TOWARD AN ADAPTION-INNOVATION STRATEGY FOR ENGINEERING DESIGN

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ABSTRACT
A cognition-based strategy for managing the stages of product design and development is illustrated with the aid of a new Cognition-Based Design (CBD) framework. This paper briefly introduces the CBD framework and demonstrates how Adaption-Innovation theory can be used to build an integrated strategy for engineering design based on a common set of cognitive variables, with particular attention to the design process, the designer's problem solving functions, and the resulting product. Data gathered through an exploratory application of Adaption-Innovation theory with design engineers in industry are discussed. Recommendations for making use of the new strategy within design activities are provided, as well as suggestions for future research.

Keywords: Engineering design, design cognition, adaption-innovation theory, cognition-based design

1 INTRODUCTION
Designing and developing new products that satisfy customers through the life cycles of those products continues to be a challenge for design teams in modern corporations. How should an organization align its financial, technological, and human resources to understand market needs, and then design and develop the right products and support them successfully? How should design teams be organized, motivated, and managed for designing and developing products at a faster rate with excellent quality? What are the processes that must be optimized and managed well for product development?
Many approaches have been suggested to meet these challenges, including the relatively recent focus on design cognition and design thinking. Although these terms may have different meanings for different scholars, both relate in some capacity to the application of principles from cognitive psychology and/or cognitive science to the ways in which designers work – i.e., how designers think. This paper contributes to this effort by integrating core principles from traditional engineering design with key constructs from cognitive psychology to explore a new design framework that includes the people, processes, products, and environment of design, along with the original customer need. We begin with a brief description of some of the cognitive constructs relevant to our work.

2 DESIGN AS PROBLEM SOLVING
Engineering design has been acknowledged as a creative problem solving activity by many scholars [1,2,3,4,5]. In particular, Harrisberger notes [6]: "The crux of the design process is creating a satisfactory solution to a need … it is what engineering is all about— using knowledge and know-how to achieve a desired outcome. Designing is problem solving. It is creative problem solving." In 1961, Rhodes [7] introduced his well-known "4P" model for creative problem solving, which includes Person, Process, Press, and Product as its key elements. Rhodes argued that the Person, Process, and Press operate together to create the Product, where Person denotes the skills and characteristics of the problem solver, Process represents the procedures and methods of problem solving, Press refers to the problem solving environment, and Product is the outcome of the problem solving activity.

2.1 The 5P Model
While Rhodes' 4P model is useful, its application to product design lacks explicit acknowledgement of the need that causes customers to seek a product or solution to get a job done. Therefore, we propose adding a new fifth term to Rhodes' model that identifies this motivational element. We call it "Purpose" – i.e., the higher level need that motivates designers to create new products for customers. The structure of the 5P model is shown in Figure 1; it starts with unmet or poorly satisfied customer

need(s), as indicated by the term “Purpose”. A provider with the appropriate process and technology capabilities can exploit the unmet needs by aligning their internal Processes, People, and Press to create the right Product. Therefore, these three elements must be managed well to create Products that satisfy the original Purpose and also meet the objectives of the provider. The effective management and exploitation of these elements is the essence of design excellence.

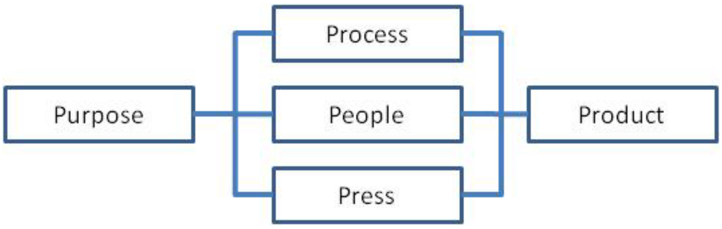

Figure 1.The 5P model for Design Problem Solving

Digging deeper into the 5P model, we note that the Process and Press elements are relatively well defined. Process accounts for the design steps, their inputs and outputs, the techniques applied in each step, and key indicators of success; Press refers to the design environment, which must support the individuals working within it. Here, our aim is to shed new light on the Person (People) element of the model by highlighting some key variables of cognitive diversity incorporated within it.

3. ADAPTION-INNOVATION THEORY

In agreement with many respected scholars (e.g., [9,10,11]), Kirton [12] developed Adaption-Innovation theory based on the assumption that all human beings are creative and solve problems. However, they do so with different capacities, to different degrees, and in different characteristic ways. Figure 2 provides a schema for the cognitive function of the Person as described by Kirton. It provides a simplified view of the complex operations of the human brain as a group of collaborating (yet independent) “departments” focused on survival.

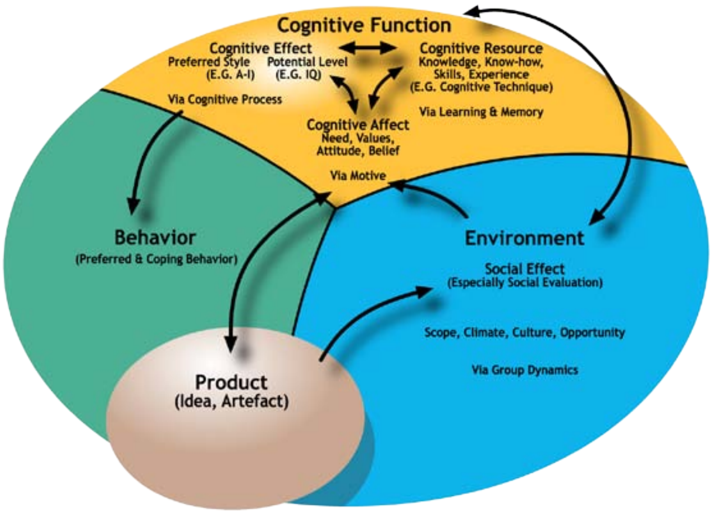

Figure 2.Cognitive Function Schema (adapted and used with permission from [8])

Within the Cognitive Function Schema, the key domains undertaking problem solving include Cognitive Affect, Cognitive Effect, and Cognitive Resource. Cognitive Affect selects the problems to be solved and determines the type of answer needed; it amasses and channels the energy required, via motive, to solve problems. Cognitive Effect implements problem solving via the cognitive process and is governed by two key variables – cognitive style and potential level (one element of cognitive level). Cognitive style determines each individual’s *preferred* strategy for problem solving (creativity, invention), while potential level indicates the maximum capacity that can be leveraged by an individual to problem solve. Cognitive Resource (the brain’s “database” and the manifest portion of cognitive level) is the center of knowledge and skills, amassed through learning, which are accessed

by memory. These internal departments of the brain are also affected by external environmental factors, such as social climate and culture.
In summary, there are three key variables that affect how the brain operates in problem solving (design) activity: Motive, Level, and Style – all aimed at finding and exploiting Opportunity. At this point, it is important to note that cognitive style and cognitive level are independent; that is, knowing a person's style gives no indication of that person's level, and vice versa. So, the style and level that are "best" for a particular design problem are not what any one person prefers, but the right combination to solve the current problem, at the current moment, with the current team. We now provide further details about cognitive style, as it will feature in our discussion of design strategy in Section 4.

3.1 Cognitive (Problem Solving) Style: the Adaption-Innovation (A-I) Continuum

According to Adaption-Innovation theory, cognitive style describes an individual's preference for the manner in which a problem is perceived, managed, and resolved. Cognitive style can be described on a continuous bipolar scale ranging from strong Adaption to strong Innovation (Figure 3).

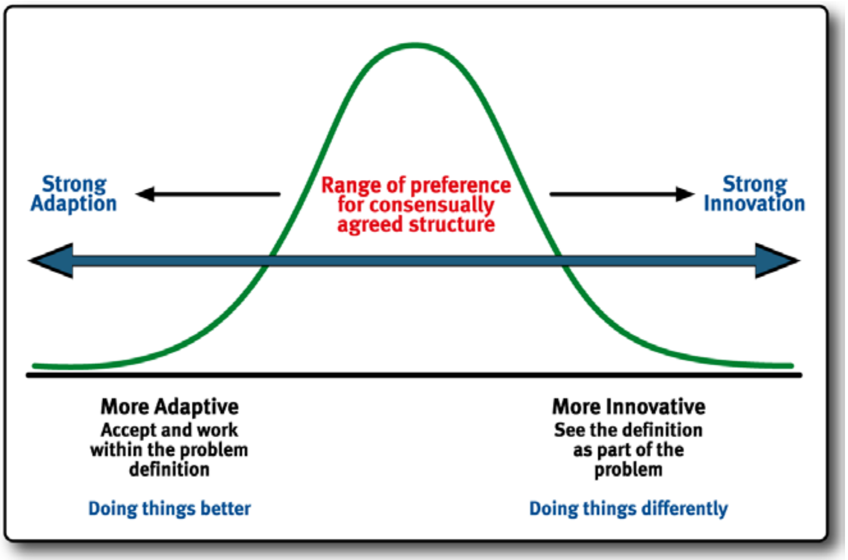

Figure 3.The Adaption-Innovation Continuum

In general, people who are more adaptive prefer more structure, with more of it consensually agreed, working within existing guidelines to achieve improved solutions. In contrast, the more innovative prefer less structure and are less concerned about consensus; they often feel constrained by rules and tend to operate across structures in order to solve problems "differently". It is important to note that the distinction between Adaption and Innovation is not one of dichotomy but a spectrum, which is both more accurate and more useful in the real world. Every individual is more adaptive than some individuals and more innovative than others. In describing A-I cognitive style, it is useful to consider individual characteristics from several practical perspectives, as discussed below.

3.1.1. Idea generation and originality

In terms of generating ideas, more adaptive people tend to focus on residual problems within the current paradigm. They prefer to offer a few novel ideas that are manageable, relevant, sound, and safe for immediate use. Often, they are seen as sound, conforming, safe, and dependable; they expect a high success rate from their ideas. The more innovative, on the other hand, tend to search for "different" problems and alternative solutions, cutting across paradigms. They prefer to offer many novel ideas, which may be considered exciting or "breakthrough". They may be seen as unsound, impractical, and shocking in social situations; they tolerate higher failure rates from their ideas.

3.1.2. Methodology and details

During problem solving, the more adaptive person often approaches tasks in a precise, reliable, and methodical manner. They are thorough and pay greater attention to detail. They welcome change as an improver and seek solutions to problems in tried and understood ways, with a maximum of stability and continuity. The more innovative, on the other hand, tend to approach problems from unsuspected angles, may appear undisciplined, and like to think tangentially. They welcome change as a mould breaker and tend to manipulate the problem, querying its basic assumptions.

3.1.3. Rule and group conformity

When it comes to managing structure (personal and impersonal), the more adaptive prefer to solve problems by the use of rule (i.e., standards, protocols, traditions, etc.). They are more cautious when challenging rules and generally only do so when they have strong support. In general, they are an authority within given structures. In contrast, the more innovative can act as a catalyst to settled groups and consensual views. They find it easier to alter rules to solve a problem and often challenge rules with (seemingly) little concern for past customs. They may take control in unstructured situations.

4. COGNITION-BASED DESIGN (CBD)

Cognition-Based Design (CBD) is based on a systems view that integrates core principles from traditional engineering design with the fundamental constructs from cognitive psychology described above. As shown in Figure 4, the CBD framework incorporates the 5P model explained earlier, which includes the People, Process, Product, and Press of the design team, along with the original design Purpose (customer need). We will refer to this Purpose as Problem A [8,13,14]), i.e., the original problem the design team has come together to solve.

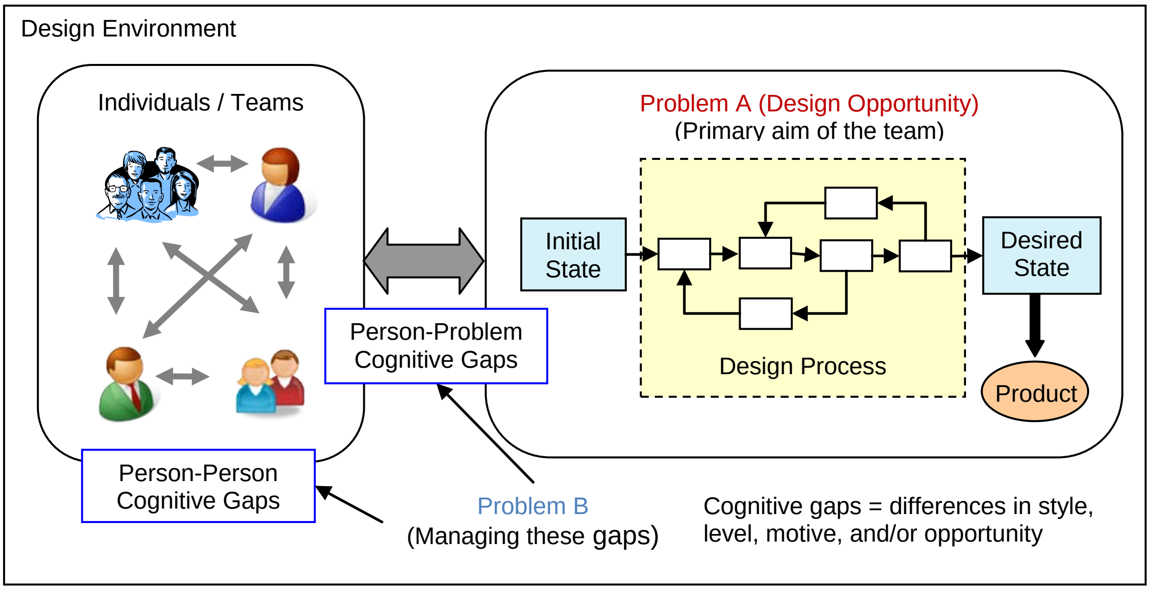

Figure 4: The Cognition-Based Design (CBD) Framework

Key constructs related to cognitive diversity and its management (based on Kirton's Adaption-Innovation theory [12] and other related works [15,16]) are then overlaid on the 5P model. These constructs help establish rigorous definitions and descriptions of the cognitive variations that exist among individuals and groups, including differences in cognitive level (capacity), cognitive style (preferred cognitive strategy), motive (driving energy), and perceptions of opportunity. These differences between people and between people and the problems they solve are called *cognitive gaps* [8,13,14]. We will refer to the management of these cognitive gaps as Problem B [8,13,14], a challenge that must ultimately be addressed successfully if the design team is ever to resolve the original Problem A! Further details about the principles and constructs that form the foundation for the CBD framework may be found in the works of Kirton [8] and Jablokow [13,14], as well as those of Thompson & Lordan [17] and Lopez-Mesa, et al.[3]. For the present, we will focus primarily on the design process and its stages, and their intersection with the preferred cognitive strategy (i.e., more adaptive or more innovative) of the designer.

5. A COGNITION-BASED DESIGN STRATEGY FOR THE 5P MODEL

Based on the CBD framework described briefly above, we have developed cognitive style-based design strategies for each element of the 5P model. In other words, different strategies take on the characteristics of different cognitive styles (from more adaptive to more innovative), as described in Section 3. Here, we will provide descriptions of how these strategies might be applied within the Process and Product components of the 5P model.

5.1. The Design Process and Adaption-Innovation Strategies

In this section, we highlight the Process component of the 5P model for design problem solving, in which we consider (first) which stage of the design process we are working in, and (second) which cognitive strategy we might apply based on the original client need (Purpose). Although design process models developed by various scholars and practitioners may differ in their details, most share a common architecture or flow with the following general stages or steps [18,19,20]:

1. Problem identification (customer needs)
2. Concept or idea generation that satisfies the problem (conceptual design)
3. Elaboration and detailed design of the solution in terms of systems and subsystems (detailed design)
4. Testing and implementation of the solution (pilot/prototype)

For our purposes here, we will use the simple four-stage design model shown in Figure 5. The stages involved are as follows: first, *define* the design opportunity; then, *discover* ideas for addressing it; next, *develop* the details of the resulting design; and finally, *demonstrate* the solution. Of course, this 4-step process is somewhat overlapping – e.g., as discovery becomes understood, there is further re-defining and even the starting of development.

It is also useful to note that each of the four stages is associated with both divergent and convergent cognitive operations. In general, divergent operations involve searching for and increasing one's options through elaboration of the design problem, redefinition of the problem, and exploring, connecting, and/or combining potential ideas/solutions. In contrast, convergent operations involve evaluating ideas and narrowing or reducing one's options through the imposition of value judgments, exploiting the information available about the ideas, prioritizing, and selecting. In both cases (divergent and convergent thinking), the resulting ideas/solutions may fall inside, at the edges of, or outside the relevant technical domain/paradigm (i.e., they may be of different cognitive styles).

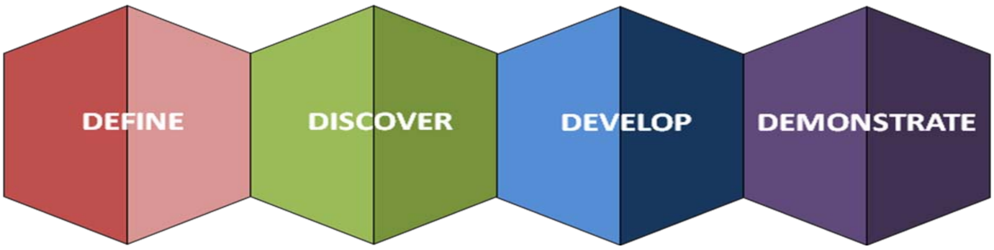

Figure 5: A Simple Four-Stage Model for Engineering Design

So, in this simple process flow, we can now apply a *more adaptive strategy* or a *more innovative strategy* within each stage of design. However, Adaption and Innovation take on slightly different interpretations when put into the context of different design stages, as follows:

5.1.1. Define the opportunity

In defining a design opportunity, the *more adaptive strategy* is to accept the problem definition as given and, beginning with the original boundaries, to search more deeply inside them once they have been refined and solidified. On the other hand, the *more innovative strategy* is to question the given problem definition and reframe it from a variety of angles – then look for solutions within those reformulated boundaries. At the end of the Define stage, the designer must choose a formulation of the design problem before moving to idea generation (Discover). Here, we must remember: by accepting the problem definition as given as a start, working within it constantly changes it. So, those who are more adaptive make change *even as* they solve Problem A, while the more innovative make change (often to the problem) *in order* to solve it – a prime example of Kirton's Paradox of Structure [8].

5.1.2. Discover ideas

This stage involves generating ideas for the design problem chosen in the Define stage. A more adaptive or more innovative strategy for idea generation can be applied either to the adaptive formulation of the design problem or to the innovative formulation of the design problem (see Figure 6). The *more adaptive strategy* for generating ideas is to find solutions closer to the core of the prevailing paradigm; these ideas tend to be viewed as sound and more immediately efficient, and a precise and methodical approach may be used to find them. The *more innovative strategy*, on the other hand, is to search for alternative and “unusual” solutions, possibly cutting across paradigms. These solutions may be found by linking ideas from loosely connected paradigms; many of these ideas may be seen as unsound or impractical. At the end of the Discover stage, the designer must choose a particular idea or ideas for further development.

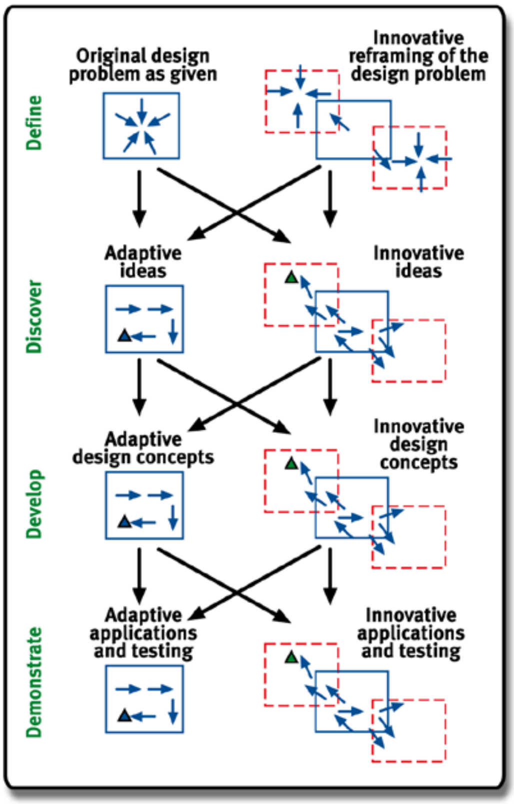

Figure 6: Adaption-Innovation Strategies for the Define, Discover, Develop, and Demonstrate stages

5.1.3. Develop detailed design

The key idea(s) chosen from the Discover stage is/are further developed during this stage at the sub-system and components level. Again, for the development of design concepts and detailed design, one can choose (or switch to) a more adaptive or a more innovative strategy. Design concepts are developed by breaking the main function into sub-functions and identifying sub-system level solutions. During this process, one can find sub-system level solutions at the core of the paradigm (*more adaptive strategy*) or outside and at the edges of the paradigm (*more innovative strategy*). The process is continued until component level design is complete. The output of this stage is a more adaptive or a more innovative embodiment of the chosen idea from the Discover stage.

5.1.4. Demonstrate the solution

The objective of the Demonstrate stage is to collect knowledge regarding the application of the design in real life or a simulated environment. This is done by building prototypes and testing them under various conditions. A design that was developed during the previous stage can be tested, evaluated, and improved using a more adaptive or a more innovative strategy. The *more adaptive strategy* is to build prototypes in a traditional manner, meticulously designing test conditions and collecting data methodically and thoroughly. The *more innovative strategy* is to quickly build prototypes using unexpected means or materials and in conditions that are not customarily observed, tolerating more failures in the process. Using the more innovative strategy, one might even demonstrate the application of a design for an unintended Purpose.

5.1.5. Summary

The process of moving through the four design stages using more adaptive and more innovative design strategies is depicted in Figure 6. As the figure shows, a designer or design team can apply a more adaptive or a more innovative strategy at any stage of the design process, leading to a great variety of outcomes. This depiction of the cognitive strategies that underpin the design process lies in contradiction to some current models of problem solving that tend to associate more adaptive thinking with particular design stages (e.g., Develop) and more innovative thinking with others (e.g., Define). We will discuss the implications of this difference below.

5.2. The Design Product and Adaption-Innovation Strategies

Next, we turn our attention to the Product component of the 5P model – i.e., the outcome of applying the Process, People, and Press elements to the designated Purpose. In their cognitive characterization of the products of design, Jablokow and DeCristoforo [21] proposed a classification of design features related to cognitive level and cognitive style, respectively. Furthermore, they proposed a set of six continua to be used in assessing the cognitive style nature of a product, where each continuum ranges from high Adaption on one end to high Innovation on the other, thereby extending Kirton's assessment of cognitive style from people to the products they create.

Synthesizing Jablokow and DeCristoforo's proposed classification with the results of several other design-related studies [22,23], we can consider the application of more adaptive and more innovative strategies to Product. A more adaptive product strategy is to create a product that remains within or closely connected to the technical domain of interest, making incremental changes that leverage the existing domain more thoroughly for solutions before looking elsewhere [22,23]. Such products may be perceived as "evolutionary", representing sound, incremental improvements to existing technologies that are readily recognized as efficient and relevant to the current Problem A (customer need) – and which are typically more readily implemented as well. In contrast, a more innovative product strategy would be to create products that stretch the boundaries of the relevant technical domain or that span several domains [24]. Such products may be perceived as "revolutionary", bringing together diverse areas of technology and combining them in unexpected ways.

In summary, the "best" (most appropriate) product strategy must be chosen based on the original customer need (Problem A), not on any one designer's personal preference or the latest popular trend (e.g., "Innovate or die!"). Just as there is no ideal cognitive style for individuals (the species requires great diversity in order to survive), so also there is no ideal style for products in order to ensure success; as good designers know, both "evolutionary" and "revolutionary" designs can succeed.

5.3. Preliminary Investigation

It is certain that in large, complex problems, a range of cognitive levels (capacities) <u>and</u> a range of styles will be needed. But the problem solvers (designers, in this case) within the team may disagree about when and by how much these shifts of style and level are appropriate. Referring back to Figure 4, the design team can divide into factions, creating a very difficult Problem B rather than solving their common Problem A.

In the interests of exploring such phenomena, we have begun investigating the application of the CBD framework with various design teams; some preliminary results of a simulation carried out by an industrial design team are reported here. This design team was part of a subsidiary of a multi-national firm and is involved in design, development, and testing of high integrity polymer solutions for harsh offshore environements. The team consisted of 23 engineering members from cross-functional departments, such as R&D, product design, process design, tooling design, design analysts, and CAD/CAM technologists.

The cognitive characteristics of the design team members were assesssed using Kirton's Adaption-Innovation (KAI) Inventory®, a highly validated and reliable psychometric instrument for measuring individual cognitive style. KAI scores for the general population are normally distributed with a mean of 95, standard deviation of 18, and a range from 45 to 145; a score of 45 denotes the most adaptive style, and 145 denotes the most innovative style. KAI scores for the design team ranged from 71 to 140, with a mean of 102 and standard deviation of ~20 (see Figure 7). Kirton [12] reported a mean

KAI score of 97 for a wide and general spectrum of engineers (N=800). Thus, we see that this particular design team had a more innovative skew, a quality that might be expected of a design team creating custom solutions. Note, too, that the style range for this team is very wide (69 points). Kirton has shown that cognitive style gaps of 10 points are usually noticed after a while; gaps of 20 points are quite noticeable and can require careful attention. With even larger gaps (>20 points), problems are almost certain to arise at some stage usually sooner than later; even if this range of style diversity is potentially enabling, its practical value (as taught by A-I theory) may not be realized!

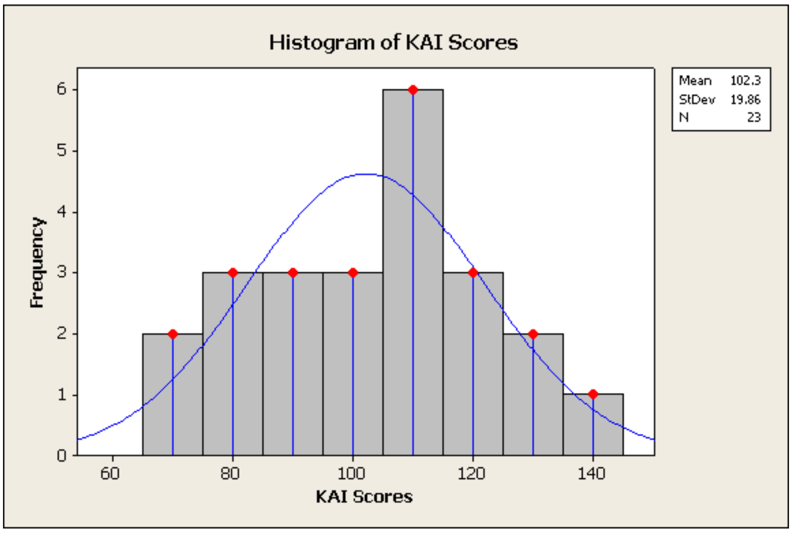

Figure 7: Histogram of KAI Scores for the Sample Design Team

We carried out a simulation exercise with the design team to test the preferred cognitive strategy they would use to assess problems (Define) and generate ideas (Discover). The group was divided into five homogeneous groups based on their Adaption-Innovation cognitive styles, i.e., each group consisted of members with similar preferred styles (within 10 points). Each group was then given the same problem and asked to evaluate it and generate solutions using the first two stages of the design process framework described earlier (Define and Discover).

Each group, ranging from the most adaptive to the most innovative, was asked to solve the problem using their preferred approach to problem solving. The teams were assured that there were no right or wrong answers for the simulation. The problem statement was as follows: “Your Company is in the business of producing and selling tea in bags. Lately, the coffee companies are taking market share away from you by converting tea drinkers to coffee drinkers (Starbucks has been effective with their campaigns). As a result, your company is losing revenues and will become bankrupt unless serious actions are taken. In your assigned groups: (1) brainstorm what the problem is (Define the opportunity) and (2) generate new ideas on how you can save your business (Discover new ideas). Make appropriate assumptions to solve this problem.”

Sample outputs from the more adaptive groups and the more innovative groups are given in Tables 1 and 2. Table 1 shows results related to the groups’ different perceptions of the problem (Define), while Table 2 shows selected ideas generated by the two groups (Discover). As expected, the more adaptive design groups accepted the problem as given and generated ideas about solutions that remained closely connected to the original domain of interest (tea bags), searching and leveraging that domain thoroughly for solutions before looking elsewhere. In contrast, the more innovative design groups questioned the original problem definition and generated ideas that stretched the boundaries of the original domain or that spanned several domains (e.g., food, pharmaceuticals). In both cases, similar numbers of ideas/solutions were generated, demonstrating the independence of cognitive level and cognitive style, in accord with theory [8].

Table 1. Define Stage Results from More Adaptive and More Innovative Groups

More Adaptive Perceptions of Problem	More Innovative Perceptions of Problem
Collect voice of the customers Focus groups and surveys with customers Consult with marketing firms Benchmark other tea companies Conduct a taste study with customers Assess the quality of tea Assess the cost structure of the company Assess cost of making tea including supply side Evaluate the manufacturing process for efficiency Conduct a study of tea versus coffee on multiple dimensions	Identify non-drinkers of tea Identify the benefits of mixing tea with other drinks The problem is with coffee politics The problem is with marketing Identify buyers of tea processing equipments Identify other uses of bags Problem is with smear campaigns from Starbucks Analyze legality of supplementing tea with additive substances

Table 2. Discover Stage Results from More Adaptive and More Innovative Groups

More Adaptive Ideas/Solutions	More Innovative Ideas/Solutions
Improve taste of tea Reduce time to prepare tea Instant tea (similar to instant coffee) Create variety of tea based on taste and quality Marketing campaign to promote tea benefits Open "Tea Houses" to create ambiance to enjoy Hire a celebrity as spokesperson Create multiple distribution channels Merge with other tea companies Import tea products from Asia Offer home delivery Reduce price Create new products using tea Sponsor cost cutting initiative	Promote non-traditional use of tea "Tee Time Tea" "Creativity Tea" "Vodka Tea" "Viagra Tea" Attack Columbia and control coffee markets Partner with Starbucks to promote tea Sell soup in tea bags Coffee in tea bags Sell tea processing machines Redesign tea processing machines to do something else Add addictive substance to tea Start smear campaign against Starbucks

6. RECOMMENDATIONS AND FUTURE WORK

While our presentation of the CBD framework has been necessarily brief here, our work demonstrates that the application of cognitive constructs need not be confined to the Person within the 5P model – i.e., an understanding of cognitive diversity provides valuable insights when applied to the Process and Product elements as well. In particular, we have shown how the design process might be deconstructed in a new way, adding a cognitive style dimension to the familiar stages and divergent/convergent operational understanding. We believe this new perspective is key to understanding the richness and complexity of design, where the solutions to real design problems are likely to involve both more adaptive and more innovative elements, rather than the homogeneous treatments that are so often assumed (e.g., a bias toward continuous improvement or "breakthrough thinking", respectively). These cognitively diverse elements must be managed well if the customer's original Problem A is to be solved successfully; a solid understanding of that cognitive diversity within the design context is a critical first step.

In terms of the design product, we can see similar advantages in adopting this view. Our preliminary investigation suggests a predictive relationship between designers of different cognitive styles and the types of product ideas they are likely to offer (in agreement with theory) – a result that can be leveraged within design teams by shifting roles depending on which Adaption-Innovation design strategy has been chosen in a particular design stage. Future work will be focused on testing these relationships in both corporate and academic settings, as well as expanding the details of the CBD framework in relation to the design environment (Press) and the customer need (Purpose).

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