INSTITUTO TECNOLOGICO Y DE ESTUDIOS SUPERIORES DE MONTERREY

CAMPUS MONTERREY

SCHOOL OF ENGINEERING AND INFORMATION TECHNOLOGIES
GRADUATE PROGRAMS

TECNOLÓGICO DE MONTERREY®

Innovative Optimal Design Methods

A DISSERTATION IN

INDUSTRIAL ENGINEERING

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE ACADEMIC DEGREE OF:

DOCTOR OF ENGINEERING SCIENCES

BY:
DIANA PAOLA MORENO GRANDAS, B.S., M.T., M.S.

MONTERREY, NL. **DICIEMBRE, 2013**

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DECLARATION

This is to certify that I am responsible for the work submitted on the present dissertation, that the original work is my own and does not include the outcome of collaborative work, except where stated otherwise.

Diana Paola Moreno Grandas, B.S, M.T., M.S.
Monterrey, NL, México
Diciembre, 2013

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Diana Paola Moreno Grandas

DEDICATORIA

“GOD WORKS IN MISTERIOUS WAYS”…

Cuando empece a escribir esta dedicatoria esta fue la primera frase que vino a mi mente. Yo creo debido a que mi doctorado estuvo salpicado de experiencias y encuentros únicos que vistos en retrospectiva hicieron de esta una etapa maravillosa, satisfactoria en inolvidable en mi vida.

Tengo que agradecer a tantas personas que temo dejar a alguien por fuera por las prisas y nervios asociados a la entrega de este documento, asi que intentare hacer mi mejor esfuerzo.

Agradezco a Dios padre, por haberme puesto en este mundo, por haberme dotado de una incanzable curiosidad, talentos y la persistencia para culminar todo lo que me propongo.

Agradezco a mis padres por haberme dado la vida, a mi mami le agradezco especialmente el haberme retado siempre a mejorar, a investigar, a cuestionar, a ser disciplinada (aunque a veces el animo decaiga), a dar siempre lo mejor de mi, a ser generosa y siempre dar todo lo mas posible a los demás.

Agradezco a mi hermanita el ser un motor y soporte… ella sabe que es mi roca y que sin ella yo no lograría ni la mitad de mis cosas. Ella siempre me motiva a que persevere con energía (no se de donde saca tanta). A ella le debo tantas cosas… por ella aprendi ingles! y por ser ella la hermanita mayor siempre puso una barra alta que siempre quise llegar a alcanzar… es mi gran modelo.

Agradezco a Eduardo, mi único y maravilloso sobrino, que desde que nacio ha sido mi luz y mi inspracion. El es mi bálsamo personal… me calma, conforta y alegra la vida. Gracias a sus preguntas me di cuenta que tenia muchas áreas para mejorar en cuanto a la forma de presentar mi investigación, la cual siempre muy atento escucho, me cuestiono y me dio su opinion. Gracias chinito lindo!

Agradezco al Doctor Hernandez… Ay Doc! No sabe cuanto le agradezco… ud me dio una familia en Monterrey, con alegrías, enojos, reconciliaciones, retos, apoyo, y sobre todo mucho afecto. En el grupo Seis Sigma siempre hay calor de hogar, Ud incluso nos abrió las puertas de su casa para celebrar cumpleanos, graduaciones, posadas… hasta partidos de futbol! Gracias Doctor por apoyarnos siempre tanto, por retarnos para que mejoremos academica y profesionalmente, recuerdo muchas reuniones en su oficina estresantes pero también recuerdo otras muchas en la cuales intentaba animarnos y animarse con música… A ud tambien le debo haber contado con los

mejores coasesor y sinodales que se pueden tener, ya que me ayudaron a crecer y seguirme proponiendo nuevas metas. Gracias Doc por todas sus bondades!

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Tengo que hacer un aparte para Erikiux quien no solamente es el brazo derecho (y más de ¾ del cerebro del Doc), sino también una maravillosa mujer y amiga… Erikiux siempre estuvo dispuesta a escuchar y ayudar logrando hacer cosas imposibles. Siempre muy apacible puede calmar a un huracán, siempre muy organizada logra sacar todo adelante. Gracias amiga por todo tu apoyo y cariño!

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A las aproximadamente 4 generaciones de Seis Sigma que he podido conocer y he llegado a compartir (enero de 2006 a diciembre de 2011) junto con Mayris y Angie les agradezco su apoyo personal y profesional, su cariño, compañerismo… su paciencia…ya que creo que todos han tenido que lidiar con mis problemas de la espalda y siempre lo han hecho de manera generosa… muchas gracias a todos!

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A todos aquellos que de una u otra forma estuvieron durante esta aventura y que no están explícitamente nombrados les pido disculpen mi falta de memoria, tiempo y espacio, pero les reitero que están en mi corazón y que siempre les agradecere su amistad y apoyo.

A los lectores, este documento les pertenece y espero les sea de utilidad e inspiración.

Que Dios los bendiga siempre!

DIANA MORENO

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Chapter 1. Introduction

1.1 Problem Description

These days, it is getting harder and harder for many companies to remain competitive, as manufacturing spreads to lower-cost regions and product life span is shortening, in this environment, innovation is becoming a continuous race that gives little to none place to rest.

Market conditions have change from a pure manufacture focus to an intellectual focus. This intellectual focus means to improve not only product and service but innovation and design (I+D) processes as well as its outcomes.

To make this transition from one focus to the other, I+D activities and methods have been facing the need to be revised, modified or strengthened in order to have first, a sustainable and consistent I+D results, and second, to deploy them in an effective way across the enterprise.

Enterprises are now aware that in order to survive market conditions and obtain the best possible results -remaining competitive- three key goals have to be achieved:

- Increase the number and quality of innovative product/process ideas (ideation).
- Reduce cycle time for I+D[1] activities.
- Assure quality and robust performance for the designed product/process.

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[1] The word Design used on present dissertation encloses design and redesign activities

Therefore, the research proposed here intends to answer the following question:

Is it possible to develop and integrate methods for Innovative Optimal Designs of products and services to enhance quantity of ideas, enables quality on their performance and reduce the number of iterations on development?

1.2 Objectives

1.2.1 General

The main goal of present dissertation is to develop and integrate methods for Innovative Optimal Designs of products and services to enhance quantity of ideas, enable quality on their performance and provide means to reduce the number of development iterations.

1.2.2 Specific Objectives

The proposed methodology will help designers to deploy innovation and design initiatives through the following specific objectives:

- Explore the cognitive process behind idea generation techniques and methods to evaluate design by analogy as a path for innovative idea generation and test it under different conditions to identify factors that could improve idea generation outcomes.
- Analyze Toyota Design System and its western version Set-Based Concurrent Engineering, to validate an approach to reduce development cycle time.

- Develop an optimization approach for the robust performance of coupled designs with nonlinear responses.

1.3 Hypothesis

H1: Is it possible to integrate methods and tools for the development of innovative optimal designs.

H2: Is it possible to increase the generation of ideas by searching means to re-represent the problem and explore analogous domains for solutions.

H3: Range and Domain functions of Labeled Fuzzy Sets (LFS) work the same than Giachetti's Image and Domain, to reduce development iterations.

H4: Preferred robust designs can be achieved by integrating Axiomatic Design, Response Surface Methodology and Labeled Fuzzy Sets.

1.4 Research Questions

- Could prior product knowledge be more likely to be retrieved and used for innovative design solutions when analogous products and design problems are described using general or specific language?
- Could analogical prose aids be more likely to increase the quantity and quality of transactional innovative solutions?
- Could a design method that considers simultaneously possibility and preference functions reduce development cycle time?

- Could coupled designs (nonlinear relation among inputs and outputs) be optimized and controlled assuring quality and robust performance?

1.5 Research Environment and Contributions

In order to understand where present research is located, some visual aids and summary tables of literature review will be presented. The purpose of this section is to have a deep understanding of the research surroundings, that is, previously researched areas/topics, which will allow the identification of improvement opportunities where present research will contribute.

Figure 1. Development Process Components

Development process (which includes Innovation and design) can be divided into technical aspects (that enclose but are not limited to tools, methods, procedures, algorithms, etc.) and behavioral issues (including cognitive processes, mental states, team work, etc.) which are graphically presented on Figure 1.

These two components were represented as gears, because they had to work together in order to achieve best possible results, therefore, present research will work in both components through the exploration of three main topics: Set-based Design, Optimization and Design By Analogy (see Figure 2).

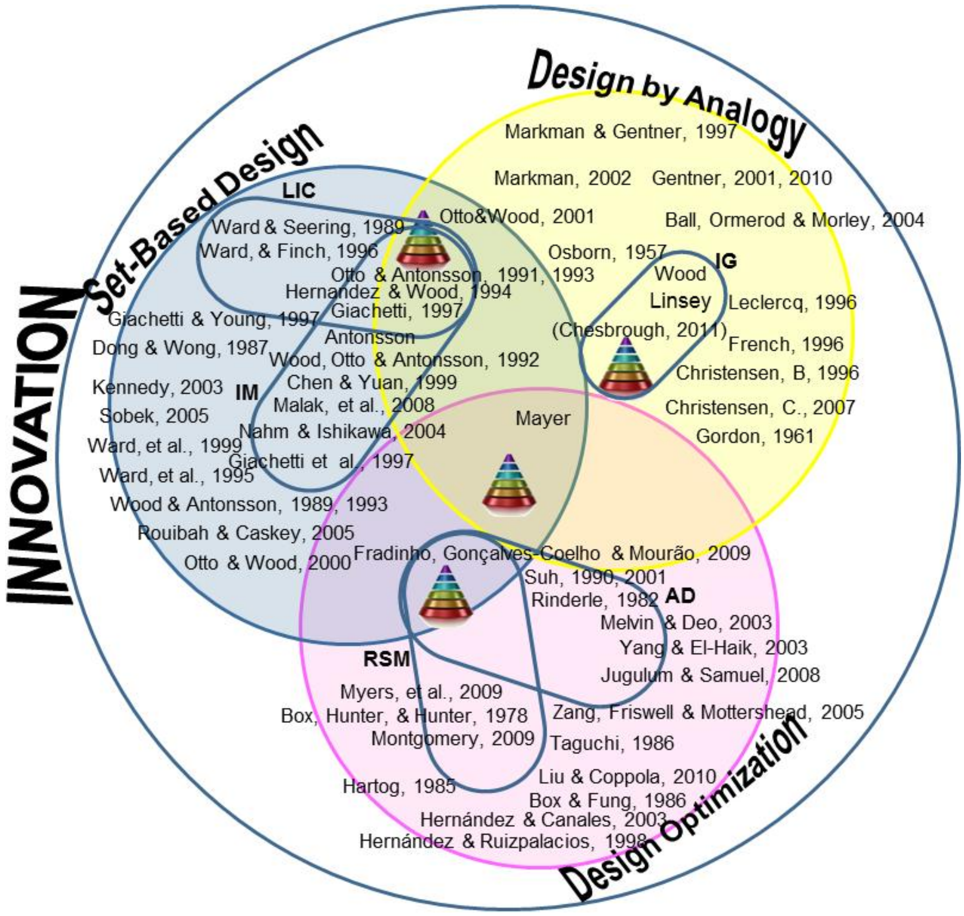

Figure 2. Research Environment and Contributions

Figure 2 maps authors from body of knowledge and revised literature into their corresponding contribution field, and also relevant areas within those fields are highlighted to explicit where research contributions (conical shapes) will be located in the body of knowledge.

Previous figure was developed based on the literature review for Set-based Design, Optimization and Design by Analogy. All authors and contributions where thoroughly revised and their specific contributions are discussed in the corresponden chapter of present dissertation. A condensed table of authors and contributions is presented on Table 1. The areas of contribution correspond to the spheres presented in Figure 2, and the labels DBA, DO, SBD corresponds to Design by analogy, Design optimization and Set-based design

Table 1. Research´s Literature Overview

AREA	SPECIALTY	TOPICS	AUTOR
DBA	Biomimetic	Biological analogy	Hacco & Shu
DBA	Biomimetic	Biological analogy	Shu, Hansen, Gegeckait, Moon, & Chan
DBA	Biomimetic	Promote use and power	French
DBA	Brainstorming	Tools	Osborn
DBA	idea generation	evidence use of analogy for design	Leclercq & Heylighen
DBA	Problem Solving / Scoping	Problem Statement / Definition	Christensen, C.
DBA	Psychology	Data analysis	Clark-Carter
DBA	Psychology	Data analysis	Von Eye
DBA	Solving problem techniques	divergent tree	Cai, Yang, & Lin
DBA	Synectics	concept generation - analogies	Jones
DBA	Synectics	concept generation - analogies	Polonyi
DBA	Synectics	concept generation - analogies	Ueda
DBA	Synectics	concept generation - metaphors	Grant & Oswick
DBA	Synectics	concept generation - metaphors	Lakoff & Johnson
DBA	Synectics	concept generation - metaphors	Osterloh & Von Wartburg
DBA	Synectics	Promote use and power	Gordon
DBA	wordtree method	analogy, idea generation techniques	Linsey, Wood, & Markman
DBA		Analogical reasoning, learning	Gentner
DBA		Analogical reasoning, learning	Markman
DBA		Analogical reasoning, learning	Markman&Gentner
DBA		analogy	Clement, Mawby, & Giles
DBA		analogy	Itkonen
DBA		analogy cognitive process	Linsey, Laux, Clauss, Wood, & Markman
DBA		analogy retrieval	McAdams & Wood
DBA		Analogy use by engineers (novel and experts)	Ball, Ormerod & Morley
DBA		Analogy use by engineers (novel and experts)	Kolodner
DBA		Cognition on engineering, design fixation, group cognition, analogy, commoditized of product quality	Cagan
DBA		concept generation - modality representation and analogy	Linsey, Wood, & Markman

AREA	SPECIALTY	TOPICS	AUTOR
DBA		concept generation - representation	Linsey, Laux, Clauss, Wood, & Markman
DBA		concept generation - representation	Linsey, Murphy, Wood, Markman, & Kurtoglu
DBA		Creative behavior model	Rouse
DBA		Creative behavior model	Zhu, Nagalingam, & Hsu
DBA		evidence use of analogy for design	Christensen, B.
DBA		idea generation techniques	Linsey, Laux, Clauss, Wood, & Markman
DBA		Innovation in services	Chesbrough
DBA		Promote use and power	Otto & Wood
DBA		semantic networks	Collins & Loftus
DBA		semantic networks	Roediger, Marsh, & Lee
DBA		Synectics, creative design, TIPS	Blosiu
DBA		Visual analogies for design problem solving	Casakin & Goldschmidt
DO	Axiomatic design	Axioms, principles, theorems, Design matrix, coupling,	Suh
DO	Axiomatic design	Coupling measures Reangularity, Semangularity	Rinderle
DO	Axiomatic design and Taguchi	Noise factors to robust responses	Melvin & Deo
DO	DFSS	Axiomatic Design	Yang & El-Haik
DO	DFSS	Axiomatic Design, Response Surface Methodology	Jugulum & Samuel
DO	Dynamic vibration Absorber	Numerical methods	Liu & Coppola
DO	Dynamic vibration Absorber	parameter design nonlinear programming	Box & Fung
DO	Dynamic vibration Absorber		Canales
DO	Dynamic vibration Absorber		Hartog
DO	Dynamic vibration Absorber		Hernández & Canales
DO	Dynamic vibration Absorber		Hernández & Ruizpalacios
DO	Response Surface Method	Experimental Design	Montgomery
DO	Response Surface Method		Box, Hunter, & Hunter
DO	Response Surface Method		Myers, Montgomery, & Anderson-Cook
DO	Response Surface Method and Axiomatic design	Coupled design cost optimization	Fradinho, Gonçalves-Coelho & Mourão
DO	Response Surface Method and Axiomatic design		Arcidiacono, Schurr & Rossi
DO	Robust design	Application to dynamics of tuned vibration absorber (parameter uncertainty) using non-linear programming	Zang, Friswell & Mottershead

AREA	SPECIALTY	TOPICS	AUTOR
DO	Taguchi Method		Taguchi
SBD	Fuzzy logic	Parametric representation of fuzzy numbers, arithmetic operators	Giachetti & Young
SBD	Fuzzy sets, imprecision		Dong & Wong
SBD	Imprecision	Fuzzy Mapping, define parameter behavior and operators	Giachetti
SBD	Imprecision	Calculations with fuzzy parameters	Wood Otto & Antonsson
SBD	Imprecision	Optimization, Imprecise Design tool, Trade-off	Antonsson
SBD	Imprecision and variability	Multi-attribute utility theory, probabilistic uncertainty, defines probability bounds analysis. Conceptual design decision making strategy	Malak, Aughenbaugh & Paredis
SBD	Imprecision and variability	Precision convergence and imprecision coefficient	Giachetti, Young, Roggatz, Eversheim & Perrone
SBD	Imprecision Method	Preference	Wood & Antonsson
SBD	Labeled Fuzzy Sets	Integration of labeled interval calculus with imprecision method	Hernandez & Wood
SBD	Labeled Interval Calculus (LIC)	Feasible component selection, defines interval operations and labels. Suggest analyzing abstraction principles.	Ward & Seering
SBD	LIC + IM	Feasibility, preference	Giachetti
SBD	LIC + IM	Feasibility, preference	Hernandez
SBD	Product design		Otto & Wood
SBD	Quantified relationships for LIC	Introduces uncertainty on variables values, predicate logic, temporality, causality and dependency	Ward, & Finch
SBD	selection de ideas		Pugh Ulrich, Eppinger, Clark y Wheelwright
SBD	Toyota design System	Benefits, potential, modeling, team work, knowledge management	Kennedy
SBD	Toyota design System	Benefits, potential, modeling, team work, knowledge management	Sobek
SBD	Toyota design System	Main principles and characteristics	Ward, Liker & Sobeck
SBD	Toyota design System	Philosophy, cross functional teams	Ward, Liker, Cristiano & Sobeck
SBD	Uncertainty	Probabilistic design model	Chen & Yuan
SBD	Uncertainty dominance	Preference set-based design. Propose Preference number and preference graph	Nahm & Ishikawa
SBD		Bounding set theorem and interval propagation theorem. Computational capabilities.	Ward, & Finch
SBD		Design Evaluation	Giachetti & Jurrens
SBD		Integration of labeled interval calculus with imprecision method	Otto & Antonsson
SBD		Parametric engineering process for Concurrent Engineering	Rouibah & Caskey

1.6 Dissertation Organization

Present dissertation goals are described in correspondence with the order of chapters, and will be outlined in a more detailed way below:

Chapter 2. Innovative Ideas: will address general objective and related research questions related to explore ideation process in order to propose a first phase of the methodology that supports designers to increase the quantity and quality of innovative product/process ideas. The cognitive process behind idea generation thorough design by analogy was explored, confirming its power in developing innovative design solutions.

Chapter 3. Feasible Design Space: will address general objective and related research questions related to design process exploration in order to propose a second phase of a strategy and methodology that may help designers reduce development iterations. On this chapter, set-based concurrent design methods were explored to propose a methodology that allow designer to reduce develop iterations by configuring possibilities as a catalog of their current design parameters ranges. The main idea was to provide designers with a wider range of feasible designs with different levels of preference, without investing additional design resources, because different configurations could be anticipated and pre-calculated for design parameters. This approach also allows allocation of “saved” resources for innovation activities, while remaining competitive.

Chapter 4. Prefered Design: will address general objective and related research questions for design optimization process in order to propose a third phase of a strategy and methodology that assist designers to assure quality and robust performance for the designed products/processes. This design deals with yet another critical design topic, which is optimization of coupled designs.

Unfortunately, not all designs come to life with an uncoupled configuration between design parameters and functional requirements, so even thought they could be satisfying a customer need they have a great deal to improve on controllability and robustness. This chapter proposed integration of axiomatic design and response surface methodologies in order to identify design vulnerabilities regarding controllability and robustness, calculations of semangularity and reangularity for nonlinear responses are proposed through canonical analysis, in order to identify system´s coupling level and the order in which the design parameters should be fixed or tuned. This procedure provides a better understanding on how to operate in presence of coupled designs, so the best possible results for system configuration could be obtained when re-design is not an option.

Chapter 5. Roadmap for Innovative Optimal Design: proposes a general roadmap for problem solving highlighting specific places where present research is contributing. This chapter articulates findings from previous chapters on a general roadmap for problem solving, focusing on a methodology for Innovative Optimal Designs of products and services deployment.

Chapter 6. Contributions and Future Work: this chapter highlights research findings and contributions, addresses research hypothesis and revisit research goals to validate present research and determine future work that can be derived and extended from research topics.

Chapter 2. Innovative Ideas

On previews chapter relevant literature was presented to help readers to understand present research contributions and background.

On present chapter will explore ideation process in order to propose a first phase of an integrated and systematic methodology that may help designers to increase the number and quality of innovative product/process ideas.

2.1 Experiments to Evaluate Design by Analogy for Innovative Solutions

2.1.1 Abstract

Design by analogy is well recognized for its power on innovation processes. Analyzing how analogies are developed on designers' minds as a cognitive process could help to understand the concept of generation process, in order to develop new design approaches and methods to increase the quantity and quality of innovative solutions. This paper presents a series of experiments applied to students of engineering design at a graduate program at Tecnológico de Monterrey (México) to understand the influence of representation on the design by analogy process. The results obtained showed that the representation of a product on a person's memory and the representation of the design problem influence a person's ability to solve the design problem based on an analogous product.

2.1.2 Keywords

Lean Design, Design by Analogy, Innovation

2.1.3 Introduction

Design-by-analogy is a powerful tool for developing ideas [1]. It is very usual to find that designers**,** when facing design problems or developing new product, tend to inspire their designs on products they have seen before. Professional designers often use analogies [2, 3].

Numerous examples of innovative products based on analogies can be found in technology magazines and related literature. Examples of the use of analogies when designing can be found on Leonardo Da Vinci´s journals (see Figure 3), which contain detailed studies of the flight of birds and several different designs for wings based on the structure of those of bats which he described as being less heavy because of the impenetrable nature of the membrane.

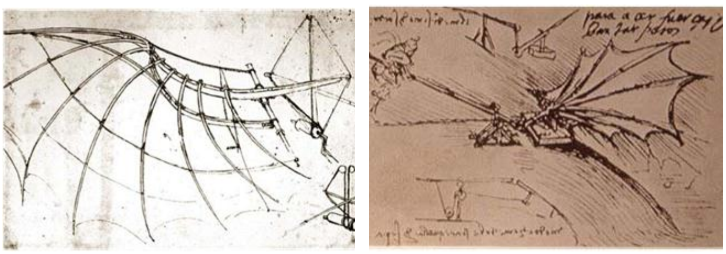

Figure 3. Leonardo´s flying wing designs.

To understand the use of analogy in design, this paper presents a series of experiments applied to students of engineering design at a graduate program at Tecnólogico de Monterrey (México) to identify the influence of representation on the design by analogy process, so that the outcomes serve as a basis for future development of a robust design by analogy method.

2.1.4 Previous work on Design by Analogy

2.1.4.1 Design-by-Analogy Methods

A few formal methods have been developed to support design by analogy such as Synectics which is a group idea generation method that uses four types of analogies to solve problems: personal (be the problem), direct (functional or natural), symbolic and fantasy [4]. Synectics gives little guidance to designers about how to find successful analogies. Other methods also base analogies on the natural world. French [5, 8], highlights the powerful examples nature provides for design. Biomimetic concept generation provides a systematic tool to index biological phenomena [6, 9]. From the functional requirements of the problem, keywords are derived. The keywords are then referenced to an introductory college textbook and relevant entries can be found. Analogous concepts can also be identified by creating abstracted functional models of concepts and comparing the similarities between their functionalities**.** Analogous and non-obvious products can be explored using the functional and flow basis [7]. This approach requires a database of products represented in the function and flow basis.

2.1.4.2 Prior Analogy in Design Experiments

Even though design by analogy is a well-recognized method for design, few human experiments exist. Casakin and Goldschmidt found that visual analogies can improve design problem solving by both novice and expert architects [3]. Visual analogy had a greater impact for novices as compared to experts. Ball, Ormerod, and Morley investigated the spontaneous use of analogy with engineers [10]. They found experts use significantly more analogies than novices do. The type of analogies used by experts was significantly different from the type used by novices.

Novices tended to use more case-driven analogies (analogies where a specific concrete example was used to develop a new solution) rather than schema-driven analogies (more general design solution derived from a number of examples). This difference can be explained because novices have more difficulty retrieving relevant information and have more difficulty mapping concepts from disparate domains due to a lack of experience [11].

Prior research in analogical reasoning found the encoded representation of a source analogy (the analogous product) can ease retrieval if it is entered into memory in such a way that the key relationships apply in both the source and target problem domains [12, 13]. This work shows that the internal representations in memory play a key role in retrieval.

2.1.4.3 Semantic Memory Retrieval

Designers frequently base their concepts on ideas they have seen and/or experienced previously. These designs are retrieved from their long-term memory, specifically semantic memory. Semantic memory refers to the storage of meaningful, factual information. In the psychological literature, the structure of human semantic memory is often conceptualized as a network of concepts that are associated with each other.

For example, in Figure 4, the concept of a bed is represented by associations as a web with nodes and links. When one thinks about beds, the node representing that concept becomes active, and this activation can spread out along its associative links to other connected ideas [1].

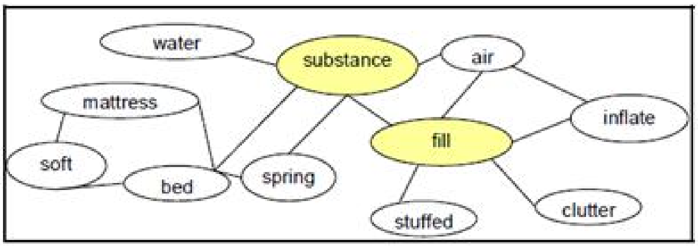

Figure 4. Example Semantic Network

However, nodes pass along only a fraction of their activation to neighboring nodes, and so the activation weakens as it gets more distant from the source of activation. The probability that a concept will be remembered increases as the path distance (i.e. number of links traversed) shortens, or if multiple active paths converge on it. Nodes that are more general concepts, such as “substance”, tend to be connected to a much greater number of other nodes, becoming hubs in the network. Thus, linking new concepts through them shortens path distances, increasing the probability of retrieval [10, 14, 15, 16].

2.1.5 Experimental approach

Inspired by the set of experiments conducted at the University of Texas at Austin [1, 17, 18, 19] an experiment was conducted on students of engineering design at a graduate program at Tecnólogico de Monterrey (México) consisting of a total of three design problems with corresponding analogous products, to understand the influence of semantic representation and other factors in analogical design. Three different design problems were selected in order to break possible ties between the options, and that represent innovative products which designers were not familiarized with.

2.1.5.1 Experiment research questions and structure

Specifically the research questions that motivated the experiment were:

- Question 1: could prior product knowledge be more likely to be retrieved and used to formulate innovative design solutions when analogous products and design problems are described using general or specific language? Prior psychological literature [12, 13] implies that the general descriptions should be more likely to be retrieved.

- Question 2: does the fact of having a wisely constraint design problem statement affects the designer´s ability to retrieve and use analogous product solutions to propose a new design solution?

The experiment explored the effects of the analogous product representation on a designer’s ability to later use the product to solve a novel problem. The analogous solutions for the three design problems were presented as a combination of visual and semantic information to represent the source design analogy. The visual representation consisted of a printed image of the product, and the semantic information consisted of a series of sentences that describe the product using either specific or general terms.

The experiment was carried on a group of 20 engineering design students. The group was divided into 2 sub-groups of description types: a) “Specific Description” Group, and b) “General Description” Group.

All participants were given five (5) pictures of products and to each group its corresponding (General or Specific) short functional descriptions (13) as shown in Table 2.

Table 2. Products and number of descriptions per type

Product	Number of General Descriptions	Number of Specific Descriptions
Airplane	3	3
Film in a camera	2	2
Shape-o-toy	3	3
Pepper mill	2	2
Football	3	3
TOTAL	13	13

The experiment consisted of two tasks: 1) Memorize the Analogous Products; and 2) Solve the Design Problems.

For the first task, both groups had 30 minutes to memorize the descriptions and then were given fifteen minutes to answer a quiz, writing out the memorized descriptions. Finally, the groups evaluate their results, as shown on Figure 5:

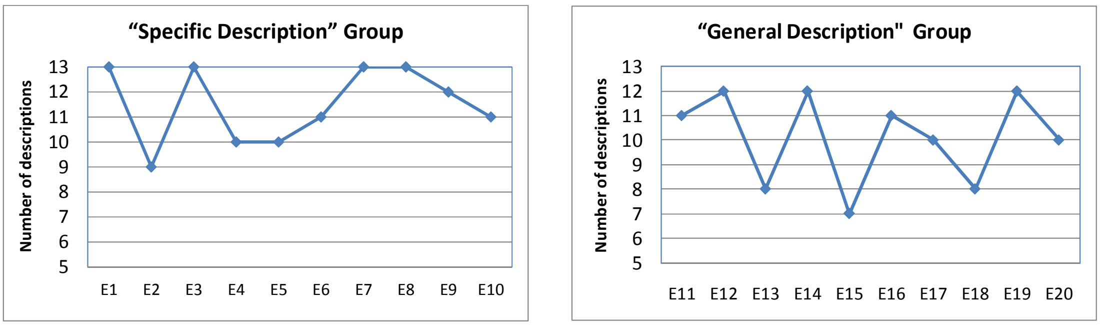

Figure 5. "Memorize the Analogous Products" task results

On average the "specific description" group had a higher number of correct (complete) memorized descriptions (88.5%) with respect to "general description" group (77.7%).

On the second task, “Solve the Design Problems”, participants were given three (3) design problems (DP) to be solved in the following four phases:

- Phase 1: Unconstrained design problems
- Phase 2: “Wisely” constrained design problems
- Phase 3: Identify analogies and try using analogies
- Phase 4: Inform that task 1 products are analogous

The design problems, analogous products and task 1 products are presented on Figure 6.

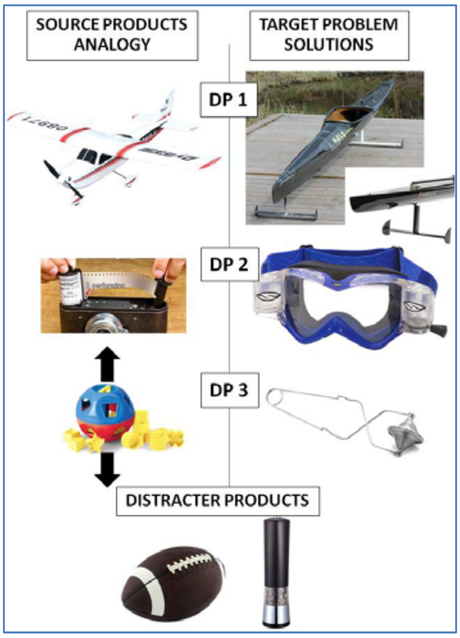

Figure 6. Experiment’s design problems, analogous products and distracter products

As it can be seen, some of the products from task one were distracters, and some of them were expected to be used as analogy source of solution (source of inspiration of a design problem solution) for the presented design problems.

Results and details for every design problem are presented next.

Design Problem 1 (DP1)

DP1 statement for specific and general groups on phase 1 was: “Design a fast kayak”. For phase 2, the additional requirements (wise constraints) were:

- A person is the only available power source.
- It must have a top speed of greater than 14 mph. Currently, typical human-powered boats have a top speed of less than 6 mph even for top athletes.
- The top speed is limited by drag; the faster a boat goes the greater the drag.
- Your design must reduce the drag.

Design Problem 2 (DP2)

DP2 statement for both groups on phase 1 was: “Design a pair of goggles that remove dirt and mud from a dirt bike racer's goggles”. For phase 2, the additional requirements (wise constraints) were:

- Forcing the dirt and mud across the goggle's surface creates scratches. The goggle system must not scratch the surface of the goggles.
- The dirt and mud cannot be forced across the surface of the goggles.
- The dirt bike racer's hands cannot leave the handle bars of the bike for more than a few seconds.
- A section of the goggles at least 1" by 2” must be completely clean.

__Design Problem 3 (DP3)__

DP3 statement for both groups on phase 1 was: “Design a kitchen utensil to sprinkle flour over a counter”. For phase 2, the additional requirements (wise constraints) were:

- The only material that is available to build the kitchen utensil from is various thicknesses of stainless steel wire.
- The entire kitchen utensil must be made from only one thickness of wire.
- The kitchen utensil must be manufactured by bending and cutting the wire only.
- The kitchen utensil must be capable of containing the flour and carrying the flour 1 meter without losing the flour.

2.1.5.2 Experiment results and findings

The results of the experiment are shown on Figure 7 to Figure 9, where it can be seen that DP1 had different trends for specific and general groups than DP2 and DP3.

Higher rates were obtained on DP2 and DP3 by the general description group on both unconstraint and constraint design problem. It also seems that when adding requirements (wise constraints) in all DP’s, the effect on participant’s analogy retrieval for both general and specific descriptions (except general group on DP1) was significant.

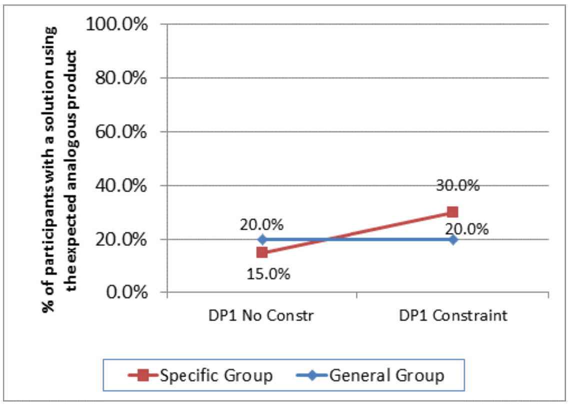

Figure 7. Design problem 1 results

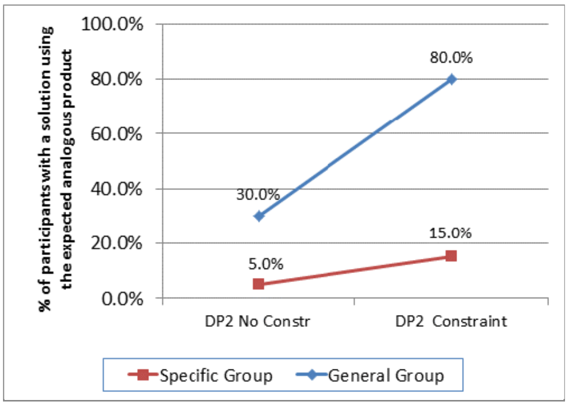

Figure 8. Design problem 2 results

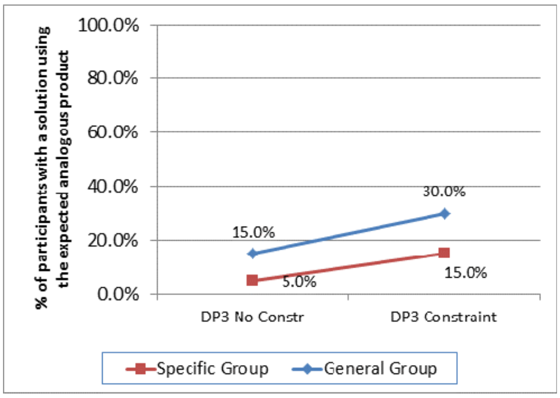

Figure 9. Design problem 3 results

When analyzing participant's phase 3 and 4 sheets for all three DP's, it was found that participants used analogies extensively even beyond the analogies that they were taught, Table 3 summarize participant's additional analogies.

Table 3. Participant's additional analogy sources

	DP1	DP2	DP3
Specific Group	Rockets, floating devices, new shapes or materials	Cell phone screen protectors, windshield wiper, and other geometric shapes	Racket, sieve, spirals and solenoids
General Group	Football for the shape, materials such as diving suits, or bird skeletons	NASCAR helmets, post-its, stickers, windshield wipers, cell phone and laptop screen protectors	Sieves, robots, cement mixer, filters, salt shaker, spoon, ice cream scoop and grids

The results of the experiment seem to indicate that both description types and the addition of constrain influence designer's ability to use analogous products or solutions.

2.1.5.3 Analysis of second task design problems

Averages of design problems for specific and general descriptions were calculated (Figure 10 and Figure 11), and showed that:

- General description group had higher percentage of use of analogy on both unconstraint and constraint design problems.
- Both groups had higher rates of analogy use when the problem was wisely constrained.

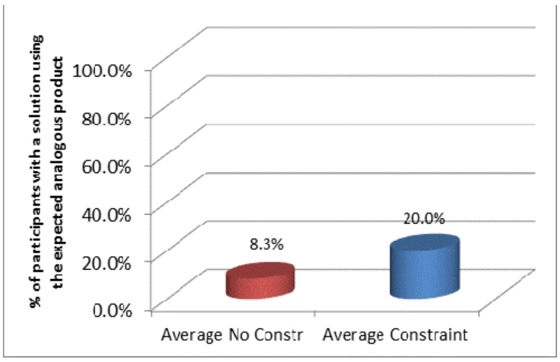

Figure 10. "Specific Description" group average

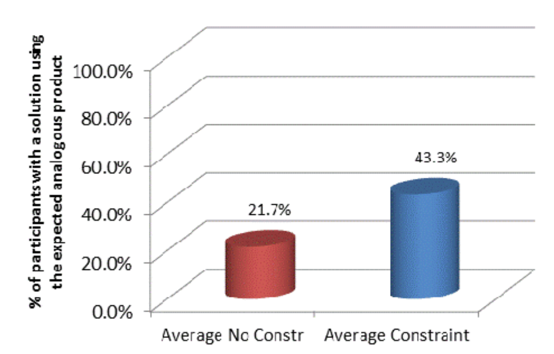

Figure 11. "General Description" group average

To evaluate the statistical significance that description type (research question 1) and the addition of requirements (research question 2) have on analogy retrieval when facing design problems, a two-predictor logistic model [20] was fit (binary logistic regression).

The experiment can be seen schematically as the illustration on Figure 12, where response is the analogy retrieval (yes=1, no=0), and the two predictors are:

- Analogous product representation: this predictor corresponds to description type used, therefore has two levels: specific/general
- "Wise" constraints: this predictor relates to additions of requirements for a given design problem, it also has two levels: unconstraint and constraint.

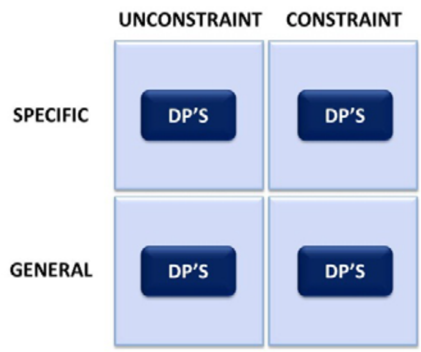

Figure 12. Experiment general schema

The logistic model shows no significant interactions between the two predictors and therefore the interactions were removed from the model. The remaining predictors show that the analogous product representation (description type) to be a statistically significant predictor (β=0.826, p=0.06) and the "wise" constraints (requirements addition) to also be a statistically significant predictor (β=0.826, p=0.06).

The odds ratio for description type is 2.28, which means that the odds of retrieving a targeted analogy is more than twice when general descriptions are used than when using specific descriptions. The odds ratio for requirements addition is 2.28, which means that the odds of retrieving a targeted analogy is more than twice when the problem is wisely constrained than when it is not.

Using binomial pairwise comparisons between “specific description” group and “general description” it was found a statistical difference (p =0.07 for unconstrained design problems, and p=0.04 for constrained problems), which meant that general description rates were statistically higher than specific description rates.

This results make the authors analyze results where it can be seen that to solve a problem with a targeted analogy in some cases general descriptions worked better, and in other didn’t, which can be interpreted as follows: a design problem should be presented in multiple ways (re-represented) so designers are able to retrieve more analogies.

These results will indicate that the way the products are described (functional descriptions) allows reaching to different domains where other analogous solutions may be, because using functional general principles could be more easily translated to functional needs of a given design problems.

Using binomial pairwise between unconstraint and constraint conditions, it was also found a statistical difference (p=0.007 for “specific description” group, and p=0.08 for “general description” group), which meant that constrain design problems rates were statistically higher than specific description rates.

In order to identify if there were interactions between the experiment factors, a design of experiments approach with 2 factors (restriction type, description type) and each result of the design problems was a replicate. The interaction had a P-value of 0.6, so there were no significant interactions on the experiment.

2.1.6 Conclusions

This experiment explores a reduced set of influences, but demonstrates the impact that a right representation has on the design by analogy process. General descriptions were proved to be better with far field analogies. Across the problems the general descriptions were better, but they both had influence, so it will be needed to represent the problems in multiple ways to the designer in order to reach different domains where other analogous solutions may be.

The representation of the design problem has a large effect on the analogies designers retrieve to assist in developing a solution. The representation of the design problem and the representation in memory significantly impact the designers' abilities. Most of the time, the form of representation in memory is not known so multiple design problem representations should be used to retrieve more analogies. Representation clearly matters and seeking improved representations has great potential for significantly enhancing the innovation process.

Wisely constraint design problems were statistically proved to lead designers to analogies that they would not be lead to in the unconstraint problem, so it will be important to explore how to add requirements to a design problem so that the problem can be related to other feasible solutions that may have the same physical principles or physical meaning form analogies**.**

The experiment also shown that both groups used analogies extensively, specifically, there were 2 types of analogies generated by the groups: 1) physical meaning form analogies, and 2) physical principles. Physical meaning form analogies were tangible, and physical principles were abstract. Within the physical meaning form analogies, it was found that there were biological inspired analogies that could have been better product analogies. It will be interesting to explore if these types of analogies affect the ability of solving design problems.

The importance of this research approach is that ideation, and in particular, design-by-analogy is critical to the design process and a deeper understanding of the mechanisms within analogical reasoning and their implications within design is necessary and could guide the development of design-by-analogy methods and tools for innovation design.

This research allow the identification of key factors that affect the use of analogies when facing design problems, and reveal the necessity of developing a method to constraint design problems and help designers to break design fixation by using multiple representations of analogous solutions. This will benefit designers because they will reduce the time they invest solving design problems by examining alternative solutions or ways to describe solutions and narrowing the feasible design space with “smart” restrictions, and may also help increasing the quantity, quality and novelty of innovative solutions.

Design by analogy is a powerful tool in a designer’s toolbox, but few designers have the methods to harness its full capacity. Designers need structured methods and tools to support this process. They need approaches for when they feel they have run out of ideas. They need methods to represent the problem in a multitude of representations. A structured design-by-analogy methodology would be useful for minimizing the effects of the experiential gap between novices and expert designer and to further enhance experts’ abilities.

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2.2 Design by Analogy for Transactional Innovative Solution Development

2.2.1 Abstract

Design by analogy is well recognized for its power as part of innovation processes. Previous work on concept generation processes have provided basic insights into an understanding of how analogies are developed cognitively in designers' minds and new design approaches and methods to increase the quantity and quality of innovative solutions. However, in current market conditions, where – according to the Organization for Economic Cooperation and Development (OECD) – service (transactional focused) processes are adding more than 65% of global economic value and continue to increase their share over industry and agriculture processes, designers are now facing design problems immersed not only in physical systems but transactional as well, making imperative to learn how to innovate in transactional process, transferring and evaluating product design approaches

This paper explores the development of innovative solutions for transactional problems through Design by Analogy principles and methods. First, an understanding of the nature of transactional systems problems (intangibility, simultaneity, heterogeneity and perishability) is described with respect to physical systems as well as research on innovation and the cognitive processes that support it. Then a series of experiments where a Design by Analogy approach using a semantic word based ideation method with a group of transactional domain experts show significant improvement on the quantity of innovative solutions generated for transactional problems. A qualitative evaluation (benchmarking) on the quality of solutions generated is also presented. Finally a discussion about the implications of these results on design-by-analogy theory and tools to support innovation is discussed

2.2.2 Keywords

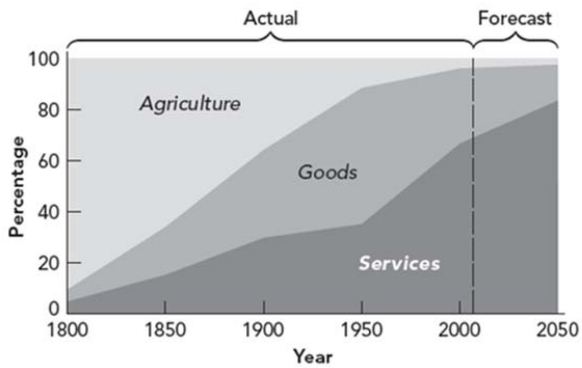
Innovation, Lean service Design, Design by Analogy, Transactional Process Innovation.

2.2.3 Introduction

Innovation has always been perceived as a challenge. These days, it is getting harder and harder for many companies to remain competitive, as manufacturing spreads to lower-cost regions and product life span is shortening [1], therefore innovation is becoming a continuous race that gives little to none place to rest.

Many companies and industries are now making a shift towards services since products are becoming a smaller and smaller share of the economic pie, yet we know much less about how to innovate in services than how to develop new products and technologies. [1]

The future for advanced companies and economies require rethinking business to innovate and develop process to make them sustainable. Today services comprise roughly 80 percent of economic activity in the United States (see Figure 13), and more than 60 percent of economic activity in the top forty economies around the world (see Table 4), according to the Organization for Economic Cooperation and Development (OECD) [2].



Source: J. Spoher, presentation at Haas School of Business, University of California, Berkeley, May 1, 2006.

Figure 13. Shift Toward Services in the United States Since 1800

OECD reports [2, 3] that service's share for country members has grown almost a 10% over the past 3 decades (see Table 4). Services consists of retail and wholesale trade; transport and communications; real estate, finance, insurance and business services; education, health and other personal services; public administration; and defense.

Table 4. Share of value added by activity (%) from total value added

	1978	**2008**	**Δ**
Services	56.2	65.8	9.5
Industry	34.2	29.4	-4.7
Agriculture	8.52	3.6	-4.9

Source: OECD Factbook 2010: Economic, Environmental and Social Statistics © OECD 2010.

In order to grow in this new economy, it is becoming imperative to learn to innovate in services; design is turning into a hot service topic because of its documented innovation effect within the field of product design. Traditional design skills, such as customer-insight, creativity and the ability to create products that meet customer needs are now being used in the design of services oriented towards service innovation.

Many organizations approach service innovation through methods, processes and terms from product development [4]. Many of the existing approaches to innovation emerged from business models focused on product- or manufacturing-based thinking. The rise of services in this new era requires that these traditional approaches must change and transcend its limits if companies are to be successful and sustainable [1].

Service innovation and design (I+D) also requires collaborative work from different disciplines such as: management, marketing, engineering, psychology, ethnography and architecture [5, 6]

This paper explores the development of innovative solutions for transactional problems through Design By Analogy principles and methods, considering that previous research has shown effectiveness in the use of design-by-analogy methods for increasing innovation in engineering fields, one interesting question that will be the focus of the present paper is: Could Design by Analogy, and in particular a semantic word based ideation method, provide transactional domain experts the ability to increase the quantity and quality of innovative solutions generated for transactional problems?

First, research about services and products definitions, characteristics and relationship is presented, then research and theory on ideation and the cognitive processes that support it will be described. Then a series of experiments exploring if the use of design by analogy techniques improves the quantity and quality of ideas generated for transactional problems. Finally we discuss the implications of these results for a robust theory of design-by-analogy and for the development of tools to support innovation processes.

2.2.4 Services and Physical Products

Transactional processes (services) have been described and classified in several ways. According to Cook et al. (1999) [7], no single definition of a service is capable of encompassing the full diversity of services and complex attributes that accompany them.

De Jong et al. (2003), researched innovation in services and listed a wide range of definitions for services [8], such as:

- An activity or series of activities of more or less intangible nature that normally, but not necessarily, take place in interactions between the customer and service employees and/or physical resources and/or systems of the service provider, which are provided as solutions for customer problems [9].
- Any act or performance that one party can offer to another that is essentially intangible and does not result in the ownership of anything [10].
- The delivery of help, utility or care, and experience, information or other intellectual content - and the majority of the value is intangible rather than residing in any physical product [11].
- To organize a solution to a problem (a treatment, an operation) that does not principally involve supplying a good. It is to place a bundle of capabilities and competences (human, technological, organizational) at the disposal of a client to organize a solution, which may be given to varying degrees of precision [12].

From these definitions, it can be seen that services appear to have a number of distinguishing characteristics. Vermeulen (2001) [13] presented four service features: intangibility, simultaneity, heterogeneity and perishability as opposed to products and we added to Vermeulen's original table the last two rows (Table 5), that are related to data attributes for services and products to have a wider understanding and comparison of services and products.

Table 5. Differences between services and products (expanded from Vermeulen, 2001)

Services tend to be…	**Products tend to be…**
Intangible	Tangible
Simultaneous production and consumption: costumers participate in production	Separation of production and consumption: costumers do not normally participate in production
Heterogeneous	Homogeneous
Perishable: cannot be kept in stock	Can be kept in stock
Not normally distributed (non-parametric)	Normally distributed (parametric)
Qualitative data	Quantitative data

Examining the large number of studies that explore the specific characteristics of services as compared with products, it seems inevitable to think of them as opposite environments and develop specific approaches catering to service innovation. However, in regular business operations it is harder to separate services from products, as many product companies are now including services around their products, and also since a lot of services require products and associate technologies to be carried out; therefore, transactional and physical systems should not be considered as absolute states but rather as part of a continuum as illustrated in (see Figure 14), where tools and methods for conceptual design from the engineering domain-knowledge field have the potential to successfully assist idea generation on transactional fields.

Figure 14. Transactional to physical systems continuum illustration

2.2.5 Service ideation methods

Lin et. al. (2006) [14] analyzed the results from surveys of 280 transactional companies in Taiwan and China to identify from a list of idea generation techniques which ones were the most frequently used, finding that top 5 techniques according to application frequency were: 1) Brainstorming – 43.6%, 2) Checklist – 27.1%, 3) 1H-5W method (How, When, Where, Who, What) – 11.8%, 4) 5Why method – 7.9%, and 5) Mind mapping method – 2.5%. The less used techniques on the other side were Delphi, TRIZ, and SCAMPER.

D'Alvano & Hidalgo (2012) [15] reported –among other metrics- utilization percentage of idea generation techniques, analyzing questionnaire responses from 30 organizations in Venezuela of three service sectors (trade, health-care and education). Their results showed Brainstorming as the most used technique (86.7%), while techniques such as SCAMPER, and TRIZ were not mentioned (0%).

These studies were conducted in distant geographical regions and their results appear to be starkly similar and convergent in the most and least used techniques by transactional organizations; where, considering that Brainstorm has been proven to not being robust for consistent development of high quality and novel ideas, provides a fertile ground for application of better techniques to assist designers in transactional systems.

About contexts where the most and the least used techniques are applicable, Lin et. al (2006) [14] found that both extremes require a flexible time constraint; in addition, Brainstorming is applicable when there is diversity among participants and idea variety is required; while robust tools such as TRIZ and SCAMPER are a suitable when participants have a strong knowledge background and thoroughness and detail of ideas is required.

D'Alvano & Hidalgo (2012) [15] concluded that the most used Idea generation techniques belong to well-known and easy to use tools. This statement is shared by McAdam & McClelland (2002) [16], which commented that Brainstorming was the best known technique in UK followed by morphological analysis, because they require little training.

These findings suggest that design-by-analogy can be a suitable alternative for ideation in transactional organizations due to its availability, usefulness and low intensive training requirements, as well as for the context it will be applied, i. e. likely to have knowledge background and diversity of the participants and where variety and detail of ideas is required.

2.2.6 Previous work on Semantic Design by Analogy

Prior work in the design research field has focused on the development of formal design-by-analogy methods and understanding relevant cognitive processes

2.2.6.1 Creativity-Enhancing Model for Innovative Design Concepts

Rouse [17] propose Figure 15 to summarize those behaviors that tend to be associated with engineers and scientists who are judged to be creative. The relationships depicted in this figure emphasize four issues: 1) information seeking, 2) information processing, 3) meta behaviors and 4) products of creativity.

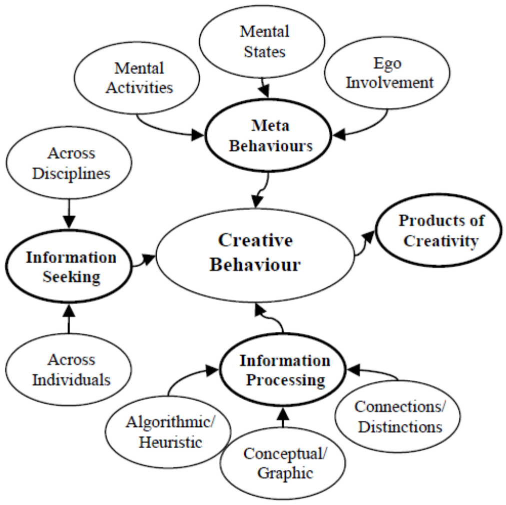


Figure 15. Elements of creative behavior

With respect to information seeking, individuals judged to be creative tend to have a greater variety of exposure to information content across disciplines, and the ways in which information is processed appear to be central to creative behavior. Some elements for “meta” behaviors are: mental activity, mental states, ego involvement, but while been interesting, it is difficult to determine direct implications of these types of behavior for design. And finally products of creativity tend to be more diverse and original design solutions [17].

Here is important to notice that information seeking is hard for novice designers for have not been previously exposed to a wide information source, due mainly to lack of experience, and also it is important that information seeking gets enriched when it goes across disciplines, that is, when can be extracted from domains different to the current in which the design problem lies.

2.2.6.2 Divergent tree method

Divergence is expressed as one matter could have many characteristics; a characteristic could be shared by many matters; a value can be used to describe the characteristics of many matters [18]. The method employing divergence to solve problems is called divergent tree method.

The divergent tree method extends the views and perspectives of studying the objects by diverging the names, characteristics, and values of the matters. The original solution domain can be expanded after divergence. New connections may be established across varied domains and thus creative solutions can be achieved by reference to the information in previously remote domains. [19]

The properties of divergent trees could be used in idea generation stage by expanding the range of ideas. It can provide a significant amount of divergent vocabulary, and improve idea generation performance from association.

2.2.6.3 Analogy

Analogy is defined as the correspondence between the members of pairs or sets of linguistic forms that serves as a basis for the creation of another form [20]. Itkonen [21] stated that "analogy plays a central role in human creative thinking", and described how the concept of analogy was used in linguistics as well as in other cognitive sciences.

Definition and relationship between analogy and metaphor was presented by Gentner and Markman [22] on a space bounded by relations shared and attributes shared as shown on Figure 16, where analogous items share relational and structural similarity, while metaphors span the spectrum of relational similarity at one end, and appearance similarity at the other.

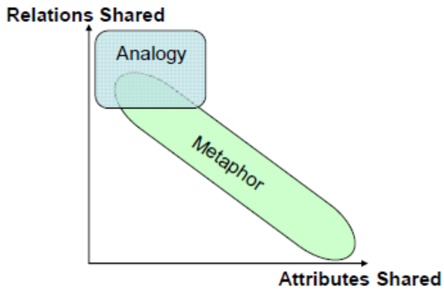


Figure 16. Definition and relationship between analogy and metaphor as present by Gentner and Markman [22]

A third dimension, *purpose,* was later proposed by Hey, Linsey, Agogino and Wood [23] (see Figure 17) to describe analogy and metaphor as used within the design context. Some comparisons are both an analogy and a metaphor. Metaphors frame and assist the designers in defining the design problem. Metaphors are commonly used to map users' understanding, activities and reactions to a product. They help make sense of customer needs or physical attributes from the source of inspiration. Analogy, in contrast, primarily maps the causal structure between the source products in one domain to the target design problem being solved. The causal structure includes a devices' functional solutions, geometry or component configuration.

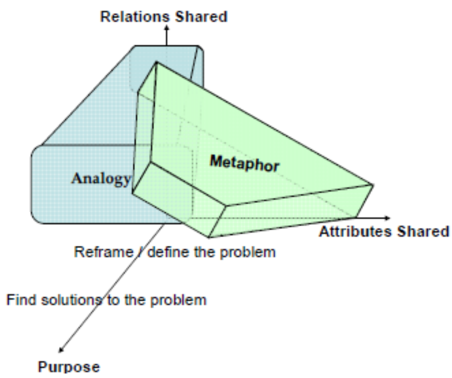


Figure 17. Definition and relationship between analogy and metaphor proposed by Hey, Linsey, Agogino, and Wood

2.2.6.4 Synectics

It is a common believed that new design ideas are attributed to chance, sudden enlightenment, and luck. Research analysis indicates that, having a given problem, any new concept is generated through several steps compiled as a process. If and when the process is more or less formalized, three main steps are considered in the process: the Ideal Function or Situation concept; the mental engagement of Metaphors [24, 25, 26]; and the use of the parallel mental path of Analogies [27, 28, 29].

The closer the new concept performance is to the desired ideal performance, the higher the new design's creativity ranking is considered. Imagination and creativity are stimulated by the mental utilization of metaphors and analogies. Supplies of ideas in the universe are inexhaustible [30].

The availability of a diversified knowledge base of physical, chemical, and biological effects and phenomenon augmented by application examples will again exercise metaphors and analogies to develop new designs for implementation of the above revolutionary biomorphic functions. The integration of ideal functional performance with knowledge base and the use of metaphors and analogy open the door to the concept of synectics.

Webster's dictionary describes synectics as the "the theory or system of problem-stating and problem-solutions based on creative thinking that involves free use of metaphor and analogy in informal interchange within a carefully selected small group of individuals of diverse personality and area of specialization."

The inclusion of the metaphors and analogies in the context of synectics provides the brainstorming group plenty of practice in the use of spontaneous activities of the brain and nervous system.

2.2.6.5 Wordtree Design-by-Analogy Method

The WordTree Method [28] provides designers with a systematic approach for re-representing their design problems and identifying potential analogies and analogous domains. This method is based on prior experimental results focused on understanding the cognitive processes involved during analogical reasoning and concept generation.

The method first identifies the “problem descriptors” which are the key functions and customer needs. These descriptors are then linguistically re-represented in a diagram know as a WordTree. From wordtree diagram potential analogies and analogous domains are identified. The potential analogies are researched and the analogous domains are used to find solutions in distant domains. New problem statements ranging from very domain specific in multiple domains to very general statements are written. Finally the analogies, patents, analogous domains and new problem statement are implemented in a group idea generation session. This session further refines the method’s results into conceptual solutions to the design problem and provides additional inspiration for the designers.

2.2.6.6 TRIZ

This is another design by analogy method that has a different approach than Wordtree method, because here design problems are also linguistically re-represented but as the conflict between two generalized engineering parameters [32, 33].

TRIZ is the Russian acronym for the Theory of Inventive Problem Solving. This proven algorithmic approach to solving technical problems began in 1946 when the Russian engineer and scientist Genrikh Altshuller studied thousands of patents and noticed certain patterns. From these patterns he discovered that the evolution of a technical system is not a random process, but is governed by certain objective laws. These laws can be used to consciously develop a system along its path of technical evolution - by determining and implementing innovations [34].

TRIZ Method [35] starts by identifying technical contradiction, that is, when a variable is improved, that action causes that other variable gets deteriorated. After the contradiction and its improving and degrading elements have been identified, the next step is to translate each element into its associated problem parameter (there are 39 such parameters in the TRIZ system). This step entails using Altshuller contradiction matrix where in the intersection of the problem parameters it can be found any of 40 inventive principles by which you can solve your contradiction.

The key to the 40 inventive principles is that they were derived from an extensive analysis and categorization of more than 2 million patented innovations. In each and every case, the patented innovations employed at least one of the 40 inventive principles to solve some identified technical contradiction. This is why some call these 40 principles the genetic code of innovation, and why TRIZ experts will tell you that someone else in another field at another time has already solved your contradiction.

Inventive principles have to be applied to solve the technical contradictions. This requires good analogical thinking skills because it requires considering the identified inventive principles as a guide for coming up with a specific solution for the original specific problem, or technical contradiction.

2.2.6.7 Idea generation methods

Ideation methods intend to overcome creativity blocks. The existent methods can be classified into intuitive and logical methods [36]. Intuitive methods attempt to generate ideas (solutions) based on self knowledge or experience (e.g. Brainstorming and C-Sketch) while logical methods attempt to expand the solution space throught the use of external promts such as charts, databases, patent searches, etc. (e.g. morphological charts and TRIZ).

Acording to Vargas, et. al. (2010), intuitive methods possess high chances of producing novel ideas compared to logical methods, since these last ones tend to determine the solution space while intuitive methods attempt to expand it.

Chiu & Shu (2008) found in a study with engineering students that TRIZ method provided a dichotomous stimulus that enable generation of concepts that were judged by raters to be more novel than others. The study also found that when generating concept solutions, students use words such as verbs that could appear to be not directecly connected to the design task [37].

When comparing intuitive and logic method performance, a study conducted by Vargas, et. al., (2012) tested sketching and TRIZ showed that both techniques improve quantity and novelty compared to a control scenario. TRIZ was the best in enhancing novelty, however, it was also concluded that TRIZ does not come naturally to participants as opposed to sketching and therefore, requires training and time to become proficient and take advantage of its full potential by retrieving design principles that are not immediately thought by own intuition. [38]

Other studies on graduate and undergraduate groups comparing control (no technique) against TRIZ reached same conclusions that Chiu & Shu (2008) and Vargas, et. al. (2012) about novelty outcomes for TRIZ but decreased the quantity of ideas generated. These authors also highlighted that the use of TRIZ method enable designers to reach analogous domains or concepts specially if they method is suported with software enabling tools to access patent content (successful novelty and analogous solutions). Finally the authors conclude that “some ideation methods are better for some tasks, depending on the outcome sought”. [39]

Therefore, complementary and not competitive approaches for idea generation that are able to offer improvement without compromisising of creativity metrics are required, in order to provide designers with a suite of methods and approaches that anable them to overcome creativity blocking and achieve innovation.

2.2.6.8 Semantic Memory Retrieval

Designers frequently base their concepts on ideas they have seen and/or experienced previously. These designs are retrieved from their long-term memory, specifically semantic memory. Semantic memory refers to the storage of meaningful, factual information. In the psychological literature, the structure of human semantic memory is often conceptualized as a network of concepts that are associated with each other.

For example, in Figure 18, the concept of a bed is represented by associations as a web with nodes and links. When one thinks about beds, the node representing that concept becomes active, and this activation can spread out along its associative links to other connected ideas [29].

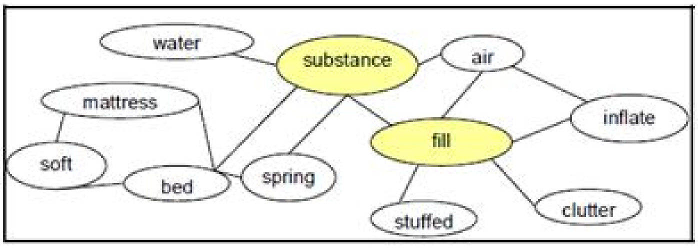


Figure 18. Example Semantic Network

However, nodes pass along only a fraction of their activation to neighboring nodes, and so the activation weakens as it gets more distant from the source of activation. The probability that a concept will be remembered increases as the path distance (i.e. number of links traversed) shortens, or if multiple active paths converge on it. Nodes that are more general concepts, such as “substance”, tend to be connected to a much greater number of other nodes, becoming hubs in the network. Thus, linking new concepts through them shortens path distances, increasing the probability of retrieval [41, 42, 43, 44].

2.2.6.9 Designer’s expertice level

There have been research studies that have found that a factor that can impact design outcome is expertise [46, 47] but there have been different positions about expertise having a positive or negative effect in design, use of analogies, space exploration, ideation metrics, etc.

Identification of the key elements for outstanding performance will enable design learning and practice improvement. There are published results that indicate that novices generate more original concepts [48, 49]; other researchs show that experts get fixated easily due to convergence to a solution [48]. Experts have been exposed to a wider range of examples of problems and solutions that are stored in their memories which are retrieved and applied by means of reliable strategies, and well-structured mind process and design steps [47]. Some researchers have also identified that experts are able to generate more ideas than novices, but it has also been identified that they get fixated easier due to convergence to a solution [48].

That is why present study explores idea generation in participants with not an extensive design expertise (students) but with familiarity in transactional problems, to evaluate if novice performance can be improved by means of a design by analogy approach.

2.2.7 Experimental approach

An experiment was conducted on students of engineering design at a graduate program at Tecnólogico de Monterrey (México), to understand the influence of semantic design by analogy method on transactional design problems innovative solution generation. Two different transactional design problems were selected that represent common transactional problems which participants were familiarized with.

This experiment was conceived while reflecting about following questions: What makes a transactional problem different than a manufacture problem? Why is it difficult to come up with innovative design solutions in both cases? Previous research shows effectiveness of idea generation methods on engineering fields, but what about transactional process?

First, a definition of what a service (transactional process) is has to be developed. A transactional system can be defined as a dynamic configuration of resources (people, technology, organizations and shared information) that creates and delivers value between the provider and the customer through service (intangibles). In many cases, a transactional system is a complex system in that configurations of resources interact in a non-linear way. Primary interactions take place at the interface between the provider and the customer.

The main difference between manufacture and transactional processes is the nature of what has to be delivered, that is, an artifact, a tangible object in the manufacture case; and a service, a transaction, an intangible object in the case of transactional processes.

Manufacture processes have been studied since industrial revolution and the different patents databases keep track (knowledge management) of the evolution of design problems solutions. This is not the case for transactional processes, and that could be a reason why is it appears to be harder to relate to a solution that someone else perhaps even in another field at another time could have already developed to solve your transactional problem.

2.2.7.1 Experiment research questions

Specifically the research questions that experimental approach will address are:

- Question 1: could analogical prose aids be more likely to increase the quantity and quality of transactional design problems innovative solutions?

- Question 2: does the fact of exploring other domains affect the designer´s ability to develop new transactional design solution?

2.2.7.2 Experiment Design

Two transactional design problems were selected, the criteria for its selection was based on the frequency that they were expressed by black and green belt participants on their companies that were difficult to solve through traditional lean six sigma approaches. Selected transactional problems were:

- Reduce stock/inventory levels, considering here virtual stock such as transactions, requests, approvals, formats, etc.
- Reduce overdue accounts/unpaid credits.

Both design problems were first analyzed using professor's Clayton Christensen and coauthors [45] job to be done (JTBD) concept, to come up with a better problem statement that expressed the higher purpose or unmet need behind it.

Then students were presented with the problems statements and were asked to write down all possible solutions they could come up with, using only their own knowledge and creativity (no other tool or software was allowed at this point), participants had 15 minutes to complete this task.

Sheets with listed ideas were picked up, and then rated by two different raters to evaluate the number of ideas generated by the group. The rating criteria were the number (count) of different ideas, that is, to evaluate that every idea correspond to an original concept or version and not to a modification of other previously listed. The reason for using more than one rater was to establish if the number of ideas considered different from the other ones that were generated was consistent.

For each design problem, key problem descriptor (KPD) such as funtional requirements (jobs), customer requirements and key words from problem statement were selected to be presented to participants on a second session so they could explore them with more depth through analogical prose aids such as hypernyms, troponyms, synonyms, anthonyms using wordtree softwares such as Princeton's WordNet® and Thinkmap's Visualthesaurus© that could lead participants to other domains where an analogous solutions could be found.

A second session was programmed 2 days apart from the first, were participants were taught on the use of selected wordtree sofwares (how to search for KPD's and how to interpret the outcomes that each software offers), and then were asked to work again on the same transactional problems statements, this time searching on the wordtree softwares for the selected KPD's. For the searching task participants were given 15 minutes.

During this task, participants were required to selecte words that allow them to re-represent the design problem. The goal was that participant's minds switches domains while developing new problem statements and within these new domains found analogous solutions for the transactional problems. Participants were also required to list all alternative solutions that they were able to develop after using wordtrees softwares, this task had 15 minutes to be completed.

And once again sheets with listed ideas were picked up, and then rated by the two same raters used before to evaluate the number of ideas generated by the group. The rating criteria were not modified.

On the following sections specific details for each design problem are presented, and research questions will be addressed.

<u>Transactional Design Problem 1 (TDP 1)</u>

The problem statement was the following: *Reduce stock/inventory levels, considering here virtual stock such as transactions, requests, approvals, formats, etc.*

This transactional design problem was applied to a small sample of students to tune the experiment validating times for each task, supporting material it will be required to explain the use of wordtree softwares, etc. It was also included on this research, because results even though been affected by noise variables showed that the method increased the number of ideas generated.

This statement is not a Job to be done, but a consequence of an uneven flow between stages, and therefore the causes that could have trigger the uneven flow have to be analyzed for each case. But if general and innovative solutions to this problem are required, a better statement could be: “Increase working/available space”, “Clean office”, “reduce inventory cost”; “reduce number of failed transactions”.

The selected key problem descriptors to be search by participants are presented below, also some of the wordtrees generated with Thinkmap’s Visualthesaurus© (see Figure 19 and Figure 20).

- Customer Need: reduce stock cost
- Function: assure process continuity
- Cost/spend/save
- Stock/accumulate
- Reduce/Eliminate

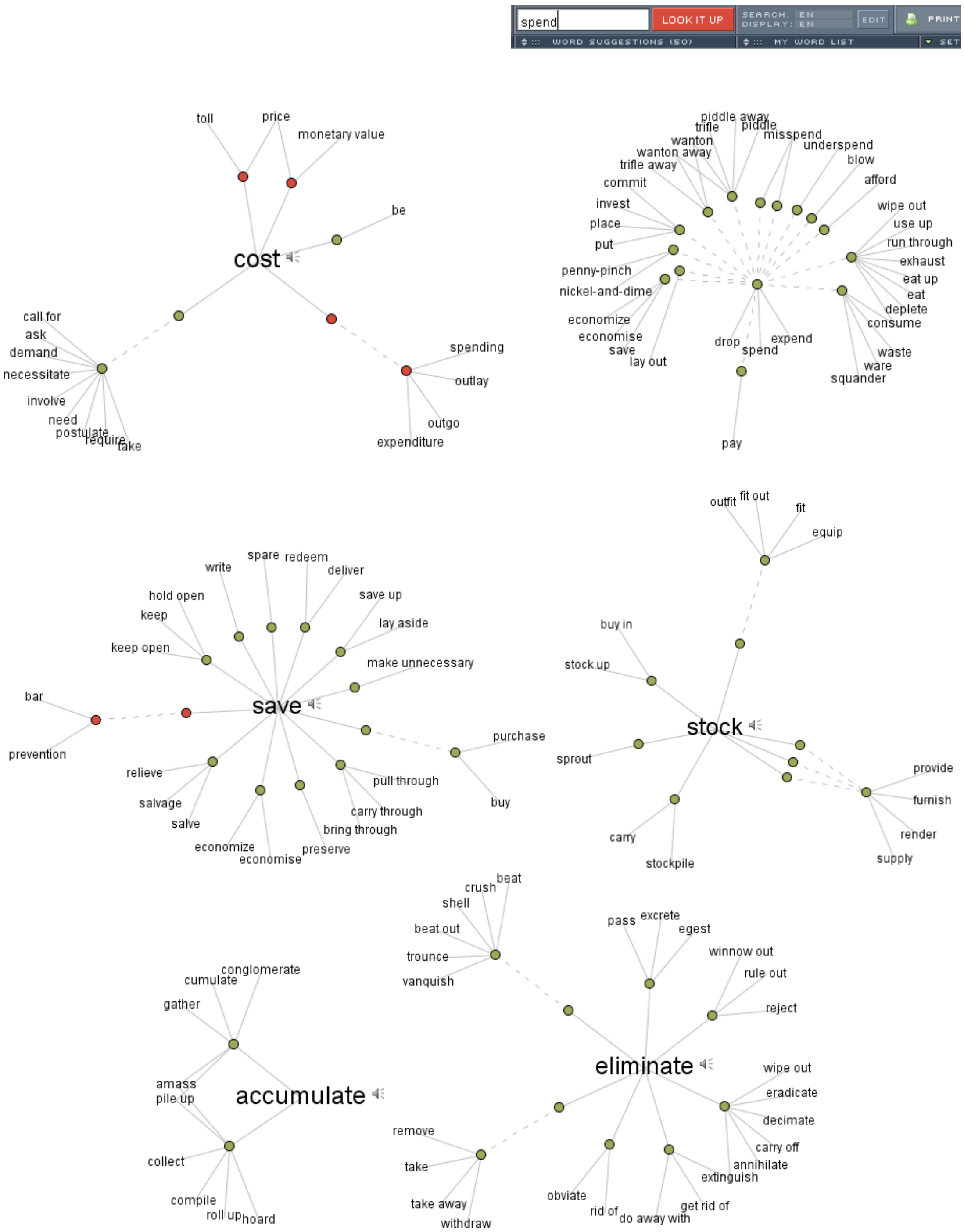


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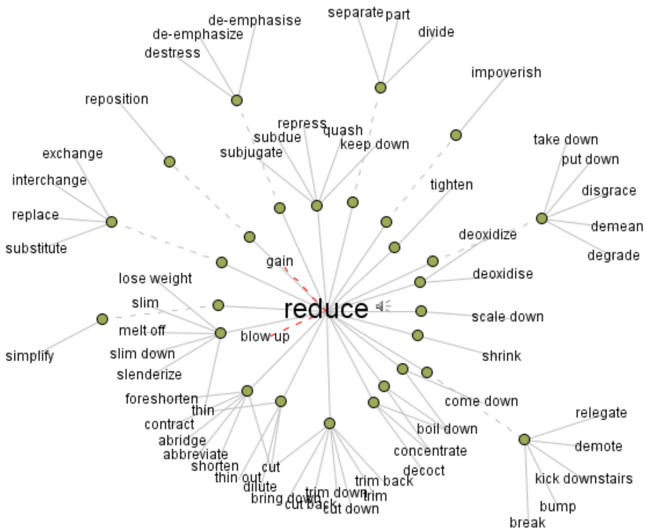
Figure 19. Key problem descriptors displayed by Thinkmap's Visualthesaurus©



"Image from the Visual Thesaurus, Copyright ©1998-2011 Thinkmap, Inc. All rights reserved."

Figure 20. Key problem descriptors displayed by Thinkmap's Visualthesaurus©

For each key problem descriptor (KPD) participants selected words summarized on Table 6 for re-represent the design problem:

Table 6. Analogous verbs for selected KPD's

KPD	**Analogous verbs**					
Cost	Demand					
Spend	Consume					
Save	Economize	Preserve (earnings)	Make unnecesary			
Stock	Equip	(in a different manner)				
Accumulate	Gather	Pile up				
Reduce	Simplify	Scale down	Fragmentate/ divide	Slender		
Eliminate	Get rid of	Eradicate	Wipe out	Remove	Exchange	Substitute

Once participants selected the alternative analogous verbs proceed with next task which was to re-represent original problem statement some of the new problem statements are presented on Table 7.

Table 7. Transactional Problem 1 statement re-representation

Original Statement → "Increase working/available space", "Clean office", "reduce inventory cost" • CN: reduce stock cost • Function: assure process continuity	
Problem statement re-representation	
Demand support from areas stocking Reduce inventory spend capital Consume less due to inventory Save resources available (space, money, movement) Preserve areas clean Preserve available space Preserve earnings Change magnitude of stock and/or associated cost Make stock unnecessary Exchange stocks with other entity Give someone else stock	Reward/penalize stock levels Equip process different to avoid stock Get rid of accumulation, pile up work Wipe out of stock available spaces Simplify processes to eliminate stock Scale down stock to reduce cost Fragment stock piles Divide stock to other place Manage stock elsewhere Substitute accumulation standard for other methods Make profit of stock Exchange stock levels for compensation

The goal was that participant's minds switches domains while developing new problem statements and within these new domains found analogous solutions for the transactional problems.

Participants were required to list all alternative solutions that they were able to develop after using wordtrees softwares, and the sheets with listed ideas was picked up to be rated and compared with the list of possible solutions without using any other tool.

When analyzing the experiment data (see Table 8), from the count made by the raters, subjects proposed on average near 5 additional (and different from the ones proposed Before using Analogical Prose Aids) ideas, which meant that they were able to at least double the number of ideas generated after using analogical prose aids with wordtrees softwares.

Table 8. Transactional problem 1 results

	Before using Analogical Prose Aids			After using Analogical Prose Aids		
Subject	**Cumulative**	**Rater 1**	**Rater 2**	**Cumulative**	**Rater 1**	**Rater 2**
1	3	3	3	14	13	12
2	5	5	5	16	15	15
3	3	3	3	6	5	6
4	3	3	3	9	7	7
5	5	3	4	7	4	5
6	4	4	4	6	6	6
TOTAL	**23**	**21**	**22**	**58**	**50**	**51**
AVERAGE	**3.83**	**3.5**	**3.67**	**9.67**	**8.33**	**8.5**

A Paired T test was performed to identify if there were a statistically difference between the two experimental conditions: **Before** using Analogical Prose Aids and **After** using Analogical Prose Aids, Minitab's ® results for each rater are shown below:

Paired T-Test and CI: Rater 1_B, Rater 1_A

```
Paired T for Rater 1_B - Rater 1_A

             N   Mean  StDev  SE Mean
Rater 1_B    6   3.50   0.84     0.34
Rater 1_A    6   8.33   4.55     1.86
Difference   6  -4.83   4.12     1.68


95% upper bound for mean difference: -1.44
T-Test of mean difference = 0 (vs < 0): T-Value = -2.87  P-Value = 0.017
```

Paired T-Test and CI: Rater 2_B, Rater 2_A

```
Paired T for Rater 2_B - Rater 2_A

             N   Mean  StDev  SE Mean
Rater 2_B    6   3.67   0.82     0.33
Rater 2_A    6   8.50   4.04     1.65
Difference   6  -4.83   3.76     1.54


95% upper bound for mean difference: -1.74
T-Test of mean difference = 0 (vs < 0): T-Value = -3.15  P-Value = 0.013
```

The P-values obtained for rater 1 (0.017) and rater 2 (0.013) indicates that there is a statistically significant difference between the two conditions, and also indicates that with a 95% confidence level the cumulated number of ideas of condition “**After** using Analogical Prose Aids” is higher than condition “**Before** using Analogical Prose Aids”.

Considering that the metric for the screening experiment was the number of ideas generated, and that metrics that measure human behavior or cognition need to be reliable, the use of two different raters, allows performing an inter rater agreement.

The percentage agreement between two observers was 66.67%, but this measure alone does not take into account the amount of agreement that could have been expected by chance [53] and the correlation between raters. Therefore, an agreement analysis [54] was performed using Minitab®, to calculate Cohen’s kappa (K) measure to take into account both situations with the following results:

Attribute Agreement Analysis for response

Between Appraisers

```
Assessment Agreement

# Inspected  # Matched  Percent      95% CI
         12          8    66.67  (34.89, 90.08)

# Matched: All appraisers' assessments agree with each other.


Fleiss' Kappa Statistics

Response     Kappa  SE Kappa         Z  P(vs > 0)
3          0.79832  0.288675   2.76546     0.0028
4          0.40000  0.288675   1.38564     0.0829
5          0.40000  0.288675   1.38564     0.0829
6          0.61905  0.288675   2.14444     0.0160
7          1.00000  0.288675   3.46410     0.0003
12        -0.04348  0.288675  -0.15061     0.5599
13        -0.04348  0.288675  -0.15061     0.5599
15         1.00000  0.288675   3.46410     0.0003
Overall    0.59664  0.125512   4.75362     0.0000

Cohen's Kappa Statistics
```

```
Response  Kappa  SE Kappa        Z  P(vs > 0)
3         0.800  0.282843  2.82843     0.0023
4         0.400  0.288675  1.38564     0.0829
5         0.400  0.288675  1.38564     0.0829
6         0.625  0.267609  2.33550     0.0098
7         1.000  0.288675  3.46410     0.0003
12        0.000  0.000000        *          *
13        0.000  0.000000        *          *
15        1.000  0.288675  3.46410     0.0003
Overall   0.600  0.120761  4.96847     0.0000


Kendall's Coefficient of Concordance

    Coef  Chi - Sq  DF       P
0.983725   21.6420  11  0.0273
```

From Minitab's® report it was found that Overall Cohen's Kappa was 60% agreement, once chance and correlation has been accounted for. This Kappa value corresponds to a *"good"* level of inter-rater agreement on Robson's [55] interpretation of Kappa, or to a *"substantial"* level of inter-rater agreement on Landis and Koch [56] interpretation of Kappa; that is, the raters classified in almost the same way the number of different ideas generated, making this measures reliable.

From overall Cohen's kappa Z-value (4.9685) it can be seen that agreement between the two raters is significantly better than chance. Finally Kendall's coefficient of concordance was 98.37%, which is also good; since it measures how much the two raters agree when asked to put a set of objects in rank order.

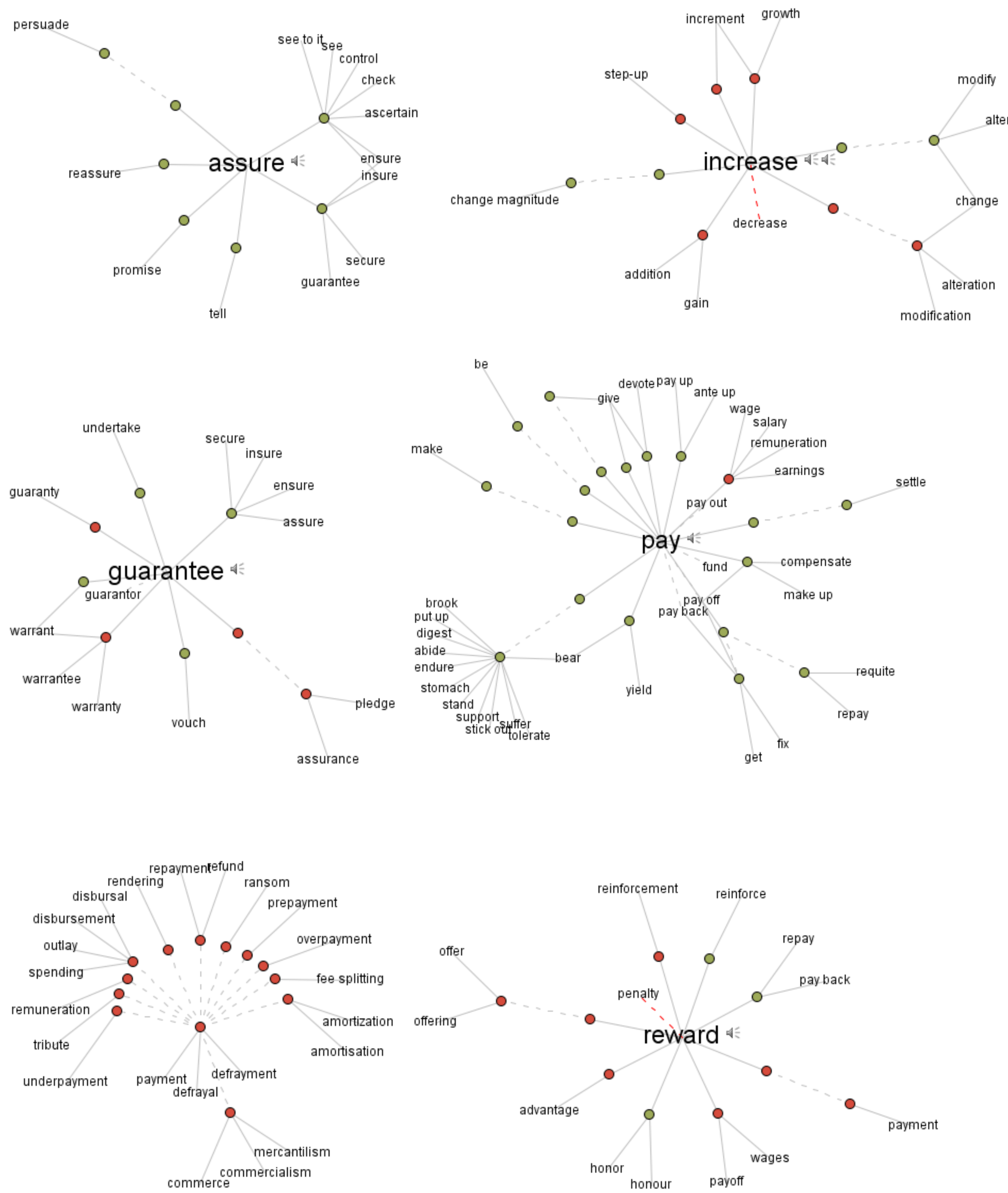
Transactional Design Problem 2 (TDP 2)

The problem statement was the following: *Reduce overdue accounts/unpaid credits.*

This statement is a typical need expressed by companies that provide financial services and it is also not a Job to be done, but a consequence of something that failed on a previous stage. If innovative solutions are required to address this problem, a better statement could be: “Assure/Increase clients´ payment of credits”.

The key problem descriptors participants selected to search are presented below, also some of the wordtrees generated with Thinkmap’s Visualthesaurus© (see Figure 21).

- Assure
- Increase
- Guarantee
- Pay /payment
- Reward



"Image from the Visual Thesaurus, Copyright ©1998-2011 Thinkmap, Inc. All rights reserved."

Figure 21. Key problem descriptors displayed by Thinkmap's Visualthesaurus©

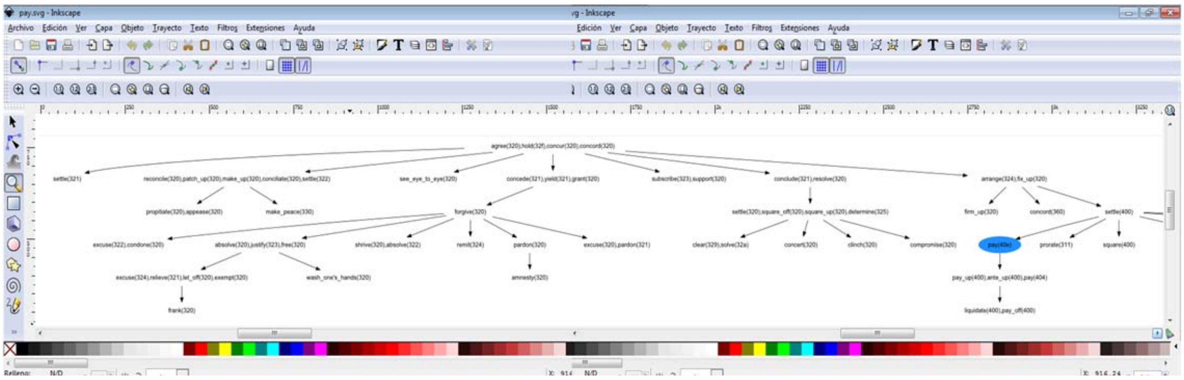


Figure 22. Key problem descriptors displayed by Linsey's [21] Wordtree

For each key problem descriptor (KPD) participants selected words summarized on Table 9 for re-represent the design problem:

Table 9. Analogous verbs for selected KPD's

KPD	**Analogous verbs**					
Assure	Persuade					
Increase	Change Magnitude	Modify				
Guarantee	Pledge (empeñar)	Guarantor				
Pay	Requite	Settle	Compensate	Fix	Make Up	Liquidate
Payment	Fee split	Amortizate	Prepayment			
Reward	Reinforce	Payback				

Once participants selected the alternative analogous verbs proceed with next task which was to re-represent original problem statement some of the new problem statements (like "Make money out of current overdue credits") are presented on Table 10.

Table 10. Transactional Problem 1 statement re-representation

Original Statement → "Assure/Increase clients´ payment of credits	
Problem statement re-representation	
Persuade Clients to pay credits	Persuade clients to compensate their credits
Change magnitude of clients' credits payment	Persuade clients to fix their credits
Change magnitudes of credit conditions	Persuade clients to make up their credits
Modify clients' payment of credits	Persuade clients to liquidate their credits
Modify credit conditions	Persuade clients to split their credits
Guarantee payment form credit clients	Persuade clients to amortize their credits
Persuade clients to pledge their credits	Persuade clients to pay in advance their credits
Assure payment of credits with a guarantor	Reinforce clients´ payment of credits
Persuade clients to requite their credits	Reward clients´ payment of credits
Persuade clients to settle their credits	Penalize clients´ payment of credits

The goal was that participant's minds switches domains while developing new problem statements and within these new domains found analogous solutions for the transactional problems.

Participants were required to list all alternative solutions that they were able to develop after using wordtrees softwares, and the sheets with listed ideas was picked up to be rated and compared with the list of possible solutions without using any other tool.

When analyzing the experiment data (see Table 11), the count made by the raters show that for experimental condition "**Before** using Analogical Prose Aids" participants proposed on average 4 ideas.

For experimental condition "**After** using Analogical Prose Aids", from the count made by the raters, participants proposed on average nearly 4 additional (and different from the ones proposed on experimental condition "**Before** using Analogical Prose Aids") ideas, which meant that they were able to almost double the number of ideas generated after using analogical prose aids with wordtrees softwares.

Table 11. Screening experiment results

	Before using Analogical Prose Aids			After using Analogical Prose Aids		
Subject	**Cumulative**	**Rater 1**	**Rater 2**	**Cumulative**	**Rater 1**	**Rater 2**
1	7	5	7	16	11	14
2	4	4	3	16	12	13
3	4	4	4	8	7	7
4	5	5	5	12	10	10
5	5	4	4	9	9	9
6	3	3	3	5	5	5
7	6	4	4	11	9	8
8	5	2	2	6	2	2
9	5	4	4	10	8	8
10	9	6	6	11	8	8
11	3	2	3	5	3	4
TOTAL	**56**	**43**	**45**	**109**	**84**	**88**
AVERAGE	**5.09**	**3.91**	**4.09**	**9.91**	**7.63**	**8**

A Paired T test was performed to identify if there were a statistically difference between the two experimental conditions: **Before** using Analogical Prose Aids and **After** using Analogical Prose Aids, Minitab's ® results for each rater are shown below:

Paired T-Test and CI: Rater 1_B, Rater 1_A

```
Paired T for Rater 1_B - Rater 1_A

             N    Mean  StDev  SE Mean
Rater 1_B   11   3.909  1.221    0.368
Rater 1_A   11   7.636  3.171    0.956
Difference  11  -3.727  2.370    0.715


95% upper bound for mean difference: -2.432
T-Test of mean difference = 0 (vs < 0): T-Value = -5.22  P-Value = 0.000
```

Paired T-Test and CI: Rater 2_B, Rater 2_A

```
Paired T for Rater 2_B - Rater 2_A

             N    Mean  StDev  SE Mean
Rater 2_B   11    4.09   1.45     0.44
Rater 2_A   11    8.00   3.58     1.08
Difference  11  -3.909  2.844    0.858


95% upper bound for mean difference: -2.355
T-Test of mean difference = 0 (vs < 0): T-Value = -4.56  P-Value = 0.001
```

The P-values obtained for rater 1 (0.000) and rater 2 (0.001) indicates that there is a statistically significant difference between the two conditions, and also indicates that with a 95% confidence level the cumulated number of ideas of condition “**After** using Analogical Prose Aids” is higher than condition “**Before** using Analogical Prose Aids”.

Considering that the metric for the screening experiment was the number of ideas generated, and that metrics that measure human behavior or cognition need to be reliable, the use of two different raters, allows performing an inter rater agreement.

The percentage agreement between two observers was 68.18%, but this measure alone does not take into account the amount of agreement that could have been expected by chance [57] and the correlation between raters. Therefore, an agreement analysis [58] was performed using Minitab®, to calculate Cohen’s kappa (K) measure to take into account both situations with the following results:

Attribute Agreement Analysis for response

Between Appraisers

```
Assessment Agreement

# Inspected  # Matched  Percent      95% CI
         22         15    68.18  (45.13, 86.14)

# Matched: All appraisers' assessments agree with each other.


Fleiss' Kappa Statistics

Response      Kappa  SE Kappa         Z  P(vs > 0)
2           0.77436  0.213201   3.63207     0.0001
3           0.32308  0.213201   1.51537     0.0648
4           0.74118  0.213201   3.47643     0.0003
5           0.77436  0.213201   3.63207     0.0001
6           1.00000  0.213201   4.69042     0.0000
7           0.64228  0.213201   3.01254     0.0013
8           0.77436  0.213201   3.63207     0.0001
9           0.64228  0.213201   3.01254     0.0013
10          1.00000  0.213201   4.69042     0.0000
11         -0.02326  0.213201  -0.10908     0.5434
```

12	-0.02326	0.213201	-0.10908	0.5434
13	-0.02326	0.213201	-0.10908	0.5434
14	-0.02326	0.213201	-0.10908	0.5434
Overall	0.63892	0.074948	8.52485	0.0000

Cohen's Kappa Statistics

Response	Kappa	SE Kappa	Z	P(vs > 0)
2	0.77551	0.207759	3.73274	0.0001
3	0.32653	0.207759	1.57168	0.0580
4	0.74118	0.213201	3.47643	0.0003
5	0.77551	0.207759	3.73274	0.0001
6	1.00000	0.213201	4.69042	0.0000
7	0.64516	0.199327	3.23669	0.0006
8	0.77551	0.207759	3.73274	0.0001
9	0.64516	0.199327	3.23669	0.0006
10	1.00000	0.213201	4.69042	0.0000
11	0.00000	0.000000	*	*
12	0.00000	0.000000	*	*
13	0.00000	0.000000	*	*
14	0.00000	0.000000	*	*
Overall	0.64103	0.072280	8.86866	0.0000

Kendall's Coefficient of Concordance

Coef	Chi - Sq	DF	P
0.986782	41.4448	21	0.0049

From Minitab's® report it was found that Overall Cohen's Kappa was 64.1% agreement, once chance and correlation has been accounted for. This Kappa value corresponds to a *"good"* level of inter-rater agreement on Robson's [59] interpretation of Kappa, or to a *"substantial"* level of inter-rater agreement on Landis and Koch [60] interpretation of Kappa; that is, the raters classified in almost the same way the number of different ideas generated, making this measures reliable.

From overall Cohen's kappa Z-value (8.86866) it can be seen that agreement between the two raters is significantly better than chance. Finally, Kendall's coefficient of concordance was 98.57%, which is also good; since it measures how much the two raters agree when asked to put a set of objects in rank order.

There are different ways to evaluate the quality of solution ideas generated for engineering design problems by means of criterion or dimensions such as: technical feasibility and conformance to specifications [50, 51], workability, relevance, specificity, and novelty [52], or, implementability scales [53, 54, 55].

However, due to the specific characteristics of transactional problems and the open-ended nature of the generated solutions, an alternative approach to perform a quality analysis for transactional design problem solutions is proposed here for problem 2 via Benchmarking, i.e. comparing the study results with recent, notable ideas that have been published in the innovative banking industry (and that were unknown to participants).

The qualitative evaluation for quality of solutions generated was developed comparing publicly available innovative and award winning solutions of Citibank [61, 62, 56], and of Westpac Bank [63].

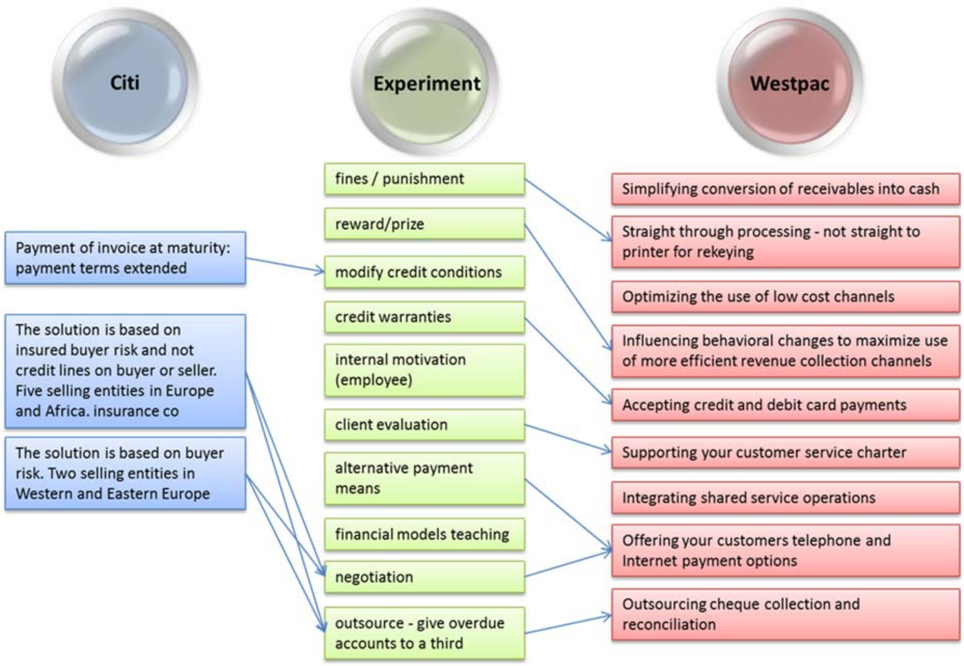


Figure 23. Qualitative comparison of innovative transactional solutions for problem 2

The solutions obtained with the experiment were sorted into bins (see Annex B. Selected transactional solutions and bins) and each one was labeled as presented on second column of Figure 23, and then compared with the solutions considered as innovative by expert practitioners.

It is very interesting that almost all of the solutions proposed by experiment participants were very close related with those implemented by the corporations, which validates the tremendous potential of the Design by Analogy approach for generate valuable (high quality ideas) on transactional fields.

Another interesting finding is that the bins that had no direct correspondence with those implemented by corporations have a great potential to be radical innovations for that kind of design problems, such is the case of the development of financial education models to be taught to customers, or the change of traditional approach of solving the problem through the customers to an approach of solving the problem though motivation of employees. There were also out of the paradigm solutions on the bins related with those listed by corporations that are not currently in the market and could solve the problem such as the use of stocks exchange or other warranties.

Addressing question 1, analogical prose aids were statistically more likely to increase the quantity and appears to match quality levels of innovative solutions for transactional design problems publicly available.

Addressing Question 2 the use of analogical prose aids allowed participants explore different domains and come up with new and different statements and solutions from other domains, so the use of analogical prose aids clearly matters.

2.2.8 Conclusions

This experiment introduces a very important topic which is idea generation for transactional problems, previous research shows the effectiveness and robustness of idea generation methods on engineering fields (manufacture, artifacts and tangible objects), but there are improvement opportunities for them to better address transactional problems.

Our findings demonstrate that the use of a word based ideation method is statistically more likely to increase the quantity of innovative solutions for transactional design problems. The experiments outcomes also demonstrate that Design by Analogy methods applied on engineering fields should not be ignored and are appropriate for successfully assist idea generation on transactional fields.

On both transactional design problems, participants on condition “before analogical prose aids” seems to run out of ideas very quickly (approximately at half of given time), and when asked about it (once the experiment was finished) many stated that it was hard to find solutions if you don’t have something to relate to (a reference, an analogous solution), some of them even commented that they feel they need to talk to customers to find different ways to approach that problem.

This experiment statistically demonstrated that re-representation of transactional problems helps designer’s to come up with analogies and analogous domains they would not be able to reach otherwise, and increase idea generation.

Design by analogy is a powerful tool in a designer’s toolbox, but few designers have the methods to take advantage of its full capacity. Designers (especially novice and transactional ones) need structured methods and tools to support idea generation, specifically when they feel they have run out of ideas.

The analogical prose aids applied here, allows a designer with limited experience to develop solutions in cases where similarity, is not initially clear. The more disruptive the new idea is, the better the concept of metaphors and analogy was engaged. Because this will mean that proposed solution comes from distant domain using current domain as reference.

An interesting finding derived from the quality qualitative analysis was that solutions generated by domain expert participants matched the ones considered as innovative and feasible to be implemented for banking corporations, which is a very positive indicator of the potential high quality of Design by Analogy approach for idea generation on transactional systems.

Acording to literature, experts designers are proficient in intuitively design by analogy by retrieving and applying examples of problems and solutions stored in their memories [47], therefore, evaluation of the method with participants that haven't developed this ability in a consistent and reliable way allowed us to test the method in the "worst case scenario" to identify practices that can be learned out of their limmitations and strengths. The method statistically significantly improved quality and quantity of ideas generated by non expert designers, which is a very positive result that lead us to believe that for expert designers the results will be positive as well by providing them with more retrieval cues to enhance idea generation results and might even help them to overcome design fixation.

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Chapter 3. Feasible Design Space

Previews chapter explored innovation process and propose the first phase of an integrated and systematic methodology that may help designers to increase the number and quality of innovative product/process ideas.

Present chapter will explore design process in order to propose a second phase of the integrated and systematic methodology that may help designers identify current design feasible alternatives and select between them according to designer's preference.

3.1 Integrating Preference and Possibility to Manage Uncertainty in Lean Design

3.1.1 Abstract

Efforts to emulate the Toyota Design System in a western version called Lean Design are focused on the manipulation of uncertainty to search for feasible alternatives within the sets of possible solutions during the design process applying tools such as the Labeled Interval Calculus (LIC) of the Set Based Concurrent Engineering (SBCE) approach. To select a preferred solution from the feasible sets of alternatives, the Method of Imprecision (MI) based on fuzzy sets has been applied. Approaching methods to integrate the LIC and MI has been proposed, such as the Labeled Fuzzy Sets and Operators to Perform Mapping with Imprecise Quantities. This research analyzes and compares both approaching methods to propose a strategy of set-based concurrent engineering for lean design.

3.1.2 Keywords

Lean Design, Uncertainty, Preference, Fuzzy Operator, Set-Based Concurrent Engineering

3.1.3 Introduction

Two situations typically arise during the early stages of product development: a) the consideration and manipulation of preference about requirements on parameters and variables to be met, especially those where every single value of a range has to be met; b) the manipulation of imprecision on design and performance parameters due to lack of precise knowledge about them and their final concept and configuration.

The challenge is more evident when mapping the multiple and interactive design and performance parameters that engineers must evaluate in order to move towards the more desirable designs.

An approach to perform this is applied at Toyota, where designers think about sets of design alternative rather than pursuing one alternative iteratively. They gradually narrow the sets until they come to a final solution [1]. This Toyota Design System, named Lean Design in the west, results in shorter time to market, higher quality and reliability at competitive costs and satisfying customers' needs [2].

Considering that Toyota´s approach is not well defined or documented [1], this research intends to make a contribution that will enable a practical application of Set-Based Concurrent Engineering. Through the definition of operators and mathematics future Lean Design will allow performing calculations, simulations and explore a larger number of alternatives in order to work on a set-based manner, instead of the traditional point based approach. .

This paper presents two developed methods to deal with situations a) and b), analyzing strengths and weaknesses in order to find robust operators to be added as foundation for a strategy of set-based concurrent engineering for lean design.

3.1.4 Labeled Fuzzy Sets (LFS)

LFS [3, 4] was developed as a unified form of representation for Labeled Interval Calculus (LIC) [5, 6] parameters and Method of Imprecision sets for preference (MI) [7, 8], to represent simultaneously parametric possibility, necessity and preference.

LIC is first applied to determine the feasible design space by filtering unfeasible design options using necessary requirements, followed by the MI to select a desirable design solution based on the manipulation of preference. These two methods offer synergies when integrated due to their compatibility with respect to their parametric representation and mathematical manipulation [3, 4].

A previous research to LFS to incorporate LIC's representation of necessity within the MI's fuzzy sets for preference is reported by Otto and Antonsson [9, 10], where necessity is represented within fuzzy sets using the degree of satisfaction α, which is assigned a value in the interval [0, 1]. A value of α=0, then only the most likely value is considered. A value of α=1 means all necessary and possible values must be satisfied. Therefore, α determines which fractions of all possible values requires that they be satisfied [10]

For example, a robotic actuator is required to provide every torque (T_a) up to 600 lb-ft. According to definition of degree of satisfaction α, using a value of α=0.9 ensures that the 90% of the possible torque range is satisfied. The necessity interval that must be satisfied is [30 570] out of the possible interval [0 600], see Figure 24.

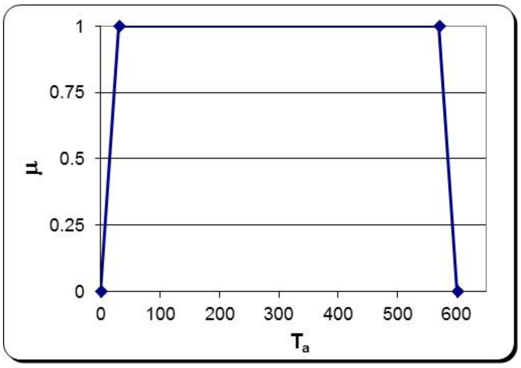

Figure 24. Fuzzy Set for Actuator Torque

The representation of necessity using the degree of satisfaction (α) must have the following capabilities to be considered for the integration of the LIC representation of necessity labels with the MI fuzzy sets for preference:

1. It must represent necessity in state variables and parameters
2. It must be compatible with the LIC`s mathematical operations

“Necessary parameters are those which every possible value needs to be satisfied… parameters in which a single value in the allowable range can be used are not modeled as necessity parameters” [10]. According to this definition, the design quantities defined in the LIC as state variables (that change during performance) can be assigned necessity, but LIC’s parameters (variables fixed at manufacturing) cannot. Therefore, the definition of necessity does not satisfy the first requirement.

With respect to the second requirement analyzing the fuzzy preference function of Figure 24, the maximum preference (μ=1) is assigned to the α-cut corresponding to the labeled interval [every T_a 30 570]. A subset of actuators C1 capable of satisfying this requirement is defined using a LIC elimination pattern [5] as:

$$\{C1 \subseteq C \mid C1 \cap [\text{every Ta } 30\ 570\ \mu=1] = C1\} \qquad (1)$$

The minimum preference (μ=0) is assigned to the α-cut corresponding to the labeled interval [every T_a 0 600]. A subset of actuators C2 capable of satisfying this requirement is defined using a LIC elimination pattern too:

$$\{C2 \subseteq C \mid C2 \cap [\text{every } T_a\ 0\ 600\ \mu=0] = C2\} \qquad (2)$$

On the basis of the MI´s concept of fuzzy sets for preference an actuator member of the subset of actuators C1 with the capability [every Ta 30 570] has the maximum preference to be chosen from a catalog, while the set of actuator C2 with the capability [every Ta 0 600] is assigned the minimum preference and should be removed from the feasible design space. However the operations of the LIC give us a different result. Using the “intersection” from abstraction operations of the LIC [5] we obtain:

$$\cap\ ([\text{every } T_a\ 30\ 570]\ [\text{every } T_a\ 0\ 600]) \rightarrow [\text{every } T_a\ 30\ 570] \qquad (3)$$

Or, $C1 \cap C2 \rightarrow C1$, which is true only if C1 is a subset of C2, that is:

$$C1 \cap C2 \rightarrow C1 \ \Leftrightarrow\ C1 \subseteq C2$$

This means that any actuator member of the subset C2 capable of satisfying [every T_a 0 600] can satisfy the [every T_a 30 570] as well, and should not be removed from the feasible design space. The contrary (that an actuator member of the subset C1 capable of satisfying [every T_a 30 570] will satisfy [every T_a 0 600]) is not necessarily true. Therefore, the subset of actuators C2 should have a higher preference than the set of actuators C1, as shown in Figure 25, rather than the representation made on Figure 24.

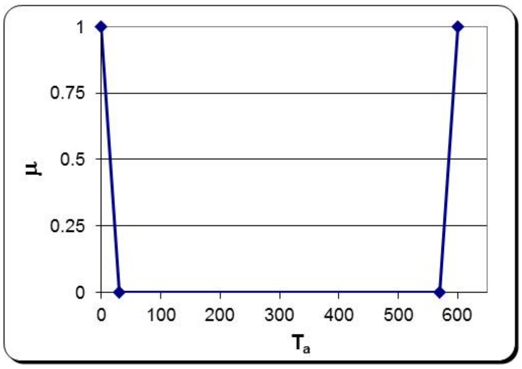

Figure 25. LFS for Actuator Torque

Therefore, the representation of necessity in fuzzy sets of preference using the degree of satisfaction α has a “similar intention”, but fails to satisfy the two requirements for compatibility with the labeled interval language of the LIC. LFS overcomes this failure of representation by unifying the labeled interval language and the fuzzy sets for preference, so that LIC’s every necessity label in a fuzzy set for preference has a correct representation.

The LFS are manipulated by means of the Labeled α-cut algorithm (LαA) [3, 4] that performs LIC operations for each prescribed number of α-cuts that a labeled fuzzy set is discretized.

The LαA takes an implicit performance parameter expression in three parameters and a pair of labeled α-cut intervals in two of the parameters, and returns the compatible labeled α-cut interval in the third parameter. The following algorithm steps lead to the execution of this process:

1. For each one of the two parameters to be propagated, divide their labeled preference function into a number of α values, α1, …, αm, where M is the number of divisions and steps.
2. Determine the labeled α-cut for each of the two parameters to be propagated for each α-cut, αj, j=1, …, M.
3. Identify the LIC inference pattern and operation (RANGE, DOMAIN, SUFPT) [5, 6] that correspond to the two labeled α-cut to be propagated.
4. For the labeled α-cut of the two parameters to be propagated apply the corresponding identified LIC inference patterns and operation.

The LFS use the same possibility intervals but with different necessity interval labels, that is, state variables with every (operating-region) and only (limit) labels from LIC. This results in the opposite interval preference, where the narrowest interval would be α=0 when in presence of every parameters, and would be α=1 when in presence of only parameters.

The conclusion here is that the proper representation of parameter preference as done in LSF is a key factor to develop coherent propagation of preference functions, and enables interpretation and physical meanings of the propagated design parameters.

3.1.5 Mapping with Imprecise Quantities [MIQ]

Giachetti [11] extended the research done by Ward [6] proposing a modification of their operations on intervals to enable performing mappings with imprecise quantities. Giachetti pointed out that two problems associated with the calculus of imprecision due to limitations of fuzzy mathematics applied to engineering systems are: lack of inverse for algebraic operators' addition and multiplication; and multiple occurrences of a parameter in a function [11].

The imprecise quantities Q are defined as a partially ordered set of real numbers. Each element $x \in Q$ has an associated membership value $\mu Q(x)$ representing the degree x belongs to Q. It is a mapping value $\mu Q: x \rightarrow [0, 1]$. MIQ limits its application to trapezoidal distributions, so the imprecise quantities are presented by a quadruple that defines the membership function's endpoints as:

$$x \rightarrow \langle \underline{\underline{x}}, \underline{x}, \overline{x}, \overline{\overline{x}} \rangle \quad (4)$$

The α-cut set of an imprecise quantity at α is represented by the interval:

$$Q\alpha = [\underline{x}_{\alpha}, \overline{x}_{\alpha}] \quad (5)$$

Where the α-cut at α=0 is called the support set $[\underline{\underline{x}}, \overline{\overline{x}}]$, and at α=1 is called the core set $[\underline{x}, \overline{x}]$ of the imprecise quantity. The author also commented that core sets are desired because they are more precise.

MQI was developed to overcome the fact that when mapping imprecise quantities strictly via the extension principle, wider ranges (less precise) are obtained which is not desirable in engineering applications. The extension principle determines the largest interval possible and does not differentiate between which values are desired but in physical systems that represents an important distinction.

When applying MIQ it is also important to distinguish causality, dependency and controllability. If the parameter is controllable, then the fuzzy set represents preference for a value. Fuzzy sets for uncontrollable parameters represent a possibility distribution that constrains the values the parameter can assume. Physically independent parameters are those that temporally occur first and determine the physically dependent parameter values. The physically dependent parameter cannot be directly specified by the designer. This notion of dependency does not correspond to the typical mathematical definition.

These distinctions between parameters allow designers to identify which operation should be applied in order to determine the set in which the parameter to be determined belongs:

- Image operator must be applied when the objective is to determine the possibility distribution of the physically dependent parameter, from the input domain. It finds the largest possible set by the application of the extension principle.

  $$\text{Image: } f(q_1, \ldots, q_n) = p \text{ then}$$

  $$p \rightarrow \left\langle f\left(\overline{\overline{D}}_f, \underline{\underline{I}}_f\right), f\left(\overline{D}_f, \underline{I}_f\right), f\left(\underline{D}_f, \overline{I}_f\right), f\left(\underline{\underline{D}}_f, \overline{\overline{I}}_f\right) \right\rangle$$

- Domain operator must be applied when the objective is to determine the physically independent parameter, such that the forward mapping will always be restricted by the physically dependent parameter p. Is an inverse of the image operator, as shown above and explained on Giachetti’s original paper [11]

Domain: $f^{-1}(q_1,\ldots,q_n,p) = q_k$

for $p \in I_{f^{-1}}$ then $q_k \rightarrow$

$$\left\langle \begin{array}{l} f^{-1}\left(\left\{\underline{\underline{D}}_{f^{-1}} \cup \underline{\underline{p}}\right\},\left\{\overline{\overline{I}}_{f^{-1}} - \overline{\overline{p}}\right\}\right), \\ f^{-1}\left(\left\{\underline{D}_{f^{-1}} \cup \underline{p}\right\},\left\{\overline{I}_{f^{-1}} - \overline{p}\right\}\right), \\ f^{-1}\left(\left\{\overline{D}_{f^{-1}} \cup \overline{p}\right\},\left\{\underline{I}_{f^{-1}} - \underline{p}\right\}\right), \\ f^{-1}\left(\left\{\overline{\overline{D}}_{f^{-1}} \cup \overline{\overline{p}}\right\},\left\{\underline{\underline{I}}_{f^{-1}} - \underline{\underline{p}}\right\}\right) \end{array} \right\rangle$$

for $p \in D_{f^{-1}}$ then $q_k \rightarrow$

$$\left\langle \begin{array}{l} f^{-1}\left(\left\{\underline{\underline{D}}_{f^{-1}} - \underline{\underline{p}}\right\},\left\{\overline{\overline{I}}_{f^{-1}} \cup \overline{\overline{p}}\right\}\right), \\ f^{-1}\left(\left\{\underline{D}_{f^{-1}} - \underline{p}\right\},\left\{\overline{I}_{f^{-1}} \cup \overline{p}\right\}\right), \\ f^{-1}\left(\left\{\overline{D}_{f^{-1}} - \overline{p}\right\},\left\{\underline{I}_{f^{-1}} \cup \underline{p}\right\}\right), \\ f^{-1}\left(\left\{\overline{\overline{D}}_{f^{-1}} - \overline{\overline{p}}\right\},\left\{\underline{\underline{I}}_{f^{-1}} \cup \underline{\underline{p}}\right\}\right) \end{array} \right\rangle$$

The research done by Giachetti [11] concluded that MIQ find more precise sets, but that further work was required to classify engineering parameters to better evaluate models that contain imprecision.

3.1.6 Application of LFS and MIQ Methods

In this section we will apply both methods to following example [3, 4]: An actuator is required to have an output torque capability up to 600 N-m only, to avoid damage to a certain specified load. As a safety measure, to avoid any possibility of failure a torque capability from 100 to 400 N-m only is preferred. The transmission to use on the actuator is required to have a ratio between 30 and 100 only, where a transmission ratio of 60 is preferred.

These parameters are related by the following performance equation for actuator torque:

$$T_a = r\,T_m \tag{6}$$

3.1.6.1 Application of LFS

The labeled preference function for these specifications is shown in Figure 26 and Figure 27.

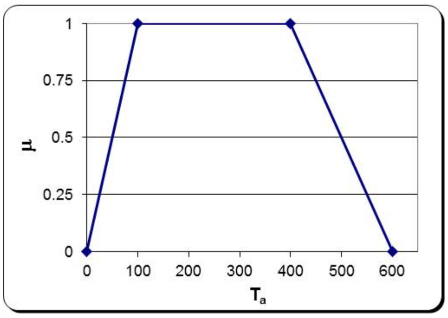

Figure 26. Actuator Torque (T_a)

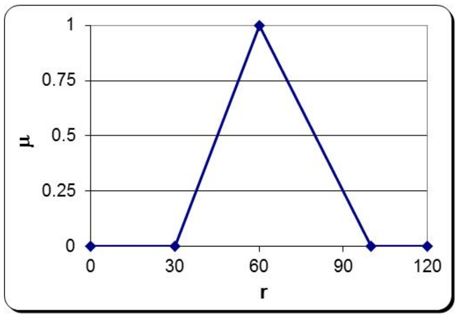

Figure 27. Transmission Ratio (r)

The labeled fuzzy sets of Ta and r are discretized into labeled α-cut intervals. The LIC's RANGE operation is identified for the propagation of the labeled α-cuts.

$$(\text{R only } T_a\ \alpha)\ \&\ (\text{A only } r\ \alpha)\ \&\ (T_a - r\,T_m = 0) \rightarrow (\text{R only } T_m\ \alpha\ \text{RANGE}) \qquad (7)$$

The propagation of the labeled fuzzy function for Ta and r, using the RANGE operation yields the labeled fuzzy function for Tm shown in Figure 28, where the feasible interval for the motor torque represented as labeled α–cut is: [T_m only 0 20 μ=0], motors with higher capacity than this interval are not feasible and should not be selected. The most preferred interval is [T_m only 1.66 6.66 μ=1], motors with a capability within this interval are preferred.

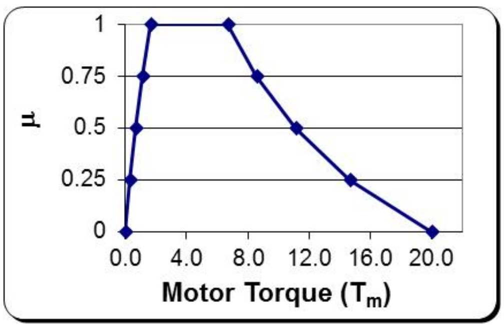

Figure 28. Motor Torque (T_m)

Now, assuming that the actuator is desired to have the capability of providing every torque from 0 up to 600 N-m, with a minimum acceptable capability of every torque from 100 to 400 as shown in the Figure 29. The same specification for a transmission restricted to have a ratio between 30 and 100 only, where a transmission of 60 is preferred as shown in Figure 27.

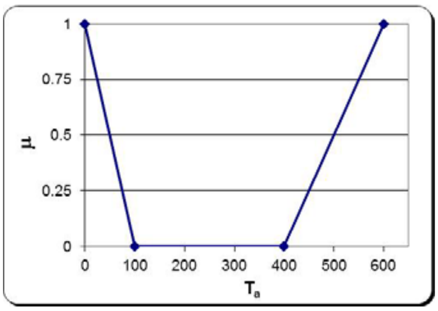

Figure 29. Actuator Torque (Ta)

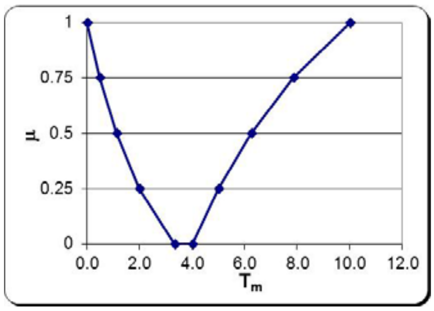

Figure 30. Motor Torque (Tm)

The labeled fuzzy sets of T_a and r are once again discretized in α-cut intervals. The LIC's DOMAIN operation is identified for the propagation of the labeled α-cuts.

$$(\text{R every } T_a\ \alpha{=}\mu)\ \&\ (\text{A only r}\ \alpha{=}\mu)\ \&\ (T_a - r\,T_m = 0) \rightarrow (\text{R every } T_m\ \alpha{=}\mu\ \text{DOMAIN}) \qquad (8)$$

The propagation of the labeled fuzzy functions for Ta and r, using the DOMAIN operation results in the labeled fuzzy function for Tm shown in Figure 30, where it can be concluded that a feasible motor must at least provide torque in the labeled α-cut [R every Tm 3.3 4.0 μ=0]. The motor must have a capacity of 3.3 N-m when combined with a transmission ratio of 30 to satisfy the requirement of actuator torque of 100 N-m, and a capability of 4 N-m combined with a transmission of ratio of 100 to satisfy the requirement of actuator torque of 400 N-m. The most preferred motors (μ=1) are those with the capability of providing every torque up to 10 N-m, which in combination with the most preferred transmission ratio of 60 results in the most preferred actuator capability of torque up to 600 N-m.

3.1.6.2 Application of MIQ

The problem is to determine motor torque (independent parameter) and MIQ version of the domain function of LIC, identified here as MIQ-DOMAIN, has to be applied.

Solving Tm from (6) we have that the increasing subset of parameters If -1 is {T_a}, the decreasing subset of parameters Df -1 is {r}, and the physically dependent parameter p is T_a.

Since the MIQ are defined for trapezoidal or triangular preference functions, it suggests that the parameters T_a and r will have the shapes shown on Figure 26 and Figure 27 respectively, so MIQ-DOMAIN application will result in the following set for the independent parameter T_m (see Table 12).

The labeled every expresses that T_a has to satisfy at least all possible values of the interval, will not be possible to represent directly via MIQ-DOMAIN, due to its definition using membership function endpoints. However, adapting the intention of the MIQ-DOMAIN a possible application can be seen in Table 13.

Table 12. MIQ-DOMAIN with only parameters for T_m

T_a	r	$T_m = T_a/r$	α
0	30	0	0
100	60	1.667	1
400	60	6.667	1
600	100	6	0

Table 13. MIQ-DOMAIN with every parameters for T_m

T_a	r	$T_m = T_a/r$	α
100	30	3.33	0
0	60	0	1
600	60	10	1
400	100	4	0

From Table 12, application of MIQ-DOMAIN with only parameters gives the same results as RANGE operation from LFS, considering the maximum (α=1) and minimum (α=0) levels of preference, except in one of the end points (see Figure 31) of the least (α=0) preferred interval (6 instead of 20). This result does not make sense, because it means that a value of 6.5 for Tm will have two values for membership at the same time.

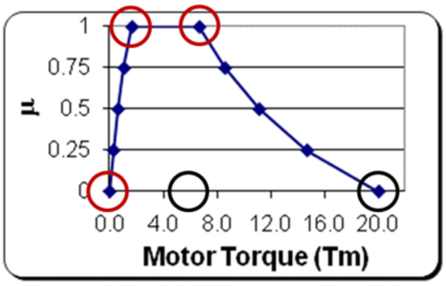

Figure 31. MIQ-DOMAIN and LFS RANGE comparison

From Table 13, application of MIQ-DOMAIN with every parameters gives as a result DOMAIN operation from LFS for the maximum (α=1) and minimum (α=0) level of preference.

Based on the result of the analysis and comparison shown on this paper, LFS is selected as the mathematical foundation of a strategy of set-based concurrent engineering for lean design to be developed and tested on our future research.

3.1.7 Conclusions

The LFS research extended the work done by Ward and Wood, and enabled its integration by identifying a proper representation of design parameter preference. The representation of necessity using the degree of satisfaction was illustrated as same possibility intervals but with different necessity interval labels, that is, state variables with every (operating-region) and only (limit) labels from LIC. This results in the opposite interval preference, where the narrowest interval would be α=0 when in presence of every parameters, and would be α=1 when in presence of only parameters.

The conclusion here is that the proper representation of parameter preference as done in LSF is a key factor to develop coherent propagation of preference functions, and enables interpretation and physical meanings of the propagated design parameters.

The research done by Giachetti extended the work done by Ward proposing alternative definition for its operators. The research does not analyze the representation of necessity; therefore, its definitions are based on trapezoidal or triangular endpoints of design parameter membership functions. The operator definitions do not provide a method to perform mapping for intermediate preference levels.

When applying both proposals into a design problem, it was found that it is important to establish the way that parameters must be considered in a design, using the labels every (parameter must satisfy at least the complete interval) and only (values of the parameter will or must be drawn from the interval). It is also important to specify the method in which mapping will be performed for all preference levels, because MIQ finds parameter preference function endpoints, that is intervals for α=0 or α =1, but does not specify a procedure to find corresponding intervals for intermediate preference levels.

Even though Lean Fuzzy Sets and Mapping with Imprecise Quantities methods represent extensions of Ward's and Wood's research, their main difference lies in the interpretation given to imprecision and preference which can lead to non-consistent mappings in the case of MIQ, as found in this paper.

Therefore, it is concluded here that LFS is a more suitable way to deal with imprecision and develop coherent mappings.

In future work, we would be using LFS as a basis to perform set-based concurrent engineering for lean design in order to:

- Avoid traditional re-work from design cycles.
- Reduce the design total cycle time.
- Explore a larger set of feasible alternatives.

References

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[2] ETI Group, 2005, "Lean Design: How to slash manufacturing costs during the product design cycle", Center for Professional Development, Oregon Health & Science University Division of Management.

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[5] (Ward & W., 1993).

[6] (Ward, 1989).

[7] (Wood & Antonsson, 1989).

[8] (Wood, 1989).

[9] (Otto, 1992).

[10] (Otto & Antonsson, 1992).

[11] (Giachetti, 1997).

Chapter 4. Prefered Design

Previews chapter explored design process and proposed a second phase of the integrated and systematic methodology that may help designers identify current design feasible alternatives and select between them according to designer's preference.

This chapter will address design optimization process in order to propose a third phase of an integrated and systematic methodology that may help designers to optimize current designs in order to assure quality and robust performance for the designed products/processes, as well as controllable performance.

4.1 Optimization of Coupled Designs

4.1.1 Abstract

An approach for design optimization integrating Response Surface Methodology (RSM) and Axiomatic Design (AD) is here presented. Response Surface Methodology is used to model the relation between design parameters (X´s) and functional requirements (Y´s). First, the overlaid response contours are developed to find regions with linear behavior that meet given constrains; then, AD is applied to determine the coupling level of the design by means of canonical analysis and coupling measures to narrow the feasible space searching for a robust region, considering the nonlinear relation among input and outputs based on the independence axiom. The proposed approach is demonstrated on the "Specification Problem" of the Box-Hunter-Hunter Book, where the goal is to maximize the yield, satisfying color index and viscosity specifications as well.

4.1.2 Keywords

Response Surface Methodology, Axiomatic Design, Design For Six Sigma.

4.1.3 Introduction

The motivation for developing an integrated design optimization approach is to provide designers a structured path which enables them to have better designs (robust and controllable), with a procedure that will allow them to identify if current design has some level of coupling, and according to that level, propose alternatives to optimize the design, or for coupled cases identify the need for redesign.

Response Surface Methodology is used to model and represent graphically the relation between design parameters (X´s) and functional requirements (Y´s). The selection of an optimum design values for optimum response is here described applying Axiomatic Design [1] to find the X's values where the independence of functional requirements is achieved. The Robust Design concept of Taguchi Method is also used to find values of X´s where the functional requirements (Y´s) are less sensitive to variations on Design Parameters (X´s).

The proposed optimization approach is demonstrated on the well-known Box Hunter & Hunter's specification problem, where the goal was to maximize the yield, satisfying color index and viscosity specifications as well. The resulting design parameters will be compared with those suggested by Box Hunter & Hunter [2], so that the specification problem accomplishes: 1) to have the maximum feasible yield, 2) meet design's specifications, and 3) to have robust performance on the specified design space.

4.1.4 Design Methods and Techniques

4.1.4.1 Response Surface Methodology

Response surface methodology (RSM) is a collection of statistical and mathematical techniques useful for developing, improving and optimizing processes. It also has important applications in the design, development and formulation of new products, as well as in the improvement of existing product designs [3]. The applications of RSM are in the industry world, particularly in situations where several input (independent) variables controlled by the engineer potentially influence one or more responses (performance measure or quality characteristic of the product or the process) [3].

Most applications of RSM are sequential in nature. That is, at first some ideas are generated concerning which factors or variables are likely to be important in the response surface study. This usually leads to an experiment designed to investigate these factors with a view toward eliminating the unimportant ones. This type of experiment is usually called a screening experiment whose objective is to reduce the list of variables to a relative few, so that subsequent experiments will be more efficient and require fewer runs or test [3].

Fitting and analyzing response surfaces are greatly facilitated by the proper choice of an experimental design. For fitting second-order models there are [4]:

- Central composite design-CCD (which for the spherical CCD requires many center points)
- Face centered design-FCD (when the region of interest is cuboidal rather than spherical)
- Equiradial designs and small composite design (reduced designs)

The objectives and applications of the RSM are [3]: 1) Mapping a response surface over a particular region of interest, 2) Optimization of the response, and 3) Selection of operating conditions to achieve specifications or customer requirements.

4.1.4.2 Axiomatic Design (AD)

This methodology was developed by Nam P. Suh from MIT as a response to the lack of scientific design principles, proposing the use of axioms as a scientific basis for design to satisfy the following two axioms:

- Axiom 1: Independence axiom. Maintain independence between functional requirements.
- Axiom 2: Information axiom. Minimize the information contained in a design.

According to axiom 1, the design process requires the definition of the following terms [5]:

- Functional Requirements (FR): minimum set of requirements that completely characterize the functional need of the product (specifies what the design does).
- Design Parameters (DP): key physical variables that characterize the design that satisfies the specified FR's.
- Process Variables (PV)

The design matrix (DM) is used to note the effect of DP's on FR's as follows:

$$\{FR\} = [DM] * \{DP\} \qquad (1)$$

Axiom 2 states that an independent design that minimizes the information is desirable, but it can be made unfeasible due to technological or cost conditions, and different levels of coupling can arise, which constitute a violation of the axiom 1 [5]. There are three coupling types in AD [5]: uncoupled, decoupled, and coupled; among these three, the most undesirable type is the coupled level that appear when there are more DP than PV, or when all the values in the design matrix are other than zero, as shown in Table 14.

Table 14. Axiomatic Design Types of coupling

Uncoupled	Decoupled	Coupled
$\begin{Bmatrix} y_1 \\ \cdot \\ \cdot \\ y_m \end{Bmatrix} = \begin{bmatrix} A_{11} & 0 & \cdot & 0 \\ 0 & A_{22} & & \cdot \\ \cdot & & \cdot & 0 \\ 0 & \cdot & 0 & A_{mm} \end{bmatrix} \begin{Bmatrix} x_1 \\ \cdot \\ \cdot \\ x_m \end{Bmatrix}$	$\begin{Bmatrix} y_1 \\ \cdot \\ \cdot \\ y_m \end{Bmatrix} = \begin{bmatrix} A_{11} & 0 & \cdot & 0 \\ A_{21} & A_{22} & & \cdot \\ \cdot & \cdot & \cdot & 0 \\ A_{m1} & A_{m2} & \cdot & A_{mm} \end{bmatrix} \begin{Bmatrix} x_1 \\ \cdot \\ \cdot \\ x_m \end{Bmatrix}$	$\begin{Bmatrix} y_1 \\ \cdot \\ \cdot \\ y_m \end{Bmatrix} = \begin{bmatrix} A_{11} & A_{12} & \cdot & A_{1p} \\ A_{21} & A_{22} & & \cdot \\ \cdot & & \cdot & A_{(m-1)p} \\ A_{m1} & \cdot & A_{m(p-1)} & A_{mp} \end{bmatrix} \begin{Bmatrix} x_1 \\ \cdot \\ \cdot \\ x_n \end{Bmatrix}$

Uncoupled and decoupled models have conceptual robustness because process variables can be modified and affect the design parameters in such way that its impact on customer attributes can be identified. Uncoupled designs are desirable for enabling control, quality and robustness. Those designs that are coupled and semi coupled have to be resolved by selecting suitable DP, modifying the application sequence of the DP or using design theories [5].

The goal of axiomatic design is improve design activities by dealing with the possible conceptual and operational vulnerabilities that can appear when developing systems, in order to have robust performance that satisfies its functional requirements under any operating condition. A more detail explanation of Axiomatic Design and case studies can be found in Dr. Suh’s books [6, 7]; extensive literature on the subject on the web and on indexed journals.

4.1.5 Design Optimization integrating Response Surface Methodology and Axiomatic Design

In this section, the specification problem [2] will be used to find the optimization path that can be followed to identify the design parameter values that accomplishes: 1) to have the maximum feasible yield, 2) to meet design's specifications, and 3) to have robust performance on the specified design space, and then compare these results with those suggested by Box Hunter & Hunter.

The proposed methodology will be developed in a two stage procedure that will be briefly explained now:

- Stage I: Response Surface Methodology is applied to fit a model that shows the effect of factors (design parameters) over responses (functional requirements). RSM also allows having a graphical representation of the relationship between design parameters (X´s) and functional requirements (Y´s) through the mapping of the response surface over a particular region of interest, which will enable identification of feasible optimal regions.
- Stage II: Axiomatic design is applied to identify the coupling levels between the functional requirements and its corresponding design parameters, in order to resolve possible couplings and make the design more robust.

4.1.5.1 Specification Problem

Box Hunter & Hunter, present a "Specification Problem" [2] where a laboratory wanted to find values for reaction time and temperature that maximizes yield Y (g), subject to a feasible color index W and viscosity Z.

It was desired to have a higher to 8 color index and maintain product viscosity in a range of 70 to 80 (stokes). The process was controlled by two reaction factors: Time (80-100 min) and Temperature (140-150 °F).

The authors stated that linear models for color index (W) and viscosity (V) were suitable on the interest region and that a second order model fitted Yield response, Figure 32 was presented showing level curves for the three responses.

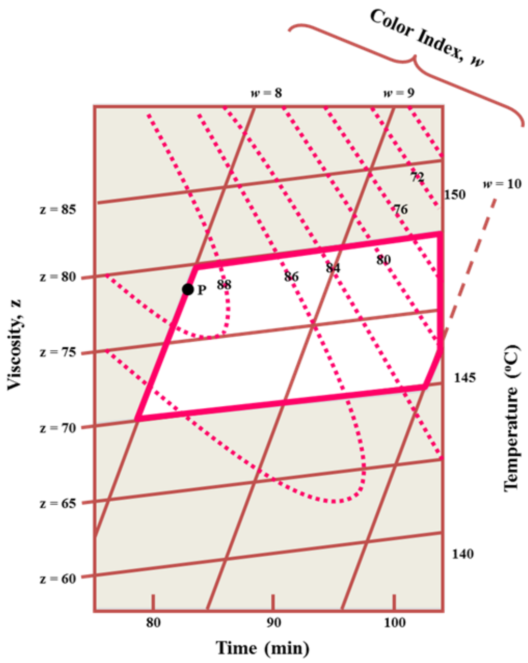


Figure 32. Overlaid contour plot for Yield, Color Index and Viscosity

Authors also commented that estimated curves suggested that on point P and its surroundings it is obtained a product with almost maximum yield (around 88 g) that satisfy both color index and viscosity specifications.

Stage I:

Minitab™ software package was used to create a Response Surface Design using the data on Table 15 in order to re-create the specification problem:

Table 15. Specification Problem Data

Time	Temp	Xtime	Xtemp	Yield	Viscosity	Color
80	140	-1	-1	78.8	60	8.4
100	140	1	-1	84.5	59	10.2
80	150	-1	1	91.2	83	7.4
100	150	1	1	77.4	82	9.3
75.85786	145	-1.41421	0	83.3	72	7.7
104.1421	145	1.414214	0	81.2	70	10.1
90	137.9289	0	-1.41421	81.2	57	9.6
90	152.0711	0	1.414214	79.5	85	8.2
90	145	0	0	89.7	71	8.9
90	145	0	0	86.9	70.5	8.9
90	145	0	0	87	71.6	8.9
90	145	0	0	86	70	8.9

After developing the Central Composite Design (CCD), an analysis was performed to find fitted models for the responses as show below:

Response Surface Regression: Yield versus Time, Temp

```
The analysis was done using coded units.

Estimated Regression Coefficients for Yield

Term           Coef  SE Coef       T      P
Constant    87.4000   0.9996  87.436  0.000
Time        -1.3837   0.7068  -1.958  0.098
Temp         0.3620   0.7068   0.512  0.627
Time*Time   -2.1563   0.7902  -2.729  0.034
Temp*Temp   -3.1063   0.7902  -3.931  0.008
Time*Temp   -4.8750   0.9996  -4.877  0.003

S = 1.99918    PRESS = 129.673
R-Sq = 88.73%  R-Sq(pred) = 39.08%  R-Sq(adj) = 79.35%
```

Response Surface Regression: Viscosity versus Time, Temp

```
The analysis was done using coded units.

Estimated Regression Coefficients for Viscosity

Term          Coef  SE Coef        T      P
Constant   70.7750   0.5251  134.794  0.000
Time       -0.6036   0.3713   -1.626  0.155
Temp       10.6997   0.3713   28.819  0.000
Time*Time   0.1125   0.4151    0.271  0.795
Temp*Temp   0.1125   0.4151    0.271  0.795
Time*Temp   0.0000   0.5251    0.000  1.000

S = 1.05012    PRESS = 39.5441
R-Sq = 99.29%  R-Sq(pred) = 95.73%  R-Sq(adj) = 98.69%
```

Response Surface Regression: Color versus Time, Temp

```
The analysis was done using coded units.

Estimated Regression Coefficients for Color

Term           Coef  SE Coef        T      P
Constant    8.90000  0.03145  282.957  0.000
Time        0.88676  0.02224   39.871  0.000
Temp       -0.48499  0.02224  -21.806  0.000
Time*Time  -0.01875  0.02487   -0.754  0.479
Temp*Temp  -0.01875  0.02487   -0.754  0.479
Time*Temp   0.02500  0.03145    0.795  0.457

S = 0.0629072  PRESS = 0.168845
R-Sq = 99.71%  R-Sq(pred) = 97.94%  R-Sq(adj) = 99.47%
```

From the response surface regression curvature test indicate that Yield had to be fitted with a second order model (p-value=0.034 and 0.008), so the fitted model equation for Yield is:

Yield = 87.4 - 1.38xtime + 0.36xtemp - 2.15xtime2 – 3.11xtemp2 – 4.87xtime xtemp

Viscosity and color index curvature test indicates that there is no curvature (viscosity p-values=0.795 and color index p-values=0.479), so the response surface regression was run again only with linear terms as presented below.

Response Surface Regression: Viscosity versus Time, Temp

```
The analysis was done using coded units.

Estimated Regression Coefficients for Viscosity

Term         Coef  SE Coef        T      P
Constant  70.9250   0.2500  283.668  0.000
Time      -0.6036   0.3062   -1.971  0.080
Temp      10.6997   0.3062   34.941  0.000

S = 0.866123   PRESS = 13.6037
R-Sq = 99.27%  R-Sq(pred) = 98.53%  R-Sq(adj) = 99.11%
```

Response Surface Regression: Color versus Time, Temp

```
The analysis was done using coded units.

Estimated Regression Coefficients for Color

Term         Coef  SE Coef        T      P
Constant   8.8750  0.01666  532.554  0.000
Time       0.8868  0.02041   43.447  0.000
Temp      -0.4850  0.02041  -23.762  0.000

S = 0.0577291  PRESS = 0.0648364
R-Sq = 99.63%  R-Sq(pred) = 99.21%  R-Sq(adj) = 99.55%
```

From the linear response surface regression the fitted linear models for Viscosity and Color Index are:

Viscosity = 70.925 - 0.603xtime + 10.699xtemp

Color = 8.875 + 0.887xtime - 0.485xtemp

Individual contour and surface plots shown on Figure 33 to Figure 35 were made for each response as follows:

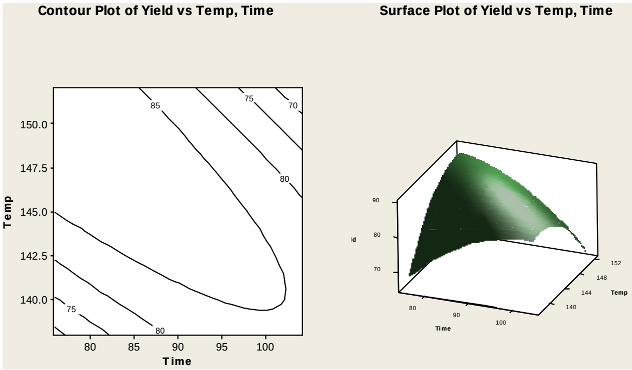


Figure 33. Contour and Surface plots for Yield

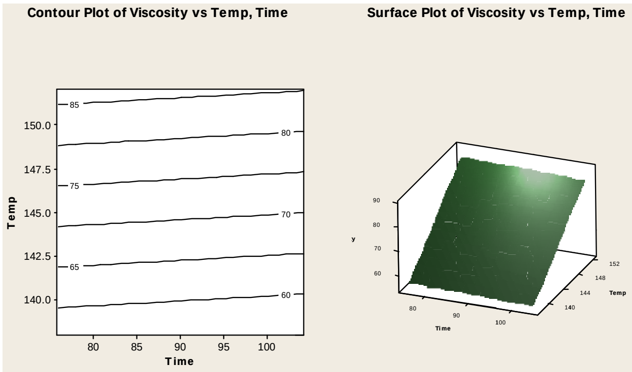


Figure 34. Contour and Surface plots for Viscosity

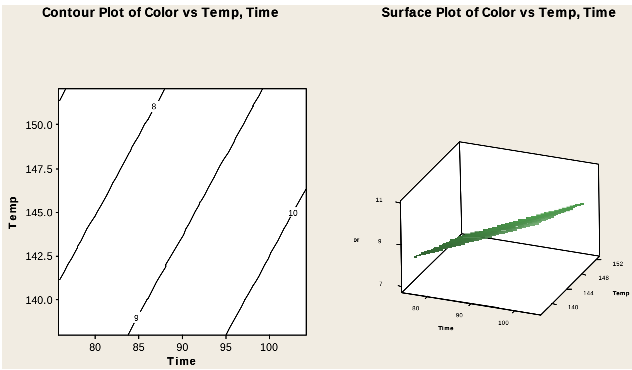


Figure 35. Contour and Surface plots for Color Index

Second order models are not easy to interpret [2], but for two factors response surface shapes can be identified by calculating their level curves, and when more than one response is being studied it is be very helpful to use a computer or projector to superimpose their correspondent level curves to locate the areas that had better compromise solutions for several responses.

Minitab™ Software Package was used to develop an overlaid contour plot for the three responses as shown on Figure 36.

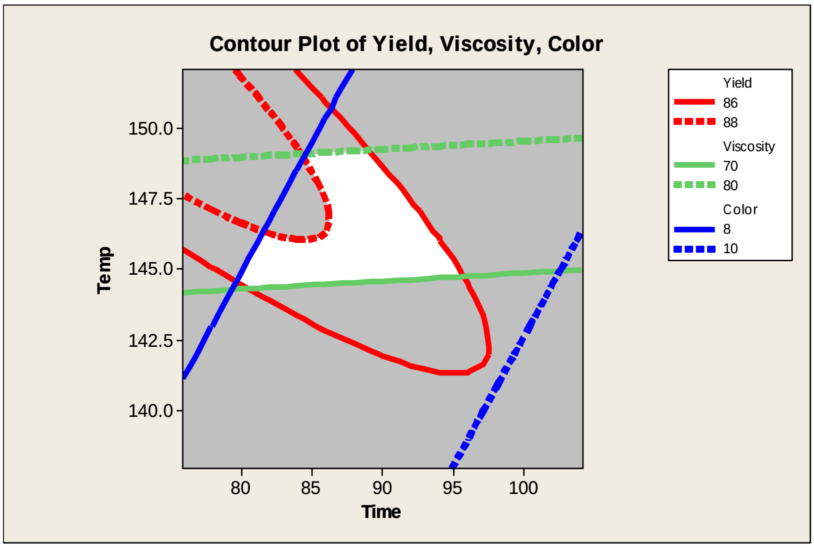


Figure 36. Minitab's overlaid contour plot for Yield, Viscosity and Color Index

The RSM analysis performed so far has led us to basically the same findings than those presented by Box Hunter & Hunter, which are the following:

- It is possible to meet constrains, through overlaid contour plot analysis which indicates that there is a feasible region (colored white on Figure 36) where constrains are satisfied and maximum feasible yield is obtained.
- Identify new conditions if constrains are changed. Through the fitted equations found for the responses.
- Shows the direction in which the process has to be modified if product characteristics do not meet constrains.

Stage II:

AD's application is not included on Box Hunter & Hunter's specification problem, so it will be here explained how this analysis is going to be conducted for this stage.

First, the terminology used on AD is going to be linked to specification problem as shown on Table 16:

Table 16. AD's Terminology for Specification Problem

Functional Requirements	**Design Parameters**
FR1: Yield (Y) FR2: Viscosity (V) FR3: Color Index (W)	DP1: Time DP2: Temperature

With this term definition the design this can be expressed in matrix form as follows:

$$\begin{bmatrix} FR1 \\ FR2 \\ FR3 \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \\ C_{31} & C_{32} \end{bmatrix} * \begin{bmatrix} DP1 \\ DP2 \end{bmatrix}, \quad \text{where design matrix C is unknown.}$$

From Stage I, it can be identify by the overlaid contour plot on Figure 36 some level of coupling because:

1. Functional requirements level curves for specification problem are not parallel to corresponding design parameters.
2. Functional requirements level curves are not orthogonal among them.

To determine the coupling level, the angles among functional requirements and design parameters were calculated. Direct angle calculation for FR1 (Yield) is not possible since it was fitted with a second order model; therefore, following canonical analysis was performed for this response.

Canonical analysis is helpful to transform the model into a new coordinate system with the origin at the stationary point $\mathbf{X_s}$ and then to rotate the axes of this system until they are parallel to the principal axes of the fitted response surface. This result in the fitted model:

$$\hat{y} = \hat{y}_s + \lambda_1 w_1^2 + \lambda_2 w_2^2 + \cdots + \lambda_k w_k^2$$

Where the w_i are the transformed independent variables and the λ_i are constants and correspond to the eigenvalues or characteristic roots of the matrix B (symmetric matrix whose main diagonal elements are the pure quadratic elements and whose off-diagonal elements are one-half the mixed quadratic coefficient).

The general solution equation was used to find the stationary point (X_s):

$X_s = -\frac{1}{2}B^{-1}b$, where b is the vector of the first-order regression coefficients.

$$b=\begin{bmatrix}-1.3837\\ 0.362\end{bmatrix},\quad B=\begin{bmatrix}-2.1563 & -2.4375\\ -2.4375 & -3.1062\end{bmatrix},\quad B^{-1}=\begin{bmatrix}-4.10605 & 3.2221\\ 3.2221 & -2.85039\end{bmatrix}$$

So the stationary point is: $X_s=\begin{bmatrix}-3.42397\\ 2.74513\end{bmatrix}$ and the predicted response at the stationary point is $\hat{y}_s$=89.76888.

The stationary point corresponds to the new coordinate origin and now though equation $|B-\lambda I|=0$, eigenvalues of matrix B had to be found as follows:

$$\begin{vmatrix} -2.1563-\lambda & -2.4375 \\ -2.4375 & -3.1062-\lambda \end{vmatrix} = 0$$

Which reduces to: $\lambda^2+5.2625\lambda+0.7564=0$

The roots of this quadratic equation are λ_1=-5.11459 and λ_2=-0.14791. Thus the canonical form of the fitted model is: $\hat{y}$ = 89.76888 - 5.11459 W_1^2 - 0.14791 W_2^2, and since are both λ_1 and λ_2 are negative, the stationary point is a maximum.

Canonical variables (w_i) and the design variables (x_i) are related by: $w=M'(x-x_s)$, where M is an orthogonal matrix. The columns of M are the normalized eigenvectors associated with each λ_i. That is, if m_i is the ith column of M, then m_i is the solution to: $(B-\lambda_i I)m_i=0$, for which $\sum_{j=1}^{2} m_{ij}^2=1$.

For λ_1=-5.11459 we have: $\begin{bmatrix} -2.1563+5.11459 & -2.4375 \\ -2.4375 & -3.1062+5.11459 \end{bmatrix} \begin{bmatrix} m_{11} \\ m_{21} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$

Solving the equation system, we have that the first column for matrix M is $\begin{bmatrix} m_{11} \\ m_{21} \end{bmatrix} = \begin{bmatrix} 0.6359 \\ 0.7717 \end{bmatrix}$

Repeating the procedure for λ_2=-0.14791 we have that the second column for matrix M is $\begin{bmatrix} m_{12} \\ m_{22} \end{bmatrix} = \begin{bmatrix} -0.7717 \\ 0.6359 \end{bmatrix}$

With the eigenvectors it is possible to calculate the rotation angle of the principal axes of the fitted response with respect to the design parameters. It is enough to only calculate the angle between DP1 and eigenvector 1 (first column of matrix M), because eigenvector 2 (second column of matrix M) is orthogonal to eigenvector 1. This procedure will be used to calculate the angle for the second order response Yield.

Since the cosine of the angle between two vectors is equal to the normalized inner product of the vectors, the next step for the linear responses Viscosity and Color Index, was to calculate the angle (θ) between each FR's and the design parameter time (axis x).

The calculated angles (θ) for linear response surfaces Viscosity and Color Index, and second order response Yield are presented on Table 17:

Table 17. Angle between functional requirements and DP1

	Viscosity	**Color Index**	**Yield**
θ	3.22°	61.32°	50.51°

For fitted second order response surface Yield, the rotational angle of the axes is 50.51°, this rotated x axis correspond to the directrix of the parabola. Since the second eigenvector of Matrix M is orthogonal to first eigenvector, the rotational angle of y axis is 90+50.51= 140.51, this rotated y axis contains the focal point of the parabola (see Figure 37).

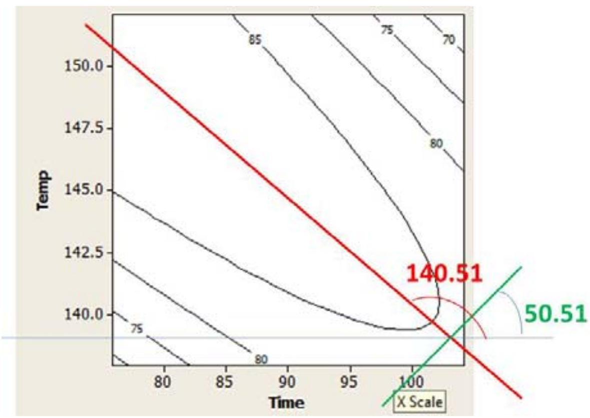


Figure 37. Rotational angles for Yield

Analyzing the individual plots and the calculated angles, it can be seen that the independence axiom is not achieved because each of the FR's are not satisfied independently by means of only one DP.

A given Yield response value has to be obtained through simultaneous adjustment of both design parameters (being temperature adjustment slightly higher than time). Viscosity is almost independent from temperature, that is, to obtain a given viscosity it is only necessary to adjust the design parameter "time". Finally, for a targeted Color Index value it also requires simultaneous adjustment of both design parameters (being time adjustment slightly higher than temperature).

This might suggest possible design matrix coefficients values (see Table 18). So for design matrix the following can be inferred:

Table 18. Possible design matrix values

FR1	$C_{11} \neq 0$	$C_{12} \neq 0$	Where $C_{11} > C_{12}$
FR2	$C_{21} \neq 0$	$C_{22} \cong 0$	
FR3	$C_{11} \neq 0$	$C_{12} \neq 0$	Where $C_{11} < C_{12}$

In order to proceed with the analysis, it is important to also address some of AD theorems [8].

> *Theorem 1 "coupling due to insufficient number of DP's". When the number of DP's is less than the number of FR's, either a coupled design results of the FR's cannot be satisfied.*

> *Theorem 4 "ideal design". In an ideal design, the number of DP's is equal to the number of FR's, and the FR's are always maintained independent of each other.*

From theorem 1, the design here presented is coupled because it has more Functional Requirements than Design parameters, therefore, in order to move towards an ideal design, FR’s pairwise comparisons should be performed.

One alternative is to identify a region on the feasible space where Yield behaves in a linear manner. This is the case of the region bounded by DP1 [90, 100], and DP2 [145, 149].

Therefore, a second CCD experiment was developed to validate if it is possible to fit a linear model for all three FR’s on the feasible space bounded by following design parameters: Time [90-100] min and Temperature [145-149] °F.

Minitab package was used to create this Response Surface Design with the data of the Table 19:

Table 19. Second CCD for Specification Problem Data

Time	Temp	Xtime	Xtemp	Yield	Viscosity	Color
90	145	-1	-1	87.4	70.925	8.875
100	145	1	-1	83.86	70.3214	9.7618
90	149	-1	1	85.70163	79.48476	8.487
100	149	1	1	78.26163	78.88116	9.3738
87.92893	147	-1.41421	0	87.64575	75.32989	8.497338
102.0711	147	1.414214	0	79.88172	74.47627	9.751462
95	144.1716	0	-1.41421	86.42768	68.85042	9.398757
95	149.8284	0	1.414214	81.26811	80.95574	8.850043
95	147	0	0	84.84188	74.90308	9.1244

With this Central Composite Design (CCD), an analysis was performed to find linear fitted models for the responses as show below:

Yield = 83.921 - 2.745 xtime - 1.824 xtemp

Response Surface Regression: Yield versus Time, Temp

```
The analysis was done using coded units.

Estimated Regression Coefficients for Yield

Term        Coef  SE Coef        T      P
Constant  83.921   0.2970  282.548  0.000
Time      -2.745   0.3150   -8.713  0.000
Temp      -1.824   0.3150   -5.790  0.001

S = 0.891043   PRESS = 10.6663
R-Sq = 94.80%  R-Sq(pred) = 88.36%  R-Sq(adj) = 93.07%
```

Viscosity = 74.9031 - 0.3018 xtime + 4.2799 xtemp

Response Surface Regression: Viscosity versus Time, Temp

```
The analysis was done using coded units.

Estimated Regression Coefficients for Viscosity

Term         Coef   SE Coef  T  P
Constant  74.9031  0.000000  *  *
Time      -0.3018  0.000000  *  *
Temp       4.2799  0.000000  *  *

S = 0           PRESS = 0
R-Sq = 100.00%  R-Sq(pred) = 100.00%  R-Sq(adj) = 100.00%
```

Color = 9.1244 + 0.4434 xtime - 0.194 xtemp

Response Surface Regression: Color versus Time, Temp

```
The analysis was done using coded units.

Estimated Regression Coefficients for Color

Term         Coef   SE Coef  T  P
Constant   9.1244  0.000000  *  *
Time       0.4434  0.000000  *  *
Temp      -0.1940  0.000000  *  *

S = 0           PRESS = 0
R-Sq = 100.00%  R-Sq(pred) = 100.00%  R-Sq(adj) = 100.00%
```

Corresponding Individual contour and surface plots are shown on Figure 38 to Figure 40 were made for each response as follows:

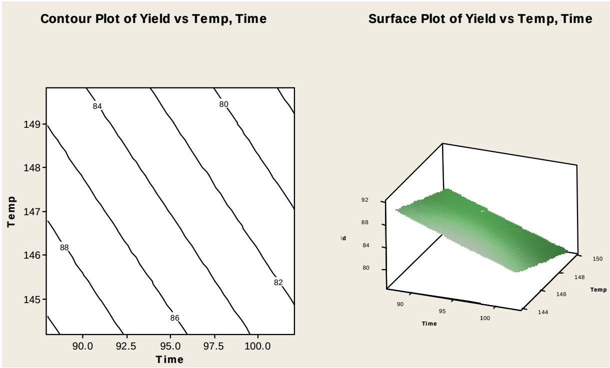


Figure 38. Second experiment Contour and Surface plots for Yield

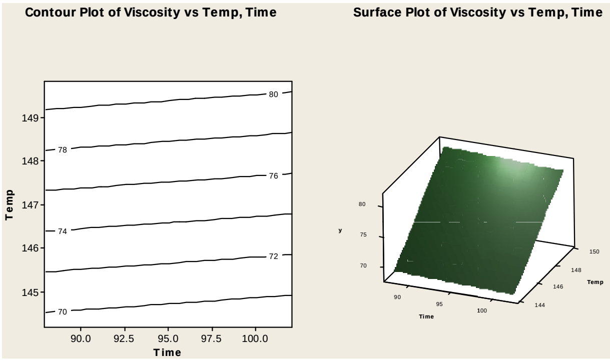


Figure 39. Second experiment Contour and Surface plots for Viscosity

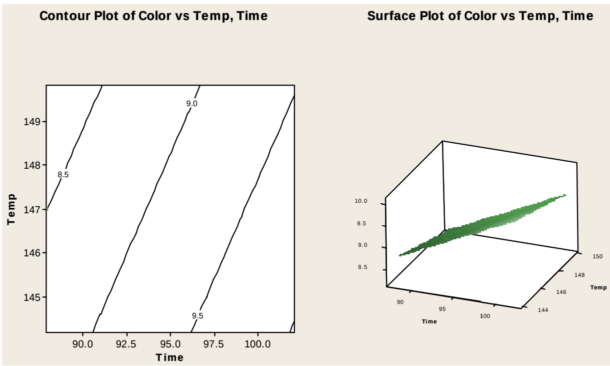


Figure 40. Second experiment Contour and Surface plots Color Index

Superimposing the individual contour plots, it is obtained the overlaid contour plot of figure:

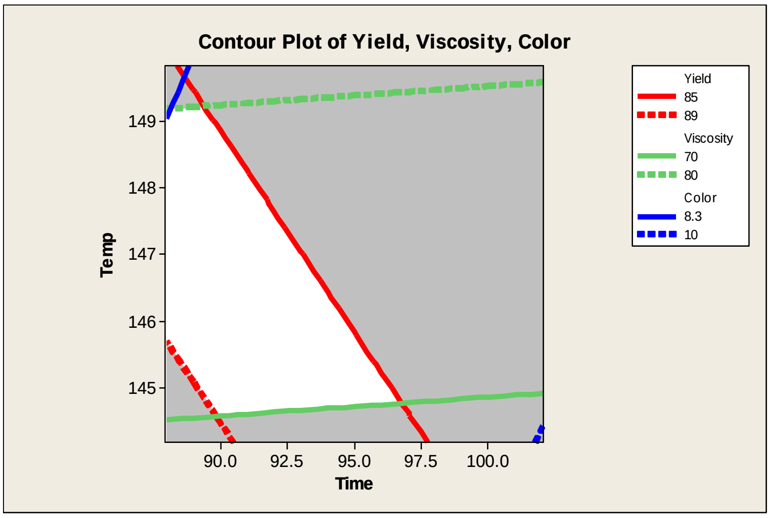


Figure 41. Overlaid contour plot

Now that all three responses could be fitted into linear models on the feasible region, the design can be expressed in matrix form with known design matrix coefficients as follows:

$$\begin{bmatrix} FR1 \\ FR2 \\ FR3 \end{bmatrix} = \begin{bmatrix} -2.745 & -1.824 \\ -0.3018 & 4.2799 \\ 0.4434 & -0.194 \end{bmatrix} * \begin{bmatrix} DP1 \\ DP2 \end{bmatrix} + \begin{bmatrix} 83.921 \\ 74.9031 \\ 9.1244 \end{bmatrix}$$

From AD's theorem 1, the design here presented is coupled because it has more Functional Requirements than Design parameters, therefore, in order to move towards an ideal design, some of the following three alternatives should be followed:

1. Add another design parameter so each FR can be achieved through only one DP. When several FR's must be satisfied we must develop designs that will enable us to create either a diagonal or a triangular design matrix.
2. Re-evaluate the process to identify if all three FR's are really expected outcomes.
3. Evaluate current design through pairwise comparisons, that allow coupling management until options 1 or 2 are developed.

4. Redesign the system to avoid coupling through DP selection (definition).

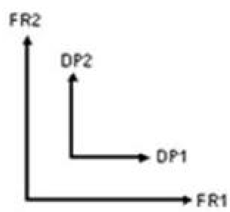
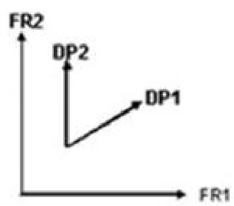
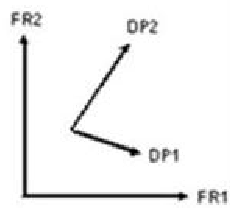
Since the goal of axiomatic design is to improve design activities by dealing with the possible conceptual and operational vulnerabilities to have a robust performance that satisfies its functional requirements under any operating condition, it is important to identify the coupling level that the design has, because this goal is achieved when in the presence of uncoupled designs. Demi coupled and coupled designs have to be optimized by selecting suitable DP values, modifying the DP sequence or through other analysis.

Now that the region where all functional requirements behave in a linear manner has been identified, FR's pairwise comparisons can be performed, so that square design matrices are obtained and a more suitable coupling analysis can be conducted.

To identify coupling (see Table 20) it is important to remember that uncoupled designs have the following characteristics:

1. All FR's are orthogonal among them.
2. All DP's are orthogonal among them.
3. And each FR is parallel to its corresponding DP.

Table 20. Graphical representation of mapping process for coupling levels

Uncoupled	**Demicoupled**	**Coupled**
		

There are also coupling measures for linear designs that can be calculated through Rinderle's reangularity and semangularity [1, 9], but here it will be presented an alternative approach for nonlinear designs to calculate coupling measures.

Reangularity is a measure of orthogonally between design parameters (DP's) in p-dimensional space; it is the absolute value of the product of sine function of all the angle pairs of the design matrix in the transfer function. Reangularity is equal to 1 (maximum) when all DP's are orthogonal. As the degree of coupling increases, Reangularity will decrease. This orthogonality measure can't assure axiom 1 satisfaction as the design parameters can be orthogonal but not parallel to the functional requirements (FR's); that is, the one-to-one mapping can't be assured. Semangularity measure reflects the angular relationship between the corresponding axes of DP's and FR's. Semangularity is the product of the absolute values of the diagonal elements of the design matrix. When Semangularity equals 1, the DP's parallel the FR's and uncoupled design is achieved. The different possibilities of design categories in these two measures are given in Table 21.

Table 21. Rinderle's functional independence measures by design category [1]

Design	Reangularity R	Semangularity S	Comments
Uncoupled	1	1	$R = S = 1$
Decoupled	<1	<1	$R = S$
Coupled	<1	<1	R could be greater or less than S

Now that all three responses were fitted into linear models on the feasible region, pairwise comparisons can be conducted to calculate reangularity and semangularity (see Table 22).

$$\begin{array}{l} \textbf{yield} \\ \textbf{viscosity} \\ \textbf{color} \end{array} \left| \begin{array}{c} \mathbf{Y} \\ \mathbf{V} \\ \mathbf{W} \end{array} \right| = \left| \begin{array}{c} \mathbf{83.921} \\ \mathbf{74.9031} \\ \mathbf{9.1244} \end{array} \right| + \left| \begin{array}{cc} \mathbf{-2.745} & \mathbf{-1.824} \\ \mathbf{-0.3018} & \mathbf{4.2799} \\ \mathbf{0.4434} & \mathbf{-0.194} \end{array} \right| * \left| \begin{array}{c} \textbf{Xtime} \\ \textbf{XTemp} \end{array} \right|$$

Table 22. Pairwise reangularity and semangularity calculations

Metric	Yield & Color Index	Yield & Viscosity	Color Index & Viscosity
Semangularity	0.10	0.92	0.83
Reangularity	0.26	0.95	0.80
Design	*Coupled*	*Uncoupled*	*Decoupled - Uncoupled*

According to the criteria the design pair consisting of responses Yield and Viscosity is *Uncoupled*, that is, Yield only depends of design parameter time, and Viscosity of temperature. Color index and Viscosity should be considered as Decoupled, according to the criteria, but for been so close to one (1) could be assumed as *Uncoupled*, where Color Index only depends of design parameter time, and Viscosity of temperature. Finally, Yield and Color Index should be considered as *Couple*, according to the criteria.

Since Color Index only depends of Time on both Color Index & Viscosity, and Yield & Color Index comparisons, to optimize this design, the first step would be to fix design parameter Time on an appropriate value in order to obtain the desired level of Functional Requirement Color Index.

Design Parameter Temperature would be a tuning parameter that can be adjusted to appropriate values in order to obtain different levels of Functional Requirements Viscosity and Yield.

4.1.6 Conclusions

Coupled Designs are very sensitive and hard to control; therefore an approach for design optimization integrating Response Surface Methodology (RSM) and Axiomatic Design (AD) to operate such designs in an optimal (robust) manner was presented.

Not all designs come to life with an uncoupled configuration between design parameters and functional requirements, so even thought they could be satisfying a customer need they have a great deal to improve on controllability and robustness. This section proposed integration of axiomatic design and response surface methodologies in order to identify design vulnerabilities regarding controllability and robustness. Taguchi method helps improving engineering quality, that is, addresses defects, failures, noise, vibrations, pollution and so on when designing for robustness improving the performance of the product/process.

Nonlinear responses does not allow direct calculation of coupling measures semangularity and reangularity, canonical analysis allows its indirect inference through identification of angles of the responses, enabling reangularity calculation. Characterization of system's coupling level explicit the optimization path (sequence for design parameters to be fixed or tuned) that could be followed to operate with robust performance.

This procedure provides a better understanding on how to operate in presence of coupled designs, so the best possible results for system configuration could be obtained when re-design is not a feasible option.

References

[1] (Yang & El-Haik, 2003)
[2] (Box, Hunter, & Hunter, 1978).

[3] (Myers, Montgomery, & Anderson-Cook, 2009).
[4] (Montgomery, 2009).
[5] (Yang & El-Haik, 2003).
[6] (Suh, 1990).
[7] (Suh, 2001).
[8] (Lee & Suh, 2006)
[9] (Rinderle, 1982)

4.2 Response Surface Optimization integrating Axiomatic Design and Labeled Fuzzy Sets

4.2.1 Abstract

An approach for design optimization under using the Response Surface Methodology is presented integrating Axiomatic Design and Labeled Fuzzy Sets for optimal parameter selection. Response Surface Methodology is used to model the relation between design parameters (X´s) and functional requirements (Y´s). First, the overlaid response contours are used to find a feasible region. Then, Axiomatic Design is applied to narrow the feasible space searching for a robust region considering the nonlinear relation among input and outputs and based on the independence axiom. The most desirable solution is selected applying the preference modeling and manipulation on the Labeled Fuzzy Sets. The proposed approach is demonstrated for the well-known optimization of the Den Hartog´s Dynamic Damped Vibrations Absorber, where the goal is to find the set of parameter values for the spring-mass-damper of the vibration absorber that results in the lowest combined displacement for the main and absorber masses with an optimum and robust performance under the frequency range close to resonance.

4.2.2 Keywords

Response Surface Methodology, Axiomatic Design, Labeled Fuzzy Sets, Design For Six Sigma.

4.2.3 Introduction

The motivation for developing a novel design approach is to help designers with a structured path that will enables them to have better designs (robust and controllable), with straight forward procedure that will result in shorter development times.

Response Surface Methodology is used to model and represent graphically the relation between design parameters (X´s) and functional requirements (Y´s). The selection of the optimum design values for optimum response is here described applying Axiomatic Design [1] and Labeled Fuzzy Sets [2]. The Robust Design concept of Taguchi Method is used to find values of X´s where the functional requirements (Y´s) are less sensitive to variations on Design Parameters (X´s). Axiomatic Design is applied to find the X values where the independence of functional requirements is achieved. Labeled Fuzzy Sets is considered to find a set of values of X where the most preferred and feasible solution is achieved.

The optimization procedure proposed here is applied to the classical problem of the Damped Dynamic Vibrations Absorber [3]. The objective here is to design dynamic vibration absorbers with the lowest possible displacement for different frequency levels. The equations proposed by Den Hartog to describe parameter behavior (principal and absorbers displacements, elasticity and damping coefficients) will be reviewed here. The resulting parameters will be compared with those proposed by Den Hartog [3], Canales [4, 5], and Hernandez [4, 6], so that the dynamic vibration absorber system accomplishes: 1) to have the lowest displacements of each component, and 2) to have robust performance for different excitation forces in the neighborhood of resonance.

4.2.4 Design Methods and Techniques

4.2.4.1 Response Surface Methodology

Response surface methodology (RSM) is a collection of statistical and mathematical techniques useful for developing, improving and optimizing processes. It also has important applications in the design, development and formulation of new products, as well as in the improvement of existing product designs [7]. The applications of RSM are in the industry world, particularly in situations where several input (independent) variables controlled by the engineer potentially influence one or more responses (performance measure or quality characteristic of the product or the process) [7].

Most applications of RSM are sequential in nature. That is, at first some ideas are generated concerning which factors or variables are likely to be important in the response surface study. This usually leads to an experiment designed to investigate these factors with the intention of eliminating the unimportant ones. This experiment is usually called a screening experiment. The objective of screening is to reduce the list of variables, so that subsequent experiments will be more efficient and require fewer runs or tests [7].

Fitting and analyzing response surfaces are greatly facilitated by the proper choice of an experimental design. For fitting second-order models there are [8]:

- Central composite design-CCD (which for the spherical CCD requires many center points)
- Face centered design-FCD (when the region of interest is cuboidal rather than spherical)
- Equiradial designs and small composite design (reduced designs)

The objectives and applications of the RSM are [7]: 1) Mapping a response surface over a particular region of interest, 2) Optimization of the response, and 3) Selection of operating conditions to achieve specifications or customer requirements.

4.2.4.2 Axiomatic Design (AD)

This methodology was developed by Nam P. Suh from MIT as a response to the lack of scientific design principles, proposing the use of axioms as a scientific basis for design to satisfy the following two axioms:

- Axiom 1: Independence axiom. Maintain independence between functional requirements.
- Axiom 2: Information axiom. Minimize the information contained in a design.

According to axiom 1, the design process requires the definition of the following terms [9]:

- Functional Requirements (FR): minimum set of requirements that completely characterize the functional need of the product (specifies what the design does).
- Design Parameters (DP): key physical variables that characterize the design that satisfies the specified FR’s.
- Process Variables (PV)

The design matrix (DM) is used to note the effect of DP’s on FR’s as follows:

$$\{FR\} = [DM] * \{DP\} \qquad (1)$$

Axiom 2 states that an independent design that minimizes the information is desirable, but it can be made unfeasible due to technological or cost conditions, and different levels of coupling can arise, which constitute a violation of the axiom 1 [9]. There are three coupling types in AD [9]: uncoupled, decoupled, and coupled; among these three, the most undesirable type is the coupled level that appear when there are more DP than PV, or when all the values in the design matrix are other than zero, as shown in Table 23.

Table 23. Axiomatic Design Types of coupling

Uncoupled	**Decoupled**	**Coupled**
$\begin{Bmatrix} y_1 \\ \cdot \\ \cdot \\ y_m \end{Bmatrix} = \begin{bmatrix} A_{11} & 0 & \cdot & 0 \\ 0 & A_{22} & & \cdot \\ \cdot & & \cdot & 0 \\ 0 & \cdot & 0 & A_{mm} \end{bmatrix} \begin{Bmatrix} x_1 \\ \cdot \\ \cdot \\ x_m \end{Bmatrix}$	$\begin{Bmatrix} y_1 \\ \cdot \\ \cdot \\ y_m \end{Bmatrix} = \begin{bmatrix} A_{11} & 0 & \cdot & 0 \\ A_{21} & A_{22} & & \cdot \\ & \cdot & \cdot & 0 \\ A_{m1} & A_{m2} & \cdot & A_{mm} \end{bmatrix} \begin{Bmatrix} x_1 \\ \cdot \\ \cdot \\ x_m \end{Bmatrix}$	$\begin{Bmatrix} y_1 \\ \cdot \\ \cdot \\ y_m \end{Bmatrix} = \begin{bmatrix} A_{11} & A_{12} & \cdot & A_{1p} \\ A_{21} & A_{22} & & \cdot \\ \cdot & & \cdot & A_{(m-1)p} \\ A_{m1} & \cdot & A_{m(p-1)} & A_{mp} \end{bmatrix} \begin{Bmatrix} x_1 \\ \cdot \\ \cdot \\ x_n \end{Bmatrix}$

Uncoupled and decoupled models have conceptual robustness because process variables can be modified and affect the design parameters in such way that its impact on customer attributes can be identified. Uncoupled designs are desirable for enabling control, quality and robustness. Those designs that are coupled and semi coupled have to be resolved by selecting suitable DP, modifying the application sequence of the DP or using design theories [9].

The goal of axiomatic design is improve design activities by dealing with the possible conceptual and operational vulnerabilities that can appear when developing systems, in order to have robust performance that satisfies its functional requirements under any operating condition. A more detail explanation of Axiomatic Design and case studies can be found in Dr. Suh's books [10, 11]; extensive literature on the subject on the web and on indexed journals.

4.2.4.3 Labeled Fuzzy Sets (LFS)

LFS [13, 14] was developed as a unified form of representation for Labeled Interval Calculus (LIC) [15, 16] parameters and Method of Imprecision sets for preference (MI) [17, 18], to represent simultaneously parametric possibility, necessity and preference.

LIC is first applied to determine the feasible design space by filtering unfeasible design options using necessary requirements, followed by the MI to select a desirable design solution based on the manipulation of preference. These two methods offer synergies when integrated due to their compatibility with respect to their parametric representation and mathematical manipulation [13, 14].

The LFS are manipulated by means of the Labeled α-cut algorithm (LαA) [13, 14] that performs LIC operations for each prescribed number of α-cuts that a labeled fuzzy set is made discrete.

The three design methods and techniques presented here have the potential to be integrated in order to help designers identify why some designs are difficult to control and optimize, so they can be partially of fully redesign in order to address possible couplings between its design parameters, and then have a path to optimize the design including the designer/customer/market preferences for the functional requirements and design parameters.

4.2.5 Dynamic Vibration Absorber

In a machine (or in part of it) subject to a harmonic force at a constant frequency an unwanted vibration can occur, especially when frequency is near to resonance [3]. One way to deal with such force is suppressing it, which is often not practical. Another way is to modify mass and spring values to modify resonance frequency, which is often not feasible. A third option is using dynamic vibration absorbers.

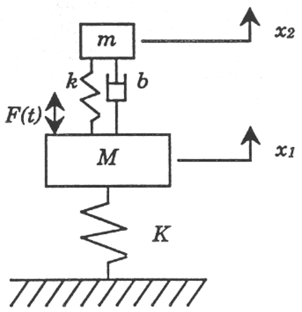


Figure 42. Dynamic Vibration Absorbers

Den Hartog proposes an optimal absorber (Figure 42) where every parameter is tuned as follows:

$$\frac{\omega_a}{\Omega_n}=\frac{1}{1+\mu} \quad ; \qquad k=\frac{\mu}{(1+\mu)^2}K \qquad ; \qquad \zeta=\frac{b}{b_c}\sqrt{\frac{3\mu}{8(1+\mu)^3}} \qquad (2)$$

$$\text{Where:} \qquad \mu=m/M \ ; \qquad \omega_a=\sqrt{\frac{k}{m}}; \qquad \Omega_n=\sqrt{\frac{K}{M}}; \qquad b_c=2m\Omega n \qquad (3)$$

Den Hartog mentions that even though main mass displacements are small, the relative movement or displacements for auxiliary mass spring are considerable (3 to 4 times bigger than main mass displacements) [3], which lead us to the problem of designing a spring that resists the stress generated by this movements.

Many authors have proposed different sets of absorbers (Figure 43), one of them being the two auxiliary mass absorbers [19]. Hernandez [4, 6] used this arrangement, and applying response surface methodology [20] found a tuning method to obtain the least auxiliary mass displacement [21]. The method uses an objective function that involves displacement mean and standard deviation for different excitation frequencies.

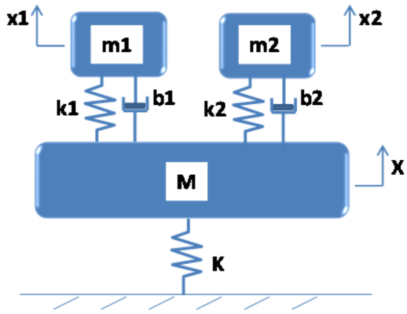


Figure 43. Dual Dynamic Vibration Absorbers

Hernandez´s method searched the minimization of objective function so that the displacement mean of each mass was small, that the standard deviation on mass movements was small, and the relative movement between masses was minimal. Hernandez concluded that in order to improve absorber performance, it has to be tuned with the following equations:

$$k=\frac{\mu}{(1+\mu)^2}K \qquad ; \qquad \zeta=\sqrt{\frac{1}{2\,(2+\mu)\,(1+\mu)}} \tag{4}$$

This meant that the "best" parameter arrangement found by Hernandez would be the one with spring calculated by Den Hartog´s equation and the best value obtained by Lanchester [6]

4.2.6 Response Surface Methodology using Axiomatic Design and Labeled Fuzzy Sets

In this chapter the absorber system will be analyzed with two auxiliary absorbers masses in order to compare the results obtained by Den Hartog, Hernandez and Canales and identify the optimization path that can be followed in order to identify the design parameter values that offer the "best" optimized set of performance parameters for the dynamic vibration absorbers.

The proposed methodology will be developed in a series of phases as follows:

- Phase I: Response Surface Methodology is applied to determine the effect of factors (design parameters) on the dynamic vibration absorbers performance and also identify the possible optimal space.
- Phase II: Axiomatic design application in order to disaggregate the dynamic vibration absorbers performance on its components (functional requirements) and identify the relations between the functional requirements and its design parameters, in order to find possible couplings and resolve them to make the design more robust.
- Phase III: Response Surface Methodology application and Labeled Fuzzy Sets (LFS) [12] narrow the possible optimal space and incorporate preference on the design.

<u>Phase I:</u>

For this system optimization, first design of experiments (DOE) was applied using the following objective function [4, 6]:

$$U = \overline{X} + \bar{x}_1 + \bar{x}_2 + \sigma_X + \sigma_{x_1} + \sigma_{x_2} + diff \qquad (5)$$

Where $$diff = \frac{\sum_{n=0}^{N}\left[\sqrt{(X-x_1)^2}+\sqrt{(X-x_2)^2}+\sqrt{(x_1-x_2)^2}\right]_n}{N}$$

The main goal is to minimize this objective function, which is composed by 3 elements:

- average of displacements of the masses
- standard deviation of displacements of the masses
- *diff,* difference on the three masses means

These three components describe system performance so that on average the three masses displacements will be the smallest possible on a consistent manner (small standard deviation), and that the relative movement of the system remains at a minimum possible level.

Later, a 2^5 full factorial was performed having as factors: the springs (fk1 and fk2), the dampers (fc1 and fc2) and the ratio of the absorbers masses (r), obtaining shown on Figure 44 the result for the 3 components and objective function U.

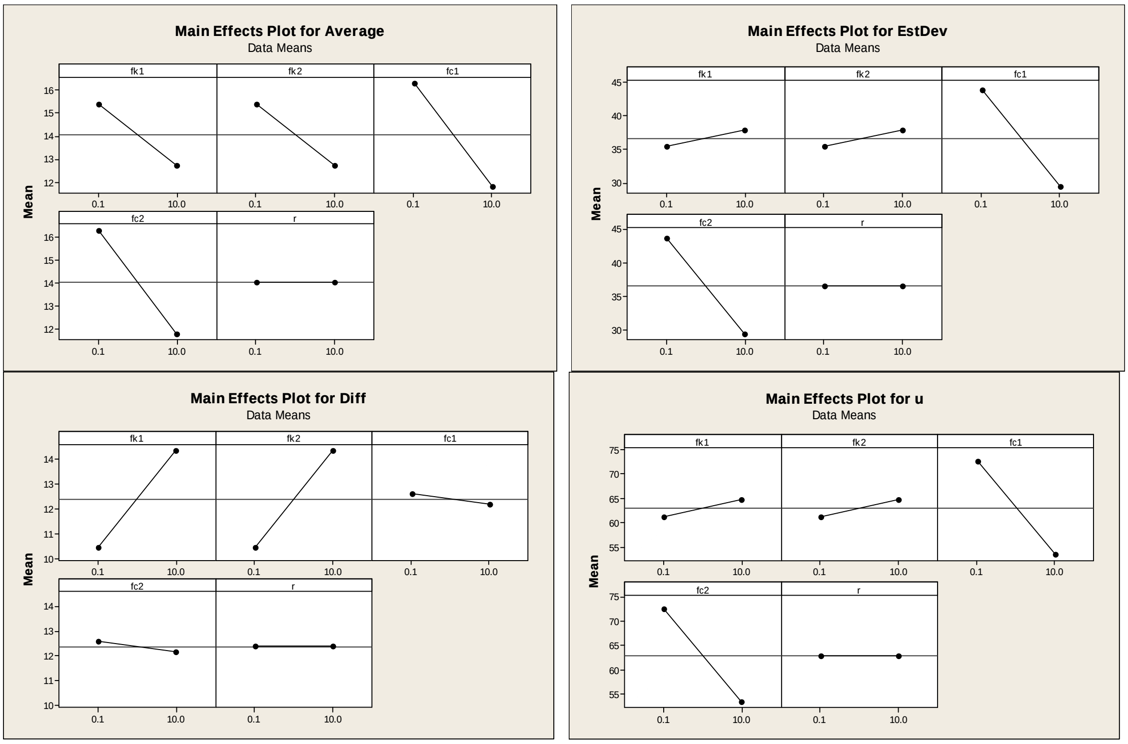


Figure 44. Main effects plots for response (U) and its components

From the main effect graphs it was found that the ratio of the absorbers mass has no influence on either of the components of the objective function and therefore on the objective function. It was also found that the behavior and contribution to the components of the objective function of the second absorber parameters (fk2 and fc2) are the same as the first.

The next phase was to use response surface method. The original factors were reduced to: fk1 y fc1, then a face centered design with one replicate and cube block was run with simulator data summarized on Table 24:

Table 24. Response Surface Data

fk1	fc1	Av_Gral	EstDev_Gral	Diff	U
0.9	1	17.683	8.296	6.758	32.737
1.1	1	17.512	8.535	6.790	32.837
0.9	3	11.403	8.533	0.083	20.018
1.1	3	11.371	8.562	0.091	20.024
0.9	2	13.257	8.058	1.533	22.849
1.1	2	13.186	8.137	1.702	23.025
1	1	17.657	8.307	6.815	32.779
1	3	11.397	8.535	0.060	19.991
1	2	13.243	8.065	1.630	22.939

The contour plot (Figure 45) shows that the optimal region for U lies somewhere between 0.9 to 1.05 for factor fk1, and 2.7 to 3 for factor fc1.

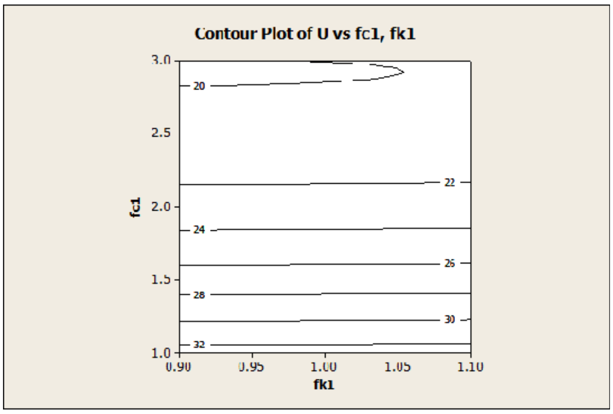


Figure 45. contour plot for the U response

Phase II:

For this phase, the objective function U was disaggregated on its more significant components. To do so, from Figure 44, it is shown that standard deviation is responsible for about 58.1% (standard deviation mean/U mean) of U total value. The average is responsible for 22.3% of U and *diff* for the 19.6%.

Using Pareto principle, only standard deviation and average is going to be considered. *Diff* is also not going to be considered because it has a dependency with average (can be considered redundant), so if average is minimized, *diff* will also be.

Summarizing, the functional requirements (FR) will be: average and standard deviation; and the design parameters (DP) will be: fk1 and fc1.

The design matrix is presented in Figure 46.

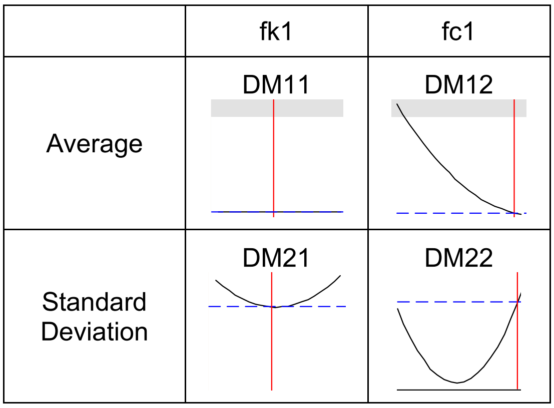


Figure 46. Design Matrix

From Figure 46, we have that the only coefficient equal to zero is DM11. In order to have a decoupled design matrix, columns fk1 and fc1 were swapped, obtaining an inferior triangular matrix which is desirable to have when developing robust designs.

Phase III:

Once couplings have been resolved response surface method can be applied to refine the design parameters values through LFS preferences to narrow the feasible optimal space.

To establish optimum values for design parameters fk1 y fc1, findings from the DOE performed on phase I and previous researches are very helpful at this point. As an illustration, the research results from Den Hartog, Hernandez and Canales are used as reference and are summarized on Table 25.

Table 25. Research results and previous optimal factors.

	fk1	**fc1**	**K**	**ζ**
Den Hartog	1	1	$\frac{\mu}{(1+\mu)^2}K$	$\sqrt{\frac{3\mu}{8(1+\mu)^3}}$
Hernandez	1	2.77	$\frac{\mu}{(1+\mu)^2}K$	$\sqrt{\frac{1}{2(2+\mu)(1+\mu)}}$
Canales	0.9237	1.32	?	?

From phase I DOE it is suggested that the appropriate sets for design parameters could be located on: fk1 [0.9 1.1] and for fc1 [2.5 3.5]. From Figure 46 and overlaid contour plot for average and standard deviation (Figure 47) there were determined the fuzzy sets of preference for functional requirements shown on Figure 48.

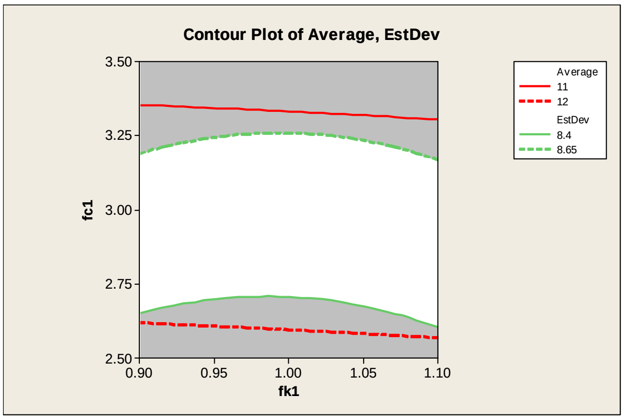


Figure 47. Overlaid contour plot for average and standard deviation

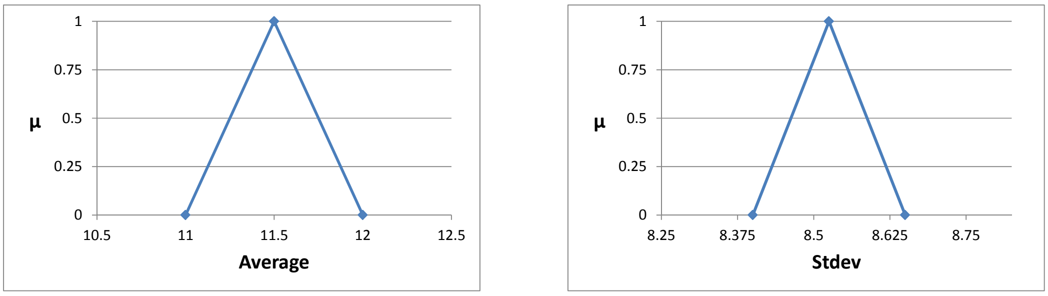


Figure 48. fuzzy sets of preference for Average and Stdev

Once fuzzy functional requirements were included on Minitab's response optimizer, the **optimum values** for design parameters were estimated as**: fk1=0.92 and fc1=2.94**. These parameter values give **U=19.9601** (11.4+8.5), and the performance for the dual dynamic absorber system illustrated on Figure 49.

The optimal response found by Hernandez is where **fk1=1** and **fc1=2.77** with **U=20.11** (11.7+8.4), and the performance for the dual dynamic absorber system illustrated on Figure 50.

The optimal design values fk1 and fc1 found by phase III, have no direct mathematical equivalent for K and ζ, and on Figure 49 it can be seen that at a frequency of 0.95 principal mass has a higher peak in comparison to optimization performed by Hernandez, where the factors have a mathematical equivalent for K and ζ.

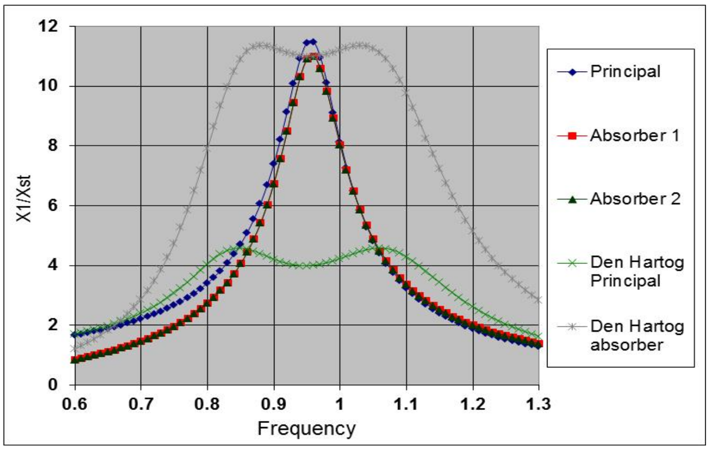


Figure 49. Principal mass and absorbers curves with fk1=fk2=0.92 and fc1=fc2=2.94 at frequencies [0.6 1.3]

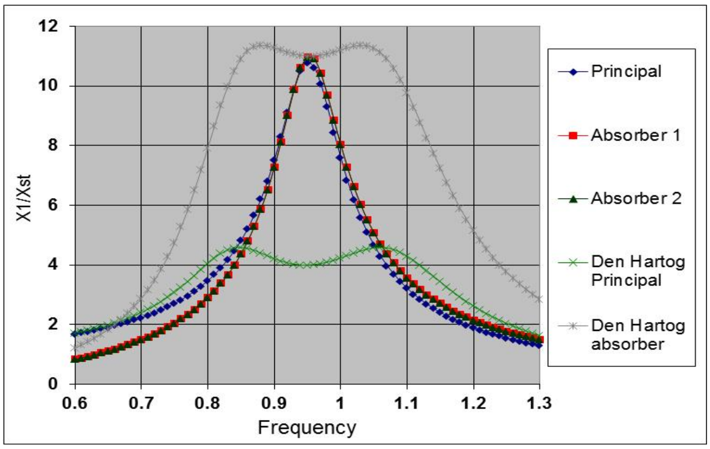


Figure 50. Principal mass and absorbers curves with fk1=fk2=1 and fc1=fc2=2.77 at frequencies [0.6 1.3]

In this chapter it the absorber system was analyzed with two auxiliary absorbers mass in order to compare the results obtained by Den Hartog, Hernandez and Canales. It was found that this system could be optimized due to the decoupled form of its design matrix (fixing one of the factors at a convenient value and then finding the other), RSM enables finding the path for optimization in an easiest way due to the uncoupling of the factors, and finally, even when the optimal response could not be related with a previously optimal factor found (Den Hartog, Lanchester, Brock, etc), it is useful to find the closest value that actually has it.

4.2.7 Conclusions

In this paper a novel approach was presented on the optimization of dynamic vibration absorbers using Axiomatic Design on Response Surface Methodology for design and performance parameters to reduce product and processes design and developing time and to improve their performance as well.

The methodology follows traditional screening designs of RSM in order to reduce factors to the “few vitals”. The added procedure is to apply Axiomatic design in order to identify and solve unwanted coupling between the factors, to make optimization easier and also, help designers to find if redesign is needed to totally uncouple the factors. Once couplings have been resolved, LFS will allow designer to establish the feasible preferred design space and select the proper preferred design parameters.

Finally, when optimal conditions and its correspondent factor values have been established, prior research and knowledge of the design problem is fundamental in order to validate its operability and performance.

Future work will elaborate on the mathematical method to extend this methodology to help designers solve optimization problems in a straight and faster manner.

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[1] (Yang & El-Haik, 2003)
[2] (Hernández-Luna, 1994)
[3] (Hartog, 1956)
[4] (Canales, 2003).
[5] (Hernández & Canales, 2004)
[6] Hernández, A., Ruizpalacios, E., 1998, “Response Surface Methodology for the Optimal Design of Dynamic Vibration Absorbers”
[7] (Myers, Montgomery, & Anderson-Cook, 2009).
[8] (Montgomery, 2009).
[9] (Yang & El-Haik, 2003).
[10] (Suh, 1990).
[11] (Suh, 2001).
[12] (Moreno, Hernández, & Wood, 2010).
[13] (Hernández-Luna, 1994).
[14] (Hernández-Luna & Wood, 1994).
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[18] (Wood, 1989).
[19] (Snowdown, 1985)
[20] (Snowdown, 1985).
[21] (Box, Hunter, & Hunter, 1978).

Chapter 5. Roadmap for Innovative Optimal Design Methods

On previews chapters there were presented different sections of desirable innovation and design systematic methodology. On innovation chapter, it was demonstrate the cognitive process behind idea generation thorough design by analogy, confirming its power in the developing of innovative design problem solutions.

Catalog design chapter explored design procedures to propose a methodology that allow designer to reduce cycle time by configuring possibilities as a catalog of their current design parameters ranges. The main idea was to provide designers with a wider range of feasible designs with different levels of preference, without investing additional design resources, because different configurations could be anticipated and precalculated for design parameters. This methodology also allows the enterprise to allocate “saved” resources on innovation activities, while remaining competitive.

The chapter design optimization deals with yet another critical design topic, which is optimization of coupled designs. Unfortunately, not all designs come to life with an uncoupled configuration between design parameters and functional requirements, so even thought they could be satisfying a customer need they have a great deal to improve on controllability and robustness. This chapter proposed integration of axiomatic design and response surface methodologies in order to identify design vulnerabilities regarding controllability and robustness, allowing designers a better understanding on how to operate in presence of coupled design, so the best possible results for system configuration could be obtained without modifying the design.

Present chapter will articulate findings of previous chapters on a general roadmap for problem solving, developing a methodology for Innovative Optimal Designs of products and services that enhances quantity and quality of ideas, improves their performance and reduce the number of development iterations

When solving a problem, the problem solver seeks to devise a method for transforming a problem from its current state into a desired state. Problem solving encloses three dimentions: (1) cognitive, that is, it occurs internally in the mind (or cognitive system); (2) process, it involves the manipulation of knowledge representations (or excute mental computations); and (3) orientation, it is guided by the goals of the problem solver.

Since this chapter intends to elaborate in the roadmap for problem solving, we are going to focus in the process dimension of problem solving. For illustration purposes, a general representation of problem solving process is the one presented in Figure 51, where a black box [f(x)] transforms input variables (x's) into output responses (y's).

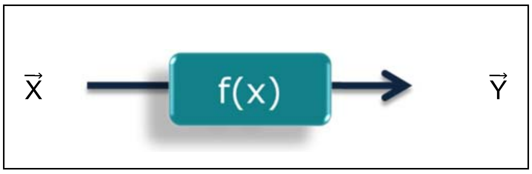

Figure 51. Problem solving process ilustration

The set of tools that can be applied depends on the part of the process where information is missing, that is, in the imput variables, in the output variables, or in the transformation process itself. Knowledge of diference's causes between the current and desirable state is an additional criterion for tool selection (see Table 26).

Table 26. Problem Scoping Q&A

Is there a difference between current and desirable?	Are the causes known?	Are the solutions known?	Solving Method
Yes	No	No	Lean Six Sigma
Yes	Yes	No	Kaizen
Yes	Yes	Yes	Just do it
Yes	No	No	Optimal Design / DFLSS
Yes	Yes/No	Yes	Process Management/BPM
Yes	No	No	Ideation / JTBD
Yes	Yes/No	Yes	Gap Analysis / Benchmarking

By combining Figure 51 with Table 26, the general problem solving process and correspondent tools is obtained (see Figure 52). As it can be seen this general schema is broad, and each of the upper and lower boxes of tools have their own techniques, methodologies and associated roadmaps.

KNOWN	Just Do It / Kaizen	Process Management/BPM	Gap Analysis/ Benchmarking
	$\vec{X}$		$\vec{Y}$
UNKNOWN	Lean Six Sigma	Optimal Design / DFLSS	Ideation / JTBD

Figure 52. Problem Solving process and tools

This general schema was developed for learning and teaching purposes. The schema in Figure 52 allows a better identification of present dissertation contributions which specifically are impacting the transformation process and output variables with Unknown causes for the differences between current and future state. Associated tools and methods for these impacted areas are:

- DFLSS with the Optimal designs, and
- Ideation with methods to increase ideas generation.

Now that the specific problem solving areas impacted with present research have been identified, a detailed possible roadmap to deploy innovative optimal design methods will be presented. Present dissertation contribution focusses in sections of the complete design process, therefore, the innovative optimal desing methods here developed will be incorporated along the second and third phases of D^4 methodology (Silverstein, Samuel, & Decarlo, 2009), which can be seen on Figure 53.

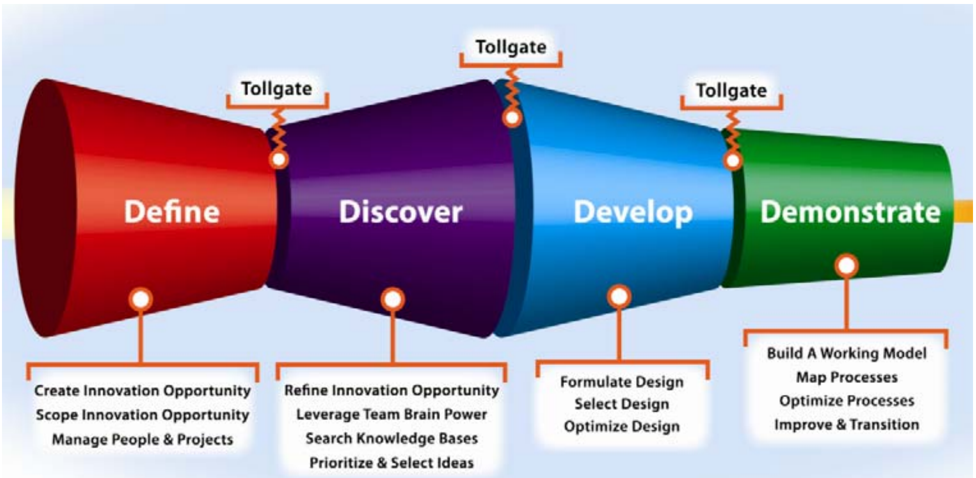

Figure 53. D^4 methodology

The contributions made on each chapter of present dissertation and its adition to D^4 methodology are shown in Figure 54, where it can be seen that "define" stage can now be assisted through the representation of design problems as well as its key problem descriptors (functional requirements, customer needs, etc). The "discovery" phase will be enhanced with the inclusion of design by analogy methods for improving idea generation metrics such as quality and quantity through re-representation and exploration of analogous domains.

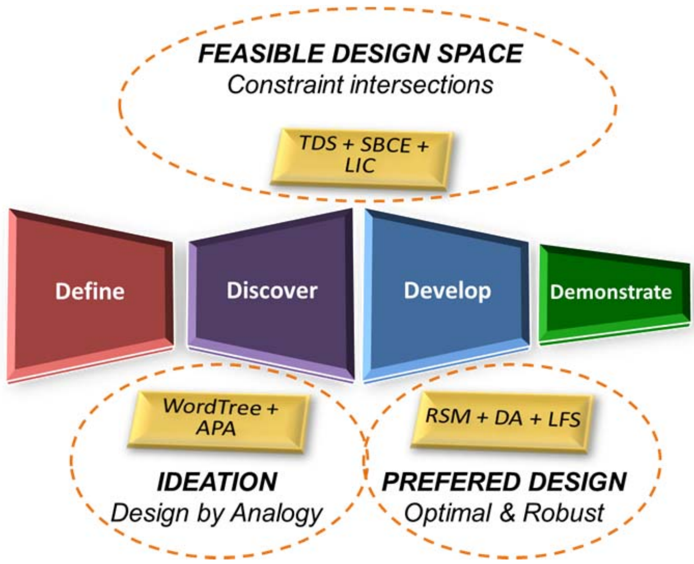

Figure 54. Roadmap for innovative optimal design

After developing sets of alternatives (concepts, ideas), the feasible design space can be properly characterized by identifiying constraints and operating ranges intersection. Finally, for D^4's "develop" phase the preferred design will allow realization of better working/operating models with robust performance and reconfigurable possibilities without the need to perform complete design process iterations (loops).

The circled areas in Figure 54 match dissertation chapters 2, 3 and 4. Ideation has as supporting tools design by analogy methods such as wordtree and analogical prose aids which are applicable in service and manufacture environments. Feasible design space tools are of two kinds TDS, which corresponds to the phylosofical and conceptual component and SBCE + LIC is the mathematical and procedimental approximation to enable intersection mapping of design possibilities to operate in sets of possibilities instead on point based alternatives, which by exchanging the selections between the feasible possibilities avoids the need to develop complete design loops that are resource consuming.

Chapter 6. Contributions and Future Work

On previews chapters was developed and presented a strategy and methodology for Innovative Optimal Designs of products and services that enhances quantity of ideas, enables quality on their performance and reduce the number of development iterations

Present chapter highlights research findings, contributions and determine future work that can be derived and extended from researched topics.

6.1 Contributions

A methodology for Innovative Optimal Designs of products and services was developed and presented. This methodology is the result of the structured aggregation of every chapter contribution, an articulated methodology that will lead designers towards the developing and operation of better designs and a better idea generation for the future.

From previous literature review, benefits of using design by analogy (DbA) were evident. Cognitive processes behind DbA (how a solution can be developed by retrieving from an analogous domain or product or service a possible solution), invites to a deep reflection about the way that this powerful tool for innovation should be supported to guide designers (specially novice designers or designers whose expertise lies in other specialty), on consistent and productive idea generation, so they would never ran out of ideas.

Multidisciplinary teamwork could be a way to re-represent design problems from different perspectives and application fields; this may also help reaching to distant analogous domains.

The experiments conducted on present research demonstrate the impact that representation has on the design by analogy process. Multiple representations of a design problem allow designer to reach for distant domains and explore analogous solution alternatives that would not been reached otherwise.

A guided process where requirements can be added not in the form of constraints (something forbidden) that may block ideation flow and/or discouraged the designer, but as a way to seek for improved representations could significantly enhancing the innovation process

Ideation chapter introduced a very important topic which is idea generation for transactional problems, previous research shows the effectiveness and robustness of idea generation methods on engineering fields (manufacture, artifacts and tangible objects), but there are improvement opportunities for them to better address transactional problems.

This experiment statistically demonstrated that re-representation of transactional problems helps designer's to come up with analogies and analogous domains they would not be able to reach otherwise, therefore, increasing idea generation.

The analogical prose aids applied here, allows a designer with limited experience to develop solutions in cases where similarity, is not initially clear. The more disruptive the new idea is, the better the concept of metaphors and analogy was engaged. Because this will mean that proposed solution comes from distant domain using current domain as reference.

Manufacture processes have been studied since industrial revolution and the different patents databases keep track (knowledge management) of the evolution of design problems solutions. This is not the case for transactional processes, and that could be a reason why is it harder to relate to a solution that someone else in another field at another time could have already developed to solve your transactional problem.

The next step of the methodology is feasible design space. Where it was concluded that proper representation of parameter preference as done in LSF is a key factor to develop coherent propagation of preference functions, and enables interpretation and physical meanings of the propagated design parameters.

Even though Lean Fuzzy Sets and Mapping with Imprecise Quantities methods represent extensions of Ward's and Wood's research, their main difference lies in the interpretation given to imprecision and preference which can lead to non-consistent mappings in the case of MIQ, as found in this paper.

Therefore, it is concluded here that LFS is a suitable way to deal with imprecision and develop coherent mappings that avoids development iterations, and this could lead to a total cycle time reduction.

Once idea had been conceived and characterized, preferred design is the next step, to assure robust performance under variation and uncertainty.

An approach for design optimization that integrates Response Surface Methodology (RSM), Axiomatic Design (AD) and Labeled Fuzzy Sets (LFS) was presented to operate such designs in an optimal (robust) manner.

Since not all designs come to life with an uncoupled configuration between design parameters and functional requirements, so even thought they could be satisfying a customer need they have a great deal to improve on controllability and robustness.

Nonlinear responses and costs coupling measures semangularity and reangularity can now be inferred through identification of rotational angles of the responses, enabling reangularity calculation. Characterization of system's coupling level explicit the optimization path (sequence for design parameters to be fixed or tuned) that could be followed to operate with robust performance.

Optimization procedure provides designers with a better understanding on how to operate coupled designs, so the best possible results for system configuration could be obtained when re-design is not an option.

Another contribution of preferred design is the possibility to be employed on both analytical and empirical designs, where the axioms of Axiomatic Design can be achieved. This approach for analytical designs could provide alternative ways to validate analytical results through empirical analysis.

6.2 Future work

Idea generation:

- Further exploration with designers with high expertice level to enhance and validate method performance.

- Continue researching on means to support analogical prose to be applied on transactional processes.

- Test the method evaluating an additional metric such as design fixation level, in order to evaluate it effectiveness to overcome this unwanted and entropic phenomenon.

- Explore if a similar analysis of solutions could be performed to identify transactional innovation principles similar to the ones that TRIZ has.

Feasible Design Space:

Apply method on a real problem to objectively evaluate saved design cycles, and calculate total cycle time contribution reduction, and compare these results with traditional design approaches.

Prefered Design:

Elaborate on mathematical method to extend the methodology to help designers solve optimization problems in a straightforward and faster manner.

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APPENDICES

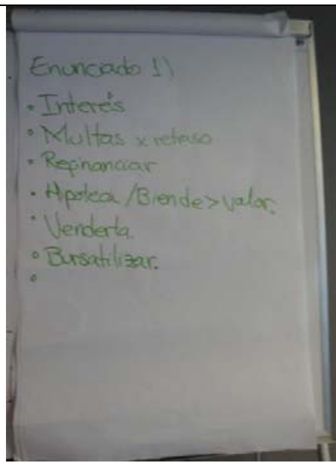
Appendix A: Group Idea Generation Experiment Materials

Innovation experiments and dynamics

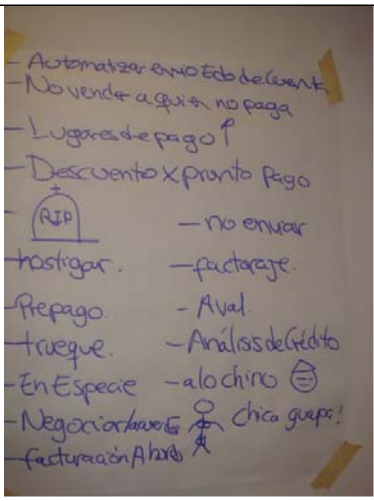




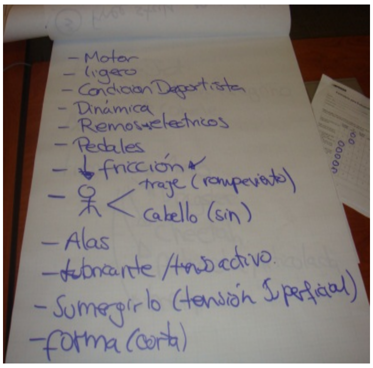

-Analisis del que pide crédito
• Rev. historial crediticio
• Garantías /Hipotecas
• Límite de crédito.
• "Calentadita" (abogado)
• Aviso telefónico/Casa/
• Embargos
• Plan Pagos
• Estímulo (Premio)



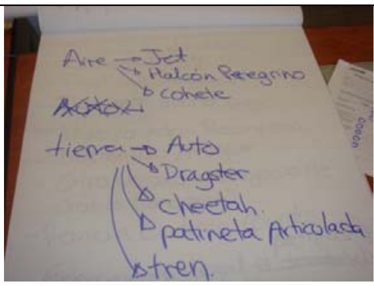
Enunciado 1)
• Interés
• Multas x retraso
• Refinanciar
• Hipoteca /Bien de > valor
• Venderla
• Bursatilizar.

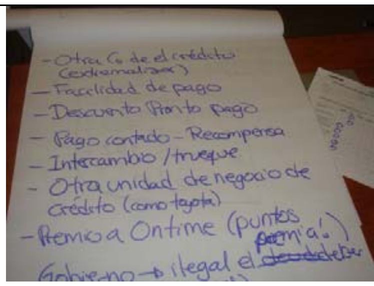


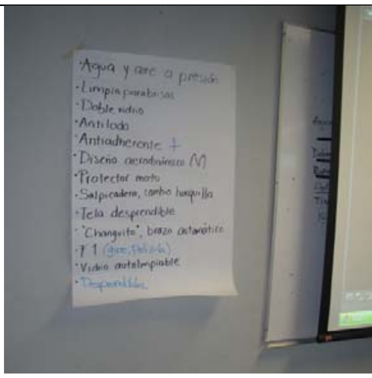
- No vender a quien no paga
- Lugares de pago
- Descuento x pronto pago
RIP
- no enviar
- hostigar.
- factoraje.
- Prepago.
- Aval.
- trueque.
- Análisis de Crédito
- En Especie
- a lo chino
chica guapa!



- Motor
- ligero
- Dinámica
- Pedales
- fricción
traje
cabello (sin)
- Alas
- Sumergirlo
- forma (corta)


Aire → Jet
Halcón Peregrino
Cohete
tierra → Auto
Dragster
Cheetah
patineta Articulada
tren


- Facilidad de pago
- Descuento Pronto pago
- Pago contado - Recompensa
- Intercambio / trueque
- Otra unidad de negocio de crédito
- Premio a Ontime

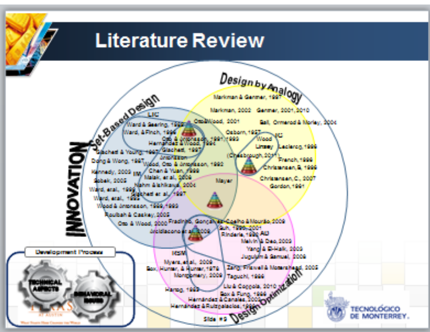

· Agua y aire a presión
· Limpia parabrisas
· Doble vidrio
· Antilodo
· Protector moto
· Tela desprendible
· Vidrio autolimpiable

Appendix B: SELECTED TRANSACTIONAL SOLUTIONS

AFFINITY DIAGRAM BIN	SOLUTION PROPOSED BY PARTICIPANTS
Client evaluation	better analysis on credit study stage
	client evaluation
	not offer credit to clients that doesn´t pay and request it
	client selection (focus on well represented and on clients that pay on time)
	process evaluation (see where is failing)
	evaluate credit requirements
	better client evaluation
	make a better investigation of clients prior giving credit
Reward/prize	generate a reward system for clients that pay on time (interest rate reduction or better prices)
	give a discount for debt liquidation
	search for means to transform overdue credits to ok credits (motivate clients)
	reward frequent customers and/or customers who pay on time
	reward clients that pay on time and make sure that overdue clients be aware of this rewards
	reward clients with higher credit line or more days
	discount on cash sales
	negotiate or offer rewards over overdue debts
	motivate clients to pay offering rewards
	reduce debt amount to clients that pay on time
	persuade clients to pay credits trought promotional prices or loyalty system (point accumulation) that guarantee payments
	give an economical reward (discount)
Internal motivation (employee)	motivate employees
Negotiation	talk to client in order to create a flexible payment plan.
	evaluate other payment means for credits trought clients assets or services they provide
	payment facilities (negotiation)
	personalize treatment to each client
Modify credit conditions	reduce interest rate if clients pay on time
	better number of payments
	not supply until payment (with risk of losing clients)
	pay in advance policy
	implement non credit policies between customer an supplier
	eliminate credits in order to eliminate overdue accounts
	evaluation of unpaid credit over time
	reduce interest rates
	allow capital payments without penalizing
	create agreements for anticipate payments
	reduce interest rate
	Do not offer very long term credits
	payment facilities
	evaluate number of credit days (reduce / increase as needed)
	increase interest rates and reduce number of credit days to overdue clients
	offer a lower interest rate for on time payments
Outsource - give overdue accounts to a third	sell overdue credits to other intermediates
	sell the overdue portfolio to a law firm
	Stocks Exchange
	use debt collectors (visit client home/office)
	Sell unpaid credits to a bank, in order to save must of the money, lose little and reduce unpaid credits index
Fines / punishment	charge higher interest rates
	create a penalty system for these transactions and recorded on sale contracts
	establish fines policy for overdue credits and remove from future credit clients list
	create cummulative interest as a penalization of not payment
	impose fines when not meet payment dates

AFFINITY DIAGRAM BIN	SOLUTION PROPOSED BY PARTICIPANTS
Credit warranties	request goods to guarantee payment
	always ask clients to have a guarantor and if client doesn´t pay charge the payment to the guarantor
	appropiate client goods as debt payment
	receive goods equivalent to debt amount
	request that loans shall be guarantee with cost equivalent goods
Alternative payment means	accept other payment means
	make agreements regarding payment means such as clients shares or assets
	emphasize on non payment consequences
Financial models teaching	develop financial education models to be taught to customers

Appendix C: Dissertation Presentation



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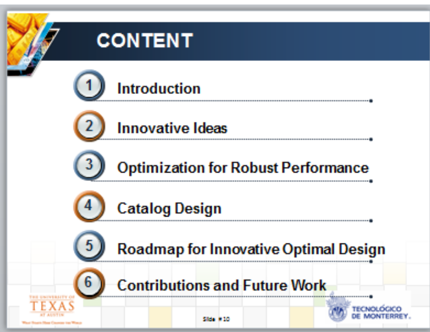

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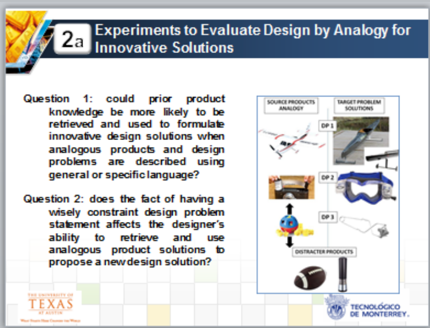

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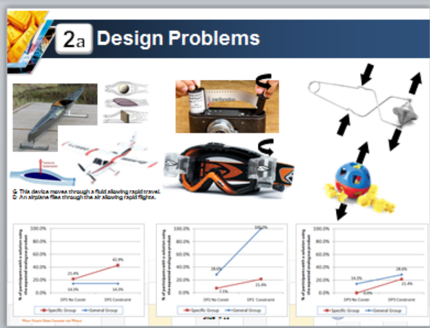

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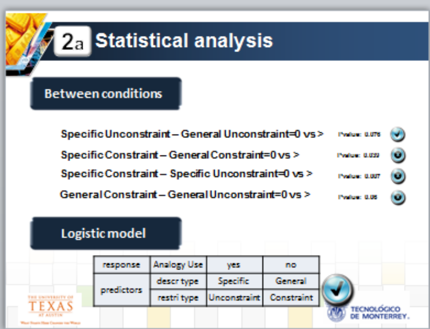

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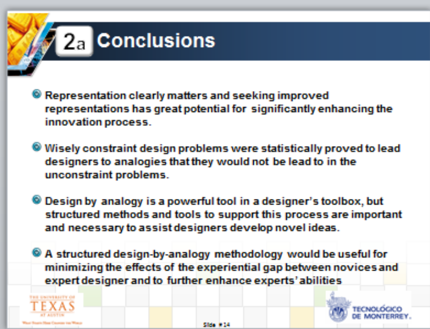

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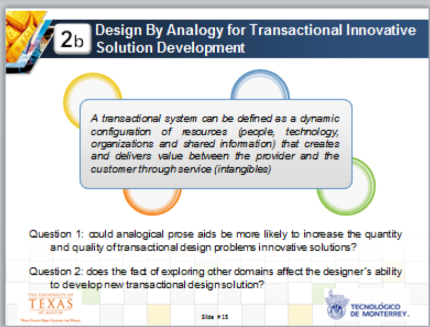

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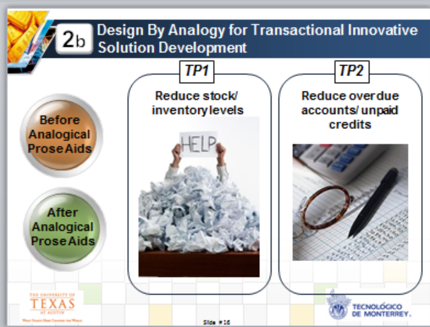

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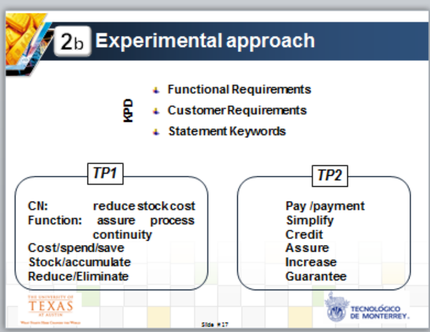

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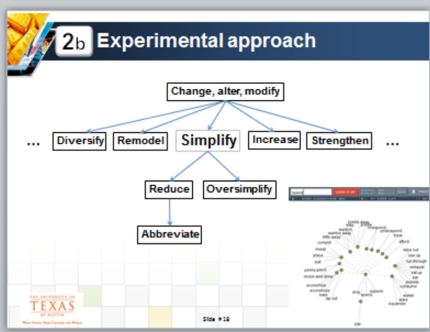

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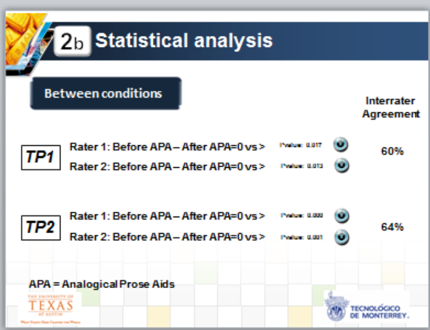

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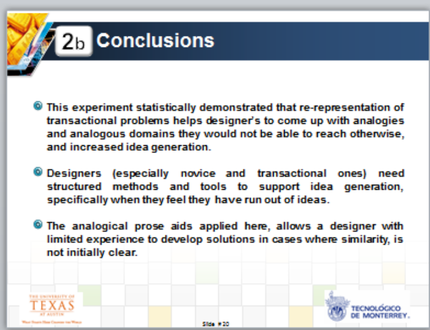

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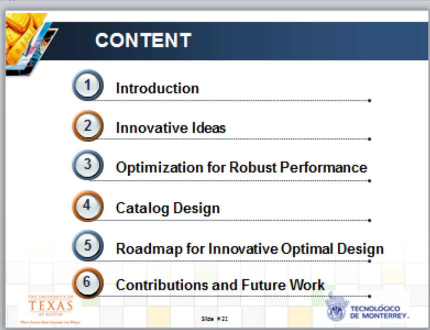

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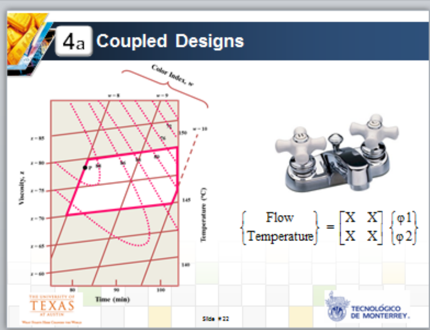

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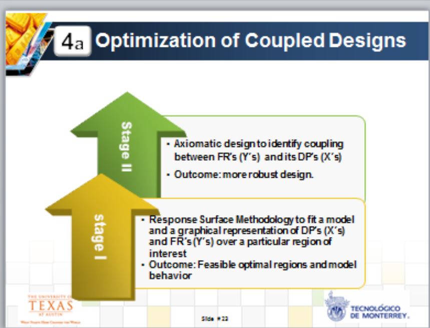

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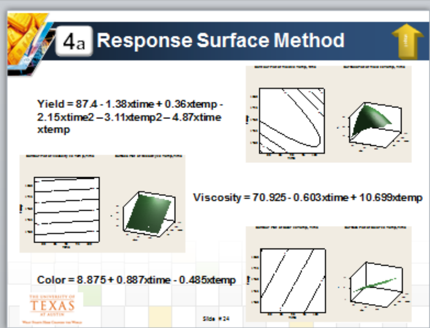

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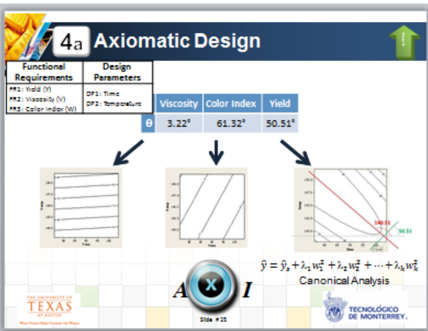

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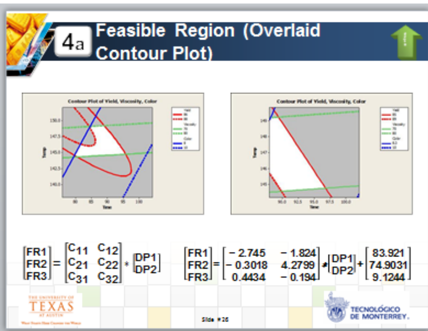

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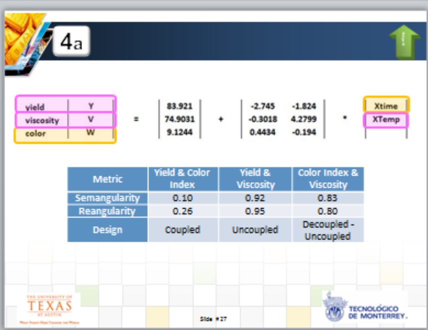

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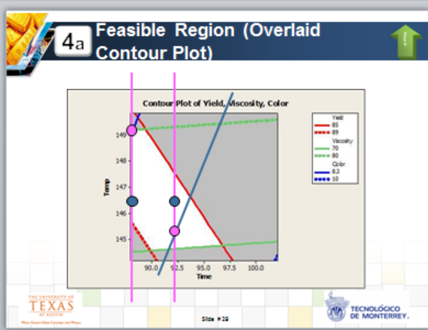

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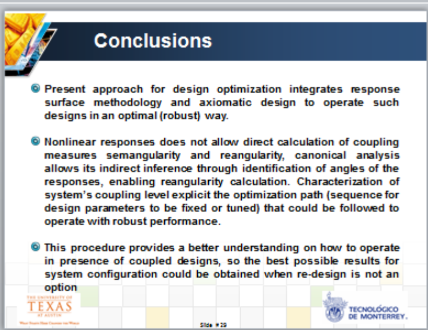

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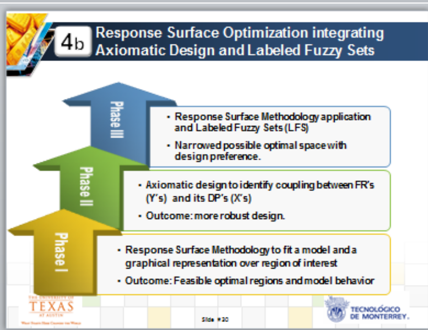

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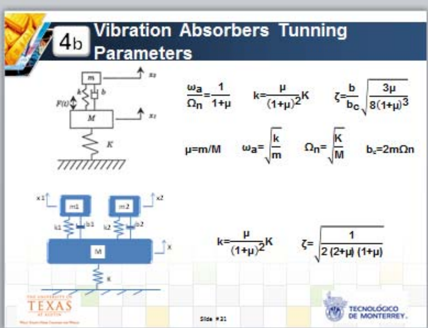

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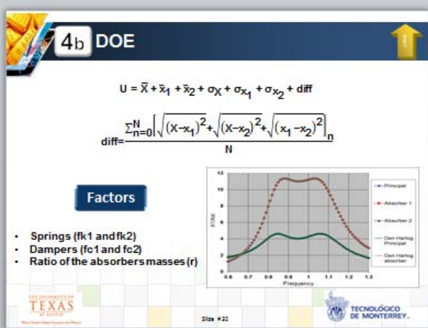

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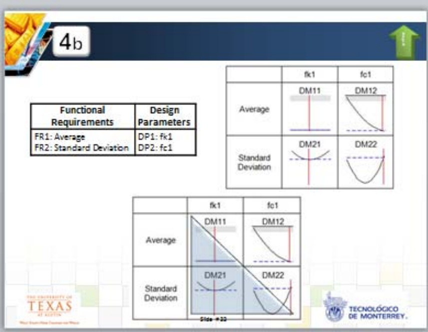

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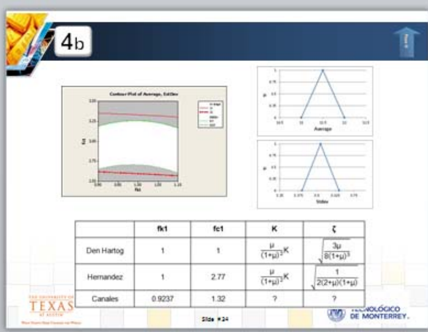

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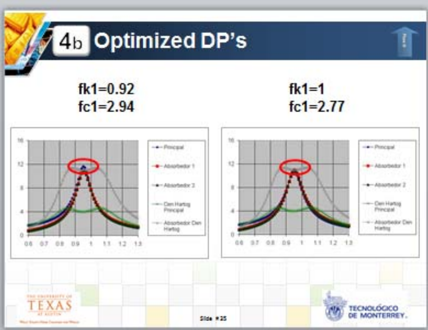

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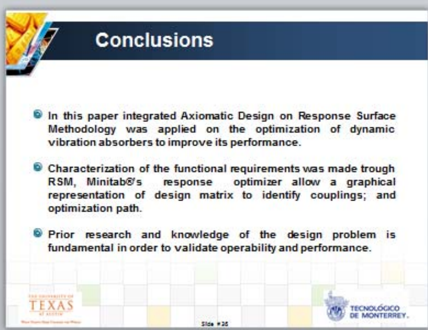

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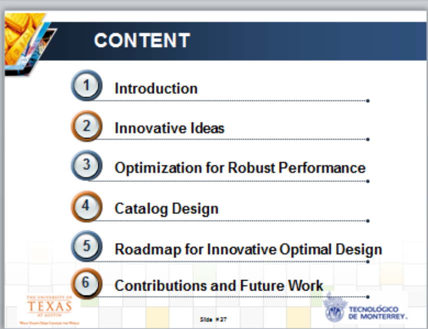

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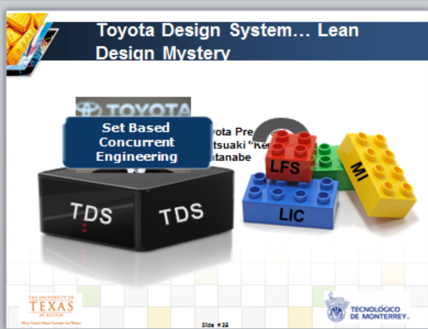

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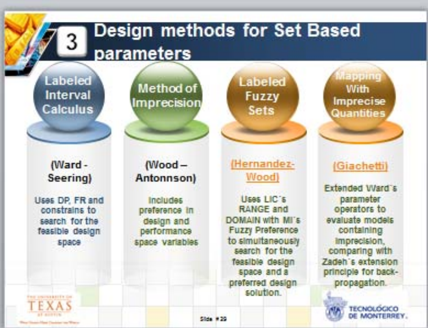

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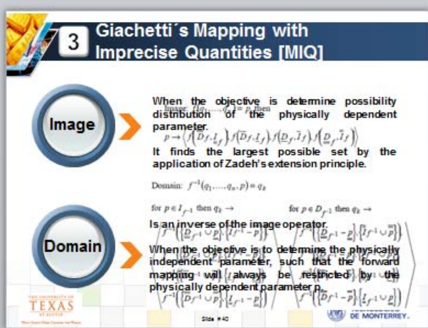

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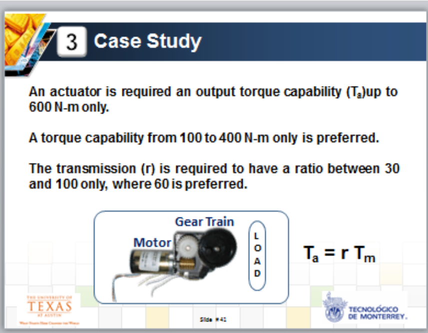

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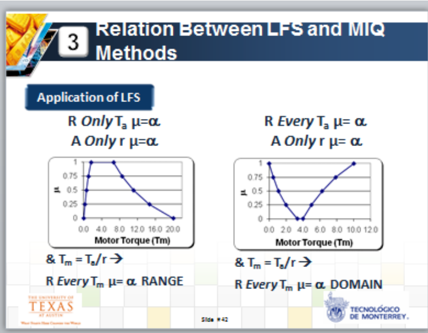

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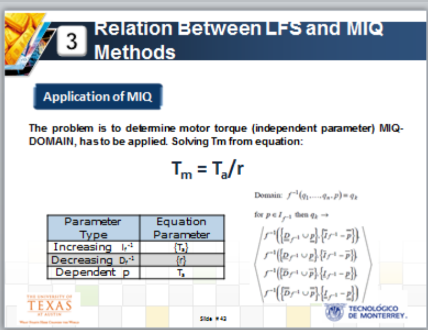

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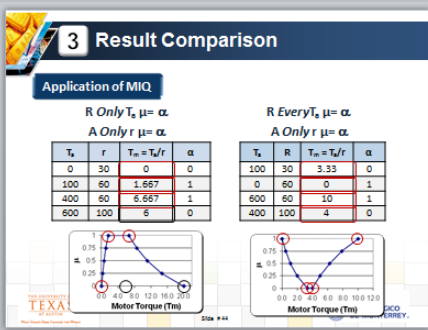

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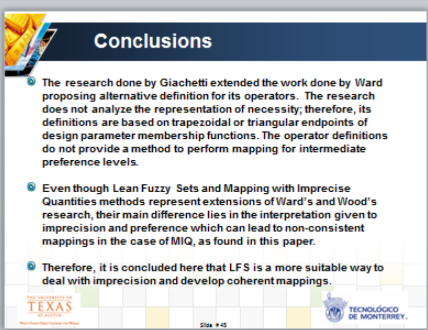

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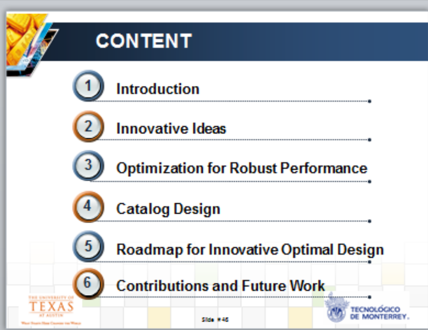

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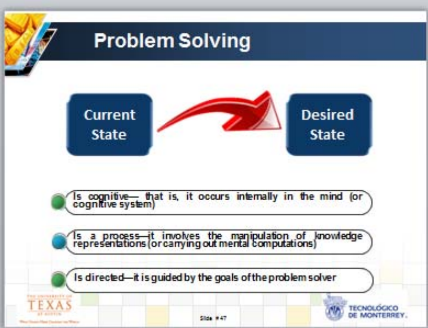

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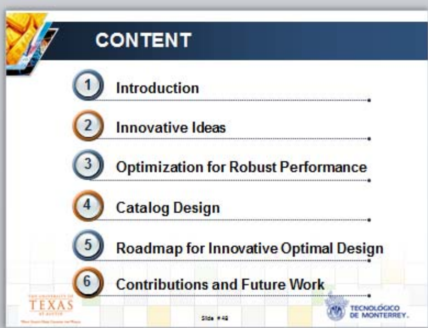

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Contributions
Design by Analogy
Set-Based Design
INNOVATION
Design Optimization
LIC
IG
IM
AD
RSM
49
Contributions
H1
Is it possible to integrate methods and tools into a structured strategy for the development of innovative optimal designs
Roadmap for Innovative Optimal Design
Proposed approach articulates innovation methods into an strategy that support designers when developing innovative optimal designs
50
Contributions
Is it possible to increase the generation of ideas by searching means to re-represent the problem and explore analogous domains for solutions
H2
IDEATION
Idea Generation
Representation (description) was prove to matter, but multiple representations have to be made to retrieve and use analogous solutions to solve design problems
The addition of requirements affects the ability of retrieval and use of analogous solutions.
Analogical Prose Aids increase the quantity of innovative solutions for transactional problems due to exploration of different domains.
Ideation, and in particular, design-by-analogy, is critical to the design process and present research contributed to the understanding of the mechanisms within analogical reasoning and their implications within design.
51
Contributions
H3
Robust designs can be achieved by integrating Axiomatic Design and Response Surface Methodology
OPTIMAL DESIGN
Robust Performance
This procedure provides a better understanding on how to operate in presence of coupled designs, so the best possible results for system configuration could be obtained when re-design is not an option.
It was demonstrated that present approach for design optimization integrates response surface methodology and axiomatic design to operate such designs in an optimal (robust) way.
52
Contributions
Range and Domain functions of LFS work the same than Giachetti's Image and Domain, to reduce development iterations
H4
CATALOG DESIGN
Reduce Iterations
Therefore, it is concluded here that LFS is a more suitable way to deal with imprecision and develop coherent mappings.
This method emulates the Toyota Design System by the manipulation of uncertainty to search for feasible alternatives within the sets of possible solutions and this could reduce iterations during design process.
53
Dissertation
1
2
3
4
5
6
54
TEXAS
TECNOLÓGICO DE MONTERREY.
Thank You!
55