convenient	short distance to most services	beautiful	airport	gov't services
	0														
congested	0	x													
no signal			x	x											
carriageway					x										
quick turnaround															
pedestrian															
access to business															
access to historical area															
occurrence of accident															
prefered /desired															
less time traveled															
attraction															
easy access to airport															
access to gov't services															
access to school															
access to residential															

Figure 4. FR-DP Mapping for Kukum Highway

Case 2. Tandai Highway

Tandai Highway / FR	DP	bottleneck	minor junction	major junction	dual	roundabout	underpass	commercial area	tourism	Accident prone	convenient	short distance to most services	beautiful	airport	gov't services
	0														
congested	0														
no signal			x	x											
carriageway					x										
quick turnaround															
pedestrian															
access to business															
access to historical area															
occurrence of accident															
prefered /desired															
less time traveled															
attraction															
easy access to airport															
access to gov't services															
access to school															
access to residential															

Figure 5. FR-DP Mapping for Tandai Highway

Case 3: Mendana Highway

Figure 6. Traffic Jam at Mendana Highway

Mendana Highway

FR	DP	bottleneck	minor junction	major junction	dual	roundabout	underpass	commercial area	tourism	Accident prone	convenient	short distance to most services	beuatiful	airport	gov't services
	0														
congested	0	x													
no signal			x	x											
carriageway					x										
quick turnaround						x									
pedestrian							x								
access to business								x							
access to historical area									x						
occurrence of accident										x					
prefered /desired											x				
less time traveled												x			
attraction													x		
easy access to airport														x	
access to gov't services															x
access to school															
access to residential															

Figure 7. FR-DP Mapping for Mendana Highway

The functional requirements (FR) in a FR-DP decomposition are listed along y axis and DP along x axis in figures 4, 5 and 7. Figure 6 shows a traffic jam at Mendana, and figure 7 shows that there is independence in this case. Also from observation of traffic congestion, Mendana is the most severely congested of the three highways because it traverses through the center of the City where the country's tourist office, Solomon Islands Visitors Bureau (located between the Yacht Club and the popular Solomon Kitamo Mendana Hotel), banks, major commercial establishments and government services such as government offices and schools. It also receives to and from the Roundabout transit as well as from Metaniko Bridge (figure 8).

Case 3.1: Metaniko Bridge

Figure 8. Metaniko Bridge 2-Lane exiting to Single Lane

Metaniko Bridge is a steel girder bridge with concrete decking in asphalt layered, sub-structure is concrete abutment and concrete piers. Length is approximately 80 m, width of 10 meters, and double lane. It lies along the Mendana Highway, adding the effect of congestion due to un-match exit lane to and from the bridge.

Metaniko Bridge

FR	DP	bottleneck	minor junction	major junction	dual	roundabout	underpass	commercial area	tourism	Accident prone	convenient	short distance to most services	beuatiful	airport	gov't services
	0														
congested	0	x													
no signal															
carriageway															
quick turnaround															
pedestrian															
access to business															
access to historical area															
occurrence of accident															
prefered /desired															
less time traveled															
attraction															
easy access to airport														x	
access to gov't services															x
access to school															
access to residential															

Figure 9. FR-DP Mapping for Metaniko Bridge

Figures 9 and 11 show strong problems of congestion. This is so because Metaniko Bridge as well as the roundabout (figure 10) runs along the Mendana Highway.

Case 3.2: Roundabout

Figure 10. Honiara Roundabout

roundabout

FR	DP	bottleneck	minor junction	major junction	dual	roundabout	underpass	commercial area	tourism	Accident prone	convenient	short distance to most services	beuatiful	airport	gov't services
	0														
congested	0	x													
no signal															
carriageway															
quick turnaround						x									
pedestrian															
access to business								x							
access to historical area									x						
occurrence of accident										x					
prefered /desired											x				
less time traveled												x			
attraction													x		
easy access to airport														x	
access to gov't services															x
access to school															
access to residential															

Figure 11. FR-DP Mapping for Roundabout

The roundabout has a diameter of 40 meters and has two arms, two double lane highways and three feeder networks.

Figure 12. Mendana Highway
(image source: Google map)

From figure 12, the three critical locations shown by circles are causing the congestions: 1) uncontrolled pedestrian crossing at the central market (figure 13), 2) the roundabout at the city council headquarters accommodates all two highways and three access roads, and 3) a single approaching lane to the 2-lane Metaniko Bridge (includes the new bridge) that funnels traffic into a bottleneck when approaching a 4 lane drive leading to the business area and the international airport. However, the cause of all these problems is the lack of road reserve for further expansion. Actually, there is none as of the conduct of this study. Commercial buildings and other structures occupied reserve spaces.

Figure 13. Uncontrolled pedestrian at central market

Table 2. Analysis of Customer Needs for various Stakeholders

Stakeholders	Customer Needs	Level
Motorists	Less vehicle operating cost, increased mobility, less frustration	Low
Passengers	Less time to commute to work/school/normal or business activities	Low
Pedestrians	Less pollution, safety on walkways used by frustrated drivers*	Low
Government/ Business	Workers arriving on time, optimum and/or increase productivity	Medium

**Normal situation in Honiara where out of frustration, motorist exploit pedestrian walkways hoping to escape congestion, compromising the safety of pedestrians using the walkways.*

2.2 The Benefit Cost Analysis

According to Hamilton (2014, 2014b) axiomatic design (AD) provides a rational and scientific way to develop and assess design alternatives, and preemptively addresses and resolves design issues that traditionally are discovered so late that only suboptimal compromises are possible. AD allows systematic examination of multiple solutions to ease the congestion at Mendana Highway, which has two alternatives: to find new road network and cost, a problem that corresponds to 'what we want to achieve" in order to ease the traffic congestion by creating a new road network that that corresponds to 'how we can achieve it' by finding which economical route(s) is viable, as shown in figure 13.

B/C Selection	DP - Design Process	pedestrian lane w traffic light	concrete road	asphalt road	aggregate surfacing	accessibility to major areas	short route	commercial area	tourism	availability of land	budget/cost	clear view
FR-Provide Non-Congested Traffic	0											
allocate pedestrian	0	x									x	
sealed potholes			x	x							x	
find new network			x	x	x	x	x	x			x	
secure road sign								x			x	
eliminate obstruction											x	x
alloacate special lane										x	x	
Provide overpass at Central market											x	
improve roundabout											x	
Improve Metaniko Bridge											x	
Improve Kukum Highway											x	
Improve Tandai Highway											x	
Improve Mendana Highway											x	

Figure 14. FR-DP B/C Selection

The need to find solution for the design problem, the design parameter (DP) is devised to fulfill the functional requirement (FR) within the specified customer needs (CNs). It quantifies the exploration needed to satisfy the FR. Also, its result is the basis for the implementation of the project that is, if the project is a case of new road construction or new road infrastructure. Finding its viability is important, and appropriate institutions can support in the realization of the problem posed by the CNs. In this case, the authors explore Benefit-Cost Analysis (Benefit Cost Ratio and Benefit Cost Difference), with Net Present Worth (PW), as constraint inasmuch as road projects do not provide an immediate return of investment (ROI). Therefore, decision makers are reluctant to decide on pursuing the project and investors to finance new road projects. Benefit-cost analysis (BCA) is simply a rational decision-making, formal technique to keep our thinking clear, systematic and rational because our natural grasp of costs and benefits is sometimes inadequate when the alternatives are complex or the data is uncertain. Even though most transportation policies are local, their influence often spreads out beyond the area of implementation, such as seeking support from international entities like the Asian Development Bank (ADB) or the World Bank.

Responding to road changes, traffic will shift from the impacted part of the network to other areas, and the intensity of the shift will depend on a Cost-Benefit Analysis. Thus, quantification of the likely changes in transportation benefits and costs associated to the expansion capacity is crucial for policy planners in order to determine the net benefits from capacity expansion projects. Such information can be used in the process to select the projects that are most likely to generate the highest return to society. This design parameter is used to determine which one of the alternative route(s) is viable.

Although there are many methods to find the solution to the problem, economic indicators are strong factors in the earlier AD analysis. Also, in economic evaluation of projects, there are several commonly used economic indicators that can be placed in a final comparable format. The Benefit-Cost ratio (B/C) and (B-C) are among of those most commonly used performance measure. The B/C ratio can be calculated using the following formula,

$$B/C = \frac{\boldsymbol{Benefits - disbenefits\ (B)}}{\boldsymbol{Cost\ (C)}} \quad (1)$$

$$B/C = \frac{\boldsymbol{Annual\ benefits\ from\ improvement}}{\boldsymbol{Annual\ cost\ of\ improvement}} \quad (2)$$

Criteria:
If the B/C Ratio is ≤ 1, reject alternative
B/C Ratio is ≥ 1, then accept alternative

And Benefit Cost Difference is calculated in the criterion as
B - C Criterion : (3)

where : B (net benefits) = overall advantage, less the disadvantage to the user
C (cost) = overall disbursement, less any savings to the investor

For the alternative to be acceptable:

The Benefit-Cost difference (B-C) between the net benefits and the net costs must be positive, that is the benefits must exceed the costs.

Boardman (2006) listed nine steps used in valuation process that comprise a generic cost–benefit analysis as follows: 1) list alternative projects/programs; 2) list stakeholders; 3) Select measurement(s) and measure all cost/benefit elements; 4) Predict outcome of cost and benefits over relevant time period; 5) Convert all costs and benefits into a common currency; 6) Apply discount rate; 7) Calculate net current value of project options; 8) Perform sensitivity analysis; and 9) Adopt the recommended choice.

2.2.1 Net Present Worth (PW)

There is a constraint in the selection of alternative route(s) that resulted from BCA because the opportunity cost today is different to that in the next future, and net present worth (NPW or PW) analysis (also called discounted cash flow techniques, DCFs) will compliment the best analysis of viability and high return of the investment.

The net present worth (PW) is the difference between the present worth of all cash inflows and outflows of a project; it is a discount rate that is used to convert future costs and benefits to present values. Since all cash flows are discounted to the present, the PW method is also known as the discounted cash flow technique. This method not only allows the selection of a single project based on the PW value but also a selection of the most economical project from a list of more than one alternative projects. To find the PW of a project, an interest rate is needed to discount future cash flows. The most appropriate value to use for this interest rate is the rate of return that one can obtain from investing the money somewhere. Alternatively, it can also be the rate that you will be charged if you had to borrow the money. The selection of this rate is a policy decision. Given the cost of the project, and given that the benefits are estimated, the net present value or worth, PW, of the project can be calculated by the equation below.

$$PW(i) = \frac{A_0}{(1+i)^0} + \frac{A_1}{(1+i)^1} + \frac{A_1}{(1+i)^2} + \cdots \frac{A_N}{(1+i)^N} \quad (4)$$

$$= \sum_{n=0}^{N} \frac{A_1}{(1+i)^N} \quad (4.1)$$

$$= \sum_{n=0}^{N} A_0 \left(\frac{P}{F}, i, n\right) \quad (4.2)$$

where PW = is the net present worth
i = interest rate
N = number of years
A_0 = initial Annuity
A_1 = first year Annuity
A_2 = second year Annuity
A_3 = third year Annuity
A_N = N^{th} year Annuity
P = Present
F = Future
n = initial year

PW Criterion:
The present worth of all cash inflows associated with an investment project is compared with the present worth of all cash outflows associated with the project.

PW(i) Decision Rule:
If PW(i) > 0, accept the alternative
PW(i) = 0, remain indifferent (5)
PW(i) < 0, reject the alternative

The PW decision rule stresses that it is not advisable to undertake projects whose NPV is less than zero, unless one is willing to 'lose money' which the authors believe to be undesirable as a means to achieve a non-financial objective.

To fully account the PW, a sensitivity analysis to account for risk is included. Risk is measurable because it refers to situations with known probabilities such as environmental damage cost and air pollution. Riabacke (2006) noted that managers defined risk as where the outcome is unknown to the decision-maker, which outcome will occur and the corresponding uncertainty that may lead to erroneous choices. Risk facing in public sector projects, such as roads, may not be independent, and the technique that can be used to accommodate risk and minimize risk in project design may be to use sensitivity analysis (SA). The values included in a cost-benefit analysis are the average estimates. Sensitivity analysis is a simple procedure for providing the decision-maker with information about the effect of errors in those estimates, as for example the cost implicated by environmental damage and cost of air pollution.

In terms of the impact on carbon dioxide emission, for example from congestion of vehicles and population increase, using environmental damage equation 6 to quantify the damage, where damage is a function (f) of three industrial and urban growth W (indicator of the degree to which culture promotes wasteful consumption of natural resources, P (population), I (index that can cause environmental damage), and D is the Environmental damage illustrated below:

$$D = f(P \times I \times W) \tag{6}$$

Solomon Islands CO_2 emissions (World Bank, 2014) is 0.38 (2009) metric ton per capita, which in 1981 reached 0.57 metric ton per capita, with a ranked number 147 from available records out of 197 countries. The CO_2 emissions of the World bank accounts for the stemming from the burning of fossil fuels and the manufacture of cement, include CO_2 produced during consumption of solid, liquid and gas flaring, but the current CO_2 emission produced by congestion is not accounted for. The value of cleaner air is another aspect which the public consider as valuable. According to World Bank (2014) health expenditure per capita of Solomon Islands is 133.99 US $ (2011) and ranked 125 out of 186 countries. Also, the record does not account the expenditure for 2012-2014.

An air pollution cost can be calculated by the equation (EPA, 2002)

$$C_{air} = Q\ (0.01094 + 0.2155\ F) \tag{7}$$

where:

$$F = 0.0723 - 0.00312Vf + 5403 \times 10^{-5}\ V^2 \tag{7.1}$$

F = fuel consumption at cruising speed (gl/mile)
V = average speed (mph)
Q = volume (veh/hr)

The fuel consumed is related to the average speed (or travel time) and to quantify the energy use, the following equation is considered:

$$F = k_1 + k_2 T \tag{8}$$

$$F = k_1 + \frac{k2}{v} \tag{8.1}$$

where,

F = Fuel consumed per vehicle per unit distance (l/km), T = Travel time per unit distance, including stops and speed changes (minutes/km), v = Av. speed measured over a distance including stops and speed changes ($10 \leq v \leq 56$ km/h), k_1 = parameter associated with fuel consumed to overcome rolling resistance, approximately proportional to vehicle weight (l/veh-km), k_2 = Parameter approximately proportional to fuel consumption while idling (l/h).

Fuel consumption is high for lower speeds and minimum for intermediate speeds. Moreover, fuel consumption increases as the number of stops of the vehicle increases.

3 ALTERNATIVE ROUTES

The alternatives in the case of Mendana Highway congestion are chosen in consultation with the Government of Solomon Islands, as the government owns the land so there is no problem with the acquisition as well as surveying the population of the country using formal and informal interviews. Among those considered alternative route(s) are: Mendana Highway rehabilitation/expansion by a flyover, pedestrian overpass, back-route and viaduct at shore-route.

Network assumptions for calculation of cost and benefits are presented in table 2.

Table 2. Network Assumptions

Network Assumptions	Measurement quality	Base Case/Alternative
Volume	Number of vehicles/unit time	5,763.00
	Number of pedestrians or cyclists/unit time	5,325.00
Speed, Delay	Time, distance, speed (time/unit distance)	<10 min., @60km/h
Growth rate	Growth rate in %	0.35
Inventory Generation	Vehicle type class	Bicycle, motorcycle, saloon car, 4WD, bus, truck
	Type of users	Elder, child, disabled, adult
Congestion	Time per vehicle	0.069-0.041 h
Duration	Days per year	260
Traffic usage Time	Use, mean duration, turnover rate	16
Travel time run	Travel time run	2 h
Safety	Fatal collision rate, injury collision rate, property damage only rate	0.23, 20, 40
Environmental Factors	Noise: dB (A, B, C) scales, L10, L50, Leq	4 dB
	Air pollution: concentration per unit volume (ppm), air temperature, wind speed	3 ppm, 28°C (84 °F); 0.45 m/s

The benefit and cost is analyzed under the criterion of the constraint PW, as well as the Benefit Cost (B/C, & B-C). The result is tossed to the FRs for mapping if it satisfies and tossed back to PVs to support the solution of the problem. The summary of Benefit Cost analysis for a 20-year period is presented in tables 3 and 4. The currency of the Solomon Islands was converted to USD at the rate of 1 USD = 7.25 SBD (Solomon Bokolo Dollar), as of July 29, 2013.

Table 3. Benefit & Cost of Alternative Route(s)

Alternate Route(s)	Length (km)	Benefit (Million USD)	Cost (Million USD)
Back route Road	12.0	53.76	89.6
Shore Route Road	1.50	27.06	23.8
Shore-Viaduct	1.50	82.79	69.85
Flyover	0.75	56.22	55.12
Pedestrian overpass	0.25	13.75	11.85

Table 4. Benefit Cost Analysis

Alternate Route	PW (USD in Million)				B/C	B-C
	7%		3%			
		SA		SA		
Shore Route	1.70	8.17	13.47	18.15	1.14	3.26
Back route	-59.19	-15.76	-50.40	-6.71	0.60	-35.84
Shore-Viaduct	-41.34	-9.59	72.2	-0.34	1.18	12.94
Flyover	-29.33	1.52	-20.80	12.67	1.02	1.10
Pedestrian overpass	3.29	13.78	13.29	23.97	1.16	1.90

The PW greater than zero is the most suitable criterion, the B/C ratio greater than 1 being the best alternative if B-C is positive. From the result of the Benefit Cost Analysis, two alternative route(s) comes up that best fit to the criterion rules: the shore route, and pedestrian overpass. In this case, the same procedure was applied to map the one that best solve the base case. After all the required possibilities are considered, one will map again to PV for system production.

4 CONCLUSION

The Axiomatic Design concept combined with Benefit-Cost Analysis is pretty suitable for the analysis of which alternative route is the best option. On the one hand, Benefit-Cost Analysis is useful for studying the viability of the alternative solutions. On the other hand, Axiomatic Design helps in the iterative process of narrowing down the existing alternatives.

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AXIOMATIC DESIGN OF MANUFACTURING PROCESSES CONSIDERING COUPLING

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ABSTRACT

Axiomatic design theory is applied to manufacturing process design. Different configurations of design domains and decompositions are considered here in order to provide options for maintaining independence while addressing the development of new products and manufacturing processes. The development of metrics and criteria for the process design is described as part of a complete design of the process variables. Value and cost are considered in the context of manufacturing. Tool design can be considered to be an extension of the manufacturing process as a means of meeting special, new processing needs.

Keywords: Axiomatic Design, Manufacturing, Process, Coupling, Surface roughness specification

1 INTRODUCTION

The objective of this paper is to advance axiomatic design (AD) theory [1] to improve manufacturing process development (MPD) within the context of new product development (NPD). Here, development is intended as a broader term than design. Design is the only part of development that is considered here. Design is the focus of this paper and used in a narrow sense intended only to encompass those activities that are integral parts of the decomposition in the axiomatic design process. Fully considered MPD would include the design of manufacturing processes and systems. In this paper, the focus is on the manufacturing process design, while recognizing that it is not always clear where or how to draw the distinction between manufacturing processes and systems. Drawing this distinction precisely is not particularly important to this discussion.

This paper addresses definitions and metrics for process variables and the coupling that occurs in some NPD-MPD situations. The manufacturing processes that are considered here could be applicable in the broadest range of those processes that perform value-adding transformations that satisfy customer needs (CNs).

AD provides a system for developing design solutions starting with CNs. Functional requirements (FRs) and constraints (Cs) are developed from the CNs. However, users of AD often focus solely on the functional and physical domains, without considering the process domain, i.e., how things are made. The design process then often stops with satisfactory fulfillment of the FRs by the design parameters (DPs). The process domain, and its elements, the process variables (PVs), are often ignored.

Consideration of the functional and physical domains is, at a minimum, required in AD to understand the relations between FRs and DPs. Extending this to consideration of the process domain, which would include the PVs, deserves more attention. This brings MPD into NPD. This is important because good MPD facilitates wealth creation and is essential to economic competitiveness.

Rigorous compliance with AD tradition in the formulation of design elements has not always been followed by some of the most skilled users of AD. For example, FRs should begin with a verb and be stated in the imperative [1]. However, valuable contributions have been made while ignoring this formality [2, 3]. Nonetheless, in teaching and developing axiomatic design, it can be useful to apply more formality in the formulation of FRs, DPs, and PVs. This would include specifying metrics and tolerances and quantitative relations between the elements.

Suh includes the process domain in the design solution and shows DP-PV interactions in the process matrix [1]. An approach to modifying DPs and FRs to reduce DP-PV coupling, by combining design and process matrices, is addressed briefly by Suh (128-131) [1].

Several types of coupling were considered by Brown [4], attempting to be collectively exhaustive with respect to relations between FRs and DPs. However, there is nothing in that work that addresses coupling between DPs and PVs or coupling that arises in the MPD as a result of constraints in the NPD.

Issues with coupling that interfere with maintaining independence can develop during the process of getting from NPD to MPD. MPD can be subject to coupling which results from the formulation of FRs and selection of DPs in the NPD. MPD can be coupled by decisions made during the NPD. For example, some coupling in the MPD can originate with the specifications that the DPs use for surface roughness characterizations that do not respond independently to the adjustment of individual process parameters. This is seen in the case of designing shaft surfaces for rotating lip seals [5]. There are product specifications made by the product designers that are typically beyond the influence of the manufacturing process engineer, such as, the specification of surface roughness parameters. MPD could benefit from approaches for dealing with these kinds of product specifications that cause coupling in the process design.

NPD in this work is intended for end-use consumer products. These are products that produce value for the consuming customer only. This value is intended to be consumed by the end user, rather than sold. It is also not intended to produce additional value that can be sold. Its value and use ends with the consumer.

Manufacturing processes and tools for facilitating manufacturing could also be considered as a type of product. It is special in that the primary function in MPD and related tool development is to create value in another, different product [6] that can be sold. In these formulations of a design problem, the manufacturer would be the consumer, although not an end-use consumer. Therefore, MPDs and manufacturing tool design could also be considered a kind of product in applying AD.

In this paper the term NPD will be used in a more limited sense that excludes all MPDs. This would also exclude important things that should be part of the complete development of a new product, like the development of new tools for new products, which can't be produced by existing processes, or for reducing cost and waste on existing manufacturing processes. These will be considered under MPD here. Design for facilitating tool development (FTD) can also be considered separately.

The approach used in this paper to advance AD for improving MPD is to first consider how to configure the domains in order to reduce coupling, and then consider how to more rigorously define and measure the processes. This will be done in the context of the dual objectives of manufacturing, adding value, and reducing costs, as proposed by Brown [6] and critiqued by Thompson [7]. Note that the definition of costs and consideration of waste are left to the manufacturer. Only the decomposition process and decomps are considered here, to the exclusion of integration.

The term "decomp" is used here to mean the design decomposition, describing the breakdown of the design into its components, e.g., lists of FRs and DPs, as opposed to decomposition as the act of decomposing.

2 METHODS: CONFIGURING DECOMPS AND THEIR DOMAINS FOR MPD

Decomps and their domains can be configured in different ways to facilitate MPD. The MPD could be included directly with the NPD or considered separately. In the latter case, there is the opportunity to introduce new FRs for manufacturing. Only the NPD-FRs relate directly to the original CNs for the new consumer product.

In any case, each element, i.e., FR, DP, and PV, at each level should have a target value, a tolerance and an expression of its relation to the adjacent domains. The expression of this relation should be an equation. This equation could be developed from known, fundamental relations or by fitting data from experiments. The former is of course preferable from time and cost perspectives. These equations describe the FR-DP and the DP-PV relations and are used to construct design and process matrices.

2.1 MPD INTEGRAL IN 4-DOMAIN NPD

The configuration for addressing MPD within NPD has 1-decomp with 4-domains (1:4) as shown in Fig. 1. The dotted arrows from the customer domain indicate that there can be an influence of the CNs beyond FR0, on the lower level FRs. In this 1:4 configuration, the context is entirely new product development, as opposed to manufacturing. The MPD is supposedly done within the NPD decomp. This decomposition process occurs in a linear manner for each branch at each level, following an FR-DP-PV progression at each level of the zigzag [1].

At the leaf level, the most detailed level of the decomp, the manufacturing process for each feature should be specified in the PV, with a target and tolerance. This PV would be traceable through a value chain to an NPD-CN.

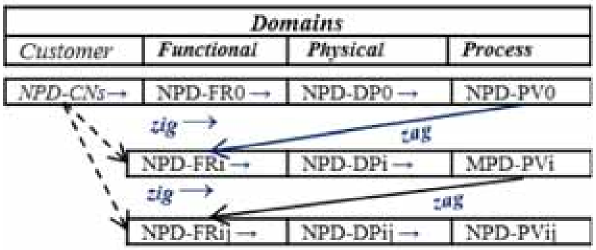

Figure 1. Zigzag decomposition with the customer-oriented single system, four domain (1:4) configuration. The zero level and top two levels with i and j representing the indices associated with different branches are shown.

In the case of the design of surface textures for shafts for rotating lip seals, the product specifications are currently standard, height parameters [5, 16, 17, 18]. The selection of these parameters and their tolerances has been developed through experimentation. They include specific ranges for average roughness, peak to valley height, and peak height. Supposing these are separate DPs, then the problem is that when one height parameter is adjusted, by changing a PV, the other two parameters change as well, and might go out of tolerance. Non-productive iterations might be required to adjust the process variables in an effort to bring all the surface roughness design parameters into tolerance simultaneously. This is a problem because there is no known system for this, nor is there any guarantee of, or test for, convergence.

In the 1:4 configuration this coupling, which is due to the specification of the roughness values for the texture design, should be addressed systematically during the decomposition. These kinds of coupling should become obvious when the target values, tolerances and relations between the elements are defined by equations and the resulting interactions are entered into the design and process matrices. In the course of maintaining the independence of the functional elements, which would be done level by level, this kind of coupling should be addressed during the decomposition.

The other kind of coupling that potentially would arise systematically from this configuration concerns the manufacturing costs. The value chain originates with the CNs and needs to be maintained throughout this NPD. The value chain also must extend through the manufacturing to the use of the actual product. Maintaining the value chain, starting with the customer and continuing through product and production development, is essential to successful design. That value should be satisfied by the FRs and fulfilled by the DPs, then produced by the PVs. The 1:4 configuration is focused on maintaining this direct value chain through the process design. However, it does not systematically allow for the control of manufacturing costs. The control of these costs has been cited as an essential part of successful manufacturing process design [6].

2.2 MPD WITH 3 AND 4-DOMAIN NPDS

Another configuration for addressing MPD is a 2-decomp 6-domain configuration (2:6) as shown in Fig. 2. This 2:6 configuration uses the first three domains -- customer, functional and physical -- in the NPD and then has a second decomp of the same three domains for the MPD. The decomposition involves taking the DPs from the NPD and using them, essentially, as special kinds of CNs, to develop FRs for the MPD. This configuration fits in with much of the current tradition of AD. Many users of AD and much of the literature on AD tend to stop at the physical domain.

Some MPD-CNs would maintain the value chain developed from the end-use customer NPD-CNs, which address the value-added criterion for manufacturing [6]. Additional MPD-CNs would be supplied by the manufacturer, acting as a customer. These would include the elements for controlling cost and waste thereby satisfying the second criterion for manufacturing [6].

The NPD and MPD decompositions might be done sequentially. This would provide a complete, finished view of the NPD for defining the needs of the manufacturing process. This could save iterations through the MPD when changes are made to the NPD. However, this kind of approach could design in costs during the NPD, costs that cannot be addressed in the MPD alone.

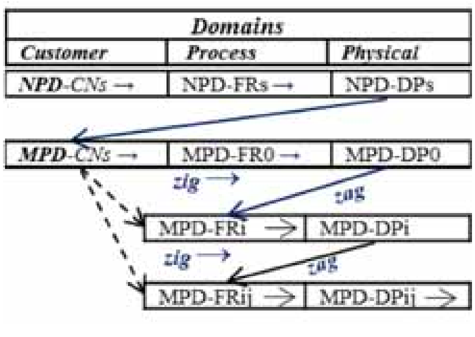

Figure 2. A representation of a 2-decomp 6-domain configuration to MPD from NPD. FTD could be constructed in a similar way from the MPD DPs.

The MPD-FRs address the MPD-CNs directly. Two types of FRs are expected: those that maintain the value chain that began with the NPD-CNs and those for reducing cost and waste. The MPD must establish the process variables that correspond to the NDP-DPs.

New, specialized tooling, FTD, could also be considered in an additional decomp, originating with the DPs of MPD in the same way, MPD is shown in Fig 2. The FTD-CNs would originate with the MPD-DPs. The process design then would not need to be constrained to existing tooling. For example, in some especially innovative projects, such as the development of manufacturing for integrated circuits in the latter half of the twentieth century, tooling for these processes did not exist and substantial, extraordinary tool design was done. Fixturing is an example of a more common tooling design problem that could require its own development. The FTD-FRs could be formulated either from the NPD-PVs or from the MPD-DPs or MPD-PVs.

In the 4-domain configuration, all process solutions link directly back to NPD-FRs. Independence is maintained in the 4-domain configuration across the functional, physical, and process domains by examining the design and the process matrices [1].

To better maintain independence during the zigzag decomposition in the 1:4 configuration, the NPD-FRs and the NPD-DPs could be adjusted or could change completely during the selection of the NPD-PVs. Sometimes, processes cannot be found that individually address specific NPD-DPs independently. In some instances, the NPD-DPs can be selected, and sometimes their corresponding NPD-FRs can be redefined to accommodate available processes [5].

Process solutions in the MPD stage of the 2:6 configuration can directly consider interactions within manufacturing systems, including multiple processes and surroundings, thereby promoting the maintenance of independence.

Consideration of the NPD-PVs in the context of a manufacturing environment could require additional FRs to satisfy the broader requirements of manufacturing. Independence in the 2:6 configuration is maintained in part through the definition of the MPD-FRs. However, one disadvantage is that this would remove the MPD sufficiently from the NPD-FRs, so that coupling with the PVs that originates in the NPD-FRs would not be so obvious and might not be addressed by changing NPD-DPs in the MPD stage, as in the 1:4 configuration.

A more elaborate, 2:4-, or 8-domain configuration, including both NPD and MPD PVs, could be used to address independence across all four NPD domains first, and then to consider interactions with the manufacturing systems in an independent MPD. This has the advantage of addressing NPD FR-PV coupling first. It has the disadvantage of requiring more work in the development of additional process domains, compared to the 6-domain configuration. Sometimes, the MPD-PVs might be obvious and not need to be developed.

2.3 FORMALIZATION OF PV DEFINITION

The discussion of this development will be in the context of the manufacture of mechanical parts. This could be extended to other kinds of design as well. Form and surface finish are NPD-DPs that are common to many mechanical parts. This discussion assumes that other important attributes, such as yield strength, are addressed in other branches of the decomp.

Formally, the NPD-PVs should start with verbs, like the FRs. PVs indicate actions, applications of energy to manufacture value-adding NPD-DPs, e.g., turn a cylinder or form threads.

The NPD-DPs in the 6-domain configuration that lead to the formation of the MPD-FRs must first be restated to begin with verbs, e.g., *manufacture* a cylinder or *create* threads. The MPD-DPs should start with a noun or an adjective. MPD-DPs might include a present participle modifying a noun, e.g., *turning* process or *forming* process. The MPD-PVs that relate to the NPD could look much like the NPD-PVs, e.g., turn on a lathe, or form threads with a tap.

Including tooling information in the MPD could avoid resorting to a formal FTD process in simple cases.

In the 6- and 8-domain configurations, there would be also FRs that relate to the manufacturing systems, e.g., maintain a material removal rate to control machining costs.

2.4 DECOMPOSITION RULES

Thompson [7] emphasizes the importance of including all the key stakeholders in establishing FRs. If this is done appropriately in the sole context of NPD, then the MPD and FTD stakeholders need to be included in one, all-encompassing, decomp. The PV decomps must provide a complete description of the processes, just as the FRs and the DPs must provide complete functional and physical descriptions [8].

And just as the FRs need to be considered in a solution-neutral environment from the point of view of the DPs [1], the DPs also must be selected in a solution-neutral environment from the point of view of the PVs. The FRs should not contain physical information [9], and the DPs should not contain process information. This would violate the distinctions intended for bimodal and tri-modal approaches. Therefore, "grind surfaces" is not a good MPD-FR, and "ground surface" is not a good NPD-DP. This consideration is important for the decomp to be valuable and creative.

3 METRICS, TOLERANCES AND RELATIONS BETWEEN THE ELEMENTS

Consideration of metrics in the design of manufacturing processes can improve the utility of AD. These metrics should be used to define targets and tolerances. Furthermore, quantitative relations between elements in the different domains should use these same metrics. Nonetheless, AD has been shown to be valuable without a formal definition of the metrics or a quantitative description of the relation between the elements in the domains. AD could be more valuable in some cases with metrics. It is not clear how to determine when the effort for quantification is merited. It is supposed that there is some kind of cost: benefit consideration that could be applied.

Metrics are domain specific. Metrics for the functional domain must relate to functional attributes, those for the physical domain to physical attributes, and those for the process domain to process attributes. For example, when designing a shaft for interfacing with a rotary lip seal, the FRs can relate to CNs for sealing and for the longevity of the seal. The functional metrics should relate to leak rates over time. The physical metrics would relate to the form and finish of the shaft. The process metrics should relate to how the form and finish are being created.

3.1 ENERGY PARTITION FOR PV METRICS

Because manufacturing processes involve the application of energy to perform value-adding transformations, it seems logical that the process metrics should relate to some kind of energy utilization.

Energy partition, where the process energy is doing work, e.g., material removal or surface modification, is discussed by Malkin in relation to grinding [10-12]. Acoustic emission can also be a metric for process monitoring [13], as can ultrasound [14]. In-process measurement has a rich history [15].

One intent of the process metrics could be to give an indication of how well the DPs are being generated. Similarly, the DP metrics should give an indication of how well the FRs are being fulfilled. Assessments of the process energies are distinctly different from the in-process measurements of NPD-DPs, which are also valuable [16]. The energies measured in process do not have to be those directly responsible for the transformations in order to be valuable, e.g., acoustic emissions.

3.2 TOLERANCES AND RESOLUTION

The resolution required for the metrics is based on the NPD-FR or the MPD-FR metrics and their tolerances, because that is what defines the success of the design solutions.

The requirements for the NPD-FRs should be mapped onto those for the NPD-DPs and NPD-PVs and then transferred appropriately to the MPD-FRs.

Directing the process work to accomplish the NPD-DPs in machining and grinding is currently done by defining the tool-workpiece interaction with the tooling, feed, speed, and depth of cut for many material removal processes. The parallels in additive manufacturing might logically include the energy used for bonding, as in selective laser sintering.

The overlap between the design range (NPD-DP tolerance) and the system range, or manufacturing capability, defines the common range [1]. MPD should seek to maximize the common range in order to comply with axiom two, thus minimizing information. The resolution of the process metrics should be good enough, relative to the common range, to control the process, maximizing the probability of keeping the process in the common range.

4 DISCUSSION

More work would be required to understand how to measure the energy partition in a process like tape finishing. During a single, short grinding operation, or hit, the energy partition on tape finishing can change. Because in tape finishing the same abrasive can remain in contact with the workpiece for a longer period of time than in other abrasive finishing operations, the abrasive tends to load with chips, and the process can transition from chip removal towards rubbing. With increasing contact time, relatively more of the energy goes into heating the workpiece and smoothing the surface than into material removal. Frequently, it could be easier to measure the DPs in process than the energy partition of the process. The heating of the workpiece will need to be compensated for in determining the form at ambient temperature. This would also influence the linearity of the

DP-PV relation, especially if time of contact is the selected PV.

This process of determining the common tolerance band when adjusting a process parameter could be applied to any situation where there are several non-orthogonal, semi-redundant DPs that must be satisfied, and coupling needs to be overcome in the selection of the PVs and their values. Semi-redundant DPs must be also non-orthogonal. The converse is not true when the correlations are negative.

5 CONCLUSIONS

Design domains can be configured several ways to address manufacturing process development.

The most comprehensive approach would be based on developing process domains for new product and for manufacturing development, although, it is not clear when there is a good return on investment for this effort.

Metrics and quantitative specifications of tolerances and relations between elements of adjacent domains might improve value of the design, although it is not clear when this extra effort would be justified.

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AN AXIOMATIC DESIGN OF A MULTI-AGENT RECONFIGURABLE MANUFACTURING SYSTEM ARCHITECTURE

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ABSTRACT

In recent years, the fields of reconfigurable manufacturing systems, holonic manufacturing systems, and multi-agent systems have made technological advances to support the ready reconfiguration of automated manufacturing systems. While these technological advances have demonstrated robust operation and been qualitatively successful in achieving reconfigurability, their ultimate industrial adoption remains limited. Amongst the barriers to adoption has been the relative absence of formal and quantitative multi-agent system design methodologies based upon reconfigurability measurement. Hence, it is not clear 1.) the degree to which these designs have achieved their intended level of reconfigurability 2.) which systems are indeed quantitatively more reconfigurable and 3.) how these designs may overcome their design limitations to achieve greater reconfigurability in subsequent design iterations. To our knowledge, this paper is the first multi-agent system reference architecture for reconfigurable manufacturing systems driven by a quantitative and formal design approach. It is rooted in an established engineering design methodology called axiomatic design for large flexible engineering systems and draws upon design principles distilled from prior works on reconfigurability measurement. The resulting architecture is written in terms of the mathematical description used in reconfigurability measurement which straightforwardly allows instantiation for system-specific application.

Keywords: multi-agent system, reconfigurability, reconfigurable manufacturing systems, axiomatic design.

1 INTRODUCTION

Manufacturing has become increasingly characterized by continually evolving and ever more competitive marketplaces. In order to stay competitive, manufacturing firms have had to respond with a high variety products of increasingly short product lifecycle [Mehrabi et al. , 2002; Pine, 1999]. One particularly pertinent problem is the need to quickly and incrementally adjust production capacity and capability. To fulfil the needs of enterprises with extensive automation, reconfigurable manufacturing systems have been proposed as a set of possible solutions [Mehrabi et al. , 2000].

Definition 1. Reconfigurable Manufacturing System [Koren et al. , 1999]: [A System] designed at the outset for rapid change in structure, as well as in hardware and software components, in order to quickly adjust production capacity and functionality within a part family in response to sudden changes in market or regulatory requirements.

Over the last decade, many technologies and design approaches have been developed to enable reconfigurability in manufacturing systems [Dashchenko, 2007; Setchi and Lagos, 2004]. These have included modular machine tools [Heilala and Voho, 2001; Ho and Ranky, 1995; Landers et al. , 2001; Shirinzadeh, 2002; Townsend, 2000] and distributed automation [Brennan and Norrie, 2001; Vyatkin, 2007] [Lepuschitz et al. , 2011]. Additionally, a wide set of IT-based paradigms such as Multi-Agent Systems [Leitão, 2009; Leitão et al. , 2012; Leitão and Restivo, 2006; Ribeiro and Barata, 2013a; b; Shen and Norrie, 1999; Shen et al. , 2003], Holonic Manufacturing Systems [Babiceanu and Chen, 2006; Ma ík et al. , 2002; McFarlane and Bussmann, 2000; 2003], Evolvable Assembly Systems [Ribeiro et al. , 2010], and Fractal Factories [Tharumarajah and Wells, 1997] have emerged. They include a number of notable reference architectures including PROSA [Van Brussel et al. , 1998], HCBA [Chirn, 2001] and ADACOR [Leitão and Restivo, 2006]. While these technological advances have demonstrated robust operation and been qualitatively successful in achieving reconfigurability, their ultimate industrial adoption remains limited [Marik and McFarlane, 2005].

Amongst the barriers to adoption has been the relative absence of quantitative multi-agent system design methodologies based upon reconfigurability measurement. Hence, it is not clear 1.) the degree to which these designs have achieved their intended level of reconfigurability, 2.) which systems are indeed quantitatively more reconfigurable 3.) how these designs may overcome their inherent design limitations to achieve greater reconfigurability in subsequent design iterations. In short, without a quantitative framework for assessing the design, potential industrial adopters are unconvinced by the technology's validation. Furthermore, and in addition to reconfigurability measurement, such methodologies must make a straightforward link between 1.) high level design principles (e.g. bionic, holonic, fractal) 2.) a reference architecture that is sufficiently general to apply to the scope of manufacturing systems it seeks to address 3.) the associated instantiation as a system-specific architecture 4.) and a detailed implementation with connected hardware. In short, even if a potential industrial adopter had confidence in a prototype implementation, there would be no certain to scale and transfer the knowledge of the prototype up to full-scale implementation. Rigorously derived reference architectures fill this gap because they provide they make all system-specific implementation simply instantiations of one design pattern.

This paper provides a multi-agent system reference architecture for reconfigurable manufacturing systems driven by a quantitative and formal design approach. In so doing, this paper makes four specific contributions. First, it roots itself in an established engineering design methodology: axiomatic design for large flexible engineering systems. Second, the architecture's design is directly informed by design principles distilled from prior works in reconfigurability measurement. Third, the resulting architecture is written in terms of the mathematical description used in reconfigurability measurement – thus facilitating its implementation. Finally, the reference architecture and its associated mathematical description straightforwardly address instantiation for system-specific application. These specific advantages have yet to be demonstrated in existing reference architectures such as PROSA [Van Brussel, Wyns, 1998], HCBA [Chirn, 2001] and ADACOR [Leitão and Restivo, 2006].

The remainder of the paper proceeds as follows. Section II qualitatively articulates the design strategy and rationale for the architecture. Section III details the underlying mathematical description of the architecture. Section IV then details the architecture's data model implementation. Finally, Section V brings the work to a conclusion.

This paper restricts its reconfigurability discussion to the shop-floor activities of discrete-part automated manufacturing system as defined in Levels 0-3 of ISA-S95 [ISA, 2005] where

Definition 2. Reconfigurability [Farid 2007]: The ability to add, remove and/or rearrange in a timely and cost-effective manner the components and functions of a system which can result in a desired set of alternate configurations; chosen here to be the addition/removal of new products and resources.

2 ARCHITECTURE DESIGN STRATEGY AND RATIONALE

The aim of this work is to develop an Axiomatic Design of a Multi-Agent Reconfigurable Manufacturing System (ADMARMS) Architecture. To this end, the central goal of the design is to conceive a multi-agent (control) system architecture that enables a highly reconfigurable manufacturing system when it is integrated with its physical devices. Here, reconfigurability is understood as the principle life cycle property which enables the desired behaviours described in the previous section. It is dependent upon the characteristics of the production's system structure [Farid, 2007; Farid, 2014b]. That said, Axiomatic Design states generally [Suh, 2001] and previous works on this subject [Farid, 2007; Farid, 2014b] have discussed that a well conceptualized architecture is also a *necessary prerequisite* for excellent production system performance. Furthermore, as a design methodology Axiomatic Design is able to highlight potential design flaws at an early conceptual stage; well before final implementation.

The architecture design strategy and rationale is directly informed by recent work in the reconfigurability measurement of automated manufacturing systems [Baca et al. , 2013; Farid, 2007; 2008a; Farid, 2008b; Farid, 2013; 2014b; Farid and Covanich, 2008; Farid and McFarlane, 2008; McFarlane and Farid, 2007]. These works showed that a high degree of reconfigurability could be achieved by fostering greater ***reconfiguration potential*** (i.e. the number of possible configurations of the system) as well as greater ***reconfiguration ease*** (i.e. the effort required to change from one configuration to another). Therefore, the architecture design strategy and rationale presented in this section is being described as a set of qualitative design principles which have been distilled from these prior works on quantitative reconfigurability measurement. The design principles for reconfiguration potential and reconfiguration ease are treated in turn and are actively used in the discussion of Section III. While a deep treatment of reconfigurability measurement is not feasible here, the interested reader is referred to these background references for the details of the mathematical developments in this work. The necessary aspects of these mathematical developments are revisited in Section III.

2.1 DESIGN PRINCIPLES FOR RECONFIGURATION POTENTIAL

The aspects of reconfigurability measurement related to reconfiguration potential were founded upon axiomatic design theory in which reconfigurable manufacturing systems may be classified as large flexible engineering systems.

Definition 3. Large Flexible Engineering System (LFES) [Suh, 2001]: an engineering system with many functional requirements (i.e. production processes) that not only evolve over time, but also can be fulfilled by one or more design parameters (i.e. production resources).

Furthermore, according to Axiomatic Design, this mapping of system processes to system resources requires adherence to the Independence Axiom.

Axiom 1. The Independence Axiom: Maintain the independence of the functional requirements [Suh, 2001].

In practice, this means that each functional requirement (i.e. production process) must be related mathematically to a design parameter (i.e. production resource). Ultimately, each match of production process to production resource is assigned an event (in the discrete-event sense) called a production degree of freedom [Farid and McFarlane, 2008] which individually and collectively have a number of interesting properties:

- Individually, they represent ***all*** of the available capabilities of the ***physical*** production system.
- Collectively, they represent the configuration of the production system.
- Their (countable) number represents the production system's reconfiguration potential.
- The production of any product can be described as a sequence of the production degrees of freedom.

In this regard, production degrees of freedom adhere to a relatively strict analogy to the mechanical degrees of freedom in a purely mechanical system [Farid and McFarlane, 2008].

Furthermore, it is important to recognize the difference between the ***existence*** and the ***availability*** of a production degree of freedom. The former is the presence of a capability regardless of whether it is currently functional or not. The latter addresses the condition of its functionality as a binary state. Therefore, the description of shop floor phenomena such as machine breakdowns may apply sequence-independent constraints that limit the number of production DOFs [Farid and McFarlane, 2008]. Additionally, there may exist sequence-dependent constraints that do the same between pairs of production degrees of freedom. Sequence-dependent constraints may arise from a rigidly implemented supervisory controller; although the relative (physical) geometry of resources ***always*** applies some sequence-dependent constraints [Farid and McFarlane, 2008].

With this production degree of freedom primer in mind, a number of design principles are distilled that maximize reconfiguration potential:

Principle 1. Application of Independence Axiom: Explicitly describe the agent architecture in terms of the production system's production degrees of freedom.

Principle 2. Existence: As a decision-making/control system, the multi-agent system must maintain a 1-to-1 relationship with the set of physical capabilities that ***exist*** on the shop floor.

Principle 3. Heterogeneity: The production degrees of freedom within the agent architecture must respect the heterogeneity of capabilities found within the shop-floor be they various types of transformation, transportation or storage processes.

Principle 4. Physical Aggregation: The agent architecture must reflect the physical aggregation of the objects that they represent.

Principle 5. Availability: The agent architecture must explicitly model the potential for sequence independent constraints that impede the *availability* of any given production degree of freedom.

Principle 6. Interaction: The agent architecture must contain agent interactions along the minimal set of physical sequence-dependent constraints.

Principle 7. Maximum Reconfiguration Potential: Aside from the minimal set of physical sequence-dependent constraints, the agent architecture should avoid introducing any further agent interactions (which may impose further constraints).

Because the production of the entire production line can be described as sequences of individual production degrees of freedom, it is logical to describe the agents in terms of these same production degrees of freedom (Principle 1). In that regard, production degrees of freedom are the quantitative equivalent of agent semantic ontologies. The production degrees of freedom must also be necessary and sufficient; neither overstating nor understating the production system's capabilities (Principles 2 and 3). The agents must also have a level of aggregation that mimics that of the physical entities that they represent (Principle 4). Next, the agent architecture must distinguish between the existence and availability of its capabilities (Principle 5). The existence of sequence-dependent constraints on the physical shop floor suggests for the need for the same amongst the agents (Principle 6). For example, a material handling process must end where another material handling process begins. Finally, adding agent interactions beyond the ones on the physical shop floor is likely to introduce unnecessary constraints (Principle 7).

2.2 Design Principles for Reconfiguration Ease

The aspects of reconfigurability measurement related to reconfiguration ease were founded upon the use of the production design structure matrix [Farid, 2008a; McFarlane and Farid, 2007]. It encourages the design of maximally cohesive and minimally coupled modules within the production system. To that end, three more design principles are added for reconfiguration ease.

Principle 8. Physical Agents: Align agents' scope and boundaries with their corresponding physical resources and their associated production degrees of freedom.

Principle 9. Encapsulation: Production system information should be placed in the agent corresponding to the physical entity that it describes.

Principle 10. Reconfiguration Method: The same reconfiguration process can require significantly different effort (measured in time, cost, or energy) depending on the method used to conduct the reconfiguration (and not just the reconfigured resources).

Principle 8 ensures that when a reconfiguration process occurs (i.e. addition, modification or removal of a production degree freedom), it does so simultaneously on the physical resource as well as on the corresponding agent. Previous reconfigurability measurement work has shown that in many cases misaligned informatic entities such as centralized controllers lead to greater coupling of production degrees of freedom [Farid, 2008a]; thus hindering reconfiguration ease. Principle 9 recognizes that information is more often used locally rather than remotely and thus encourages greater encapsulation and modularity. Principle 7 also serves to support the modularity of the production system agents. Finally, Principle 10 accounts for the potential for reconfiguration processes to be conducted manually or automatically.

3 MATHEMATICAL DESCRIPTION OF THE ARCHITECTURE

On the basis of the design principles described in the previous section, the Axiomatic Design Multi-Agent Reconfigurable Manufacturing System (ADMARMS) architecture is developed and is shown in Figure 1. It's high level structure is now discussed in terms of the mathematical treatment found in the reconfigurability measurement of automated manufacturing systems [Baca, Farid, 2013; Farid, 2007; 2008a; Farid, 2008b; Farid, 2013; Farid and Covanich, 2008; Farid and McFarlane, 2008; McFarlane and Farid, 2007].

3.1 Production System Knowledge Base

The production system knowledge base is the key matrix for describing a system's production degrees of freedom. Its usage is a mathematically explicit adherence to Principle 1.

Definition 4. Production System Knowledge Base [Farid and McFarlane, 2008]: A binary matrix J_S of size $\sigma(P)x\sigma(R)$ whose elements $J_S(w,v)\in\{0,1\}$ are equal to one when event e_{wv} exists as a production process p_w being executed by a resource r_v..

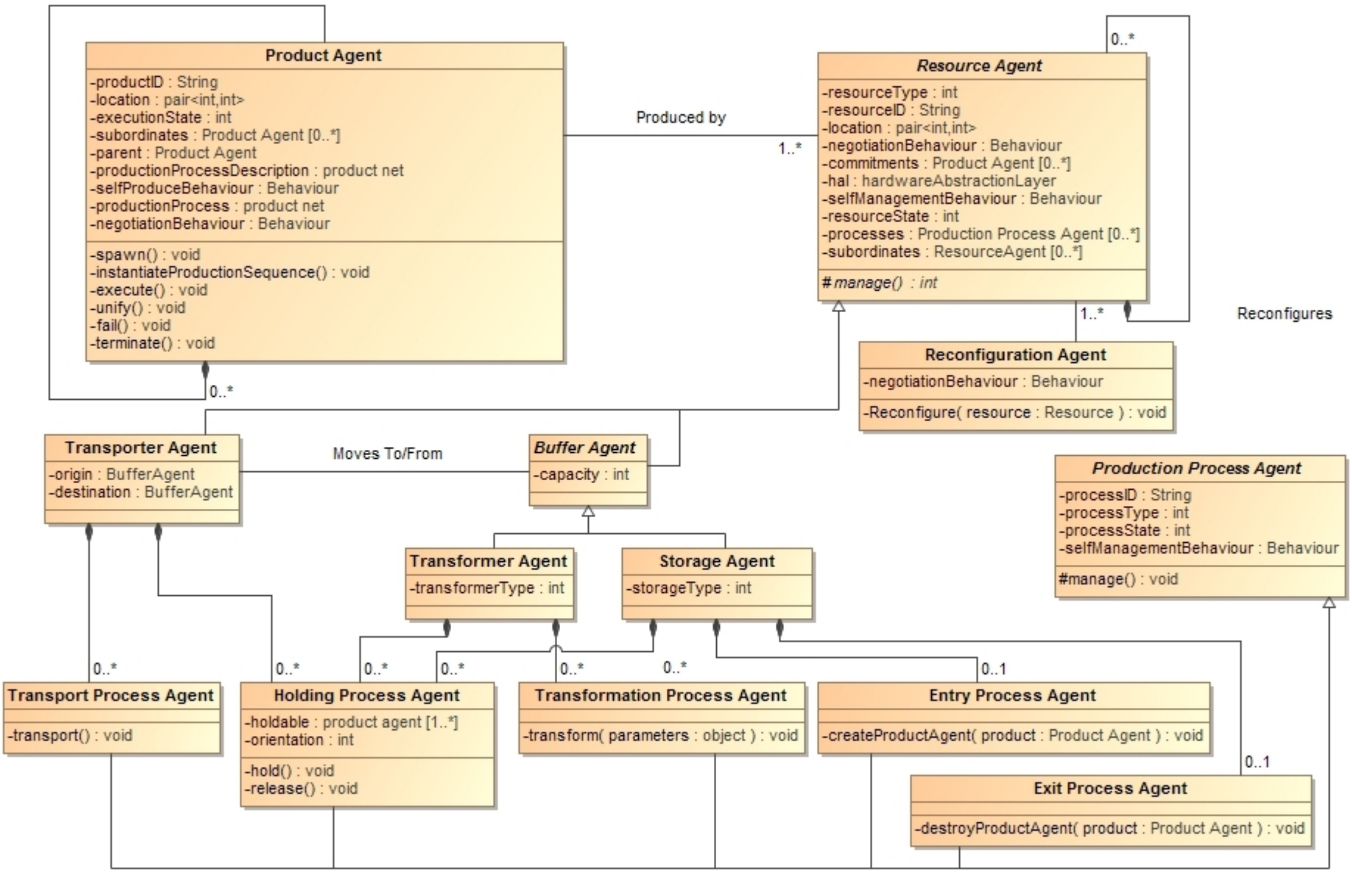

Figure 1. ADMARMS Architecture & Data Model

By Principle 2, these physical resources have their informatic counterpart in the resource agent (RA). It is decomposed into itself to allow a production system to be divided into a physical hierarchy of departments and cells (Principle 4).

Resource agents are further classified into transformer agents (TFA) M, storage agents (SA) B, and transporter agents (TPA) H to differentiate between the inherently different types of production resources. $R=M\cup B\cup H$. The first is often considered "value-adding" while the other two are often intentionally minimized. The architecture also recognizes that the transformation and storage resources and their respective agents may be grouped into a set of buffer resources and their respective agents (BA); locations in which products remain stationary (Principle 3). $B_S=M\cup B$ *[Farid and McFarlane, 2008]*.

While the resource agent effectively describes the system form, the production process agent (PPA) effectively describes the system function. While it is common that physical resources have their associated agents, a novel aspect of the ADMARMS architecture is the decision to assign agents to each production process. They act as component slaves of their resource agent masters. This serves to emphasize the distinction between the form of physical resources and the (potentially variable) set of behavioural production processes they can perform.

As with resource agents, the production process agents must be classified to account for the different types of activities on the shop floor (Principle 3). These include the entry and exit processes agents (ENPA and EXPA) for crossing the system boundary and transformation processes (TFPA) for value-adding processes [Farid, 2014a]. Mathematically, they have often been lumped into a single set of production processes P_μ. Transportation process agents (TPPA) P_η are defined between individual buffers. $\sigma(P_\eta)=\sigma^2(B_S)$ where $\sigma()$ gives the size of a set. Notice that the only resource-agent-to-resource-agent interaction occurs here because a transporter agent needs to know the identity of the origin and destination buffers. Holding process agents (HPA) P_γ account for the ability to fixture/hold a product during storage or transportation.

The overall production system knowledge base J_S can then be reconstructed straightforwardly. The transformation system knowledge base J_M relates P_μ to M. The transportation system knowledge base J_H relates P_η to $R=M\cup B\cup H$. M and B are included here to account for their "null-transportation" or storage processes where no motion occurs. The holding system knowledge base J_γ relates P_γ to R. Then J_S becomes [Farid, 2013; Farid and McFarlane, 2008]

$$J_S = \begin{bmatrix} J_M & | & \mathbf{0} \\ & J_{\bar{H}} & \end{bmatrix} \tag{1}$$

where [Farid, 2013]

$$J_{\bar{H}} = \left[J_\gamma \otimes \mathbf{1}^{\sigma(P_\eta)} \right] \cdot \left[\mathbf{1}^{\sigma(P_\gamma)} \otimes J_H \right] \tag{2}$$

and $\otimes$ is the kronecker product and 1^n is a column ones vector of length *n*.

3.2 Production System Scleronomic Constraints Matrix

Each of the resource and process agents (and their specific types) can potentially be unavailable due a physical fault or some rigidity in the control system (Principle 5). To account for this, the agents have an "on-off" status. These are described mathematically in the production system scleronomic (i.e. sequence-independent) constraints matrix.

Definition 5. Production System Scleronomic Constraints Matrix [Farid and McFarlane, 2008]: A binary matrix K_S of size $\sigma(P)x\sigma(R)$ whose element $K_S(w,v) \in \{0,1\}$ is equal to one when a constraint eliminates event e_{wv} from the event set.

It is calculated ***analogously*** to the production system knowledge base [Farid, 2013; Farid and McFarlane, 2008]:

$$K_S = \begin{bmatrix} K_M & | & \mathbf{1} \\ & K_{\bar{H}} & \end{bmatrix} \quad (3)$$

where [Farid, 2013]

$$K_{\bar{H}} = \left[K_\gamma \otimes \mathbf{1}^{\sigma(P_\eta)}\right] \cdot \left[\mathbf{1}^{\sigma(P_\gamma)} \otimes K_H\right] \quad (4)$$

From these definitions of J_S and K_S, follows the definition of sequence-independent production degrees of freedom.

Definition 6. Sequence-Independent Production Degrees of Freedom [Farid and McFarlane, 2008]: The set of independent production events E_S that completely defines the available production processes in a production system. Their number is given by:

$$DOF_S = \sigma(E_S) = \sum_{w}^{\sigma(P)} \sum_{v}^{\sigma(R)} \left[J_S \ominus K_S\right](w,v) \quad (5)$$

where the $A \ominus B$ operation is boolean subtraction.

3.3 Production System Rheonomic Constraints Matrix

Once the individual agents have been defined around production system degrees of freedom, the design of the architecture turns to defining the resource-agent-to-resource-agent interactions. In that regard and as mentioned previously, the only such interaction occurs because transporter agents need to know the identity of the origin and destination buffers (Principle 6). These minimal interactions are reflected in the production system rheonomic constraints matrix.

Definition 7. Rheonomic Production Constraints Matrix K_ρ [Farid, 2013; Viswanath et al. , 2013]: a square binary constraints matrix of size $\sigma(P)\sigma(R)x\sigma(P)\sigma(R)$ whose elements $K_\rho\ (\varphi_1, \psi_1) \in \{0,1\}$ are equal to one when string $z_{\varphi 1 \psi 2} = e_{w1v1}e_{w2v2}$ is eliminated and where $\psi = \sigma(P)(v\text{-}1)+w$.

Previous work has shown that K_ρ must be non-zero so as to account for basic rules of continuity; the destination of one production degree of freedom must occur at the same location as the origin of a subsequent one [Farid, 2013; Farid and McFarlane, 2008]. This includes transformation degrees of freedom which explicitly state where the corresponding transformation process must occur. Aside from these minimal constraints, the architecture does not introduce any other resource-agent-to-resource-agent interactions on the resource side (Principle 7).

3.4 Production Model

The design of the ADMARMS architecture then includes product agents (PA) as the informatic counterpart of the physical products (Principle 2). A product agent maybe decomposed into itself to allow a physical hierarchy of subassembly and component products (Principle 4). It is also important to note that the product agent must have some awareness of how it should be produced. This has been achieved previously with a product net.

Definition 8. Product Net [Farid, 2008b; McFarlane and Farid, 2007]:

Given product l_i, it may be described as:

$$N_{li} = \{S_{li}, E_{li}, F_{li}\} \quad (6)$$

where N_l is the product net, S_l is the set of product places, E_{li} is a set of product events, and F_l is set of product flow relations.

Definition 9. Product Event [Farid, 2008b]: A specific transformation process that may be applied to a given product.

In addition to the events, places and flow relations all have physical meaning. Each of the places represents a product or component at a raw, work-in-progress, or final stage of production. Finally, the flow relations describe which products or components receive which product events.

The presence of an instantiated product agent in the production system is achieved by the entry and exit process agents found within a given storage agent (Principle 5).

3.5 Product Feasibility Matrices

Once the individual product agents have been defined, the design of the architecture turns to defining the product-agent-to-resource-agent interactions. These are absolutely necessary operator-to-operand relations (Principle 6). The relationship between product events to transformation degrees of freedom is achieved with the product transformation feasibility matrix.

Definition 10. Product Transformation Feasibility Matrix $\Lambda_{\mu i}$ [Farid, 2008b; Farid, 2013]: A binary matrix of size $\sigma(E_{li})x\sigma(P_\mu)$ whose value $\Lambda_{\mu i}(x,j) = 1$ if e_{xli} realizes transformation process $p_{\mu j}$.

The relationship between products and the required holding/transportation processes is similarly defined.

Definition 10. Product Transportation Feasibility Matrix $\Lambda_{\gamma i}$ [Farid, 2008b; Farid, 2013]: A binary row vector of size $1x\sigma(P_\gamma)$ whose value $\Lambda_{\gamma i}(g) = 1$ if product l_i can be held by holding process $p_{\gamma g}$.

3.6 Production Design Structure Matrix

The subsections above collectively address the reconfiguration potential of the production system and so the attention now turns to reconfiguration ease. In that regard, the production system design structure matrix (PDSM) shown in Figures 2 &3 [Farid, 2008a] has been previously used for measurement. It captures the physical, energy, and informatic couplings between production system entities. While the PDSM is highly sparse, it does have heavy coupling on both sides of the main diagonal[Farid, 2008a]. As a result, this paper advocates heuristic-based approaches to usage rather than optimization. The latter being extremely computationally intensive (e.g. NP-hard job-shop NP-hard scheduling problems.)

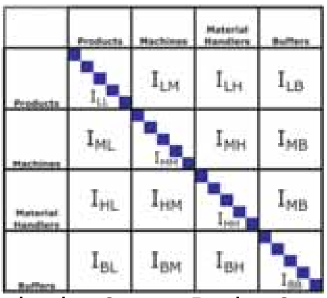

Figure 2. Production System Design Structure Matrix

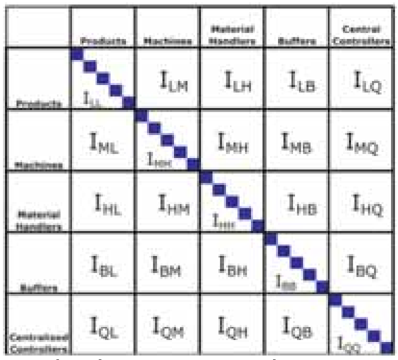

Figure 3. Production System Design Structure Matrix (with centralized controllers)

In the case of multi-agent systems in production systems, the scope of each agent aligns with the underlying production system resource or product (Principle 8). In such a case, the coupling between production degrees of freedom can be minimized. In contrast, centralized controllers introduce new blocks to the production system design matrix which appear as off-diagonal coupling between resources and their associated production degrees of freedom. As this architecture is developed to include the specific behaviours of agent-to-agent interactions and negotiations, care will be taken to demonstrate that each agent is maximally cohesive and minimally coupled (Principle 9).

3.7 Reconfiguration Processes

The final element of the ADMARMS architecture is to specify the method of conducting reconfiguration processes (Principle 10). In that regard, the reconfiguration agent (RCA) is an automatic way of changing the production degrees of freedom of a given resource agent. Mathematically, it is responsible for conducting the reconfiguration process [Farid and Covanich, 2008; Farid and McFarlane, 2008]:

$$(J_s, K_s, K_\rho) \rightarrow (J_s', K_s', K_\rho') \qquad (7)$$

Examples of reconfiguration agents are automatic tool changers (change of transformation degree of freedom), automatic fixture changers (change of holding degree of freedom) and conveyor gates (change of transportation degree of freedom).

4 ARCHITECTURE DATA MODEL IMPLEMENTATION

As shown in Figure 1, the previous section provided a high level mathematical description of the ADMARMS so as to identify its member agents. This section now discusses the contents of these agents from an implementation point of view. It is understood that these agents would be implemented in a multi-threaded programming language such as JAVA and adhere to the latest multi-agent standard platforms (e.g. FIPA, JADE) [Bellifemine et al. , 2007].

4.1 Resource Agent (RA)

The RA is an abstraction for all the potential manufacturing entities in the system. It encapsulates the common features of the specialized classes. Its parameters are described as follows:

-resourceType : int - a type that identifies the implementation class.

-resourceID : String - a unique identifier in the form of a serial number.

-location : pair<int,int> - a coordinate to keep track of its location.

-negotiationBehaviour : Behaviour - a negotiation behavior to mediate the interaction between the RA and a PA.

-commitments : Product Agent [0..*] - a list of commitments to various production agents.

-hal : hardwareAbstractionLayer - a hardware abstraction layer (HAL) that mediates low-level execution.

-selfManagementBehaviour : Behaviour - a persistent behavior that generically allows for self-management.

-resourceState : int - a state of the resource linked to its availability in the scleronomic constraints matrix.

-processes : Production Process Agent [0..*] - a list of production process agents that are associated with resource agent.

-subordinates : ResourceAgent [0..*] - a list of resources that are under the control of a specific resource in a master-slave relation.

Additionally, the resource agent has a single method:

manage() : int - an abstract management method invoked by the selfManagementBehavior parameter that monitors and updates the resource state.

Furthermore, the commitment parameter gives a measurement of the anticipated load on a resource and is fundamental to robust system operation when making further negotiations. It is necessarily updated after each successful execution of a production process. Also, the HAL serves as a generic interface that enables resources of the same type to operate similar physical devices regardless of the specific low-level implementation details. Therefore, the HAL decouples the agent environment from controller specific implementations [Ribeiro and Barata, 2013a].

4.2 Specializations of the RA

As shown in Figure 1, the RA is specialized as a BA, TFA, SA and a TPA. These are discussed in turn.

4.2.1 BUFFER AGENT (BA)

The BA is a specialized resource that denotes a resource with the ability of storing PAs. It has a single additional parameter:

-capacity : int - a finite capacity of PAs.

The TFA and SA stand as specializations of the BA.

4.2.2 TRANSFORMER AGENT (TFA)

The transformer agent abstracts shop-floor entities with transformation capabilities and therefore hosts both transforming and holding process agents (inherited from the BA). It has a single additional parameter.

-transformerType : int - a parameter that identifies the various types TFAs be they assembly, additive and subtractive in nature.

4.2.3 STORAGE AGENT (SA)

The Storage Agent is the implementation of the buffer concept. It is responsible for the storage, introduction, and removal of a PA within, into and from the system. Subsequently, it hosts the corresponding production processes. It also has a single additional parameter:

-storageType : int - a parameter that identifies the various types of SAs be they passive or active.

4.3 TRANSPORTER AGENT (TA)

The TA is responsible for moving a PA between buffer agents. Consequently, it has two parameters:

-origin : BufferAgent - the identity of the origin BA.

-destination : BufferAgent - the identity of the destination BA.

It hosts transportation process and holding process agents as it executes the motion between these buffers.

4.4 PRODUCTION PROCESS AGENT (PPA) AND ITS SPECIALIZATIONS

The PPA abstracts the different production processes hosted by the system's resources. It has the following parameters:

-processID : String - a unique identifier that identifies the process and its instance.

-processType : int - a type that defines the specialized class to which the PPA belongs.

-processState : int - a state of the PPA linked to its availability in the scleronomic constraints matrix.

-selfManagementBehaviour : Behaviour - a persistent behavior that generically allows for self-management.

Additionally, a production process has a single method:

manage() : int - a management method invoked by the selfManagementBehaviour.

This method, whose implementation must be provided by the specializing classes, is responsible for updating the state of the PPA and embodies the PPA's proactive behavior towards the emergence of constraints.

The PPA class has five specializations: the transformation process agent (TFPA), the transportation process agent (TPPA), the holding process agent (HPA), the entry process agent (EPA) and the exit process agent (EXPA). Collectively PPAs, Resource Agents and their associated specializations define the production system knowledge base.

4.4.1 TRANSPORTATION PROCESS AGENT (TPA)

The TPPA has a single method that is hosted by the TPA:

-transport() : void - a method responsible for executing the displacement of parts between buffers.

4.4.2 TRANSFORMATION PROCESS AGENT (TFPA)

The TFPA has a single method that is hosted by the TFA:

-transform(parameters : objective) : void - a method responsible for the transformation of a part.

TFPAs execute differently depending on their parameterization to accommodate the distinct transformation requirements.

4.4.3 HOLDING PROCESS AGENT (HPA)

The HPA has two parameters that relate to the product agent:

-holdable : product agent [1..*] - a parameter to define which parts can be held.

-orientation : int - a parameter to define the orientation of that part.

In addition, the holding process agent has two methods:

hold() : void - a method to allow the PA to be held.

release() : void - a method to allow the PA to be released.

The HPA is hosted conjointly with either a TFPA or a TPPA by a TFA or TPA respectively.

4.4.4 ENTRY & EXIT PROCESS AGENTS (ENPA & EFPA)

The ENPA and the EXPA create and destroy product agents with their respective methods.

-createProductAgent(product : Product Agent) : void - allows for a new order to spawn a new product agent.

-destroyProductAgent(product : Product Agent) - allows a completed product to be registered as a fulfilled order.

4.5 PRODUCT AGENT (PA)

The PA abstracts each active product under production in the system and has the following parameters:

-productID : String - a serial number as a string.

-location : pair<int,int> - a location coordinate.

-executionState : int - a state variable that captures the condition of the overall process.

-subordinates : Product Agent [0..*] - a list that is used when the PA has subordinate PAs. From a structural point of view, each product may be composed of other subordinated products. This composition models sub-assemblies and component parts.

-parent : Product Agent - a string that is used when the PA is subordinate to another PA. This string mirrors the composition relationship with the aggregation relationship. Parent product agents can proceed to complete their product events only after the completion of the subordinate PA's product events.

-productionProcessDescription : product net - captures the flow of product events. Its hierarchical decomposition encourages a similar decomposition of the resulting product nets hence creating different views, with levels of abstraction, over the entire set of product events that define the production of a product. Each PA establishes an identity with a final form of an assembly, sub-assembly, part or material.

The autonomy of the PA is defined by its main persistent behaviour:

-selfProduceBehaviour : Behaviour - a behaviour that controls the production process of the PA. It has two main phases: configuration and runtime.

The configuration phase is responsible for initialization routines, evaluation and instantiation of the PA's production process. These are carried out by different methods:

-spawn() : void - a method that spawns all the PA's subordinates.

-instantiateProductionSequence() : void - a method that evaluates and instantiates the production process description and subsequently populates the product net's associated production processes.

-productionProcess : product net - a net that stores the association between product events and production processes. It provides the required information to devise the path connecting all the resources allocated in this process.

-negotiationBehaviour : Behaviour - a behaviour that encapsulates the communication and negotiation logic between the PA and the system's resources. It is activated in the configuration phase to ensure the initial association of processes and resources and later, in runtime, as a response to disturbances.

The runtime phase controls and monitors the production process and disturbances. These actions are implemented in the execute method.

-execute() : void - this method implements a supervisory state machine that governs: resource activation, agent unification/termination and re-negotiation. It describes all the PA to PA and PA to RA interaction logic. This state machine is therefore supported by three methods:

-unify() : void - a method that signals the parent PA that this subordinate PA has successfully terminated its process and the resulting sub-product can be integrated in the parent's process.

-fail() : void - a method that signals the parent PA that this subordinate has encountered an unrecoverable fault and cannot be integrated in the parent's process.

-terminate() : void - a method that removes a subordinate PA from the system in a clean way or removes the top level PA at a resource hosting an exit process agent.

4.6 Reconfiguration Agent (RCA)

The RCA's behaviour is mainly defined by one function:

-Reconfigure(resource : Resource) : void - reconfigures the process agents in a specific resource and ensures that the instantiation of new process is conflict free.

The reconfiguration occurs on request from a RA and through a negotiation procedure whereby the RA asks the RCA to enable new processes or re-parameterize existing ones. The RCA will then assess the availability and potential reconfiguration conflicts on the desired processes and reconfigure the RA accordingly.

5 CONCLUSION

To our knowledge, this paper is the first multi-agent system reference architecture for reconfigurable manufacturing systems driven by a quantitative and formal design approach. This is in contrast to existing reference architectures (e.g. PROSA, HCBA, ADACOR) which were qualitatively developed on the basis of experienced design intuition. The ADMARMS architecture is rooted in an established engineering design methodology called axiomatic design for large flexible engineering systems and draws upon design principles distilled from prior works on reconfigurability measurement. The resulting architecture is written in terms of the mathematical description used in reconfigurability measurement which straightforwardly allows instantiation for system-specific application. Future work will seek to 1.) implement this architecture in virtual and hardware testbeds and measure the consequent reconfigurability and 2.) benchmark this reference architecture with respect to the existing alternatives.

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AN AD OPTIMIZED METHOD FOR THE STRUCTURAL ANALYSIS OF PRESSURE VESSELS

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ABSTRACT

The Axiomatic Design theory allows finding the right solutions in order to respond to functional needs of a product. Adopting the best solution is important in order to avoid a non-optimal design that can result in losses of time and money.

Axiomatic Design theory (or simpler AD theory) may concern not just the design of a product but it can also deal with defining processes or tools.

The usage of the most efficient and effective tools is a more and more important issue in engineering activities in order to achieve results with short times and optimized resources and funds. From this point of view the Axiomatic Design theory can be used in order to select the proper calculation method that permits to achieve these goals. Pressure vessels are quite common parts in several machines or plants, usually they present round bottoms but sometimes a flat bottom is required to minimize their sizes.

The scope of this paper is to introduce an optimized AD calculation method in order to perform structural analysis of a pressure vessel with a lower planeside and several reinforcements.

Two methods may be used to solve the structural issue. They will be introduced in the following passages. Their design matrices, according with the first axiom, will be found and on the basis of these matrices a comparison between these approaches will be carried out.

Keywords: Stress and strain evaluation, pressure vessel, energy method, reinforced flat bottom.

1 INTRODUCTION

Choosing the best solution, according to the axiomatic design theory, is increasingly important in modern engineering activities to reach maximum performance in terms of timesaving and economical convenience. The theory [*Suh,* 1990] and [*Suh,* 2001] is not valid just to perform the best design related to goods or services but it could be successfully applied also at physical models and calculation methods which are common in engineering practice. Choosing the wrong solution could lead to loss of time and higher costs for whatever these applications, not depending on their kind. The usage of calculation methods and tools, which permit to minimize the effort in order to simulate mechanical systems behaviour, is deeply important to achieve time reduction in several engineering issues and allows being able to absorb eventual delays in production or in other functions of the company. In this paper it will be shown how engineers can use Axiomatic Design in order to select and use the best model and calculation method to achieve valid results and solve some problems in designing goods with efficiency and efficacy. In this paper two different approaches will be described in order to solve the issue concerning the determination of stresses in a pressure vessel. Both of them will be compared from the point of view of the AD theory.

2 SCOPE AND USED APPROACH

This paper will show an alternative calculation approach to solve a structural problem, finding both stresses and strains at the bottom of a pressure vessel. This model will be optimized from the point of view of Axiomatic Design theory in respect of a more classical method. The design matrices for both the approaches will be drawn and their compliance with the best condition, according with the first axiom, will be examined.

Both the two methods may be used to find stresses and strains of a vessel which is steel made and has some welded reinforcements under the lower plane side (Figure 1). The found values for stresses are useful to be compared with the maximum one for the material according with the most common failure criteria (Von Mises's or Tresca's).

A case study for the validation of the proposed method is going to be presented in this paper. Both the alternative method and the FEM analysis will be applied to a pressure vessel with a cylindrical sidewall and a welded flat bottom. The vessel is pressurized inside and its upper side is tight closed by a cap. A hydrostatic pressure is assumed to be present within the vessel. Five beams are welded under the lower flat end in order to improve both the stiffness and the strength and to avoid bending. The reinforced vessel can be seen in Figure 1.

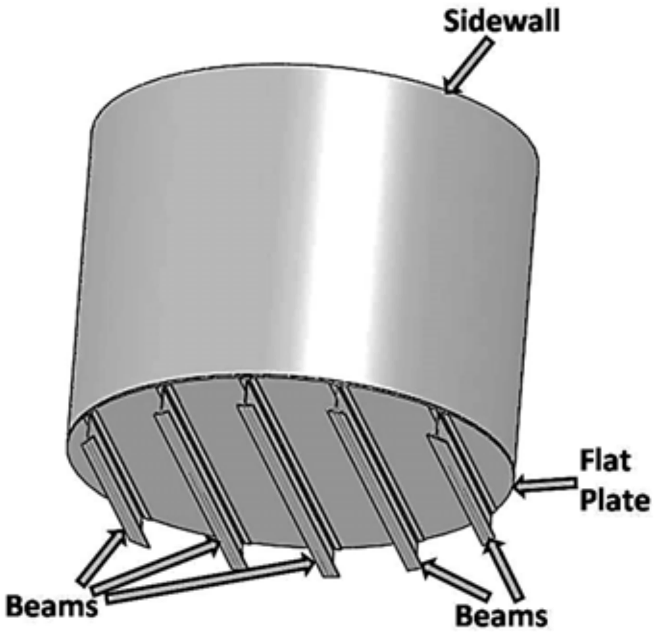

Figure 1 Pressure vessel with reinforced flat bottom.

Before taking into account how to model and find the stresses in the reinforced lower end, the issue of the structural strength under load for the whole vessel and its parts has been analyzed from an axiomatic design point of view.

2.1 DECOMPOSITION OF THE PROBLEM CONCERNING DETERMINATION OF STRESSES.

Obviously the whole vessel has to resist to the internal pressure, so the complete map of the requested checks can be defined by decomposing the highest-level functional requirement (FR) and the corresponding design parameter (DP), creating hierarchies of FRs, and DPs. This is done through zigzagging among the physical and functional domains, according with the Thompson's notes [Thompson, 2013].

The main functional requirement (FR) at the higher level expresses what the vessel should do. According with the axiomatic theory several main FRs could be found by referring to specific regulations about this kind of application.

This case deals with one FR design since the main FR is "To resist under the stresses due to pressure" and it is common for both the methods since it is a general requirement at this level of decomposition. This is valid for the whole vessel, not depending by how the calculation of stresses in the reinforced bottom is achieved. A way to achieve this main FR is obviously the right "sizing of all parts", that is DP1. The main FR is further split into several FRs at the second layer of zigzagging depending on where the vessel shall resist; so the FR1.1 is "to resist the lateral pressure, FR1.2 is "to resist the pressure on the cap" and FR1.3 is "to resist the pressure at the bottom side". The DPs that respond to the stated FRs are: "stresses in the sidewall" (DP1.1), "stresses in the cap" (DP1.2) and "stresses in the bottom area" (DP1.3). Figure 2 shows the design matrix for these upper layers of mapping which links requested checks (FRs) and corresponding design parameters (DPs).

	DP1	DP1.1	DP1.2	DP1.3
FR1	X			
FR1.1		X		
FR1.2			X	
FR1.3				X

Figure 2 Design matrix concerning first checks and upper layers decomposition.

This design matrix links through its diagonal the first checks (or functional requirements) to the corresponding design parameters. This means that each check can be solved independently from the others.

At a lower layer, continuing the decomposition, single formulas can be found. These link geometries to the stresses values at least for FR1.1 and FR1.2. Finding internal stresses in the sidewall and in the cap is quite easy using models that are dealt in literature [*Jawad*, 1994], [*Moss,* 2004] [*Nerli*, 2005], considering the hypothesis of small thickness wall because of the big ratio between thickness and diameter of the vessel. Referring to Figure 3 the values for tangential stresses σ_t, radial stresses σ_r and axial stresses σ_a are those shown through (1):

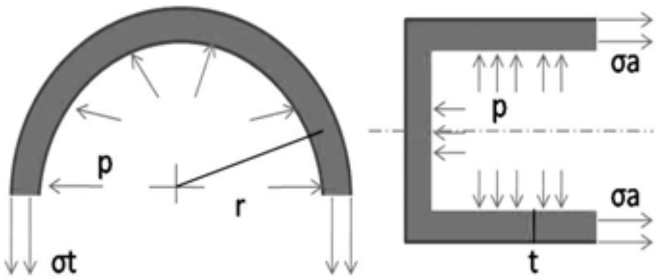

Figure 3 Pressure vessels theory small thickness walls.

$$\sigma_t = \frac{p \cdot r}{t} \qquad \sigma_a = \frac{p \cdot r}{2 \cdot t} \qquad \sigma_r = 0 \quad (1)$$

The cap and the sidewall are solved quite easily through the application of the classical theories of pressurized vessels. On the other hand, computing the contributes of the five beams on the overall strength of the bottom is a bit more complicated since we have to solve a hyperstatic system with several unknown variables. Due to this, finding the stresses and the strains in the bottom of the vessel could be expensive in terms of time and resources. An alternative is represented by an energy criterion which permits to compute stresses through the width of an equivalent system whose the elastic energy is the same as the sum of those from the single bottom and the five reinforcements. These two ways to compute stresses will be compared evaluating the agreement level to the best condition described in the first axiom of the AD theory, i.e. the decoupled design.

The algorithms are adopted as functional requirements since they express mathematical functions which link input and output variables. Each algorithm has to be deterministically solved; therefore it sets what input values are needed in order to find outputs. These FRs are different for all methods since they are the requested algorithms to solve the problem. Also the main DP is split in several lower DPs: they are all the requested variables to solve the algorithms.

As previously stated, the two methods are diversified by how they achieve these functions in the lower layers of zigzagging.

2.2 FIRST METHOD: MODELING OF REINFORCED BOTTOM LIKE AN HYPERSTATIC SYSTEM

The calculation of stresses in the lower end which is composed by a round flat plate, reinforced through welded beams, is quite difficult. A cross section of the bottom of the vessel and of the welds is shown in Figure 4. The calculations about the welds are omitted because they are well present in literature [*Caffè*, 2012]; therefore they can be executed apart.

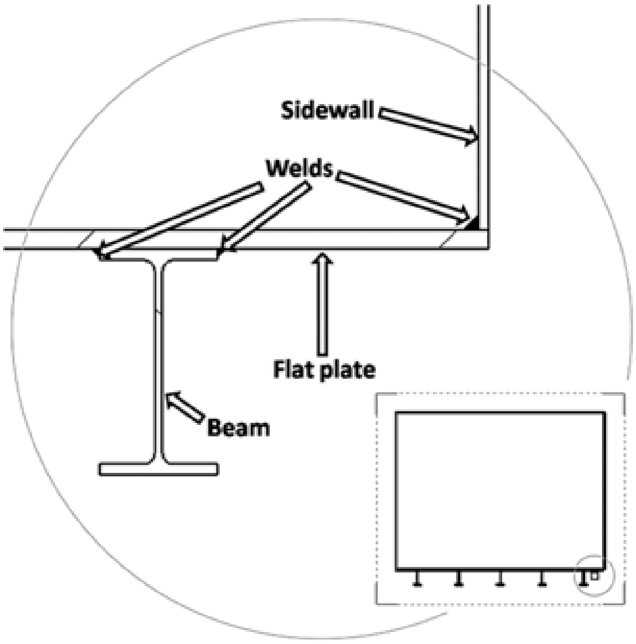

Figure 4 Detail of a section of the bottom.

The welded beams are used in order to enhance the strength and stiffness of the flat end of the vessel. These five reinforcements, which are equally spaced, have the same cross section but different lengths to follow the perimeter of the lower round shaped plate.

Due to this assumption the flat plate and these beams may be considered as a standalone structure which is welded to the sidewall. A way to reduce the 3D problem in a 2D simpler case is achieved through considering of a narrow diametric slice of this standalone part, composed by the plate and the five beams. This passage is possible because of the specific boundary condition, i. e. the internal pressure that is uniformly distributed on the surface of the plate. The result is a structure that is loaded by a homogeneous pressure distribution, whose moments of inertia of beams are calculated in the original cross section. In Figure 5 a scheme of this representation can be seen.

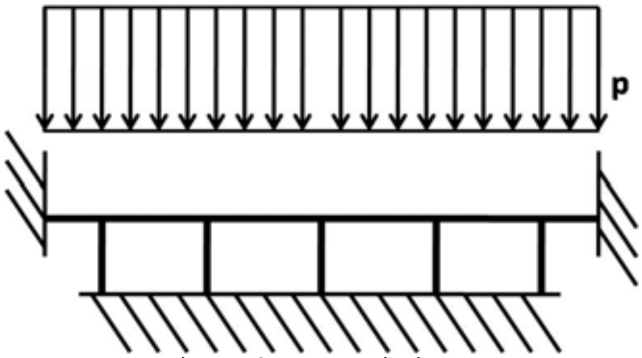

Figure 5 2D structural scheme.

This is clearly hyperstatic and quite complicated to solve, so it has usually calculated through FEM analysis. This 2D hyperstatic system has three degrees of freedom since it can be considered as a single structure. The authors suppose it has seven fixed joints. They are constraints that eliminate three degrees of freedom for each one. The degrees of hyperstaticity are counted through the difference between the degrees of constraints and the degrees of freedom. In this case the degrees of constraints result twenty one while the degrees of hyperstaticity are eighteen.

The authors assume that the functional requirements are satisfied by DPs; therefore, assuming a right handed orthonormal reference system whose axles are "x", "y" and "z" and the centre is "O", it allows defining the FRs. FR1.3.1 is the sum of all external forces along x axle which is equal to zero, FR1.3.2 is the sum of all external forces along y angle which is equal to zero and FR1.3.3 is the sum of all external moments along z axle which is equal to zero. These three equations are written below as the system (2):

$$\begin{cases} \sum F_x^{ext} = 0 & FR1.3.1 \\ \sum F_y^{ext} = 0 & FR1.3.2 \\ \sum M_z^{ext} = 0 & FR1.3.3 \end{cases} \tag{2}$$

The DPs are assumed to be the variables which appear in the three equations, therefore there are twenty one DPs numbered from DP1.3.1 to DP1.3.2. Since the three equations are not linearly independent all DPs will be present in every equation. The design matrix takes into account these considerations (Table 1).

The third layer of decomposition is represented through a complex matrix because equations are not linearly independent. To solve these equations and find the stresses in the bottom of the vessel, the hyperstatic system can be manually calculated; otherwise its behaviour can be simulated through a FEM analysis.

	FR1	FR1.1	FR1.2	FR1.3	FR1.3.1	FR1.3.2	FR1.3.3
DP1	X						
DP1.1		X					
DP1.2			X				
DP1.3				X			
DP1.3.1					X	X	X
DP1.3.2					X	X	X
DP1.3.3					X	X	X
DP1.3.4					X	X	X
DP1.3.5					X	X	X
DP1.3.6					X	X	X
DP1.3.7					X	X	X
DP1.3.8					X	X	X
DP1.3.9					X	X	X
DP1.3.10					X	X	X
DP1.3.11					X	X	X
DP1.3.12					X	X	X
DP1.3.13					X	X	X
DP1.3.14					X	X	X
DP1.3.15					X	X	X
DP1.3.16					X	X	X
DP1.3.17					X	X	X
DP1.3.18					X	X	X
DP1.3.19					X	X	X
DP1.3.20					X	X	X
DP1.3.21					X	X	X

Table 1 Design matrix of the hyperstatic system

2.3 SECOND METHOD: CALCULATION OF THE BOTTOM THROUGH THE ENERGY BALANCE.

The energy method avoids solving the structural analysis since it calculates the thickness of an equivalent lower plate taking into account the overall stiffness of the bottom area including the reinforcements and the plate. To achieve this simplified model, the effects of the reinforcements have been taken into account, decomposing them and neglecting which are not important. This way to look at the problem allows modelling the beams like springs, neglecting secondary effects like internal damping that is given by material. The authors suppose the lower plate and the reinforcements have the same displacements and strains since their material is the same and there are no clearances between them. Calculation about the welds is neglected and the boundary condition about pressure is the same as in paragraph 2.2. In Figure 6 a scheme of the model applied to the case study is shown.

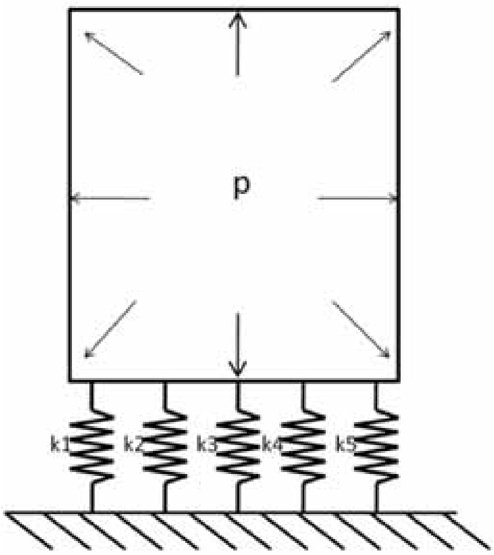

Figure 6 Scheme of the energy model applied to the case study.

Another hypothesis is that the stiffness coefficients for each spring, i.e. a single beam, are all the same, so the equation for the energy balance can be written as:

$$\sum_{i=1}^{5}(J_{beam-i}) + J_{plate} = J^* \qquad (3)$$

In the equation (3) J_{beam-i} is the amount of the elastic energy for the i-th beam, J_{plate} is the amount of the elastic energy for the flat plate and J^* is the amount of the elastic energy for a dummy system which takes into account the inertia moments of the several parts. The formula for the elastic energy is well known as:

$$J = \frac{1}{2}k\Delta l^2 \qquad (4)$$

where "k" is the stiffness coefficient and "Δl" is the elongation. It can be considered that following relationships are valid for springs and in presence of a normal force:

$$F = k \cdot \Delta l \qquad (5)$$

$$F = p \cdot A \qquad (6)$$

where "A" is the normal surface in respect with the applied force. Two more formulas have to be considered:

$$p = E \cdot \varepsilon \qquad (7)$$

$$\varepsilon = \frac{\Delta l}{l_0} \qquad (8)$$

where l_0 is the initial length (no applied loads) of these springs or the initial thickness for the plate (named $s_0$in such case). If (5), (6), (7) and (8) are substituted in (4) it can be obtained that $J = AE\varepsilon^2\Delta l_o$ and (3) becomes:

$$\sum_{i=1}^{5}\left(\frac{1}{2}A_iE\varepsilon^2 l_0\right) + \frac{1}{2}A_{plate}E\varepsilon^2\, s_0 = \frac{1}{2}A_{plate}E\varepsilon^2 s^* \qquad (9)$$

The product $\frac{1}{2}E\varepsilon^2$ is the same for all polynomials since both the vessel and several beams are made by the same steel, according with the hypothesis, so it is easily elided from the equation above and (9) becomes:

$$l_0 \cdot \sum_{i=1}^{5} A_i + A_{plate} \cdot s_o = A_{plate} \cdot s^* \qquad (10)$$

where s^* can be found using equation (10) and taking into account the moments of inertia of the system. Then the stresses can be calculated as the stresses in a round plate under a constant pressure distribution. The formulas for the calculation are present in literature [*Jawad*, 1994], [*Moss*, 2004] and [*Szilard*, 2004] and the problem is reduced just to one equation with one unknown variable.

According with the defined functional requirements and the design parameters, the two equations to calculate s^* and the equivalent state of stresses σ_{eq} are assumed as FR1.3.1

and FR1.3.2, while s^* and σ_{eq} are DP1.3.1 and DP1.3.2. The design matrix for this method is shown in Table 2.

	DP1	DP1.1	DP1.2	DP1.3	DP1.3.1	DP 1.3.2
FR1	X					
FR1.1		X				
FR1.2			X			
FR1.3				X		
FR1.3.1					X	
FR1.3.2						X

Table 2 Design Matrix for the Energy Method.

2.4 RESULTS AND VALIDATION OF THE MODEL.

The energy model has been applied to a case study in order to compare results with those achieved from a FEM analysis. The aim of this comparison is having a first validation of the proposed energy method that has been obtained considering AD first axiom. A pressure vessel made by steel with a flat bottom and a cylindrical sidewall has been considered for the case study. Under the flat plate five beams are welded and the hydrostatic pressure inside is 3 bar. The result of the FEM analysis for stresses is shown in Figure 7.

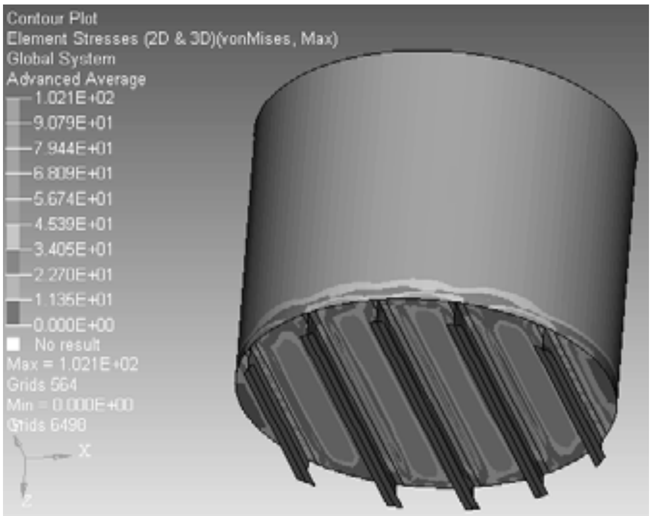

Figure 7 Results of the FEM Analysis for stresses.

The maximum value for stresses in the bottom is almost 102 MPa. The achieved stress value from the AD optimized approach is 99,7 MPa, therefore the comparison between equivalent stresses from both the methods has shown an estimated difference next to 2.3%. This slight difference between results leads to consider valid the proposed model in order to perform a first sizing or structural check using the AD optimized method.

3 CONCLUSIONS

In this paper an AD optimized example for structural analysis of pressure vessels is proposed. Pressure vessels are very common in industrial applications and although the round bottom ones are often better choices, in several cases the flat bottom vessels are requested. This kind of vessels is often reinforced through beams and two approaches to calculate stresses within the parts have been presented.

Two methods to calculate stresses into the structure have been examined according to Axiomatic Design Theory: The first method is the classical approach which is achieved through the resolution of a hyperstatic system, the second one takes into account a balance among the elastic energies of the parts under pressure. This alternative model, which is optimized from an AD point of view, has been proposed in order to solve structural analysis that otherwise would be quite complicated. The diagonal matrix, which links FRs and DPs, has been drawn out for this method, resulting in a decoupled design.

A validation of the proposed model has been performed comparing the achieved results to the obtained ones from a FEM analysis. This comparison has shown how values for stresses in the reinforced flat bottom from both the approaches are quite near and the proposed model can be used in a first structural check with good level of approximation.

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DESIGN OF THERMALLY STABILE 2D PHOTONIC CRYSTALS FOR THERMOPHOTOVOLTAIC SYSTEMS

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ABSTRACT

For maximized energy conversion efficiency on thermophotovoltaic (TPV) systems, 2D photonic crystal (PhC) selective emitters have to be operated at elevated temperature of over 1100 °C. Since 2D photonic crystal selective emitters have periodic micro/nano-scale structures at the surface, they easily lose their structural integrity at such a high temperature in much shorter time than the required system's operation life. In this work, thermal failure modes of 2D photonic crystal selective emitters are characterized and top level functional requirements to prevent thermal degradation are defined and decomposed. By uncoupling the coupled nature of the surface diffusion, we found a system thermally stable over a long operation of TPV systems.

Keywords: 2D Photonic Crystals, selective Emitters, Thermal Stability, Thermo Photovoltaic

1 INTRODUCTION

Photovoltaics (PVs) are energy conversion systems that can directly convert solar radiation into electricity. Most of the solar photovoltaics are using p-n junction solar cell, which has a theoretical limit, known as Shockley-Queisser (SQ) limit. This limit, or loss, results from the mismatch of wavelength on emitter side and PV cell side. To overcome this SQ limit, there were several tries known as the third generation solar cells, such as multi-layer ("tandem") or multi-junction photovoltaic cells. However, as of this year, the cost of multi-layers or multi-junction solar cells is still too high to use except for specialized applications.

Solar Thermo Photovoltaic (S-TPV) cells are also one of the third generation solar cells [Swanson, 1979 & Davies, 1994]. However, S-TPVs pursue a very different strategy to increase the solar-to-electricity energy conversion efficiency based on the same photovoltaic principle. Rather than focusing on the PV cell, the emphasis is shifted to controlling the spectra of the photons entering the PV cell. Figure 1 shows the strategy to achieve this effect [Andreev, 2007 & Baxter, 2009]. Broadband solar insolation is first absorbed by the surface, which heats the absorber to 1000 - 2000 °C. On the other side of the absorber is the emitter, which re-radiates photons that are optimized to match the photovoltaic cell.

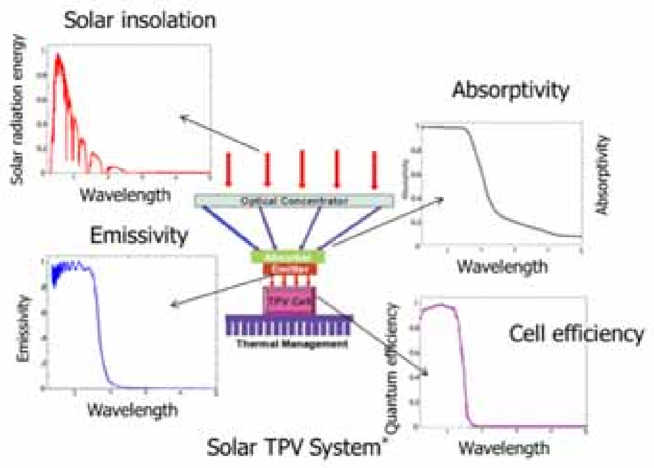


Figure 1. Illustration of a solar-TPV converting system.

The theoretical maximum efficiency of such solar TPV converters is known as 85.4 % at 2300 °C for full concentration and 54% at same temperature with no-concentration [Nils-Peter, 2003 & Martí, 2003]. These numbers came from the simple calculation of assuming black absorber, no heat losses, adiabatic and reversible. However, still, to achieve maximum energy conversion efficiency, the system has to be operated at over 1100 °C.

In detail, solar TPV's efficiency gains come from the spectral control of photons. The spectral control for solar TPV includes two parts. One part of the spectral control is absorption of solar radiation. The other part is the delivery of photons emitted from the solar absorber to the photovoltaic cell. The later part has been studied more due to the broader application of TPV, other than solar TPVs. Two strategies have been pursued for this photon emission control. One is the control of emission directly by using selective emitters based on new materials [Nelson, 1995 & Bitnar, 2002], novel surface structures [Heinzel, 2000], interference filters [Martin, 2002 & Hofler 1983], and photonic crystals. The major difficulty with this approach lies in the high temperature operation of the emitters, at which materials can lose their stability. The other strategy is spectral control on the PV cell side, by reflecting back unwanted photons, which are mostly below the band-gap. This approach has the advantage that spectral reflectors on the cell side are operated near room temperature.

So far, many problems associated with selective absorber, selective emitter, and interference filters have been solved. However, no one yet has reported intensive study on thermal stability of selective emitters. In this study, to solve thermal stability issues on selective emitters, we applied axiomatic approaches.

2 SECTIVE EMITTER DESIGN

For high efficiency of S-TPVs, or even for TPV systems, achieving good spectral control at high temperatures is the most challenging part. Because, in general, the feature size of the spectral control device (in the case of 2-D photonic crystal) is of the order of 100 nm to sub-microns. This nano/micro-scale device cannot maintain its geometrical features and optical performance at very high temperatures, 800 – 1300 °C, the general operation temperatures of S-TPV and TPV. Very little research has been reported on the thermal stability of selective emitters. To verify thermal degradation modes of selective emitters, we performed firing test with focused ion beam (FIB) milled micron-size hole at 1,200 °C.

2.1 THERMAL DEGRADATION MODES

By having 1,200 °C firing test with single-crystal and polycrystalline tungsten samples, we found four major degradation modes: grain growth, oxidation, surface diffusion and evaporation. At first, we could observe surface diffusion (figure 2) and recrystallization (figure 3). Figure 2 is thermal stability test results of micro-sized holes on poly-crystalline tungsten surface: (a) polished surface with focused ion-milled 5 μm diameter and 2 μm deep trenches; (b), (c) and (d) 100-hour annealing at 1,200 °C.

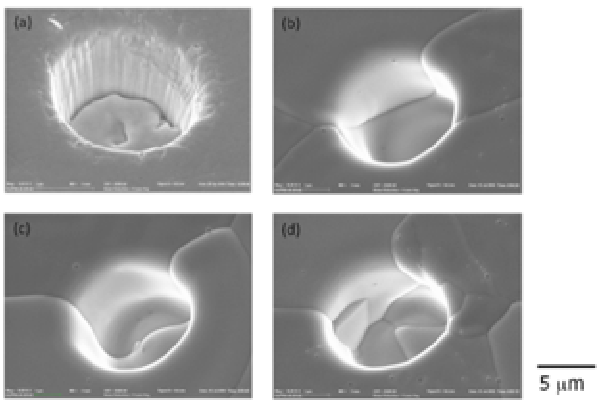


Figure 2. Thermal degradation on micro-holes

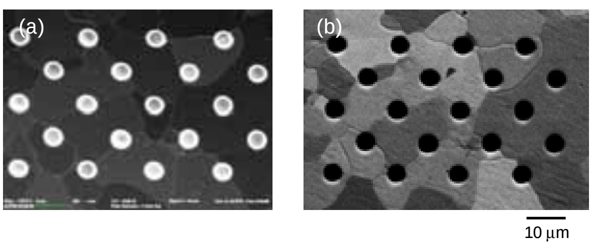


Figure 3. Grain growth and recrystallization

Figure 3 is the more zoomed out view to see the grain boundaries and their growing. Polished poly-crystalline tungsten, twenty holes were drilled using focused ion beam milling and fired for 100 hours. (a) is the SEM image of 100 hours annealed at 1,200 °C and (b) is that of additional 40 hours more annealing at 1,200 °C. Fast grain growth was observed in the beginning, but once fired at 1,200 °C for 100 hours, additional firing did not show much increase in grain size.

It was not clear whether smoothing out of the curved surface came from surface diffusion or evaporation/re-condensation. However, reviews on analytical studies revealed that both phenomena are closely related to curvature of the sub-micro meter structures. Based on Mullin's analysis, a theoretical model for the micro/nano-scale structure thermal degradation caused by surface diffusion is proposed. In the full form of Mullin's equation, the second derivative of the curvature along the surface $\partial^2 K/\partial s^2$, pressure, and temperature are the key parameters that affect the spatial distribution of surface diffusion [Mullins, 1957]. Since the operational conditions can be assumed as isothermal and isobaric, surface diffusion is fully determined by the second derivative of curvature, equation (1). The velocity of the surface in the normal direction $v_{n,d}$, is then given by [Mullins, 1957]:

$$v_{n,d} = \gamma\Omega^2 n \frac{D_s}{kT}\frac{\partial^2 K}{\partial s^2} \tag{1}$$

where n is the number of atoms per unit area and D_s is the coefficient of surface diffusion.

At high temperatures, the amount of material that is vaporized from a solid surface can be significant and creates a locally high vapor pressure promoting re-deposition on nearby surfaces. In this case, the normal surface velocity $v_{n,e}$ by which evaporation and re-condensation occurs is also derived [Balluffi, 2005]:

$$v_{n,e} = -\frac{\gamma\Omega^2 P_{eq}}{kT} K \tag{2}$$

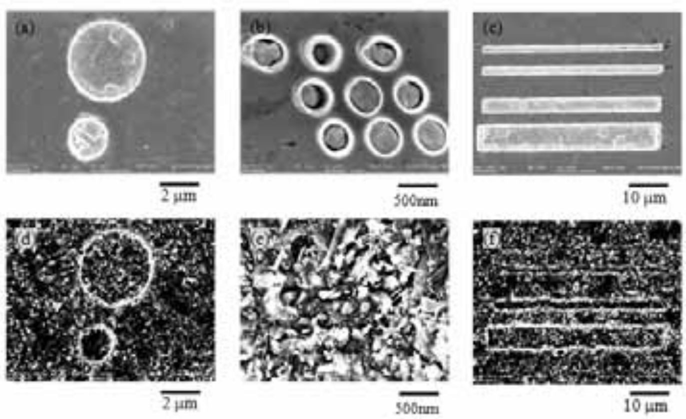


Figure 4. Thermal oxidation on sub-micron structures

where, A is a vapor transport rate constant, P_{eq} is the vapor pressure in equilibrium with a local region of the surface with zero curvature, k : Boltzmann constant, T: absolute temperature, and K: curvature.

Thermal oxidation also deformed the geometry of micro/nano-scale structures on the surfaces, figure 4, and in the case of selective emitters, any chemical change can significantly alter the emitted spectrum as well. For example, in air, tungsten begins to oxidize at room temperature with significant oxidation occurring around 400-500 °C. Tungsten trioxide (WO_3) is permeable to oxygen, which allows the oxide layer to grow quickly. If tungsten is heated, further sublimation will begin around 750 °C. It is, therefore, critical to provide the solution for preventing or minimizing thermal oxidation.

2.2 FUNCTIONAL REQUIREMENTS

From the firing tests with tungsten micro-sized samples, we could verify four independent thermal degradation modes: grain growth, surface diffusion, evaporation/recondensation, and oxidation. To obtain thermally stable 2D photonic crystals, we could define the functional requirements:

FR1: Minimize/prevent grain boundary movement
FR2: Minimize/prevent surface diffusion
FR3: Minimize/prevent evaporation/recondensation
FR4: Minimize/prevent contacting with oxygen

2.3 DESIGN PARAMETERS

Since grain boundary movement is a phenomenon for only polycrystalline materials, we could avoid grain growth or recrystallization by using single crystal materials or performed pre-annealing process in advance, DP1. It's been proved with pre-annealed samples, figure 5. The samples were pre-annealed for 100 hours at 1200 °C before drilling the holes, (b) non-treated polished tungsten with drilled holes, (c) and (d) 100-hour firing at 1200 °C in almost oxygen free condition. (e) and (f) were treated by the same method as (a) and (d) but with nano-scale holes, diameter of 300 nm, (g) and (f) are images after 100 hours firing at 1200 °C. As it can be seen from figure 5, pre-annealing could minimize the deformation of sub-micron structures.

For surface diffusion and evaporation/recondensation,

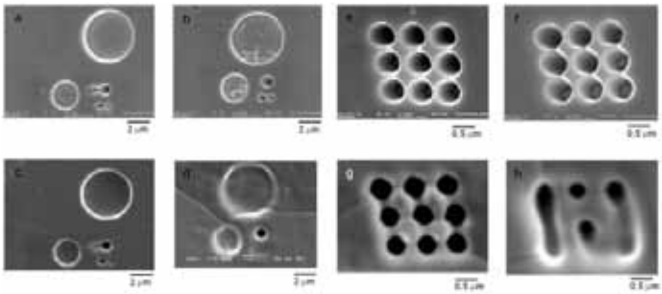


Figure 5. Firing tests with pre-annealed samples

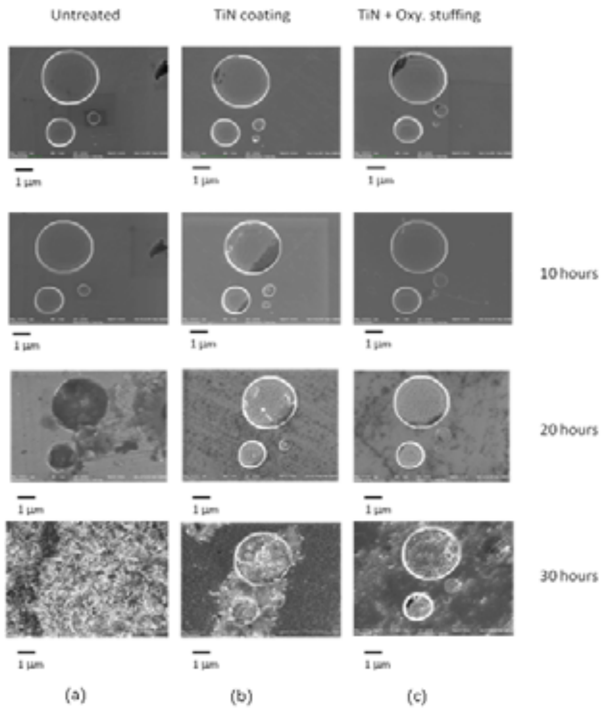


Figure 6. Oxidation barrier coating: TiN

we proposed flat surface 2D photonic crystals. Generally, 2D photonic crystals are arrays of periodic cylindrical holes. However, if we fill the holes with optically transparent materials and make the surfaces flat, there will be no driving force for surface diffusion or evaporation/recondensation. In this case, the design parameter will be "flat surface photonic crystals", but the one parameter will be cover both functional requirements of FR2 and FR3, which is known as physical coupling.

For FR4, Minimize/prevent contacting with oxygen, we proposed a method of oxygen barrier coating. By having dense diffusion barrier coating, such as TiN, we could still maintain the transmittance and prevent the contacting of oxygen to tungsten substrates. Furthermore, oxygen stuffing on TiN film makes the barrier denser by filling the grain boundary with oxygen molecules; we could achieve high resistance on thermal oxidation, figure 6.

In figure 6, Oxidation of tungsten surface and the role of oxidation barrier can be observed. (a) pristine sample, (b) TiN coated sample and (c) TiN and oxygen stuffed samples were observed every 10 hours after firing at 1200 °C with oxygen present condition. As you can see, TiN with oxygen stuffed samples showed thermal resistance on oxidation, DP4.

By summary, we could find each independent. Some of them were physically coupled (DP2 and DP3) design parameters. For each functional parameter, design parameters for thermally stable sub-micron structures are having pre-annealing, flat surface, and oxidation barrier coating.

DP1: Pre-annealing
DP2: Flat Surface
DP3: Flat Surface (physically coupled with FR2)
DP4: Oxidation (diffusion) barrier coating

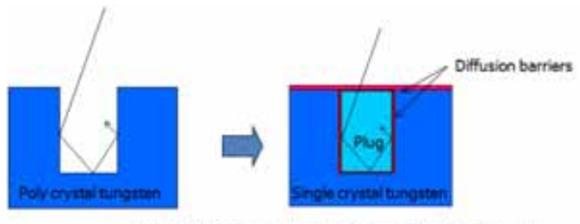


Figure 7. New design: Flat Surface Photonic Crystal

2.4 NEW DESIGN

From these design parameters, proposed new design, figure 7, of photonic crystal structure is the flat surface photonic crystal (FSPC), which is the physical realization of a flat surface that behaves like a 2-D PhC, which is achieved through plugging of the micro- and nano-structure of the PhC with an IR-transparent ceramic. The most critical components of the design are IR optical transparency of the plugging material, inter-diffusion barrier, and compatible thermal expansion between substrate and plugging material to prevent cracking and dislodging of the ceramic plugs. When ramping to the high operation temperature, establishing compressive stress while the plugging material and tungsten expand will mechanically secure the plug inside the micro-/nano-structure. For this compressive stress to be maintained, the thermal expansion coefficient (TEC) of plugging ceramic should be slightly higher than that of the substrate. For a tungsten photonic crystal (WPhC), hafnium oxide (HfO_2) is selected based on its IR transparency, TEC, and thin film manufacturability via a sol-gel deposition process. Based on the previously discussed results, the inter-diffusion barrier is 5 nm of oxygen-stuffed TiN. The flat surface photonic crystals are fabricated with hafunium oxide plug in silicon substrates, figure 8.

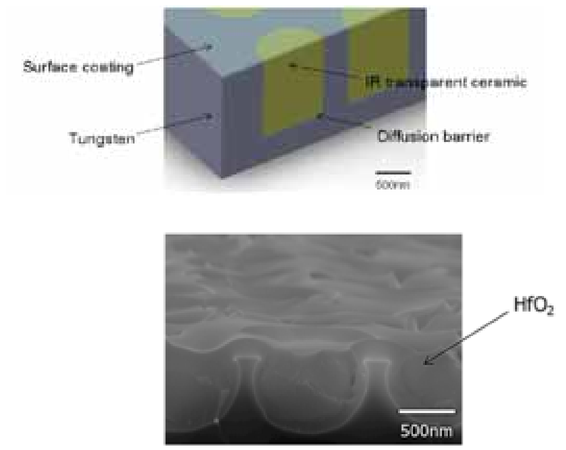


Figure 8. Flat Surface Photonic Crystal (fabricated sample)

Silicon is used for quick verification of the concept of FSPC, since its realtively easy process of fabrication and firing test at lower temperature. At first, we could confirm that the optical propertt is not changing much with plugs and oxidation barrier, figure 9.

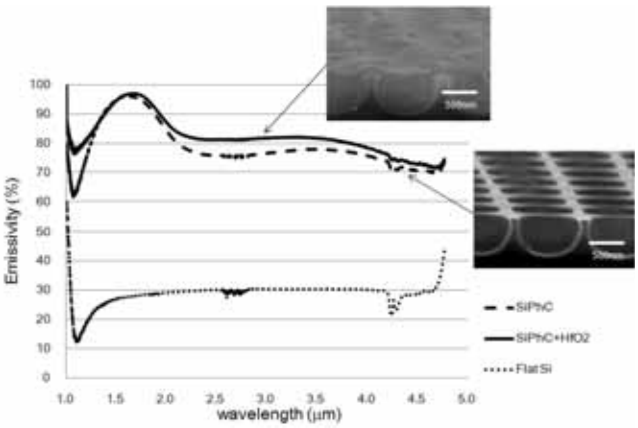


Figure 9. Optical property of flat surface photonic crystal

3 RESULTS

Thermal degradation tests of flat surface photonic crystals were performed with hafnium oxide plugged silicon photonic crystals. The samples were fired for 100 hours at 400 °C, which is equivalent temperature for tungsten at 1,200 °C in homologous temperature of 0.4. Cross sectional SEM images of each sample were taken every 25 hours and their optical properties are also measured, figure 10 & 11.

Figure 10 shows significant thermal degradation of silicon photonic crystal structure and minimal change in the flat surface HfO_2 plugged samples over 100 hours of firing. From figure 10, the effects of surface diffusion and evaporation and re-condensation on the untreated samples are clearly shown, while the flat surface photonic crystals' structure remained same and don't lose its structural integrity.

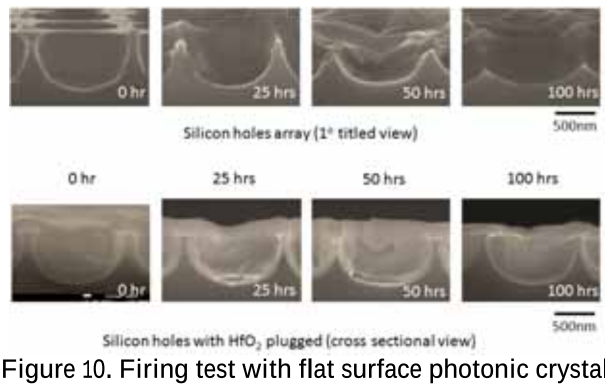
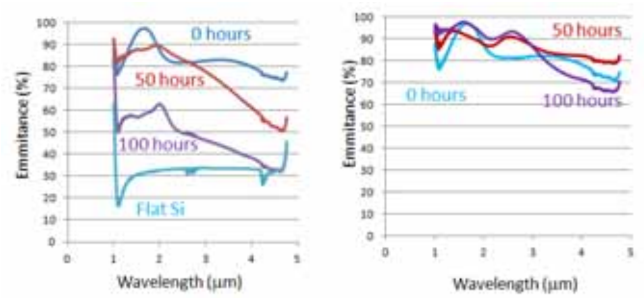


Figure 10. Firing test with flat surface photonic crystals

Finally, figure 11 shows the influence of thermal degradation on optical performance. The emissivity spectra for each sample from figure 10, after 0, 50, and 100 hours fired at 400 °C. The silicon photonic crystal emissivity is considerably reduced as the surface thermally degrades at the sample without the plugged fills, and the emission curve approaches that of a flat silicon surface. In contrast, the HfO_2 plugged silicon photonic crystal, sample (b), retains its structure when heating and does not lose its optical performance even after 100 hours of firing at 400 °C.



(a) (b)

Figure 11. Optical properties of FSPC with firing tests

4 CONCLUSION

A novel idea of flat surface photonic crystal (FSPC) was proposed by axiomatic approaches and the design was validated by experiments. Pre-annealing polycrystalline tungsten prevented the grain growth. A thin layer of diffusion barrier will prevent oxidation while maintaining the optical performance. By filling in the micro/nano-scale cavities with a damascened IR transparent ceramic, the surface of the emitter will have negligible second derivative of the curvature, and thus eliminates the surface diffusion even at high temperatures.

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COUPLING AND COMPLEXITY IN ADDITIVE MANUFACTURING PROCESSES

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ABSTRACT

This work analyzes and compares traditional subtractive machining processes (milling and turning) and additive manufacturing processes (fused deposition modeling, selective sintering, stereolithography, and 3D printing) in an Axiomatic Design context. The processes are examined from a local and isothermal perspective then as time-varying systems to determine the degree of coupling and time-dependent complexity they exhibit. It is shown that subtractive processes exhibit more coupling within the design matrix than additive manufacturing processes. However, additive processes are intrinsically coupled at the voxel level and seem to exhibit more time-dependent complexity than their subtractive counterparts.

Keywords: additive manufacturing, machining, coupling, complexity.

1 INTRODUCTION

In recent years, additive manufacturing has been hailed as a "wonder technology" [Mishra, 2013] that will eliminate the need for Design for Manufacturing [Tucker, 2013] and bring about the "third industrial revolution" [Markillie, 2012]. While such statements could be dismissed as pure sensationalism, they hint at an interesting hypothesis: additive manufacturing uncouples the artifact ('what we want to achieve') from its production ('how we want to achieve it'). If this were true, these technologies would represent ideal manufacturing processes from the perspective of Axiomatic Design Theory [Suh, 1990; Suh, 2001] and Suh's [2005] Complexity Theory.

In this work, we analyze and compare common traditional subtractive machining processes (milling and turning) and additive manufacturing processes (fused deposition modeling, selective sintering, stereolithography, and 3D printing). In the first part of the paper, each process is viewed from the perspective of a discrete operation: the individual cut or the creation of an individual voxel (or unit volume) of new material. This allows variations in time and temperature to be neglected, and simplifies the decompositions and design matrices. In the second part of the paper, each process is viewed as a time-varying system with time-dependent complexity.

2 DECOMPOSITION OF A SINGLE CUTTING OPERATION

Conventional metal cutting processes create the desired geometry by removing material from a solid workpiece. This involves clamping a tool and the workpiece, positioning the tool relative to the surface to be machined, and placing the tool in contact with the workpiece at high speed. For a single cut, the functional requirements of a conventional milling operation can be summarized as follows:

FR1 – Fix the workpiece (resist machining forces)
FR2 – Fix the tool (resist reaction forces)
FR3 – Position the tool relative to the workpiece
- FR31 – Position the tool (or part) in x
- FR32 – Position the tool (or part) in y
- FR33 – Position the tool (or part) in z

FR4 – Remove material
- FR41 – Cut (penetrate) the material surface
- FR42 – Separate material from surface (form the chip)
- FR43 – Break the chip
- FR44 – Remove the chip

Turning operations and 5-axis milling also require some or all of the rotational degrees of freedom of the tool to be defined relative to the workpiece. In this decomposition, the FRs associated with rotational positioning have been excluded for simplicity.

For many milling operations, workpieces are clamped in a vise. A tool chuck or collet assembly is used to clamp the tool. The part is positioned by moving the bed in x and y and by moving the quill in z. Material is removed by rotating the tool at high speed. The nature of the cut is dictated by the tool geometry (as well as the tool and workpiece material properties). Thus, the associated design parameters of a conventional milling operation for a single cut could include:

DP1 – Machine vise
DP2 – Tool chuck / collet assembly
DP3 – Positioning system
  DP31 – CNC controlled slide (x direction)
  DP32 – CNC controlled slide (y direction)
  DP33 – CNC controlled quill (z direction)
DP4 – Tool geometry
  DP41 – Lead angle
  DP42 – Rake angle
  DP43 – Rake face geometry
  DP44 – Flute geometry (helix angle)
DP5– Tool rotation (spindle speed)

The initial penetration of the tool into the workpiece (FR41) depends on the geometry at the tool tip and the tool rotation speed (DP41, DP42 and DP5). Similarly, chip formation (FR42) is controlled by the tool geometry and the tool rotation (DP41, DP42, DP43, and DP5). Chip breaking (FR43) depends on the curvature of the chip, the chip thickness, and the brittleness of the workpiece [Shaw, 2004]. As a result, chip breaking is highly coupled with chip formation and shares the same dependencies in the design matrix. If the flute geometry affects the chip curl or if the interaction of the flutes with the chips causes them to break, then FR43 will also be associated with DP44. Only chip removal (FR44) is relatively uncoupled – relying primarily on the flute geometry and the tool rotation (DP44 and DP5).

All cutting operations require the tool to slightly overlap the physical bounds of the workpiece. This overlap defines the depth of cut which, in turn, affects the cutting forces and chip formation. As a result, the initial penetration, chip formation, and chip breaking (FR41-FR43) all depend on the position of the tool (FR3). This is reflected in the high degree of coupling shown in the lower half of the design matrix (figure 1).

Finally, each cut involves the transmission of forces and moments from the tool to the workpiece. Reaction forces propagate from the tool through the tool chuck and the positioning system, and into the machine frame. Similarly, reaction forces propagate from the workpiece through the vise and into the machine frame. Because all physical components of the system are connected, errors in one machine element can impact other seemingly independent functions. For example, low stiffness or backlash in the positioning system can significantly change the position of the tool, induce vibration, and increase the cutting forces. This increases the reaction forces in the vise and the tool chuck and thus impacts their functionality. The result is a design matrix that is almost completely coupled.

Vargas *et al.* [2011] suggested additional design parameters (tool length/width ratio and tool material) to ensure that the tool can withstand the cutting forces. Similar requirements could also be defined for the vise, the tool chuck, the positioning system, and the machine frame. These design parameters can reduce the deflections caused by the transmission of forces but cannot eliminate them completely. This analysis neglects these considerations for simplicity.

FR1	X	X	X	X	X	X	X	X	X	X	0	X
FR2	X	X	X	X	X	X	X	X	X	X	0	X
FR3	X	X	X				X	X	X	X	0	X
FR31	X	X		X	0	0	X	X	X	X	0	X
FR32	X	X		0	X	0	X	X	X	X	0	X
FR33	X	X		0	0	X	X	X	X	X	0	X
FR4	X	X	X	X	X	X	X					X
FR41	X	X	X	X	X	X		X	X	0	0	X
FR42	X	X	X	X	X	X		X	X	X	0	X
FR43	X	X	X	X	X	X		X	X	X	X	X
FR44	0	0	0	0	0	0		0	0	0	X	X

=

DP1
DP2
DP3
DP31
DP32
DP33
DP4
DP41
DP42
DP43
DP44
DP5

Figure 1. Upper level design matrix for a single cutting operation on a vertical mill.

3 DECOMPOSITION OF SELECTED ADDITIVE MANUFACTURING PROCESSES FOR A SINGLE VOXEL

Additive manufacturing processes create the desired geometry by adding, solidifying, or fusing source material (filament, powder, sheet stock, etc.) until the desired shape has been produced.

3.1 FUSED DEPOSITION MODELING

Fused deposition modeling (FDM) processes create the desired geometry by positioning a nozzle, extruding new material, and bonding the new material to the existing bulk (or the build plate). The newly deposited material is separated from the nozzle by the shear forces generated by the movement of the nozzle away from the print location. The FRs for creating a generic FDM voxel (i.e. for the extrusion of a unit volume of material at a single location) can be summarized as:

FR1 – Position the nozzle aperture relative to the workpiece
  FR11 – Position the aperture in x
  FR12 – Position the aperture in y
  FR13 – Position the aperture in z
FR2 – Extrude new material
  FR21 – Heat material to glass-transition temperature
  FR22 – Advance material
  FR23 – Shape heated material
FR3 – Fuse new material to existing bulk
FR4 – Detach new material from source filament

If there is a need to orient the nozzle at an angle related to the workpiece, the rotational position of the nozzle would also need to be defined. Again, the FRs and DPs associated with rotational positioning been excluded from the decomposition for simplicity.

Most FDM machines either mount the nozzle on a three-axis gantry that moves relative to a stationary workpiece or mount the nozzle on a two-axis gantry and move the build plate in z to create each new layer. A heater softens the source material and an actuator is used to advance the filament and thus extrude the heated material. The nozzle shapes the heated material as it is extruded. Finally, the residual heat in the newly extruded material fuses the new voxel to the existing bulk. Thus, the DPs for creating a voxel using FDM could include:

DP1 – Positioning system
  DP11 – CNC controlled stage (x direction)
  DP12 – CNC controlled stage (y direction)
  DP13 – CNC controlled stage (z direction)
DP2 – Extrusion system
  DP21 – Resistive heater
  DP22 – Motor driven sprocket with filament guide
  DP23 – Nozzle geometry

It could be argued that DP3 should be defined as the bonding temperature at the new voxel interface. However, the temperature of the newly deposited material is directly controlled by DP21 (the heater). Similarly, it could be argued that DP4 should be the shear forces created by the movement of the nozzle away from the interface. However, the shear forces are created by the adhesion of the new voxel on one side and the movement of the nozzle (DP1 and its sub-DPs) on the other. As a result, the decomposition only has 2 DPs for 4 FRs. The resulting design matrix is rectangular and coupled (figure 2).

$$
\begin{Bmatrix} FR1 \\ FR11 \\ FR12 \\ FR13 \\ FR2 \\ FR21 \\ FR22 \\ FR23 \\ FR3 \\ FR4 \end{Bmatrix}
=
\begin{bmatrix}
X & & & & 0 & 0 & 0 & 0 \\
 & X & 0 & 0 & 0 & 0 & 0 & 0 \\
 & 0 & X & 0 & 0 & 0 & 0 & 0 \\
 & 0 & 0 & X & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & X & & & \\
0 & 0 & 0 & 0 & & X & 0 & 0 \\
0 & 0 & 0 & 0 & & X & X & 0 \\
0 & 0 & 0 & 0 & & X & X & X \\
0 & 0 & 0 & 0 & X & X & 0 & 0 \\
X & X & X & X & X & X & 0 & X
\end{bmatrix}
\begin{Bmatrix} DP1 \\ DP11 \\ DP12 \\ DP13 \\ DP2 \\ DP21 \\ DP22 \\ DP23 \end{Bmatrix}
$$

Figure 2. Design matrix for an FDM process.

3.2 Selective Sintering Processes

Selective sintering processes (selective laser sintering (SLS), selective heat sintering (SHS), etc.) start with the bulk material as a powder on the print platform. To create a new voxel, a heat source is positioned over the desired area at an appropriate offset in the z direction and activated. The incident heat sinters the power and bonds the new material to the surrounding bulk. For a single voxel, the FRs for a selective sintering process are:

FR1 – Position the heat source relative to the workpiece
  FR11 – Position the heat source in x
  FR12 – Position the heat source in y
  FR13 – Position the heat source in z
FR2 – Sinter material into new voxel
FR3 – Bond new voxel to the existing bulk

The corresponding DPs for selective sintering are:

DP1 – Positioning system
  DP11 – CNC controlled stage for heat source (x direction)
  DP12 – CNC controlled stage for heat source (y direction)
  DP13 – CNC controlled stage for build platform (z direction)
DP2 – Heat source

New voxels are bonded to their neighbors (FR3) by the same thermal process that sinters them (FR2). This process requires a sufficient overlap between the old and new material to ensure that the bond is strong. Thus, FR3 is dependent on FR11, FR12, and FR2. In addition, the energy output of a heat source often depends on the distance to the material being heated. Thus, FR2 and FR3 both depend on FR13. The resulting design matrix is rectangular and coupled (figure 3).

$$
\begin{Bmatrix} FR1 \\ FR11 \\ FR12 \\ FR13 \\ FR2 \\ FR3 \end{Bmatrix}
=
\begin{bmatrix}
X & & & & 0 \\
 & X & 0 & 0 & 0 \\
 & 0 & X & 0 & 0 \\
 & 0 & 0 & X & 0 \\
0 & 0 & 0 & X & X \\
X & X & X & X & X
\end{bmatrix}
\begin{Bmatrix} DP1 \\ DP11 \\ DP12 \\ DP13 \\ DP2 \end{Bmatrix}
$$

Figure 3. Design matrix for a selective sintering process.

3.3 Stereolithography and 3D Printing Processes

The decomposition and design matrix for light polymerised processes (e.g. stereolithography) are essentially the same except the starting material is liquid photopolymer instead of powder and DP2 is a light source instead of a heat source. This is a higher level design matrix than the one presented by Lee *et al.* [2004; 2007] and differs substantially from their work.

The decomposition and design matrix for 3D printing (binder jetting) processes are also the same except that a chemical binder is used instead of a thermal one. Thus, the heat or light source must be replaced with a droplet dispensing mechanism.

4 A Comparison of Real Complexity in Additive and Substractive Manufacturing Processes for Individual Voxels

The decompositions above show that both additive and subtractive manufacturing processes are coupled on a voxel-by-voxel basis. However, the nature of the coupling in these systems is very different. Machining processes are highly coupled because of the forces and moments generated by the contact of the tool with the workpiece and the complex nature of the interaction of the tool with the part. Additive manufacturing processes have low contact forces (FDM) or no contact with the workpiece (SLS, SHS, stereolithography, 3D printing, etc.). As a result, additive manufacturing processes are not coupled through the positioning system. This partially explains why these systems are easier and less expensive to build, optimize, and control.

However, because additive manufacturing systems create and join individual voxels using the same mechanism, these two functions cannot be controlled independently. This results in less control over the geometry of the voxels and may partially explain why most additive manufacturing processes still produce parts that are “near net shape” [Levy *et al.*, 2003] while machining operations can be extremely precise.

5 TIME DEPENDENCE IN SUBTRACTIVE MACHINING OPERATIONS

While the analysis of conventional machining operations at the voxel level provides insight into the coupling and real complexity of these processes, machining is a time-dependent operation in practice. For example, end mills repeatedly make and break contact with the workpiece many times per second. Thus, milling can be viewed as a series of cuts and advancements along a desired tool path. In contrast, lathe tools rarely leave the surface. Thus, turning can be viewed as a process of uninterrupted cutting and advancement along the desired tool path.

For both milling and turning, the time between cuts and advancements is small (or non-existent). As a result, heat is constantly generated by the friction between the workpiece and the tool, leading to an increased temperature at the interface. Cut material can build up on the edge of the tool, the tool can wear down, and the interaction of the tool and the workpiece leads to vibration in the machine frame. From this perspective, machining processes exhibit significant time-dependent complexity.

One strategy to compensate for these effects is to use periodicity. For example, tools are regularly resurfaced or replaced to remove the built up edge and compensate for tool wear. A similar strategy could be used to manage the temperature increase at the tool / workpiece. For example, one could increase the amount of time between cuts to allow the tool and the workpiece to cool naturally. However, this greatly increases processing time. Instead, one additional functional requirement and one additional DP are used to compensate for the transient thermal behaviour:

FR5 – Control the temperature at the interface between the tool and the workpiece

DP6 – Apply lubricant / coolant to the interface

The application of the lubricant / coolant is independent of the other FRs and DPs. However, the quality and geometry of the cut depends on the frictional behavior at the interface. Thus, all aspects of the process, except for chip removal, depend on DP6 (figure 4).

	DP1	DP2	DP3	DP31	DP32	DP33	DP4	DP41	DP42	DP43	DP44	DP5	DP6
FR1	X	X	X	X	X	X	X	X	X	X	0	X	X
FR2	X	X	X	X	X	X	X	X	X	X	0	X	X
FR3	X	X	X				X	X	X	X	0	X	X
FR31	X	X		X	0	0	X	X	X	X	0	X	X
FR32	X	X		0	X	0	X	X	X	X	0	X	X
FR33	X	X		0	0	X	X	X	X	X	0	X	X
FR4	X	X	X	X	X	X	X					X	X
FR41	X	X	X	X	X	X		X	X	0	0	X	X
FR42	X	X	X	X	X	X		X	X	X	0	X	X
FR43	X	X	X	X	X	X		X	X	X	X	X	X
FR44	0	0	0	0	0	0		0	0	0	X	X	0
FR5	0	0	0	0	0	0	0	0	0	0	0	0	X

Figure 4. Design matrix for machining operations on a vertical mill.

6 TIME DEPENDENCE IN ADDITIVE MANUFACTURING PROCESSES

Most additive manufacturing processes are also more accurately modeled as continuous operations. For example, FDM machines continuously extrude material along a tool path instead of printing individual voxels. Similarly, SLS and SHS processes do not sinter the powder source material for contiguous features one voxel at a time. Instead, the heat source usually moves at a constant velocity, sintering along the pre-defined tool path. The dynamic nature of these processes can introduce significant time-dependent complexity.

6.1 THERMALLY-BASED TIME-DEPENDENT COMPLEXITY IN FDM

In FDM processes, the constant addition of new material introduces complex thermal transients that are difficult to predict. For example, the material at the beginning of the first strand of a build using a single nozzle machine will have warm material behind it, the build plate at ambient temperature below it (if unheated), and air at ambient temperature on the other four sides. The material in the second row will have material from the first row on one side. The temperature of the adjoining material will depend on how long it has had to cool, which depends on the length of the previous strand. Similarly, the strands in the layers above will have material below whose temperature will also depend on how long it had to cool and to what extent it has been warmed and/or insulated by the surrounding build. As the workpiece is created, the air surrounding the extruded material may develop temperature gradients that affect and further complicate the cooling process.

The thermal gradients in the workpiece are important because the heating and cooling of the extruded material play a substantial role in determining the final material properties and the geometry of the part. For example, the bonding process, and thus the bond strength, between the old and new material depends, in part, on the temperature difference between them [Li *et al.*, 2002]. Insufficient bonding can lead to reduced strength of the overall part and peeling or internal de-bonding.

Thermal gradients can also affect the geometry of the final part. For example, temperature differences in the workpiece can lead to thermal stresses that cause warping in the final part [Wang *et al.*, 2007]. Differences in thermal expansion can generate internal voids and other dimensional errors after the part cools. Finally, the workpiece is subject to gravitational loads during construction. Materials, especially polymers, are relatively weak when warm. As a result, the bottom layers of a large workpiece may deform under the weight of the new material, altering the geometry of the final part.

Adding new functions associated with temperature control can mitigate some of these problems. For example, some FDM machines have heated build chambers. This leads to one new FR/DP pair:

FR5a – Maintain workpiece temperature slightly below glass transition temperature
- FR51a – Measure the temperature in build chamber
- FR52a – Add thermal energy to build chamber
- FR53a – Distribute thermal energy evenly throughout the build chamber

DP3a – Thermal management system
- DP31b – Temperature sensor
- DP32b – Heater
- DP33b – Fan

The new FR/DP pair is uncoupled (as long as the influence of the control system is not considered). However, a heated build chamber can introduce thermal expansion effects in the positioning system (FR1), the filament advancement mechanism (FR22), and the extrusion nozzle (FR23). Thus, these FRs are coupled through the new DP. In addition, the filament heater output will need to be adjusted to compensate for the higher build chamber temperature (FR21). The fusing of the new material (FR3) and the shearing of the source material (FR4) are also temperature dependent. Thus, the introduction of a heated build chamber reduces thermal time-dependent complexity in the part (and part quality) while increasing the overall coupling and complexity of the system (figure 5).

FR1	X				O	O	O	O	X	O	X	X	DP1
FR11		X	O	O	O	O	O	O	X	O	X	X	DP11
FR12		O	X	O	O	O	O	O	X	O	X	X	DP12
FR13		O	O	X	O	O	O	O	X	O	X	X	DP13
FR2	O	O	O	O	X				X	O	X	X	DP2
FR21	O	O	O	O		X	O	O	X	O	X	X	DP21
FR22	O	O	O	O		X	X	O	X	O	X	X	DP22
FR23	O	O	O	O		X	X	X	X	O	X	X	DP23
FR3	O	O	O	O	X	X	O	O	X	O	X	X	DP3
FR4	X	X	X	X	X	X	O	X	X	O	X	X	DP31
FR5	O	O	O	O	O	O	O	O	X				DP32
FR51	O	O	O	O	O	O	O	O		X	O	O	DP33
FR52	O	O	O	O	O	O	O	O		O	X	O	
FR53	O	O	O	O	O	O	O	O		O	O	X	

Figure 5. Design matrix for an FDM process with a heated build chamber.

While heated build chambers have been shown to reduce warping in ABS parts produced by FDM, it is a global solution to a local problem. Heating the build chamber does not control the temperature gradients in the workpiece or the print bed. It only reduces the difference between the ambient temperature and the newly printed or sintered material, lessening the difference's effects.

Another common solution is to heat only the build plate. In this case, the FR/DP pair is defined as:

FR5b – Maintain workpiece temperature slightly below glass transition temperature

DP3b – Build plate resistance heater

Since the surrounding air will not be heated (except by the workpiece), a heated build plate will lead to higher thermal gradients than a heated build chamber, and thus greater time-dependent complexity. However, the overall coupling in the design matrix is lower because the positioning and extruding elements of the machine are unaffected by the build plate temperature (figure 6).

FR1	X				O	O	O	O	O	DP1
FR11		X	O	O	O	O	O	O	O	DP11
FR12		O	X	O	O	O	O	O	O	DP12
FR13		O	O	X	O	O	O	O	O	DP13
FR2	O	O	O	O	X				O	DP2
FR21	O	O	O	O		X	O	O	O	DP21
FR22	O	O	O	O		X	X	O	O	DP22
FR23	O	O	O	O		X	X	X	O	DP23
FR3	O	O	O	O	X	X	O	O	X	DP3
FR4	X	X	X	X	X	X	O	X	X	
FR5	O	O	O	O	O	O	O	O	X	

Figure 6. Design matrix for an FDM process with a heated build plate.

In both cases, increasing the overall temperature of the workpiece during the build does not improve, and may actually worsen, the effect of gravity on the lowest layers of the build.

6.2 THERMALLY-BASED TIME-DEPENDENT COMPLEXITY IN SINTERING PROCESSES

Thermal transients and thermally-based time-dependent complexity also exist in sintering processes. The first voxel in a sintered process will be surrounded on four sides by powder at ambient temperature and by air on the top. The second voxel will have warm sintered material behind it, powder on three sides, and air on the top. The heat from the newly sintered material is transmitted into the powder bed, which then develops thermal gradients [Dressler *et al.,* 2010] and affects the cooling of the workpiece. The air above the print bed will also be heated. As new layers of powder are added, they may trap the heat in the print bed and/or be heated by the workpiece in the print bed. The exact behavior will depend on the densities and thermal properties of the materials involved. The result is a temperature profile in the workpiece, in the print bed, and in the air above the print bed, that is difficult to predict and control.

Thermal gradients in selective sintering processes can lead to residual stresses in the final part like those observed in FDM. Since the heat required for bonding is applied directly to both the new voxel and to the surrounding material, thermal gradients have a much smaller effect on the bonding process. However, the heat will continue to diffuse through the bulk. Thus, the movement of the heat source will make and re-make the internal boundaries of the workpiece. This can have a substantial impact on the microstructure and thus material properties of the final part.

6.3 GEOMETRICALLY-BASED TIME-DEPENDENT COMPLEXITY

In all additive manufacturing processes, the workpiece must be able to support the layers that have been, or will be, created on top of it. Voxels cannot be placed without support and the weight of the voxels in higher layers must be taken into account when creating the lower layers. Sometimes this means that the part must be created in an orientation that will provide the necessary support during the manufacturing process. This makes many additive manufacturing processes path dependent.

To reduce the path dependence and increase geometric freedom, many additive manufacturing processes have additional FRs and DPs to provide mechanical support during the build. For example, many FDM machines print support material to allow over-hangs to be created. 3D printing and selective sintering processes use the un-sintered or un-bonded powder to provide this support. However, there are added constraints associated with this geometric freedom. The support layers must be removable using a mechanical or chemical process that does not affect the newly created structure. There also must be a path to allow the support material to be removed [Levy *et al.,* 2003; Vayre *et al.,* 2012] or the support material must be permitted to stay in the finished part.

7 SUMMARY AND CONCLUSION

This work has examined traditional subtractive machining processes and some of the major additive manufacturing processes from the perspectives of Axiomatic Design Theory and Complexity Theory. It was shown that subtractive processes exhibit more coupling within the design matrix than additive manufacturing processes. However, additive processes tend to have rectangular design matrices, with more FRs than DPs, and are thus inherently coupled. The additive manufacturing processes also seem to exhibit more time-dependent complexity than their subtractive counterparts. This analysis fails to support the hypothesis that additive manufacturing processes are inherently less coupled than subtractive manufacturing processes. However, it does provide some insight into the differences between the two types of processes and highlights sources of coupling to be addressed in future work.

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AXIOMATIC DESIGN OF A DROP ON DEMAND DEPOSITION PROCESS FOR SOL-GEL PZT

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ABSTRACT

Of the readily available piezoelectric engineering materials perovskite phase lead zirconate titanate (PZT) has the strongest mechanical to electrical coupling and allows electro-mechanical devices have the highest performance. However, processing of thin film PZT is not readily compatible with existing micro-electromechanical systems (MEMS) fabrication processes and significant design constraints exist when integrating thin film PZT.

While some recent work has demonstrated novel ways of forming sol-gel based films, spin coating remains the dominant method of depositing thin film PZT for MEMS. Spin coating is not the best fabrication method for PZT based MEMS but it is currently the most easily integrated into a MEMS process flow. Not only is spin coating inherently wasteful of the expensive and difficult to manufacture sol, but it prevents the deposition of PZT films on or around out of plane features. The sol-gel material is also very sensitive to other deposition parameters including humidity, particle contamination, and substrate material. As a result device yields are often low. Consequently a flexible new approach is needed to easily and effectively deposit high quality PZT thin films for MEMS applications. Presented here are the functional requirements and design parameters that characterize a sol-gel ink jet printing process as well as the design matrices that guide successful development.

Keywords: PZT, Drop on Demand, Ink Jet, Sol-Gel

1 INTRODUCTION

In recent years drop-on-demand (DOD) printing has been studied as a robust, flexible, and inexpensive method of material deposition for MEMS [Fuller, *et. al.*, 2002]. Digital deposition eliminates the need for photolithography and subsequent etching steps in the manufacturing process flow. A further advantage of direct printing is the cost savings due to a reduction in the material consumption during manufacturing and in chemical waste produced. The result is a manufacturing process that is cleaner and cheaper than other common deposition techniques. Perhaps the most compelling benefit of direct printing of PZT is that it provides a freedom of geometry that eliminates many of the design constraints currently associated with PZT MEMS [Kim and Koo, 2000].

Recently we presented a new PZT ink jet deposition method that included ink development and printing process based on axiomatic design. Film coalescence and drying processes were modelled and the conditions for uniform deposition were established. These efforts culminated in the fabrication of a printed PZT based ultrasonic transducer that demonstrated the effectiveness of the PZT printing process and also enabled a full characterization of the properties of the printed PZT film. Dielectric and piezoelectric properties of the printed thin film were measured through device deflection test and complex impedance analysis. To our knowledge, this is the first report on the full characterization of a printed PZT thin film.

2 DESIGN OF A PZT SOL-GEL INK

A sol-gel based drop-on-demand ink must have the correct balance of surface tension and viscosity so as to ensure reliable and repeatable drop formation. Furthermore, the ink solvents must not interfere with the sensitive hydrolysis reaction that forms the gel film. An ink was formulated for this work by adding chemically compatible solvents to a PZT sol-gel spin coating solution to achieve the correct physical properties.

2.1 A JETTABLE PZT SOL-GEL INK

The starting point of the ink formulation for this research was two commercially available sol-gel solutions purchased from Mitsubishi Chemical Corp. One sol-gel was based on 2-methoxyethanol (Mitsubishi Chemicals ID: A6) and the other was based on 1-butanol and 1,2-propanediol (Mitsubishi Chemicals ID: E1). As purchased the solutions are designed for spin coating and while they provide a reliable source of precursor material they do not make good drop-on-demand inks. The base solvents evaporate slowly which adversely affects both the process rate and uniformity after drying. Also, the concentrations of spin coating solutions are too high to be printed reliably. Printing for this research was carried out with an HP thermal ink jet printer that is normally limited to a weight concentration of <5%. The A6 and E1 sol-gel are both 15% (wt) metal-organics and required significant dilution to jet from small nozzles.

A high concentration ink can prevent drop formation by reducing the decap time and causing the solution to behave as a non-Newtonian fluid. The acceptable concentration limit depends both on the molecular weight of the solutes and the sizes of the nozzle and firing chamber. Due to the low molecular weight of the metal-organics in the PZT, sol-gel printing of relatively high concentrations is possible provided that condensation polymerization does not occur. PZT ink development began with a characterization of the concentration limits for different drop volumes. Anhydrous 2-methoxyethanol (2-ME) was used as the primary solvent with 4% wt of 2-ethyhexanioc acid (EHA) added. EHA is a common drop-on-demand ink additive. It has a high boiling point (226°C) and adding a small amount of EHA improves nozzle health and increases decap time. Different printer nozzle diameters are used to deposited different drop volumes that therefore have different decap times. Five solutions of PZT sol-gel were primed and printed through a range of seven nozzle sizes design to produce drops volumes between 10pl and 220pl. The smallest drop size to print reliably for approximately 1 hour over a 40°C substrate for each solution was considered the size limit for that concentration. This result provides a guideline for sol-gel metal-organic concentration limits for thermal ink jet printing. It should be noted that the concentration limits for piezoelectric printers would be higher. Regardless of the printing method, identifying the concentration limits enables the formulation of an ink with the right amount of solute material for a given drop volume and resolution limit.

As solvents were added to dilute the ink the balance of viscosity and surface tension was controlled to ensure reliable drop formation for the specified nozzle size. The inverse of the Ohnesorge number (commonly referred to as Z) is a dimensionless parameter relating viscous and surface tension forces that has been used successfully as a design parameter to control droplet formation dynamics [Fromm, 1984]-[Reis and Derby, 2000].

$$Oh^{-1} = \mathrm{Z} = \frac{\sqrt{\rho\gamma L}}{\eta} = \frac{Re}{\sqrt{We}} \tag{1}$$

where η, ρ, γ, and L are the fluid viscosity, density, surface tension, and a characteristic length scale respectively. In this case L is taken as the radius of the printer nozzle. Z should be between 1 and 10 for successful printing. As the stock sol-gel solution was diluted the viscosity and surface tension of the resulting ink were estimated to ensure that the inverse Ohnesorge number, Z, was within the jettable range.

The surface tension of a liquid blend tends to be dominated by the low surface tension elements. All of the inks in this work were based on a primary diluting solvent (either 2-ME or 2-propanol) that was at least 50% (wt) of the solution and as such the surface tension of these solvents was used to calculate the inverse Ohnesorge number. The viscosity of the ink was used as the primary design parameter for controlling jettability. The measured viscosities of the stock A6 and E1 sol-gels were 1.7 and 8.8 mPa.s respectively. The viscosities of the inks developed for this work were adjusted between 1.8 and 2.2mPa.s. This required increasing the viscosity of the A6 solution by 15%-20% and reducing the viscosity of E1 solution by approximately 80%. High and low viscosity solvents compatible with sol-gel chemistry were used as viscosity modifiers. Stable drop formation began around Z=11, but a value of around 6 was found to have the best drop control.

2.2 CHEMICAL COMPATIBILITY OF THE INK

The final step in creating a jettable PZT solution was to confirm that hydrolysis was limited within the ink. All of the solvents in this work are used in sol-gel synthesis and their effects on the metal organic precursors have been studied. 2-methoxyethanol, 1,2-propanidiol, and 1-butanol are used in the synthesis of the A6 and E1 sol-gels and are likely to have little effect on the degree of hydrolysis and condensation in the solution. 2-propanol and 2-ethlyhexanoic on the other hand are not often used in PZT sol-gel solutions and may result in unwanted increase in the molecular complexity or precipitation of the precursors. In has been shown that 2-ethlyhexanoic acid for example, will react with sol-gel metal-organic precursors dissolved in 2-methoxyethanol and increase molecular complexity [Vasiljev, *et. al.*, 1998]. This reaction however, occurs during distillation and should not readily occur under printing conditions. 2-propanol is usually neutral towards sol-gel metal-organics and has been used to dilute solutions previously [Nakao, *et. al.*, 1991].

Direct measurement of the state of hydrolysis was also used for confirmation. Previous work has related the viscosity of PZT sol-gel solutions to the increase in particle size caused by hydrolysis and condensation polymerization [Zhang, *et. al.*, 1998]. To confirm that the polymer chains in the PZT inks were not growing after dilution viscosity measurements were taken for the stock PZT sol-gel and the highest dilution ink (mixed for a 10pl nozzle) over a period of 8 months. Both solutions showed a viscosity change within the margin of error (<2%) after 30 days and a small reduction in viscosity after 8 months (approximately 5%). This unexpected reduction in viscosity was attributed to a precipitation of a small amount of metal organic material over time that was visible around the edges of all of the ink vials. While precipitation did raise concerns that some material had polymerized enough to leave solution, the small amount of precipitated material and the overall reduction in viscosity indicate that the reaction is limited. Regardless of source of the precipitation, the effect on the sol-gel chemistry was minimal and occurred over a long time. This confirms that the added solvents did not significantly alter the sol-gel chemistry. Combining the chemical and physical functional requirements for a sol-jet ink, and analysing the design interactions, yields a solvable lower triangular design matrix (2).

$$\begin{bmatrix} \text{Decap} \\ \text{Jetablility} \\ \text{Drop Dynamics} \\ \text{Hydrolysis} \end{bmatrix} = \begin{bmatrix} XOOO \\ XXOO \\ XXXO \\ XOOX \end{bmatrix} \begin{bmatrix} \text{Concentration} \\ \text{Viscosity} \\ \text{Ohnesorge Number} \\ \text{Solvent Compatibility} \end{bmatrix} \tag{2}$$

3 PROCESSES PARAMETERS FOR UNIFORM THIN FILMS

The final morphology of an ink jet deposited film is determined primarily during drying. The internal fluid flows that occur as the film evaporates drive the solutes within the film and determine the distribution of solute material. Printing of uniform PZT films was achieved by using substrate temperature to balance the outward and inward capillary flows to form uniform single drops, and then joining those drops into lines and films. Evaporation driven flow drives solute material outwards towards the drop edge while surface Marangoni flows draw solute material inwards towards the drop center. The thermocapillary surface flow increases with temperature and therefore substrate temperature was used as the primary design parameter to balance these flows and ensure uniform deposition. Once internal flows are balanced drop deposition rate and spacing may be used to control drop coalescence and ensure that the uniform drops are joined into uniform lines and films.

3.1 UNIFORM SOLUTE DISTRIBUTION IN SINGLE PRINTED DROP

It has been widely observed that solutes tend to collect in a ring around the edges of a drop as solvent dries. This phenomenon is referred to as the coffee stain effect after the solute ring that forms when spilled coffee dries. The non-uniform solute distribution that results from coffee stain effect is a particularly difficult challenge for drop-on-demand printing of uniform single layer films. In 1997 Deegan et. al. identified evaporation driven capillary flow as the main cause of this outward solute movement [Deegan, *et. al.*, 1997]. They showed that if the contact line of a drying film is held fixed then the resulting surface evaporation and droplet geometry evolution requires an outward fluid flow. To maintain a fixed contact line position fluid from the interior of the drop must be constantly flowing outwards to replenish the evaporating solvent. However, approximately 10% of the mass flow measured by Deegan is towards the droplet center and is not described through the evaporative driven flow analysis. In experiments with other solvent systems the mass flow not captured by the capillary flow model is even greater and in some cases the dominant flow is inward [Hu and Larson, 2006]. Subsequent work has shown this inward flow of solute in a drying drop is a surface flow phenomenon caused by the Marangoni effect. The Marangoni effect refers to flow along an interface between two fluids (in this case the solvent and the atmosphere) that arises due to a surface tension gradient. If the solvent surface tension is higher in a particular region of the drop then surface flow in that direction will occur. In the case of a drying droplet a convective thermo-capillary flow is caused by the surface tension gradient that results from a non-uniform surface temperature [Hegseth, *et. al.*, 1996]. For most liquids surface tension decreases with increasing temperature, therefore if the edge of the drop is heated by a warm substrate then a surface tension gradient will be formed and inward surface flow will occur.

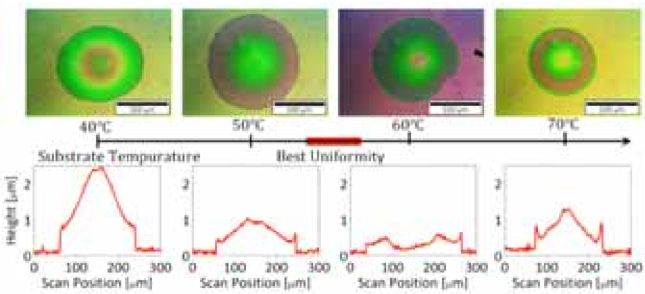

Figure 1. Profilometry of PZT sol-gel drops printed at different temperatures on a PZT substrate. This result indicates an optimum deposition temperature of approximately 55°C.

Internal flows of individual printed drops were characterized by examining the solute patterns of dried drops. The distribution of the solute after drying was examined visually and with profilometry in order to infer the balance of capillary flows. The nonuniform surface temperature required for Marangoni flows depends on high substrate thermal conductivity and a minimum contact angle. The contact angle for the drops in each printed layer is determined by the wetting between the ink solution and the pyrolyzed PZT of the previous printed layer. The capillary flows for PZT inks deposited onto PZT films were measured by printing single drops of 0.1nl onto a flat substrate coated with PZT by spin coating. The temperature was then increased to tune drop uniformity and ultimately an optimum deposition temperature of between 50°C and 60°C for an E1 sol-gel based ink printed on PZT (Figure 1).

3.2 DROP COALESCENCE AND THE FORMATION OF UNIFORM THIN FILMS

Once the conditions for uniform drop deposition were established coalescence was studied to ensure the formation of smooth lines and films. The effect of drying time on drop coalescence was characterized by varying substrate temperature and measuring the profile of the dried solute. The morphologies that resulted were similar to 1-D line morphologies that have been previously reported but extended to a close packed 2-D film [Soltman and Subramanian, 2008]. When ink drying is slow the drops coalesce completely and the aggregate film dries together in a single drying event. If the resulting combined liquid film is large (minimum feature size of approximately 1mm or greater) the high Bond number and resulting shape of the liquid film eliminates nearly all surface tension driven flows. This leads to a significant net outward flow of solute and distinct coffee ring morphology at the edges of the coalesced film. If the drying time is rapid relative to the drop deposition period then drops dry in individual drying events. The resulting morphology is the sum of the individual drying events as if they were stacked on top of each other that leads to drop scale non-uniformities in the final film. As expected the best uniformity occurs when drop deposition and drying times are similar.

The strong influence that substrate temperature has on the uniformity of both single drops and lines/films indicates the potential for a coupled design in which satisfying the requirements for both may be impossible. If substrate temperature is to be used as a design parameter to control the internal capillary flows within the drying liquid then another design parameter is needed to control drop coalescence. However, the parameter that controls drop coalescence is the ratio of drying time to drop deposition period. If drops are deposited more slowly more time is allowed for drying. Therefore substrate temperature was used to balance capillary flows and deposition frequency and spacing was used to control line and film uniformity (3).

$$\begin{bmatrix} \text{Marangoni Flows} \\ \text{Coalescence} \end{bmatrix} = \begin{bmatrix} X & O \\ X & X \end{bmatrix} \begin{bmatrix} \text{Substrate Temp} \\ \text{Dry Time/Dep. Period} \end{bmatrix} \quad (3)$$

4 CONCLUSION

A new manufacturing method for the deposition of PZT thin films based on ink jet printing has been developed. A solvent system was designed that is compatible with the sol-gel material and also prints reliably and repeatably. Processes parameters were established that enable the deposition of well-defined uniform thin films. To achieve uniform solute distribution, substrate temperature and ink drying were optimized to balance outward, evaporating driven, and inward, surface tension driven, capillary flows. Drop spacing was determined and deposition patterns were developed that produce uniform lines and films. Ultimately the morphology of the deposited films was controlled well enough to meet the requirements of most PZT based MEMS devices.

Printing reduces manufacturing costs for current thin film PZT based devices and has the potential to enable new device geometries in the future. Most importantly however, this process makes it easy to deposit an excellent piezoelectric material which, up until this point, has not been widely used due to manufacturing difficulty.

This process would not have been realized without the decoupling of the complex functional relationships between the controlling design parameters. Axiomatic design analysis uncovered the lower triangular sequential nature of this design problem and provided the correct order in which to address each FR/DP pair. Observing that each of the ink properties will impact the printing process design we can combine (2) and (3) into one equation which governs the design of a sol-gel drop on demand printing process (4).

$$\begin{bmatrix} \text{Decap} \\ \text{Jetablility} \\ \text{Drop Dynamics} \\ \text{Hydrolysis} \\ \text{Marangoni Flows} \\ \text{Coalescence} \end{bmatrix} = \begin{bmatrix} \text{XOOOOO} \\ \text{XXOOOO} \\ \text{XXXOOO} \\ \text{XOOXOO} \\ \text{XXXXXO} \\ \text{XXXXXX} \end{bmatrix} \begin{bmatrix} \text{Concentration} \\ \text{Viscosity} \\ \text{Ohnesorge Number} \\ \text{Solvent Compatibility} \\ \text{Substrate Temp} \\ \text{Dry Time/Dep. Period} \end{bmatrix} \tag{4}$$

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AXIOMATIC DESIGN OF AN IMPROVED EGG CARTON MANUFACTURING PROCESS

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ABSTRACT

An egg carton fabrication process was developed and evaluated using the Axiomatic Design principles. The process is improved via new approaches that could better match the functional requirements. In addition, this new egg carton design should have better protection against bacteria.

Keywords: Axiomatic design, egg carton, design matrix

1 INTRODUCTION

1.1 OBJECTIVES

The objective for this project is to decrease waste energy, reduce cost, and improve production of an egg carton by refining the manufacturing process.

1.2 RATIONALE

Eggs in the United States have a high market penetration, with 92.8% of households purchasing eggs at least once per year [Nielson, 2010]. The traditional egg carton manufacturing process is inherently wasteful. Increasing energy efficiency will reduce operating costs. Egg carton surfaces favor microbial growth and can increase the possibility of transmission of diseases to consumers [Parker et al. 2011].

1.3 STATE-OF-THE-ART

The two most popular materials for egg cartons are polystyrene and pulped paper. Compostable materials have also been used; in Japan egg cartons have been manufactured using bamboo [Pacific Research Company, 2004]. Initial scientific research has been made into food packaging made of polylactic acid derived from corn [Gross et al. 2002]. Polystyrene can be delivered in bulk as pellets ready for extrusion or can be synthesized from styrene monomer and peroxides on site [Zabaniotou et al. 2009, Hungenberg et al. 2005]. Polystyrene uses less raw material and is cheaper than pulped paper [Hocking, 2003].

Raw materials must be processed to prepare it for manufacturing. Polystyrene pellets are extruded into foam sheets. Pellets are fed into a single screw extruder where heat, foaming gas and friction are applied [Total Petrochemicals, 2013]. This causes the pellets to melt and small gas pockets to form and expand upon exiting the extruder to form the desired solid foam [Harold et al. 2007, Schüler et al. 2012]. Pulp processing requires raw recycled paper blended with water and pulp slurry is continuously stirred in a blending drum. The pulp is then siphoned off and screened [Zabaniotou et al. 2009].

Dating back to early 1950s', engineers started to make egg carton using collapsible cardboard [Gilchrist, 1953]. Semi-rigid materials, such as fiberboard or cardboard, were mainly produced to make egg cartons by folding and stretching processes [Randles, 1968]. Egg cartons from pulped paper are produced though a drying and punching processes [Lord et al. 1965, Jie, 2013]. Thermoforming of thermoplastic and punching of polystyrene is also used to make egg cartons [Pavuk et al. 1976, Pearl et al. 1971].

The purpose of printing on the egg carton is to provide production information to the customers. Brand, production date, size, weight, number of eggs, barcode and nutritional data should be printed on the cartons [Colorado Department of Agriculture, 2013]. For clear plastic cartons, information is printed on a paper label that is applied to the cartons. For paperboard cartons, information is printed directly on the carton [Carlson et al. 1991]. Flexographic printing has also been used [Hashimoto et al. 1990]. Patents have also been filed for a process for printing on both sides of the egg carton using a rotary cylinder [Provan, 1973]. Board printers can also be used to control the pressure to ensure every product is printed with same quality [Cavagna, 1990]. Laser marking system uses a laser in order to etch directly on to the egg carton requiring no physical interaction [VideoJet Technologies Inc., 2012].

1.4 APPROACH

This paper presents an improved approach of designing egg carton production. The manufacturing process is improved by reducing both the production energy and time, as well as decreasing product susceptibility to bacterial growth [Harutunian et al. 1996]. Several new methods are used in this paper. To reduce the bacterial growth a TiO2/Polystyrene surface treatment is used on the material. The incorporation of TiO_2 nanoparticles into the polystyrene matrix increases the crystallinity and improves the barrier properties of the composites [Zhu et al. 2011]. To reduce the waste of energy, the foaming process is optimized by controlling the CO_2 concentration and the pressure [Naguib et al. 2003].

Table 1. Decomposition.

#		[FR] Functional Requirements		[DP] Design Parameters
0	FR	Manufacturing Styrofoam Egg Carton	DP	Manufacturing Process for Egg
1	FR	Process Raw Polymer into Foam Sheet	DP	Single Screw Foam Extruder
1.1	FR	Feed Polystyrene Pellets into Extruder	DP	Extruder hopper feeder
1.2	FR	Transport pellets through extruder	DP	Screw pump
1.3	FR	Melt pellets by heating	DP	Heating element in extruder walls
1.3.1	FR	Create heat transfer surface area	DP	Cylindrical surface area of extrduder
1.3.2	FR	Provide heat transfer coefficient	DP	Material and mixing property
1.3.3	FR	Create Temperature gradient	DP	Distance from pellets to heater
1.4	FR	Create density of polystyrene foam	DP	Add foaming gas agent
1.5	FR	Form foam into sheet	DP	Nozzel unit
1.5.1	FR	Create desired sheet width	DP	Width of extruder die
1.5.2	FR	Create desired height	DP	Lip gap of extruder output
2	FR	Form Sheet Into Egg Carton Geometry	DP	Thermoforming Press
2.1	FR	Insert foam sheet into mold	DP	Mold feeder trav
2.2	FR	Maintain sheet temperature above the glas	DP	Oven conveyor
2.3	FR	Deform sheet	DP	Hydraulic mold press
2.4	FR	Remove polystyrene sheet from mold	DP	Carton extractor
3	FR	Finish Surface	DP	Finishing process
3.1	FR	Apply nano particle coating to innersurface	DP	Spray coating applicator
3.1.1	FR	Seal workpiece from atmosphere	DP	Sealed Treament Space
3.1.2	FR	Mix nano particle and binder	DP	Mixing tank
3.1.3	FR	Spray Particle/Binder Mix	DP	Surface coating applicator
3.1.3.1	FR	Driving Pressure	DP	Centrifugal pump
3.1.3.2	FR	Develop microdroplet spray	DP	Nozzle
3.2	FR	Print labeling information	DP	Ink jet printer
4	FR	Package Cartons for Shipping	DP	Packager
4.1	FR	Remove carton from sheet	DP	Vertical punch press
4.2	FR	Stack cartons on pallet	DP	Punch stacking machine
4.3	FR	Encase pallet in protective sheathing	DP	Shrink wrapping machine

2 DESIGN DECOMPOSITION AND APPLICATION OF THE AXIOMS

2.1 AXIOM I

The zeroth level FR defines the overall objective of the decomposition. The objective of this project is to design a manufacturing process for a polystyrene egg carton. A linear manufacturing line for egg cartons is the physical realization for the top-level functional requirement. The first level of the decomposition follows a sequential theme. By considering the functional requirements as a series of physical transformations on the polystyrene work piece, then the decomposition is collectively exhaustive. If the transformations are independent, then the functional decomposition will also be mutually exclusive. A sequential theme suggests design parameters for a manufacturing line. This allows organizing the design parameters to avoid DP-DP interactions. Design pictures and specified geometries can be found in the appendix.

2.1.1 CURRENT DECOMPOSITION

The current decomposition is shown in Table 1.

2.1.2 THE RELATION BETWEEN FRS AND DPS

FR1 Process Raw Polymer into Foam Sheet
DP1 Single Screw Foam Extruder

The governing equation for this function requirement is the conservation of mass. The "mass in" must equal the "mass out". The overall decomposition for this function requirement is based on this principle. The metrics and tolerances for this can be found in Table 2.

FR1.1 Feed polystyrene pellets into extruder
DP1.1 Extruder hopper feeder

The metric for FR1.1 is the mass flow rate (dm/dt) of the polystyrene pellets into the extruder. This relates to the output flow rate of polystyrene foam according to the law of conservation of mass. Nomenclature for this equation and all others included in this paper can be found in the appendix.

$$\text{Mass in} = \text{Mass out}$$

$$\frac{dm}{dt} = \pi r^2 \rho_{pellets} \frac{dx}{dt} \tag{1}$$

The density of the pellets including the void fraction is 1.033 g/cm2 [Sharp, 1950].

FR1.2 Transport pellets through extruder
DP1.2 Screw pump

The metric for FR1.2 is the velocity of the polystyrene.

FR1.3 Melt pellets by heating
DP1.3 Heating element in extruder walls

The extrusion process involves a phase transition in which heating elements heat the polystyrene pellets above the melting temperature. Fourier's law expresses heat transfer for this part of the extrusion process. Fourier's Law gives the relationship between thermal conductivity and heat flow rate as shown in equation (2) [Moore, 2002]. Figure 1 implies the relationship between thermal conductivity (q), the negative local temperature gradient (k), and the temperature difference (ΔT).

$$\frac{q}{A} = -k\frac{d\theta}{dx} \tag{2}$$

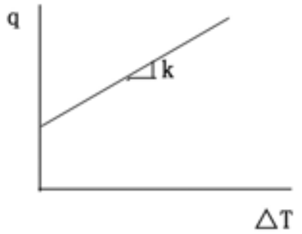

Figure 1. Heat transfer relationship.

The range of melt temperatures is limited to the given range by two constraints. The viscosity of the melt must be low enough to allow it to flow smoothly through the extruder, thus the temperature must be at least 200 °C. Polystyrene begins to decompose at high temperatures, so the temperature must stay below 240°C to ensure product quality.

FR1.3.1 Create heat transfer surface area
DP1.3.1 Cylindrical surface area of extruder

The walls of the extruder provide a surface for heat transfer.

FR1.3.2 Provide heat transfer coefficient
DP1.3.2 Material and mixing property

The material in the extruder walls is thermally conductive to allow for heat transfer.

FR1.3.3 Create temperature gradient
DP1.3.3 Distance from pellets to heater

The distance provides a temperature gradient for heat transfer.

FR1.4 Create density of polystyrene foam
DP1.4 Add foaming gas agent

Figure 2 shows the interaction between density and concentration of CO_2 as a foaming agent. FR1.4 (Choice of foaming gas) was based on cost analysis. The proportion of gas to polystyrene was chosen based on mid-weight foam.

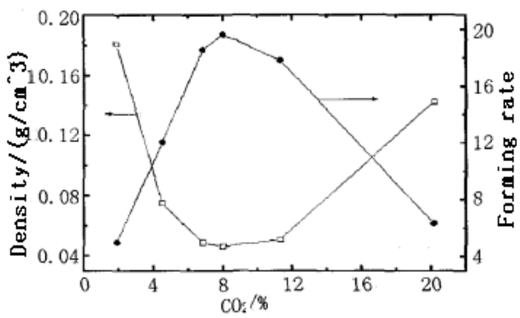

Figure 2. Relations of CO2 percentage, density and forming rate [Xin et al. 2008].

The chosen foaming product was CO_2 because it provides good performance at a more cost efficient price [Perrot, 2009].

FR1.5 Form Foam into Sheet
DP1.5 Nozzle Unit

The final step of the extrusion process is carried out at the outlet of the extruder by mechanical tools and nozzle. The foam exits the extruder as a thin sheet. Equation (3) below relates to the children of FR1.5.

$$\frac{dm}{dt} = \frac{dx}{dt}HD\rho_{foam} \tag{3}$$

FR1.5.1 Create desired sheet width
DP1.5.1 Width of extruder die

The die has the same width as the product.

FR1.5.2 Create desired sheet height
DP1.5.2 Lip gap of extruder output

The height of the lip is 1.3 times the desired height sheet.

FR2: Form sheet into egg carton geometry
DP2: Heating element in thermoformer

Fourier's law shows that if the flow rate is controlled, then the thermal conductivity can also be controlled and is directly related to the amount of heat needed and the duration of thermal forming. The physical component for this FR is close to the exit of the extruder as a means to reduce the energy loss in the form of wasted heat.

The temperature of the extruded polystyrene needs to be greater than that of the glass transition temperature (100°C), so that the produced sheet is amorphous and moldable.

FR2.3: Deform sheet
DP2.3: Hydraulic mold press

Table 2. Assigned Metrics.

FR	Metrics	DP	Metrics
1.1 Feed polymer pellets into extruder	65.5 g/s ±1 g/s	Extruder hopper feed	Pellet density 1.033g/mL
1.2 Transport pellets through extruder	180rpm±2%	Screw pump	20cm/s±0.2cm/s
1.3.3 Create temperature gradient	240°C>T_{melt}>200°C	Heating element in extruder walls	T_{wall}-T_{melt}=10°C
1.4 Create desired density	10% mass CO_2 ±2%	Inject carbon dioxide gas	.05g/cm^3 ±.005cm
1.5.Create desired sheet width	Width of sheet 131cm ±5cm	Width of extruder die	131cm ±2mm
1.5.2 Create desired sheet height	.5cm ±.03cm	Lip gap	.75cm ±.03cm
2.2 Maintain Temperature of Styrofoam sheets	T>T_g~100°C	Conveyor Oven	T_{oven}=120°C

Table 3. Design matrix.

	DP0: Manufacturing Process for Egg	DP1: Single Screw Foam Extruder	DP1.1: Extruder hopper feeder	DP1.2: Screw pump	DP1.3: Difference between wall and melt temperature	DP1.3.1: Cylindrical surface area of extrduder	DP1.3.2: Material and mixing property	DP1.3.3: Temperature difference between melt and wall	DP1.4: Add foaming gas agent	DP1.5: Nozzel unit	DP1.5.1: Width of extruder die	DP1.5.2: Lip gap of extruder output	DP2: Thermoforming Press	DP2.1: Mold feeder tray	DP2.2: Oven conveyor	DP2.3: Hydraulic mold press	DP2.4: Carton extr	DP3: Finishing process	DP3.1: Spray coatiolicator	DP3.1.1: Sealelement Space	DP3.1.2: Mixing	DP3.1.3: Surfacting applicator	DP3.1.3.1: Cugal pump	DP3.1.3.2: h	DP3.2: Ink jet printe	DP4: Packager	DP4.1: Vertical puress	DP4.2: Punch stackachine	DP4.3: Shrink wrapmachine
FR0: Manufacturing Styrofoam Egg Carton	O																												
FR1: Process Raw Polymer into Foam Sheet		X																											
FR1.1: Feed Polystyrene Pellets into Extruder			X																										
FR1.2: Transport pellets through extruder				X																									
FR1.3: Melt pellets by heating				X	X																								
FR1.3.1: Create heat transfer surface area						X																							
FR1.3.2: Provide heat transfer coefficient							X																						
FR1.3.3: Driving force for heat								X																					
FR1.4: Create density of polystyrene foam									X							X													
FR1.5: Form foam into sheet										X																			
FR1.5.1: Create desired sheet width											X																		
FR1.5.2: Create desired height												X																	
FR2: Form Sheet Into Egg Carton Geometry													X																
FR2.1: Insert foam sheet into mold														X															
FR2.2: Maintain sheet temperature above the glass temper															X	X													
FR2.3: Deform sheet																X													
FR2.4: Remove polystyrene sheet from mold																	X												
FR3: Finish Surface																		X								X		X	
FR3.1: Apply nano particle coating to innersurface of carton																			X										
FR3.1.1: Seal workpiece from atmosphere																				X									
FR3.1.2: Mix nano particle and binder																					X								
FR3.1.3: Spray Particle/Binder Mix																						X							
FR3.1.3.1: Driving Pressure																							X						
FR3.1.3.2: Develop microdroplet spray																								X					
FR3.2: Print labeling information																									X				
FR4: Package Cartons for Shipping																										X			
FR4.1: Remove carton from sheet																											X		
FR4.2: Stack cartons on pallet																												X	
FR4.3: Encase pallet in protective sheathing																													X

From the law of conservation of energy, the relationship between the molding speed and the pressure can be found. Once the pressure is fixed, the speed of the mold can be calculated. Since the speed and time are fixed, then the speed of the die can be found.

$$W = \frac{1}{2}mv^2 + PAH \quad (4)$$

Table 2 contains the assigned metrics that could influence the decision-making on the design parameters and on the process variables.

2.1.3 COUPLING

There are several off diagonal interactions in the design matrix, as shown in Table 3:

FR1.3 Heating the polystyrene melt and DP1.2 Screw pump are coupled because the friction heating from the screw pump accounts for 90% of the heat energy in the extruder [Total Petrochemical, 2013]. Thus, the work done by the extruder should be specified first and then the heater settings adjusted to avoid iterative adjustment.

FR 1.4 Density of polystyrene foam and DP 2.3 Hydraulic mold are coupled because pressure can collapse the open cells created by the foaming process and cause the density to increase.

FR 2.2 Maintain heat and DP 2.3 Hydraulic press are linked because temperature is a function of pressure.

FR3 Surface finish and DP4 Packager. The surfaces of the cartons touching during packaging could cause deposition of the surface treatment and defects in surface finish.

2.2 AXIOM II

Equation (6) for probability of success is shown below:

$$\mathrm{I} = \ln\left(\frac{1}{P}\right) \quad (5)$$

$$\mathrm{p} = \frac{1}{e^{I}} \quad (6)$$

For equations 5 and 6, I is the information content. In this case, I relates to each FR-DP pair and p is the corresponding probability of success.

In the initial design, there are four children for FR1.4, which produce four FR-DP pairs under FR1.4. So, the probability of success in this case equals to 0.02. Table 4 shows the initial FR-DP matrix for FR1.4.

Table 4. Initial FR-DP matrix for FR1.4.

	Content	DP	Content
FR1.4	Extrude foam in sheet	DP1.4	Nozzle unit
FR1.4.1	Control Flow Rate	DP1.4.1	Centrifugal pump
FR1.4.2	Change flow shape from cylindrical to flat	DP1.4.2	Fish tail die
FR1.4.3	Create desired height	DP1.4.3	Lip gap
FR1.4.4	Normalize flow regime	DP1.4.3	Land

The pump should be decoupled in order increase the probability to success. FR1.4 was separated and reformed as FR1.3, FR4, and FR1.5 as shown in Table 5.

Table 5. Adjusted FR-DP pairs.

1.3	FR	Melt pellets by heating	DP	Difference between wall and melt temperature
1.3.1	FR	Create heat transfer surface area	DP	Cylindrical surface area of extrduder
1.3.2	FR	Provide heat transfer coefficient	DP	Material and mixing property
1.3.3	FR	Driving force for heat	DP	Temperature difference between melt and wall
1.4	FR	Create density of polystyrene foam	DP	Add foaming gas agent
1.5	FR	Form foam into sheet	DP	Nozzel unit
1.5.1	FR	Create desired sheet width	DP	Width of extruder die
1.5.2	FR	Create desired height	DP	Lip gap of extruder output

In this condition, there are only three pairs of FR-DPs under FR1.3, so that the probability of success is improved from 2% to 5%. As for FR1.5, it would have two children with a 13.5% probability of success, and the FR-DPs becomes collectively exhausted and mutually exclusive.

3 PHYSICAL INTEGRATION

The physical integration matrices are shown in Table 6 and Table 7. The DPs are decomposed into each level to allow analyzing the relationships between them.

Table 6. DP-DP interactions.

	DP1	DP2	DP3	DP4
DP1: Single Screw Foam Extruder	-	0	0	0
DP2: Thermoforming Press	0	-	0	0
DP3: Finishing Processes	0	0	-	0
DP4: Packager	0	0	0	-

The physical integration matrix is different from the FR-DP matrix of the former section. In the FR-DP matrix, FR3 and FR4 are coupled, however here DP3 and DP4 are not coupled because finishing and packing are not physically operated at the same location. DP2.2 and DP2.3 do not interact due to the same reason.

Table 7. Physical Integration Matrix for DP2.

	DP2.1	DP2.2	DP2.3	DP2.4
DP2.1: Mold feeder tray	-	0	0	0
DP2.2: Oven conveyor	0	-	0	0
DP2.3: Hydraulic mold press	0	0	-	0
DP2.4: Carton extractor	0	0	0	-

DP-DP interaction commonly happens when two physical parts are in direct contact or two processes are carried out in the same device or place. In our system, all the processes take place in different machines or different locations, so that there is no DP-DP coupling.

4 INNOVATION

A problem with current egg cartons is that surface microbial growth can lead to egg spoilage or contamination. The innovation that was added to the egg carton to address this issue was a TiO_2 nanocoating to the interior of the carton. Similar nanocoatings has been shown to have anti-microbial effects when applied to polystyrene [Loddo et al. 2012]. A spray application chamber was added to the design of the manufacturing line in order to decouple the new spraying process from the other already existing processes.

Traditional polystyrene foam egg cartons are not environment-friendly at the end of the product life cycle. A possible innovation that was explored was to use low-density polylactic acid (PLA) derived from corn as the base material for the cartons. This material has similar thermal and mechanical properties to that of polystyrene [Parker et al. 2011]. Since this material is compostable, it was felt that it would not be as beneficial to the process as the antimicrobial nanocoating.

5 CONCLUDING REMARKS

This paper shows an improvement in the design of an egg carton manufacturing process through the application of Axiomatic Design. The process is improved by new approaches that could better match the functional requirements. To eliminate unnecessary coupling in the process, decomposition and mapping matrices were used to make the structure of the system more clear, so that the processes could be rearranged. The improved process would reduce production time and energy waste. In addition, the eggs will have better protection against bacteria via the newly designed egg carton surface coating. Future works will include improving the material's performance, especially what concerns to the environmental aspects, and recycled polystyrene and biodegradable materials will be considered.

6 ACKNOWLEDGMENT

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8 APPENDICES

DP-DP interactions for all FRs

	DP1	DP2	DP3	DP4
DP1: Single Screw Foam Extruder	-	0	0	0
DP2: Thermoforming Press	0	-	0	0
DP3: Finishing Processes	0	0	-	0
DP4: Packager	0	0	0	-

	DP1.5.1	DP1.5.2	DP1.5.3
DP1.5.1: Fish tail die	-	0	0
DP1.5.2: Lip gap	0	-	0
DP1.5.3: Land	0	0	-

	DP2.1	DP2.2	DP2.3	DP2.4
DP2.1: Mold feeder tray	-	0	0	0
DP2.2: Oven conveyor	0	-	0	0
DP2.3: Hydraulic mold press	0	0	-	0
DP2.4: Carton extractor	0	0	0	-

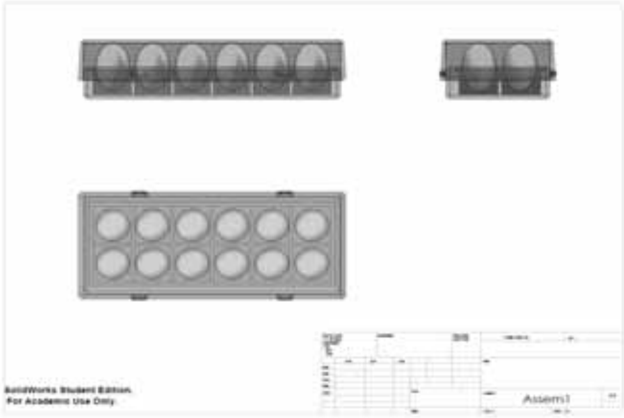
	DP3.1	DP3.2
DP3.1: Spray coating applicator	-	0
DP3.2: Ink jet printer	0	-

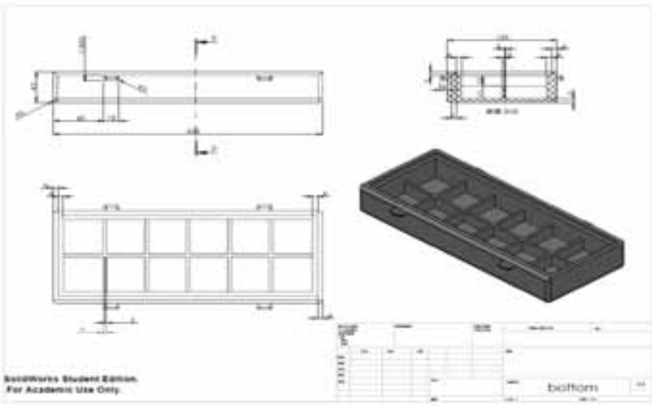
	DP4.1	DP4.2	DP4.3
DP4.1: Vertical punch press	-	0	0
DP4.2: Punch stacking machine	0	-	0
DP4.3: Shrink wrapping machine	0	0	-

Nomenclature

H - depth of foam sheet (cm)
D - width of foam sheet (cm)
ρ_{foam} - density of foam sheet (g/cm^3)
dx/dt - rate of foam output (cm/s)
dm/dt - mass flow rate of sheet (g/s)
$\frac{q}{A}$ - heat flow rate per unit area
k - thermal conductivity
$\frac{d\theta}{dx}$ - temperature (θ) gradient in the direction of heat flow, x
W - total energy supplied by the electrical system of the molding machine (J)
H - vertical movement distance of the die (cm)
v - speed of the upper mold (cm/s)
m - mass of the upper mold (g)
P - pressure applied to the product (Pa)
A - area (cm^2)

Design of Egg Carton





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