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Comparing the strategies and outputs of designers using Algorithm of Inventive Problem Solving, Axiomatic Design, or Environment-Based Design

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Abstract This paper presents the results of a study designed to compare the processes followed by practitioners of three design methods: the algorithm of inventive problem solving, axiomatic design, and environment-based design. Prior literature has postulated the complementary nature of these design methods, and in some cases, has provided case studies of their mutual application on a design problem. However, prior studies have not focused on the detailed activities used in each method to examine the similarities and differences in the outputs of the activities. In this study, a series of three one-day and three three-day design exercises were conducted simultaneously by three international research groups, each focusing on one method. The objectives of this study were to examine the early stages of the design process that deal with macro activities: problem analysis, problem synthesis, and design evaluation and decision making. Several micro design activities were conducted within these, depending on the design method: clarification of requirements, gathering information on existing technologies, initial conceptualization of an assembly of technologies, the identification of system contradictions/coupling, and the solution of contradictions. The objectives of this comparative study were to establish, from observations of practitioners—rather than from a theoretical point of view—the differences and complementarities between the design methods. The problems presented to designers covered a range of design tasks that spanned multiple disciplines, multiple levels of open-endedness/specificity of the task, and various levels of inventiveness required. The comparison showed the complementary nature of the design methods, highlighted their respective strengths, and suggested the outlines of an integrated method based on the main benefit of each.

Keywords: *Algorithm of Inventive Problem Solving (ARIZ), Theory of Inventive Problem Solving (TRIZ), Axiomatic Design (AD), Environment-Based Design (EBD)*

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1. Introduction

Prior research has proposed a wide variety of design theories and methods, and there are many schools and traditions of design research: Altshuller's theory of inventive problem solving (TRIZ) (Altshuller, 1984), domain theory (Andreasen, 1991), environment-based design (Zeng, 2004; Zeng, 2011; Zeng & Cheng, 1991; Zeng & Gu, 1999a, 1999b, 2001; Zeng & Jing, 1996), function-behavior-structure modeling (Gero, 1990; Gero & Fujii, 2000), function-behavior-state modeling (Umeda *et al.*, 1996; Umeda *et al.*, 1990; Umeda & Tomiyama, 1997), the theory of technical systems (Hubka & Eder, 1988; Hubka & Eder, 1992), axiomatic design (Suh, 1990), functional basis of design (Hirtz *et al.*, 2002; Stone & Wood, 2000), decision-based design (Hazelrigg, 1996, 1999; Lewis *et al.*, 2006), and many others. These theories and methods can be compared and contrasted with one another and possibly integrated together (Sheu, 2010; Tate & Nordlund, 1995).

The goal of design research is "the study of how designers work and think, the establishment of appropriate structures for the design process, the development and application of new design methods, techniques and procedures, and reflection on the nature and extent of design knowledge and its application to design problems" (Cross, 1984) quoted in (Cross, 1993). To fully cover the field of design, the knowledge areas that must be included in a *paradigm* for design research are the design process, the design object (the product of the design process), designers, specific field knowledge (e.g., of technologies and environments), and resources (e.g., time and money) (Tate & Nordlund, 2001).

According to Blessing and Chakabarti, design research should integrate the "two main strands of research: the development of *understanding* and the development of *support*." Pursuit of the practical aims of design has resulted in "an exceedingly large number of different means of support" including "strategies, methodologies, procedures, methods, techniques, software tools, guidelines, information sources, etc." Moreover, research that has focused on understanding design has happened "rather independently" of research focused on improving design through development of these means of support: Increased understanding of design has rarely been used in informing the development of support. This has given rise to three issues: lack of overview of existing research, lack of use of results in practice, and lack of scientific rigor (Blessing & Chakrabarti, 2009). In particular, some methods have been proposed as *general* or *universal* methods for the whole process of design (Lindemann & Birkhofer, 1998). Theoretically they fit the whole design and development process, but how can they be applied practically? Have the methods developed homogenously for each step of the design process?

A rigorous assessment of different design methods needs to be made for each of the different activities of the design process in order to be able to compare their benefits (Tate & Krishnamoorthy, 2010). As Frey and Dym have said, "If the engineering profession does choose to extend an objective concept of validation to design methods and tools, it will need a supporting set of practices and standards for the provision of evidence" (Frey & Dym, 2006). This paper will focus on the application of three design methods during the initial stages of the design process.

This paper examines the early stages of the design process and covers multiple activities at two levels of granularity (Blessing, 1994; Evbuomwan *et al.*, 1996; Sim & Duffy, 2003). "A stage has been defined as a sub-division of the design process that relates to the state of the product under development. An activity has been defined as a sub-division of the design process related to the individual problem solving process" (Blessing, 1994). Design activities in this paper at the *macro* level are problem analysis, problem synthesis, and design evaluation and decision making. The design activities at the *micro* level include clarification of requirements, gathering information on existing technologies, initial conceptualization of an assembly of technologies, the identification of system contradictions/coupling, and the solution of contradictions. The details at the micro level depend on the particular method used.

This paper presents the results of an exploratory study designed to compare the processes followed by practitioners and the main outputs of three current design methods[1]: the algorithm of inventive problem solving (ARIZ)—a part of the theory of inventive problem solving, axiomatic design (AD), and environment-based design (EBD). Prior literature has hypothesized in various ways—based on theoretical considerations or individual case studies—that ARIZ, AD, and EBD have different main outputs and that these outputs could be complementary rather than contradictory. (See for example (Duflou & Dewulf, 2011; Kremer *et al.*, 2012; Mann, 1999; Nordlund, 1994; Nordlund, 1996; Ogot, 2011; Shirwaiker & Okudan, 2008; Tate & Nordlund, 1995.)

A series of six design exercises were conducted by graduate students through the cooperation of three international research groups. The exercises were designed to focus on the processes followed by each designer and how the design method each designer used influenced the processes and their outputs. The goal was to examine the early stages of the design process dealing with design activities including clarifying requirements, gathering information on existing technologies, initial conceptualization into an assembly of technologies, the identification of system contradictions/coupling, and the solution of contradictions. The problems presented a range of design tasks that spanned multiple disciplines, levels of open-endedness/specificity of the task, and required inventiveness.

In this paper, the three design methods—ARIZ, axiomatic design, and environment-based design—are briefly introduced in section 2. Section 3 presents an overview of the study, selection of design problems, designers' backgrounds, and procedure for administering the exercises. The analysis of collected data from the exercises is given in section 4 with discussion. Section 5 presents conclusions and sketches a proposal for an integrated method based on the elicited complementary aspects of the three methods used.

2. Brief Introduction to the Three Design Methods

2.1. Algorithm of Inventive Problems Solving (ARIZ 85A and 85C)

ARIZ is the Russian acronym for algorithm of inventive problem solving, which is a family of methods belonging to the corpus (Altshuller & Vertkin, 1988; Litvin *et al.*) that comprises the theory of inventive problem solving developed by Altshuller between 1956 and 1985 (Altshuller, 1984). TRIZ methods follow from grounding hypotheses and evidence about technical system evolution: any system evolves according to its environment and general features (laws); system evolutions can be described in terms of overcoming contradictions. The three types of contradictions are termed *administrative*, *technical*, and *physical contradictions* respectively, and generic frames to overcome technical and physical contradictions are provided (such as ideality tactics and separation principles (Fey & Rivin, 2005)). A problem that requires overcoming a technical or physical contradiction is called an *inventive problem*. Thus, the methods of TRIZ allow designers to perform the conceptual design stage of the design process by stating the design problem as an inventive problem.

ARIZ comprises a set of methods, techniques, and knowledge bases of TRIZ; however, there are multiple versions, each of which can be very different (Altshuller, 1986). Thus, in order to distinguish the versions, the year of the version is given followed by a letter that indicates multiple versions within a year. In this study, depending on the design problem, either ARIZ 85A and/or 85C (Altshuller, 1985,

[1] Strictly speaking, it might be preferable to continually distinguish between methods (such as ARIZ, use of design matrices, and EBD) from theories (such as TRIZ, axiomatic design, and the axiomatic theory of design modeling) but for brevity, we will just use the term "design methods" for the three approaches considered here. "Methodology" is considered to concern the study of methods. See (Tate, 1999; Tate & Nordlund, 2001) for the distinction between theories and methods in design research.

1989) was used as the methodological framework for addressing the design problems at the conceptual stage.

ARIZ 85A was used to deal with analysis of the initial situation, to transition from a spread (between actors) and partial understanding of the problem to a shared and global vision to what has to be achieved. The main steps consist of determining the final goals of a solution, investigating "bypass" approaches, choosing which problem formulation to solve, determining required quantitative characteristics, increasing the required quantitative characteristics, defining the requirements of the specific conditions in which the invention will function, examining direct application of the inventive standards, using patents to define the problem more precisely, and using size-time-cost operators (Altshuller, 1985).

The ARIZ 85C sequence was used as a framework due to time restrictions and the specific conditions of the present study, and not all of the steps between part 1 and part 4 were performed. For instance in some cases, the possible use of inventive standards at each problem reformulation was skipped in order to go directly to a better (deeper) description of the problem thus allowing the emergence of a more inventive (less standard) solution concept. The reader can refer to (Altshuller, 1984; Becattini *et al.*, 2012; Cascini, 2009; Cascini & Russo, 2007; Cascini *et al.*, 2007; Cascini & Zini, 2008; Fey & Rivin, 2005; Li *et al.*, 2012; Zanni-Merk *et al.*, 2011) for complementary information about concepts and tools used in these methods. A paper in this issue presents a survey of TRIZ postulates, models and tools that can be used for anticipatory design of future technical systems (Cascini, 2012).

2.2. Axiomatic Design

Design is the process of developing or selecting the means to fulfill certain needs subject to constraints. Design may be characterized "as the epitome of the goal of engineering [that] facilitates the creation of new products, processes, software, systems, and organizations through which engineering contributes to society by satisfying its needs and aspirations" (Suh, 1990). Axiomatic design is a design theory developed by Suh that is intended to provide a basis for making good decisions in design. "In order to obtain better performance, both engineering and management structures require fundamental, correct principles and [methods] to guide decision making in design; otherwise, the ad hoc nature of design cannot be improved" (Suh, 1990). The main concepts of axiomatic design are 1) the existence of design domains through which designers map during design processes, and 2) using a zigzagging approach to develop 3) design hierarchies in the functional, physical, (and process) domains. As the design process unfolds, designers map between what they want to do and how they propose to do it, while operating in the presence of constraints (Cs). The choice of good design solutions is governed by two design axioms: 4) the independence axiom requires independence between functional requirements (FRs) be maintained in selecting design parameters (DPs), and 5) the information axiom selects design parameters based on maximizing the probability of success of achieving the functional requirements (equivalent to minimizing the information content). Notable extensions to the theory, though not considered in this study, include strategies for managing large-scale, time-varying functions (Suh, 1995) through reducing complexity using functional periodicity (Suh, 2005). The reader is referred to the paper in this issue for recent applications of axiomatic design to large, complex systems (Suh, 2012).

The AD methods used in the study consisted of the basic concepts of axiomatic design: mapping; hierarchies; zigzagging; and independence in problem formulation, concept generation, and analysis for the six design scenarios.

2.3. Environment-Based Design

Intuitively, design is a human activity that aims to change an existing environment to a desired one through introducing a new artifact into the existing environment. In this process, design requirements and design solutions evolve simultaneously (Zeng & Cheng, 1991; Zeng & Jing, 1996). The Environment-Based Design methodology, which was logically derived to address the recursive nature of design (Zeng & Cheng, 1991; Zeng & Jing, 1996) following the axiomatic theory of design modeling (Zeng, 2002), provides step-by-step procedures to guide a designer throughout this process of environment change. The underlying principles behind EBD are that design comes from the environment, serves for the environment, and goes back to the environment.

Environment-Based Design includes three main steps: environment analysis, conflict identification, and solution generation. Designers perform these three steps progressively and simultaneously to generate and refine the design specifications and design solutions. Semantic analysis algorithms and tools are applied throughout the entire EBD process (Wang & Zeng, 2009; Zeng, 2008). Another paper in this issue uses EBD to derive a theoretic model of design creativity, which is used to interpret design phenomena related to use of sketching (Nguyen & Zeng, 2012).

In the study reported in this paper, however, the designer focused mainly on the environment analysis part due to the limited training in the method.

3. Experimental Procedure

3.1. Scope of design study and variables considered

The objective of this study is to identify the impact of the three design methods on design activities conducted. The critical variables in this study are the design problems, designers, design methods, and design documents. The operating variables can be classified as *method variables* that depend on the specific idea generation method; *design problem variables* that depend on the nature of the design problem to be solved; *human factors*, including the various characteristics of designers that also influence the idea generation process; and *environment variables* that define the situation or design environment in which the group is working (Shah *et al.*, 2000).

In this exploratory study, not all the influencing variables were considered. The independent variables considered were the method variables influencing the three groups of the study and the design problems to be solved. The dependent variables in this case were the outputs of the macro design activities: design problem formulation, design synthesis, and design evaluation and decision making.

The study thus only focused on the method variables, i.e. on the way each set of practitioners tackled, solved, and evaluated the different design problems according to one specific method. The design documents generated by a designer are dependent on the interactions between the designer, design method, and design problem as shown in Figure 1, yet the design documents recorded the final design solutions and the outputs of the intermediate activities that led to the final solutions. Design method (bold) variables were controlled, and human factors/designer and environment variables were not controlled in the study.

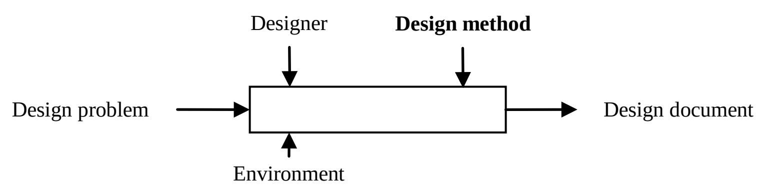


Fig. 1. Critical factors in the study.

Empirical studies have shown that the process followed and the quality of design solutions contained in a design document strongly depends on the designer's experience, knowledge, and skills (Cross, 2006). It would be difficult to allocate the weight of the design method and the background of the designer in assessing the quality of final design solutions. If this were the goal of the study, a large pool of designers would have to be carefully recruited to solve a large number of different design problems to objectively assess how a design method impacts the quality of design solutions. In order to analyze at a macro point of view which steps of the standard design process are realized and how the methods influence the practitioner throughout the design process, the analysis of the detailed cognitive processes (micro steps) inherent to the different methods is not necessary.

It must be noted that a factorial analysis was not followed in choosing the number of subjects and design problems, nor was any control group added to the design processes. Hence, the study reported in this paper cannot be called an *experiment* in a strict sense. It is rather property a type of case study (Yin, 1994); however, to be consistent with current terminology in the design research community, the term *experiment* or *study* is used to describe the work. This issue will be discussed in a future paper.

3.2. Creation of design problems

Three research groups with expertise in the algorithm of inventive problem solving, axiomatic design, and environment-based design, respectively, worked together to conduct the study. Two types of design problems were used. The first type consisted of a one-sentence design problem, such as "design a file naming standard for university students," for which the output was required to be provided by the designer within one day. The second type of design problem provided more information to the designer and required the designer to complete it within three days. The Appendix provides examples of this type of problem. The six problems covered building engineering, industrial engineering, mechanical engineering, electrical engineering, bio-medical engineering, and information management. In total, three one-day design problems and three three-day design problems were proposed, one of each duration by each research group.

Table 1. Summary of all six design problems

Problem#	Time limit	Summary of design problem description
1	1 day	Design a data file naming standard for university students.
2	1 day	Design a brace to prevent back injury for workers who lift heavy objects.
3	1 day	Design spray nozzle for a perfume bottle.
4	3 days	Design a system for video recording surgical procedures.
5	3 days	Design an intelligent robot that can interact with people vocally with emotions.
6	3 days	Design a ventilation system for a thin flooring system.

One designer from each group was invited to solve all six design problems. The invited designer was not aware of the hypotheses of the research. A CV was produced by each designer following a standard template that covered the designer's knowledge, skills, and design-related experience.

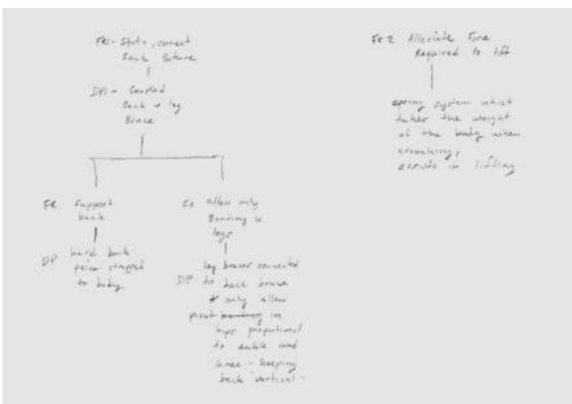
The entire study lasted approximately three weeks. In a typical scenario, on Monday of each week, each designer was given a one-sentence design problem. Following a break on Tuesday, the designer was given on Wednesday a 3-day problem to complete. The designer would work on his/her design while keeping a log book to record his/her actions during the design process. Before starting each design, the designer was asked to record the procedures that he/she was planning to follow; subsequently the designer would summarize the design results using a design document template that included the final design requirements, design solutions, and description of how the solutions satisfy the requirements. The designers were free to seek help and search for information from outside resources as long as the actions were documented.

Once the entire study was completed, the three groups exchanged the exercise materials/data that had been generated. Discussions were made to finalize the research hypotheses for further data processing and analysis.

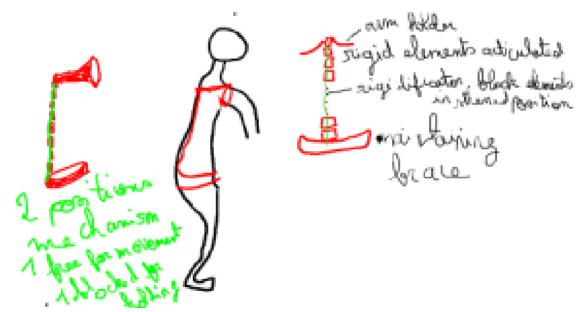
4. Results and Discussion

4.1. Data collection

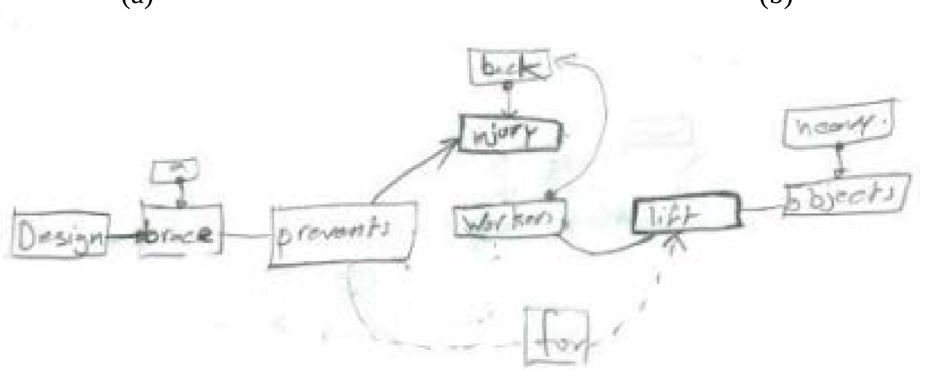
In the study, the ARIZ group assigned three designers to solve the six problems respectively due to other professional obligations during the three weeks dedicated to the study. Two of them were experienced in TRIZ. The third one was a TRIZ beginner. The AD group did not use a detailed log book to record the intermediate design processes. However, the analysis given later in this paper was able to show the main outputs of the AD methods. Figure 2 shows some examples of the collected exercise data from the three research groups for the 1-day back brace design problem. Each group generated data following their design method. The data was then analyzed in three ways: descriptive analysis of the results, comparative analysis, and sequence analysis.



(a)



(b)



(c)

Fig. 2. Examples of experimental data for the back-brace design problem: (a) AD (b) ARIZ (c) EBD.

4.2. Data processing and analysis: comparison of the three design methods

In this section, several widely accepted assumptions about design will serve as a basis for data processing and analysis. The authors make several observations relevant to the improvement of design methodology or for design theory building. While suggestive, the data set produced during this study is insufficient to validate these assumptions.

Nevertheless, the study does provide observations sufficient for proposing an integrated method that incorporates the main benefits of each design methods that were observed. To validate this proposal a new set of experiments would need to be designed. For this new set of experiments, the integrated method used would be the same for the three different groups, so the influencing variables could be taken into account and the biases evaluated.

4.2.1. Design activities supported by the methods

The effectiveness of a design method depends, among other factors, on the existence of step-by-step guidelines for each type of design activity within the scope of the method. Following a common understanding of design activities in the design research community, the analysis and discussion of the results are divided into the macro activities of problem analysis, design synthesis, and design evaluation and decision making. (In other literature, these activities are referred to as a cycle of analysis–synthesis–evaluation (Evbuomwan, *et al.*, 1996).) The analysis of the three methods is shown in Table 2.

Limitations and Bias: It was not possible to assess the effectiveness at a very fine granularity of each part/tool/sub-method for supporting each design activity among the three methods. Due to differences in the skills and knowledge background of designers, the limited time of the exercises resulted in some of the parts/tools/sub-methods not being performed.

Nevertheless, for each method, the various steps/guidelines/concepts were applied at the level of the major design activities, as shown in Table 2.

As presented is table 2, three main steps could be recognized and are present in each design method:

- In the problem analysis activity, designers start with a first perception of the situation (possibly starting with the “voice of the customer” (Clausing, 1994) and produce a clearly stated conflict for which resolution is a priority or a clear list of requirements that have not been satisfied by prior solutions.
- Design synthesis starts with a clearly formulated problem and produces a proposal for an overall solution concept. The synthesis activity has been described as “a mapping of dependencies between function, behaviour and form” that includes “putting together of parts or elements to produce new effects and to demonstrate that these effects create an overall order...that satisfies design requirements...in a given environment” (Sim & Duffy, 2003).
- Design evaluation activities “seek to analyse and evaluate the feasibility of potential design solutions and, by discarding infeasible solutions, reduce the design solution space” (Sim & Duffy, 2003) through decision making.

4.2.2. Requirements set gathered in applying the methods—the problem analysis

Description of outputs for each design method

Requirements enable designers to define what is to be designed by means of the relationship of a system to its environment (*functional requirement*) and various constraints concerning its internal structure (*structural requirement*). Thus, the type of requirements disclosed in applying a design method provides information and indications about the scope of the method. The designers following the three methods produced quite different outputs for problem analysis. The identification of requirements in each method will be illustrated with data from the one-day back-brace design problem.

Figure 2 showed examples of experimental data for the back-brace design problem. For EBD, the designer followed a process that progressed through several ROM diagrams that were used to elicit questions about the understanding of the problem and the environment system. Figure 2(c) shows the ROM diagram for the initial problem statement. Figure 3 shows the ROM diagram for the back-brace design

Table 2. Comparison of the three design methods in terms of design activities

	AD	EBD	ARIZ
Problem analysis: A1-understand the current situation; A2-identify and elicit requirements; A3-identify conflicts.			
A1	Ask repeated "why" questions to elicit solution-neutral needs. Collect customer needs and prioritize. Identify must-be, attractive, and one-dimensional CNs. [Ultimately go back to check whether the design solution satisfies the CNs.]	Ask generic questions through ROM based linguistic analysis.	Elicit administrative contradiction.
A2	Separate CNs into functional requirements, constraints, and design parameters. Identify system-level constraints and top-level FRs. Define tolerances on FRs and limits on Cs. Use "solution-neutral language" for FRs. Check whether the set of FRs is "collectively exhaustive and mutually exclusive."	Ask domain specific questions following a roadmap of design requirements classified based on the product's potential working environment.	Clarification of requirements, constraints. Quantitative definition of a ratio to be improved.
A3	Apply design matrix to check for coupling. [Note that DPs have to be synthesized first.] During decomposition check/verify that subsequent levels do not introduce new coupling.	Three rules to identify basic and potential conflicts from the ROM diagram.	Reformulation of technical contradiction at different system levels.
Design synthesis: A4-decompose problem; A5-generate design solutions; A6-assemble solutions.			
A4	Based on higher-level DPs, decompose FRs into sub-FRs. [Note that DPs have to be synthesized first.] Decompose Cs in parallel.	Identify the major conflict by ROM graph analysis	Identify operational zone, operational time and resources present in problem situation.
A5	Identify design parameters that satisfy the FRs at current level of the design hierarchy. DPs could comprise an existing solution to be analyzed or could result from the generation of a new solution.	Add a new object to, remove an object from, or separate an object from a conflicting relation.	Reformulate contradiction according to various resources in order to state the ideal final result to be achieved; apply inventive standards to generate evolutions of current situation.
A6	Integrate DPs. [Note that DPs could be physically integrated into the same part(s) as long as they remain individual elements (e.g., dimensions and material properties) for satisfying each FR.]	Update ROM diagram and re-analyze the situation	Use mini-men modeling to decompose the tasks in the problem zone; Assemble gathered partial solution features to obtain a physical embodiment of mini-men problem solving strategies.
Design evaluation and decision making: A7-evaluate solutions			
A7	1) Apply independence axiom at each level of the design hierarchy as DPs are chosen during the decomposition process. 2) Check that lower-level decisions do not introduce unanticipated coupling at previous, higher levels. 3) Check the solution against the constraints. 4) Apply independence axiom, if data exists.	Identify the newly generated conflicts.	Evaluate if the physical contradiction has been solved ideally and if a controlling resource is present in the system.

problem updated to include the environment system after several iterations. Then rules for analyzing the ROM diagram were applied to identify the potential conflicts between the environment components.

Ultimately a set of seven functional guidelines and thirteen design requirements were produced as well as identifying the need for additional information from a physiotherapist.

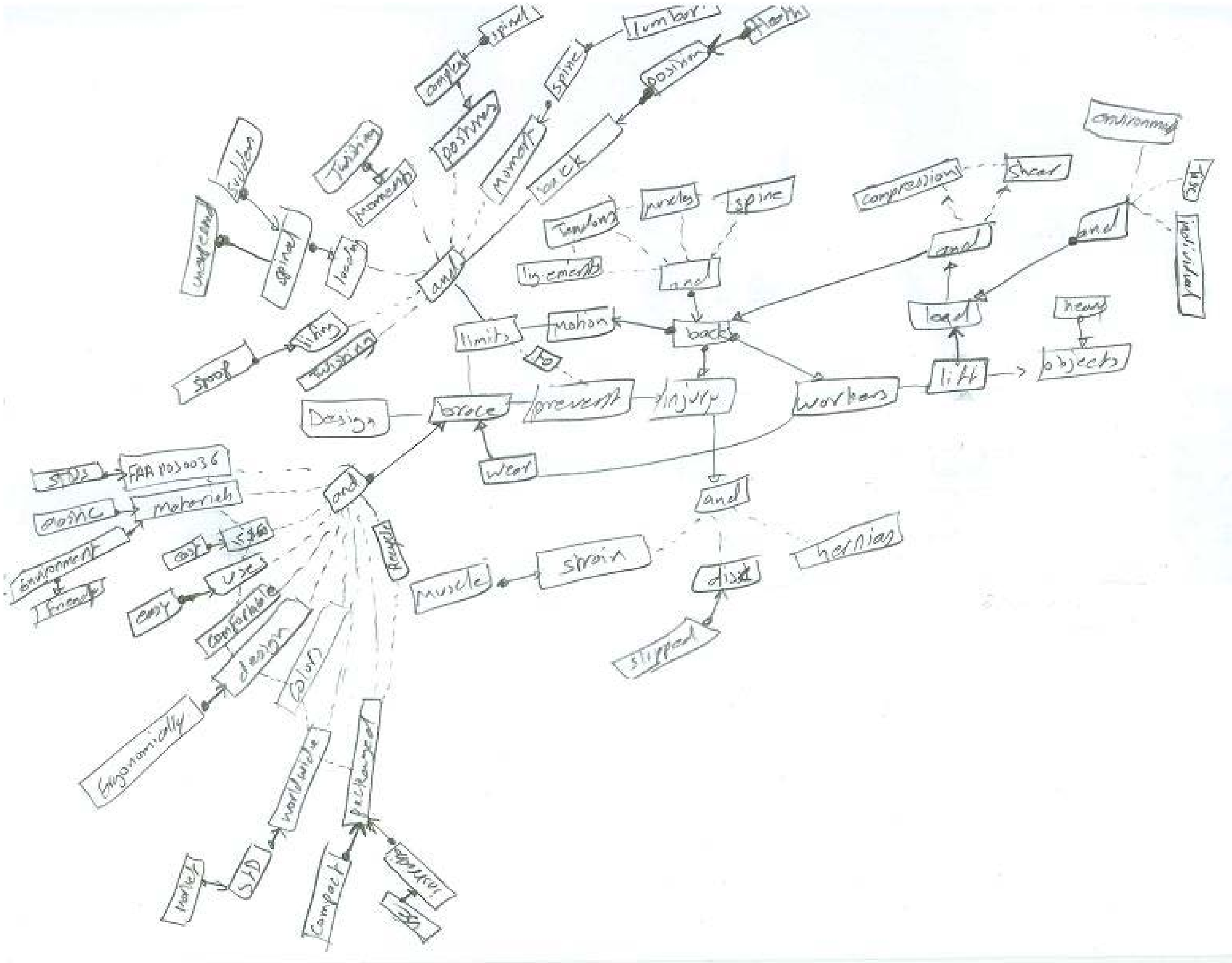


Fig. 3. ROM diagram for the back-brace design problem updated to include the environment system.

The designer using ARIZ, started with an initial situation analysis to reduce the number of health problems for lifting heavy objects, increase the ease to perform the action (including notions related to comfort, and specific working environment), and reduce the time to perform the action. ARIZ parts 1 to 3.5 were performed, and a concept proposed, shown in Figure 2(b). Figure 4 shows the interacting elements and properties for the back-brace design problem. The problem formulation progressed from rejecting a “bypass approach” that would eliminate the need for carrying heavy objects, based on the problem statement, to choosing to solve the mini-problem: “a single person should carry the heavy object without any device for helping the action.” In ARIZ parts 1 and 2, several candidate contradictions were proposed, the operational zone and time were defined, and substance-field resources were identified. ARIZ part 3 was used to define the ideal final result (IFR) and physical contradiction. The final step performed was 3.5 in which the ideal final result was given as “The back should become rigid, and straighten up at the moment the user and the heavy object [become] connected in order to give the back an appropriate position and impose appropriate movement to it.” From this IFR the designer was able to propose a concept.

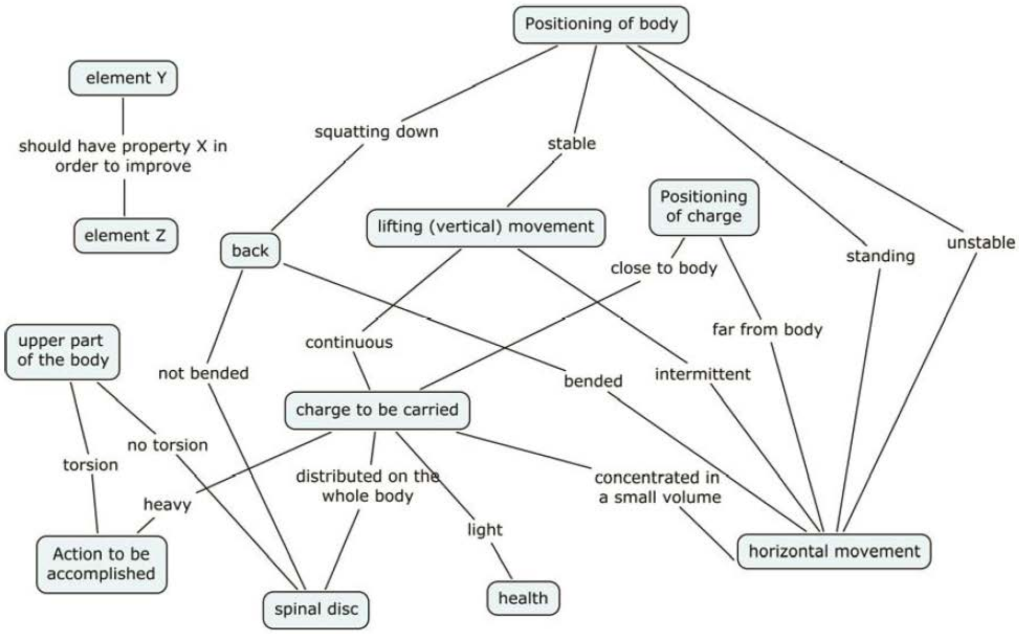


Fig. 4. Diagram produced using ARIZ showing elements and properties for the back-brace design problem.

The designer following AD defined a set of two top-level functional requirements and design parameters, which were then decomposed into two more sub-FRs. These are shown in a hierarchy in figure 2(a). The relationships between the FRs and DPs were analyzed using a design matrix (and found to be decoupled), and the physical solution was given with a sketch. Table 4 lists the FRs and constraint that define the problem as well as the DPs chosen to satisfy the FRs.

Table 3. FRs and DPs for the back-brace design problem

	Functional Requirements	Design Parameters
1	Maintain correct lifting posture	[Physically] coupled back and leg brace system
1.1	Support Back	Hard back support strapped/attached to torso preventing any harmful back movement (bend/twist/compression/elongation of spine)
1.2	Keep back in correct position relative to legs	Leg braces connected from back brace to hip rotational point, to knee rotational point, to ankle rotational point, where the pivoting at the hips is only allowed proportional to the pivoting of the knees and ankle as a function height, keeping the back vertical.
2	Reduce required lifting force	A spring or resistance system connecting the back/hips to the feet which is at the point of very small or zero deflection when the user of the brace system is standing up straight and which absorbs and stores the weight of the user when crouching down to pick up an object, assisting the user with that stored force when lifting the object.
Constraint: Prevent cumulative trauma to the spine and related structures		

Considering the problem analysis activity as generally performed by the designers following each design method during the study, the following observations can be made.

Analysis of the design materials produced in this study shows that EBD disclosed typical functional requirements that enabled the design to be accepted by consumers and that prevented large difficulties during other phases of the product life cycle. What was likely in the current environment to be perceived as a critical problem, if not solved, was collected in a systematic manner by completing the ROM diagram. In this approach, the set of requirements was detailed until the designer could identify who was able to design or manufacture each element of the system by use of the existing knowledge from the field (for most parts of the problems in the study). This was only an intention because several conflicts that the manufacturer may not be able to solve with his/her knowledge still remained at the end of the allotted time, probably due to the lack of domain knowledge on the designer's part.

The requirements disclosed during the ARIZ implementation concerned problems to be solved in the future by the next generation of product, which has to satisfy the specific objectives of the designer, which could be in contradiction with the TRIZ laws of evolution. This led to particular attention towards current unsatisfactory (but often latent) relationships with the environment. In the design materials, the requirements concerned both the problems of current devices and the problems that designers tried to solve with current devices but were not solved perfectly. That is why new concepts of solutions needed to be built. However, there is no guideline in classical ARIZ to collect those requirements in a systematic manner. A single application of ARIZ was often not be enough to detail fully the solution, and new problems would require additional applications of ARIZ to find a final detailed concept.

AD purposely identified few requirements and constraints—the approach is synthetic in nature. Functional requirements in axiomatic design are defined as the minimum set of independent requirements that completely characterize the design objectives (Suh, 1990). Only the main objectives and main constraints on the whole system, which are the reasons for existence of the system, were considered at each level. The decomposition ended when the elementary components to be manufactured independently were disclosed. The functional requirements were selected according to current customer needs.

Discussion of usefulness of each method

Limitations and Bias: The design context was not given in the problem statements. The authors have made the assumption that, in absence of context (e.g., the specific environments for developing or using the designs, because the designers are not in a real problematic situation), the designers created a context that is typical for the application of each method. Due to the allocated time, all possible requirements that may have resulted from analysis were not elicited. New problems arising from the final concepts generated were not formalized nor solved by any of the three methods, but this may also be due to the time restriction.

The observations concerning the types of requirements disclosed are consistent with reported use of the methods in case studies of real world applications. AD is effective for the design of large projects, when the design teams have to be organized hierarchically and the design requirements are clearly identified. It eases the decision making at each level of the hierarchy. EBD is effective for open-ended problems that need continual reformulation along with solution generation. It gives a direction for searching for the required knowledge and solutions; however, it does not provide means generating inventive solutions. Hypothetically, both AD and EBD are domain-independent and can be applied to different areas such as product design, software engineering, quality management systems, algorithm design, and so on. ARIZ can be used for problem solving in existing systems or redesign of systems to generate new (but not detailed) conceptual solutions. If detailed solutions are required, then ARIZ can also be used again to solve problems for the sub-parts. ARIZ addresses initial situations that can be stated with one or a few conflicting pairs of opposing technical contradictions. This comparison stresses the following contradiction in design: in order to adapt the designed object to any kind of environment and context, a design method must be generic and be able to formulate any kind of requirements; however, in order to enhance the quality of the design solution concepts for a particular context, a design method must be specific.

The observations showed that the EBD method was the most exhaustive for the analysis of the considered system and was the most helpful for the clarification of the problems related to the satisfaction of requirements. ARIZ-85C was not designed for problem clarification, and it generally starts with a previously defined contradiction. Thus, the TRIZ experts, during the exercises stated a first contradiction with the help of ARIZ-85A, but the questions of the method, even if they were exhaustive were also too generic to well guide designers in the identification of prior problem to be solved. AD, then, was defined to help to formalize functional requirements, but in practice, the observations in the solved design materials showed that in the set of requirements, information about the context are missing; it remained implicit for the designer.

4.2.3. The role and importance of conflicts in design methods—define the concept

Description of outputs for each design method

Contradictions are a bridging element between design analysis and design synthesis because they appear in the various forms (administrative, technical, and physical) when the design synthesis knowledge is not available in the designer's mind. In AD coupling is identified based on strong interactions between two or more design parameters and two or more functional requirements. Coupling is evaluated using a design matrix: A design matrix that, at least, cannot be reordered as a triangular matrix is coupled and thus does not satisfy the Independence Axiom.

Table 4. Conflict generation, management and resolution in the exercise data

	Selection of additional conflicting requirements?			**Type of conflicts elicited in the first design stage?**			**Type of conflicts elicited in the last design stages?**			**Optimization or generation of any solution?**		
	AD	**EBD**	**ARIZ**	**AD**	**EBD**	**ARIZ**	**AD**	**EBD**	**ARIZ**	**AD**	**EBD**	**ARIZ**
Camera	No (1)	Yes	-	No	AC	-	No	AC TC	-	No	Yes	-
Nozzle	No	No (2)	Yes	No	AC	TC	No	AC	PC (3)	No	No	Yes (4)
Ventilation	No (1)	No (1)	(2)	No	AC	TC	(1)	(1)	PC (3)	Yes	Yes	No
Robot	No	No (2)	Yes (5)	No	AC	No (5)	No	PC TC	TC (5)	No	No	No
File	No	Yes	Yes	No	AC	TC	No	AC	(2)	No	No	(2)
Brace	No	Yes	Yes	No	AC	TC	No	TC	PC (3)	Yes	Yes	No

(1) - the sole requirements that generate conflict or conflict themselves were given in design problem
(2) - the designer did not manage to go to that point
(3) - the conflict is a reformulation of starting conflict
(4) - because several conflicts mentioned at the beginning are not selected for solving process so not solved
(5) - for this exercise, the process started with knowledge acquisition not supported by methodology and then a technical contradiction not related to the first part of design has been chosen
AC: administrative contradiction; TC: technical contradiction; PC: physical contradiction.

Table 4 shows the results of the data analysis for the three methods as shown in the design materials. In the AD exercises, it appeared that the designer sought to avoid conflicts by formulating requirements—if allowed by design problem statement—in such a manner that no conflict appears. This is consistent with Suh's philosophy in defining the First Axiom (Independence Axiom): *Maintain* the independence of functional requirements, but it shows a clear difference in starting point in the design activities. Conflicts eventually appeared at the end of the process when the designer was dealing with details and the selection of requirements at the higher levels could not be modified. In EBD, conflicts in the form of administrative contradictions appeared from the beginning; then, technical contradictions or even physical contradiction appeared later in the process. In the design materials produced during the study, optimizations were often proposed, but, because no quantitative evaluations were performed, the designers could not attest that requirements would be so satisfied. In the ARIZ exercises, a conflict is the starting point of the process, and technical contradictions were searched for in the first stages of the method. A conflict is then continuously reformulated through various structures until a solution become straightforward at the end of the process.

Discussion of usefulness of each method

Limitations and Bias: Conflict evaluation was difficult because the designers had no time to search for new conflicts generated by their proposed solutions. The AD design exercises may have faced conflicting requirement and solved some of them, but it seems that this process depended on the designer's capacities as there were no reported elements about this process in the documents. The EBD designer did not appear to have mastery of the skills in reformulating conflicts although this step should have been performed according to the EBD method. Finally, it was difficult to know whether certain requirements generate conflict(s) or not because the designer did not know whether the requirements could be achieved with standard knowledge from the field.

According to the design materials produced during the exercises, it appeared that for easing decision making or rapidly finding solutions using an assemblage of existing elements of a body of technology, avoiding conflict (if possible) was an appropriate strategy. Existing knowledge was applied, and the risk of failure of project appeared reduced to decision makers. But, in order to search for new concepts, technologies, or paradigms at a given system level, overcoming conflicts appeared to be mandatory.

Thus, in EBD and AD the generation of new concepts seems to be dependent of the designers' capacities (similar to traditional views of inspiration and conceptualization) because the process shifted immediately from problem identification to proposed solutions without any description of the steps used in generating an idea or where it come from (Johnson, 2010). In ARIZ, this idea generation is more detailed in the documents, but it was quite predictable, as TRIZ has specifically been initiated to provide methods for this step.

4.2.4. The evaluation of concepts

As was previously described, one of the main biases concerning solution evaluation was that no real context was defined for each problem for the designers. So each designer built his/her own context, and thus it was not possible to compare the different proposed solutions for a given problem from the point of view of context. Thus it was not possible to evaluate the usefulness of the proposed concepts (Paulus & Nijstad, 2003).

Discussion of usefulness of each method

What appears from observations of the design materials was that the way of evaluation for EBD and ARIZ was clearly linked to the way the problems were formulated. In EBD the evaluation was the pointing out of how the proposed concept solutions satisfied the set of design requirements, and sometimes new conflicts linked with the new proposed solutions were also defined. But is also happened (due to lack of time, lack of knowledge, or lack of tools) that no conceptual solution was proposed out of the conflicts identified, and so the evaluation was not tackled at all. In ARIZ the evaluation was directly linked to the identified contradiction, but here also, due to lack of time, it was performed in many cases.

In AD, the step of evaluation was systematically performed by the definition of a design matrix in which the independence axiom was applied to the design parameters with regard to the different functional requirements. So AD was the only approach that systematized and proposed a way to perform the evaluation step.

4.3. Discussion

According to the design research methodology (DRM) typology given by Blessing and Chakrabarti, this work may be classified as an example of "Descriptive Study II: Evaluating Design Support" (Blessing & Chakrabarti, 2009). The goals of this type of study are determining whether proposed design "supports" have the intended effect on the tasks for which they are intended, identifying whether the supports contribute to success, identifying improvements for the support, and evaluating underlying assumptions behind use of the supports. The main difference between the current work and the DRM approach is that the three methods were compared against each other, rather than comparing one support against a baseline (control) design process identified through prescriptive design study.

The specific methodologies adopted for understanding the design process followed during the exercises as well as the methods for analyzing the documentation produced are typical. In some design research, the outputs of the design process are studied without considering the sequence of activities that have produced them. In other cases, detailed descriptions of design processes are constructed based on recordings of design activities (Cross, 2006; Cross *et al.*, 1996). The present work is similar to other research in which activities and results are analyzed retrospectively based on contemporaneous documentation produced by the designers—such as studying students' design notebooks (Walthall *et al.*, 2009; Yang, 2009).

Summary of observed benefits for each design method

EBD was the most formalized method for the initial steps of the design process, where the problem analysis had to be performed and where it was necessary to have a clear description of the studied system and of the conflicts linked with the satisfaction of the objective of the study.

The ARIZ method had clear benefits in guiding the transformation from an identified conflict towards the generation of a concept that resolved the conflict. It stressed the concept of ideality where inventive solutions had to be found inside the operational zone, during the operational time and maximizing the use of already available resources.

Then, AD proposed a clearly formalized way to evaluate the proposed solution concept. By systematizing the notion of independence and by confronting design parameters and functional requirements, AD enabled the designer to validate the fit between the defined specifications and a proposed solution concept.

Comparison of observed benefits with previous studies

Three previous studies will be discussed here as representative of various papers that have proposed complementary aspects of AD and TRIZ (though none have combined them with EBD).

Previous authors have drawn an analogy between contradictions in TRIZ and coupling in AD (Mann, 1999; Nordlund, 1996; Yang & Zhang, 2000a, 2000b, 2000c). While this seems like a plausible hypothesis, the data produced in the exercises showed either different contradictions/coupling identified between the TRIZ and AD groups, or none identified for one of the groups.

Prior authors have made contradictory statements about the connection between ideality in TRIZ and independence in AD. For example, the statement that as higher-level systems incorporate more functions, then one-to-one mapping of FRs to DPs may not apply (Mann, 1999) versus correlating ideality tactics with Corollary 2 in AD (Yang & Zhang, 2000a, 2000b). The present study sheds no light on this disagreement.

Yang and Zhang state that there is no analog to Corollary 4 in AD, use of standardization (Yang & Zhang, 2000a, 2000b). The data from the exercises showed that the AD group sought combinations of standard elements while the TRIZ group sought instead for inventive elements.

Prior authors have noted the relative importance of design hierarchies in AD in comparison with TRIZ (Mann, 1999; Yang & Zhang, 2000a, 2000b). In the exercises performed by the AD group, the process followed was in a hierarchical top-down manner. For the TRIZ group, considerations of system level were seen in some exercises (e.g. for brace, ventilation and file naming system.), but not others.

Yang and Zhang state that AD lacks the “vast knowledge base” found in TRIZ to support the application of its theory (e.g., 40 Principles, 76 Standard Solutions, and Effects Database). This means that the “creative process of conceptualization...is not very clear” (Yang & Zhang, 2000a). In the ARIZ group, appropriate problem formulation led directly to creative concept synthesis without any use of TRIZ knowledge bases for the spray nozzle, brace, and ventilation system design problems. Likewise for the EBD group, the problem formulation led directly to concept synthesis. For the AD group, synthesis was performed, but it was not clear in some cases whether any conflicts were solved during the design process.

Mann states that AD does not help to identify all functional requirements of a design (Mann, 1999). The fuzzy nature of the design exercises used does not provide an objective basis for evaluating whether all functional requirements were identified by the designers; however, the requirements that were used by each group were quite different from each other.

Shirwaiker and Okudan provide a review of some case studies in which TRIZ or axiomatic design were used and propose an approach for "applying these two techniques concurrently" (Shirwaiker & Okudan, 2008). The approach uses AD for analysis and decomposition of a main problem into more basic problems, and it uses TRIZ to separate "coupled" FRs and generate innovative solutions. The proposed flowchart provides a series of decision points during the design process in which functional requirements and design parameters are defined per AD methods and couplings—either between FRs or within a design matrix—are resolved using TRIZ tools. In particular, the authors focus on use of the 40 Inventive Principles and the 76 Standard Solutions for synthesizing solutions. The novelty of their approach is in incorporating TRIZ into the "mapping and zigzagging process" of AD, rather than after identifying a coupled design matrix. The present study did not provide data to support Shirwaiker and Okudan's proposed process because for the AD group, FRs were not considered to be coupled, and for the TRIZ group, application of ARIZ was the focus and led to directly to concept synthesis, rather than application of TRIZ knowledge bases.

5. Concluding Remarks

This paper presented the results of an exploratory study that was designed to study the main outputs produced by designers practicing three design methods—the algorithm of inventive problem solving, axiomatic design, and environment-based design—during the early stages of the design process. Prior literature has postulated the complementary nature of these design methods and sometimes presented case studies using more than one method.

However, prior studies have not focused on the detailed activities used in each method for the purpose of examining the similarities and differences in the outputs of the activities. The objectives of this comparative study were to establish, from observations of practitioners—rather than from a theoretical point of view—the differences and complementarities between the design methods.

The problems to the designers presented a range of design tasks that spanned multiple disciplines, levels of open-endedness/specificity of the task, and required inventiveness. Three one-day and three three-day exercises were conducted in parallel by three research groups, each group using a different method. The disciplines represented by the design problems ranged from building engineering, industrial engineering, mechanical engineering, electrical engineering, bio-medical engineering, to information management. The design documentation produced consisted of a priori strategies for conducting each design exercise identified by each designer, the conceptual design solution that resulted from the exercise, notes on the process followed, and justification that the solution satisfied the design objectives.

The results indicate that it is possible to observe differences in the outputs in accordance with the different steps of the design process, for each method. Notable differences included how designers following the three methods dealt with the initial problem formulation, the timing of identification and refinement of contradictions/coupling, and the level of detail sought in conceptual solutions. The results are promising in guiding and creating new ways to build design methods. Now further refinement and expansion of an integrated method will have to be performed and will lead to a new experiment having different designers but each of them using the same integrated method.

Future work

Future work will be done to generate a larger pool of data and improve the statistical significance of the experimental work. Additional studies can also be carried out to investigate the importance of the other variables described in section 3.1 that were not considered here.

Additional work will include additional design experiments, the introduction of control groups—and baselines for novice designers—formalization of the integration of the three design methods, and additional modeling of design activities to better capture, detail, and represent the iterative, yet progressive nature of design processes.

Proposed integrated method

One direction for future work is the investigation of an integrated method as illustrated in figure 4, which shows how an optimized approach could be proposed to make cross-fertilization between the three studied design methods.

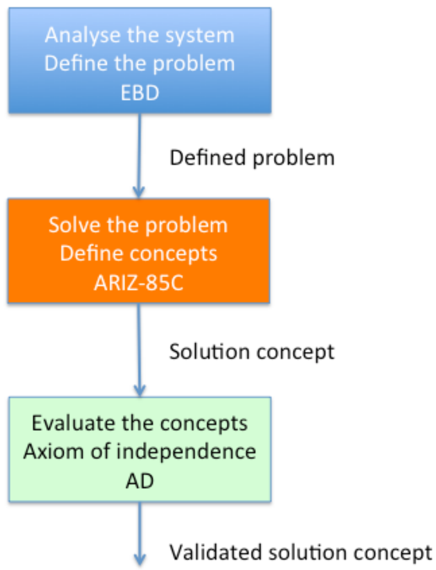


Fig. 5. Proposed integrated method.

A new set of experiments based on the use of an integrated method could be defined to see if the efficiency and/or effectiveness of the proposed method is increased in comparison to the separate design methods or a baseline design process. Efficiency, if found, will be recognized by the fact that the different design teams will perform all three steps quite homogeneously, which was clearly not the case here.

Several problems will have to be solved to make a proposed integrated method applicable, and mainly the questions are linked with the integration: How can a contradiction be recognized out of the conflict identification in the way it is performed by EBD? How can a design matrix be built out of a concept solution defined by the application of ARIZ resolution principles?

Finally, the three groups are currently heterogeneous as each group is specialized in one method, corresponding to one of the three steps of a proposed integrated method. Thus, it will be necessary to transfer to each group the knowledge related to the two other steps, to build more homogeneous groups, or an alternative approach could be to make mixed groups of designers with one specialist of each method in each group.

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Author Biographies

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Dr. Derrick Tate is an Assistant Professor in the Mechanical Engineering Department at Texas Tech University. His work impacts society through bringing design thinking to areas of strategic importance: developing sustainable approaches for buildings and manufacturing; facilitating mass innovation; and assessing innovative potential of design ideas. He received a B.S. in Mechanical Engineering from Rice University. His S.M. and Ph.D. degrees in Mechanical Engineering are from MIT in the areas of manufacturing and design, respectively. Recent projects include development of Megablock building envelopes funded by EarthCo Building Systems, evaluation of engineering properties of Greenstar Blox (papercrete) funded by a Texas Tech University commercial development grant in partnership with Mason Greenstar, an energy storage primer for Power Across Texas, and redesign of portable roll-up signs funded by TxDOT.

Ms. Thanh An Nguyen is a Ph.D. student in Electrical and Computer Engineering Department at Concordia University, Montreal, Canada. She received her Bachelor degree in Computer Science and Master's degree in Information System Security, both from Concordia University. Her research interests include design cognition, human visual perception and curve reconstruction. She can be reached at ngu_th@encs.concordia.ca.

Mrs. Céline Conrardy received her Engineering degree in Mechanic (2007) and MSc. in material sciences for sustainable construction (2008) from Ecole Polytechnique Paris Tech. She received her master degree in inventive design from INSA de Strasbourg in 2010. From 2009 to 2012 she was team coordinator of several TRIZ case studies involving both material science and civil engineering at the research center of company LAFARGE at Lyon France, where she developed customized TRIZ based approach methods. She is now in charge of developing two business units dedicated respectively to innovation processes and marketing of innovative products for the consulting firm EURINNOV. She accompanies clients operating in various sectors of industry and supports them thanks to a large range of organizational strategies, methods for opportunity detection and inventive problem solving.

Prof. Roland de Guio is professor at the National Institute of Applied Science (INSA) of Strasbourg, France. He worked 13 years in the area of application of operational research and data analysis techniques to production flow analysis and design problems. Since 2000, he manages research activities about applications of theory of inventive problem solving (TRIZ) on technical and sociotechnical multidisciplinary problems. His main interest is developing holistic approaches, technologies and computer based tools that support innovative design.

Mr. Aditya Gaikwad is currently a graduate student in the Mechanical Engineering Department at Texas Tech University. He received his B.E. (Bachelor of Engineering) Degree from Government College of Engineering, Aurangabad, India. For his Master's Thesis he is working on soil suction in compressed earth blocks. He has also previously worked on the conceptual design of a plunger pump by applying axiomatic design and evaluation of engineering properties of Greenstar Blox (papercrete).

Appendix: Three-day design problems

Three-day problem 1: Design a system for video recording surgical procedures

You have been hired to improve a system for video recording surgical procedures. The desire is to capture the use of various surgical instruments during operations with an aim to identify shortcomings of current tools and to develop new surgical devices. The current video system uses a camera mounted to a moveable light fixture and records images to a networked computer, but the quality of the images is too low and may not capture the relevant area. The proposed system should be unobtrusive and be able to record the images with a minimum of user input during the operation; i.e., the doctors and nurses should not have to stop what they are doing to position the camera.

Three-day problem 2: Design an intelligent robot which can interact with people vocally with emotions

Current robots are not able to interact with people vocally with emotions properly, according to people's emotions. You are required to design an intelligent robot to do so.

The robot should be able to

- identify a person's emotion through his/her voice and face expression;
- response with emotion through speech (simple sentences) coordinately;
- sense the environment and track the right person who is being talked with;
- learn new knowledge from the interaction if there is.

Three-day problem 3: Design a ventilation system for a thin flooring system

In order to benefit from thermal inertia provided by the hollow-core slab (additional comfort and energy savings) and to reduce the thickness of flooring systems (so as to reduce cost of the building), it is proposed to suppress the plenum.

Several unsatisfying solutions to deal with the ventilation system are proposed:

- circulation of air in the adjacent walls
- circulation or air in hollows of hollow-core slab

This is unsatisfying because a high air flow is required if we want the air to enter the room at a comfortable temperature. Otherwise, uncomfortable temperature, too hot or too cold (depending on the need of heating or cooling) may enter the room in order to keep the homogenised temperature of the room at the required value.