# The Psychological Links between Systems Thinking and Sequential Decision Making in Engineering Design

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Systems thinking is a cognitive style that deals with complex systems and is essential for systems engineering; elucidation of its underlying mechanisms allows for the development of techniques to aid in systems design. This paper sets out to test the relationships between validated psychological measures and systems thinking ability. To capture systems thinking ability and sequential design decisions, a computer-aided design task was developed. Participants designed an energy-plus house, utilizing solar energy to maximize the ratio of annual energy output to building cost. The present study offers and tests for two hypotheses. First, we expect to find a positive correlation between performance on the design problem and psychological measures of divergent thinking and cognitive ability. Second, a difference will be found in participant's sequential design decisions according to their psychological profile. The first hypothesis was supported by a correlational analysis, while the second hypothesis was not.

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## Introduction

### What is Systems Thinking?

The term, “systems thinking” was first introduced in 1987 by Barry Richmond, who saw it as a method of system comprehension and prediction [1]. Subsequent definitions see it as antithetical to reductionism [2] and linear thinking [3], both of which strive to solve problems within systems through simplification. Senge defines systems thinking as a framework for seeing wholes and the interrelationships within them rather than singular components, along with considering trends as opposed to static snapshots [4]. Upon the review of thirty-three references deemed important in the field of systems thinking, Monat and Gannon provide a broad definition: systems thinking is *a perspective, a language,* and *a set of tools* [3]. Many different perspectives on systems thinking from various disciplines can be found, and a widely accepted and accurate definition is hard to achieve. However, most definitions share two defining features: systems thinking is a specific cognitive style directed towards systems, and is supported by a set of cognitive skills that allow for one to both understand and solve problems within systems.

### Why is Systems Thinking Important?

Systems thinking is particularly powerful in handling the ever-increasing complexity of large-scale engineered systems that are not solvable using reductionist thinking [5]. Therefore, a better understanding of the role that systems thinking plays in engineering systems design offers great benefits in both engineering education and engineering practice. During a recent NSF-sponsored Workshop on Artificial Intelligence and the Future of science, technology, engineering and mathematics (STEM) and Societies, the Vice President for Digital Transformation at Lockheed Martin Jeffrey Wilcox discussed the importance of systems thinking in the creation of complex systems and products, and noted the lack of formal training of systems thinking in professional engineers [6]. Additionally, an increasing amount of governmental mission agencies and manufacturing corporations are exploring opportunities for applying systems thinking and design thinking principles in systems engineering projects [7-10].

A report prepared by International Council on Systems Engineering (INCOSE) titled, “A World in Motion, Systems Engineering Vision 2025,” called for the role of systems thinking to be explicitly introduced early in education to complement learning in STEM [11]. The report suggested that educational infrastructure needs to be established to emphasize systems thinking and systems analysis at all phases of an engineer’s curriculum.

The Council's prediction is that the education of systems engineers through the exposure to systems thinking will allow for the high demand of systems engineers with technical and leadership competencies in the engineering and management workforce to be met.

**Why is Systems Thinking Elusive?**

Research on systems thinking is challenging, as its exact structure has proven hard to concretize and define; thus, there exists no consensus on the factors that comprise systems thinking. While Sage [12] summarizes the eleven laws of systems thinking, Valerdi [13] describes seven systems thinking competencies. Meanwhile, Ballé argues for three basic points of systems thinking: the detection of patterns as opposed to events, the use of circular causality (feedback loops), and a focus on relationships rather than single elements [14].

Alongside the disagreement on the structure of the concept, systems thinking often overlaps with other related terms. This is especially apparent in the relationship between *engineering systems thinking* and *design thinking*. Moti Frank, an influential researcher on the former topic, distinguished engineering systems thinking from systems thinking [15], adapting Senge's systems thinking laws to create thirty engineering systems thinking laws. He later developed a capacity for engineering systems thinking (CEST) Cognitive Competency Model, and identified eighty-three competencies of successful systems engineers. These eighty-three competencies were aggregated into thirty-five competencies, including sixteen cognitive competencies, nine skills/abilities, seven behavioral competencies and three related to knowledge and experience [16].

In the present study we adopt the CEST Cognitive Competency Model, particularly the sixteen cognitive competencies that make up engineering systems thinking. While this model has been influential and offers an imperative base for future research on systems thinking, it was intended to serve as theoretical grounding; thus, how these competencies may be measured was not addressed. In a later work, Greene and Papalambros [17] mapped these sixteen competencies to established concepts within psychology, so that they may be studied by widely used and validated tests. In Table 1 we present Frank's competencies and Greene and Papalambros' mappings. In bold are the competencies and corresponding psychological constructs that are measured in the present study, the rationale for which can be found in the "Rationale" section.

**Table 1** Cognitive Competencies and the corresponding psychological constructs [17]

| *Frank's Cognitive Competencies* | *Greene and Papalambros' Mappings* |
|---|---|
| Understand the whole system and see the big picture | Sensemaking; information integration; mental model formation; generalization |
| **Understand interconnections** | **Induction**; classification; similarity; information integration |
| **Understand system synergy** | **Deductive inference** |
| Understand the system from multiple perspectives | Perspective taking |
| **Think creatively** | **Creativity** |
| Understand system without getting stuck on the details | Abstraction; subsumption |
| Understand the implications of proposed change | Hypothetical thinking |
| Understand a new system/concept immediately upon presentation | Categorization; conceptual learning; inductive learning/inference |
| **Understand analogies and parallelism between systems** | **Analogical thinking** |
| Understand limits to growth | Information integration |
| **Ask good (the right) questions** | **Critical thinking** |
| Are innovators, originators, promoters, initiators, curious | Inquisitive thinking |
| Are able to define boundaries | Functional decomposition |
| Are able to take into consideration non-engineering factors | Conceptual combination |
| Are able to "see" the future | Prospection |
| **Are able to optimize** | **Logical decision making** |

Systems thinking is also related to design thinking. Dym and colleagues [18] define design thinking as a complex process of inquiry and learning that designers perform in the context of a system, making decisions as they proceed and often done collaboratively. Vinnakota [19] argues that design thinking and systems thinking are connected and can be leveraged to overcome the problem of a complex system. Greene and colleagues [20] demarcate engineering systems thinking and design thinking, and describe them as two complementary approaches to understanding cognition, organization, and other non-technical factors that influence the design and performance of engineering systems. In the same paper [20], four concept models that depict plausible relationships between design thinking and systems thinking for engineering design are presented: *The Distinctive Concept Model*, *Comparative Concept Model*, *Inclusive Concept Model*, and *Integrative Concept Model*. We adopt the *Comparative Concept Model*, which suggests that the underlying mechanisms between engineering systems thinking and design thinking are similar, but that these concepts have different applications and utilize divergent methods.

In the present study, we adopt Dym's definition of design thinking, and study designers' sequential decision making [21, 22], one of the most essential components in design thinking, as well as its relationship with systems thinking. Many factors in systems thinking, such as the capability of handling problem complexity [1] and uncertainty [4, 23] can influence designers' sequential actions and the final design quality. Moreover, in a systems context, designers often receive incomplete information due to partial observability [24] and require long-term memory of past information [25] for better design iterations. To better understand and model the sequential decision making by considering individual differences, the systems thinking factors and the characteristics of systems context must be considered.

## Research Overview

The **objective of this paper** is to uncover the interrelations between systems thinking and sequential decision making.

Fine-grained data representing sequential design decisions and actions were captured through the administration of a computer-aided design problem. To complete this design problem, participants were asked to design an energy-plus home which, while utilizing solar energy, maximized the ratio of annual energy output ($E$) to building cost ($C$), i.e., $r = \frac{E}{C}$. How well participants accomplished this goal portrayed the quality of their design. The design actions as well as the iterations that participants made, along with their order, were logged automatically in a non-intrusive way, allowing for the analysis of how effective their sequential decision making was in solving the design.

To measure systems thinking, the six competencies from Greene and Papalambros' mappings of Frank's CEST Cognitive Competencies Model that best represented how one would solve the issues faced in the design problem were chosen. Established and validated measures of these six competencies were then administered.

## Research Hypothesis

The present study offered and tested for two hypotheses:

1. We expected positive correlations between participant scores on measures of six cognitive competencies and their performance on the design problem.
2. We expected a significant difference between the groups in which participants were placed in based on their scores on the psychological tests in the usefulness of their sequential decision making.

### Rationale for Hypothesis 1

The six competencies that we chose to measure in the present study are the ones listed in bold in Table 1. The first of Frank's cognitive competencies that we expected to be positively correlated with performance on the design task is the most direct mapping to an existing psychological construct: "think creatively." Creativity is a widely studied phenomenon in the field of psychology, and though a widely agreed upon definition has been difficult to reach, most definitions refer to creativity as the generation of ideas that are both novel and useful [26]. The field has received a great deal of attention since Guilford's 1950 address to the American Psychological Association [27], and through his efforts creativity was given a theoretical foundation. An important distinction made by Guilford was that between *divergent thinking* and *convergent thinking* [28].

Divergent thinking refers to idea generation and is generally viewed as the essential component of creativity. Guilford's Structure of Intellect [29] model offers the first in-depth consideration of the construct, where he explains that ideas are generated through thought that proceeds in disparate directions, thus allowing for novelty [30]. Idea generation is a critical step in the creative process, and is especially relevant in design; in fact, design of any original object would be rendered impossible without ideation. Convergent thinking, also researched as, "creative problem solving," refers to the ability to find solutions to a given problem that has only one correct answer. Both are vital to creative cognition, and it was the intent of the researchers to gather data regarding both; however, technical difficulties barred the analysis of participants' convergent thinking. To measure divergent thinking, the Abbreviated Torrance Test for Adults (ATTA) was used [31]; an in-depth explanation of and the rationale for the use of this test can be found in the, "Measures" section.

The remaining five constructs that were chosen were inductive and deductive reasoning, analogical and critical thinking, and logical decision making. A great deal of research on these and pertaining constructs can be placed in the category of, "cognitive ability," a broad term that has been used to reference ability in language, reasoning, memory, learning, cognitive speed, and many other cognitive traits [32], and has been shown to be highly positively correlated with popular standardized tests [33, 34].

To measure cognitive ability, we administered the International Cognitive Ability Resource (ICAR) test [35]; again, further explanation on this test and the rationale behind its use can be found in the, "Measures" section.

**Rationale for Hypothesis 2**

For our second hypothesis, we expected the statistical difference between participant groups in sequential decision making to be shown through the average change ($\bar{\delta}$) participants made in the ratio of annual energy output ($E$) to building cost ($C$) between their iterations, i.e., $\bar{\delta} = \sum_{i=1}^{N}(r_t - r_{t-1})$, where N is the total number of design iterations and $r_t$represents the ratio $\frac{E}{C}$ at time $t$.

Participants were divided into four groups based on their scores on the psychological measures in relation to the median scores for the sample. The groups were made for analysis purposes only; participants completed all aspects of the study individually. Group one contains participants who scored above the median score on both the ATTA and the ICAR; the second group is comprised of participants who scored high on the ATTA but low on the ICAR; group three are those who scored low on the ATTA and high on the ICAR, while the final group contains the participants who scored below the median on both measures. Table 2 offers a visualization of the groups.

**Table 2** Groups and corresponding scores on psychological measures

| | *Divergent thinking score* | *Cognitive ability score* |
|---|---|---|
| *Group 1* | Above median | Above median |
| *Group 2* | Above median | Below median |
| *Group 3* | Below median | Above median |
| *Group 4* | Below median | Below median |

We expect that group two (high divergent thinking, low cognitive ability) will show a lower $\bar{\delta}$ than those in the group three (low divergent thinking, high cognitive ability). Design can be accomplished through many avenues, and the designer must use the cognitive competencies that are available to them. For instance, successful divergent thinkers may accomplish design through the generation of many different possible designs, testing each one individually; however, without high reasoning ability their ideas are not guaranteed to be beneficial to the task at hand. In comparison, those who show high cognitive ability may quickly understand the design task and what must be done to accomplish the goal, and largely skip the ideation phase.

## The Empirical Study

### Methods

#### *Participants*

Thirteen people (nine females, four males) participated in the study[†] (mean age = 30.76, *SD* = 13.16). Participants were recruited through both advertisements in an online university newsletter and with flyers distributed across campus. All but one of the participants indicated that they had, “a little” knowledge on the engineering design process, with the other having spent time studying the topic. Three of the participants were familiar with the challenges that solar science created, and the relevant solutions to those problems; one participant was unaccustomed to the topic, and the remaining nine had heard of solar science. The present study was approved for administration through the university’s Institutional Review Board, and all participants provided informed consent.

We did not expect any of the demographic information to impact the results of the study and include them solely to give the reader a better understanding of the sample. It was our assumption that neither gender nor age would influence design, and though the design problem was complex in nature, the premise was simple enough that previous knowledge regarding solar science would not offer an advantage.

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[†] The number of participants is a major limitation of this study. However, we would like to highlight that the motivation of this paper is to share our views on the relations between engineering systems thinking and sequential decision thinking, and present the overall methodology of studying such relations from the psychological point of view. With the limitation of the number of subjects, we are cautious to draw conclusions until sufficient data are collected.

***Procedure***

The experiment was divided into two phases. In the first phase, participants were given one hour to design a solarized home, an engineering system design problem using Energy3D – a computer-aided design (CAD) software for solar systems design which is capable of supporting design thinking studies [36]. Before this phase, participants filled out a questionnaire with the demographics and domain knowledge information. To ease the learning process of the Energy3D, participants were also subjected to a thirty minute tutorial session before they completed the design task. In this session, participants were given a tutorial sheet which provided a step by step introduction to the different tools needed to perform the design task. Data collected from the tutorial were not used for analysis, and participants were allowed to utilize the tutorial information in the actual design challenge. In the second phase participants were asked to complete the ATTA and the ICAR measures; this took approximately thirty minutes. At the end of the session, participants were provided with monetary rewards determined by the quality of their final design.

## Measures

***Collecting Sequential Decision Making Data***

The design problem was to build a solarized house in Dallas, for which we provide a detailed problem description including the objective, budget, requirements and constraints. The main objective was to maximize the annual net energy while minimizing the design cost. They were able to check their progress towards this goal by performing either an energy or financial analysis of their design at any time; this was the only feedback they were given regarding the cost and energy efficiency of their design. The program logged the cost and energy output of the design each time they performed an analysis, which we used as the iterations of their design. With a construction budget of $200,000, participants needed to meet several requirements for their designs; for example, the final design required at least four windows, and a wall height of at least 2.5m. Table 3 summarizes all the requirements of the energy-plus home design problem. Participants were told that they would be compensated in accord to the degree to which they maximized their energy to budget ratio and stayed within the constraints. Though designers work to satisfy their own goals, this was done to ensure that all participants were motivated to work towards a similar goal. As the design of all components was predetermined by Energy3D, the participants worked with identical tools.

**Table 3** The design problem components and their required metrics

| *Components* | *Requirements* |
|---|---|
| Story | 1 |
| Number of windows | > 4 |
| Size of windows | > 1.44 $m^2$ |
| Number of doors | ≥ 1 |
| Size of doors (Width × Height) | ≥ 1.2m × 2m |
| Height of wall | > 2.5m |
| Distance between ride to panel | > 0 |

To complete the design problem, participants needed to consider the subsystems that made up the system as a whole; relevant subsystems ranged from, but were not limited to, the arrangement of the walls, the location of the door and windows, and the height of the roof. Participants were required to work within the given design constraints and were also forced to consider how the different variables related to each other, resulting in an intensive design problem that had to be solved through a systems thinking approach. One constraint not enforced was the design strategy that was implemented; while one participant may have moved from the wall subsystem to the roof subsystem, another could instead then begin working on the windows subsystem. This order that participants used to go about their design was driven by their sequential decision making. Both participant systems thinking ability and sequential decision making strategies were relied upon to complete the design problem, thus allowing the task to quantify and capture both.

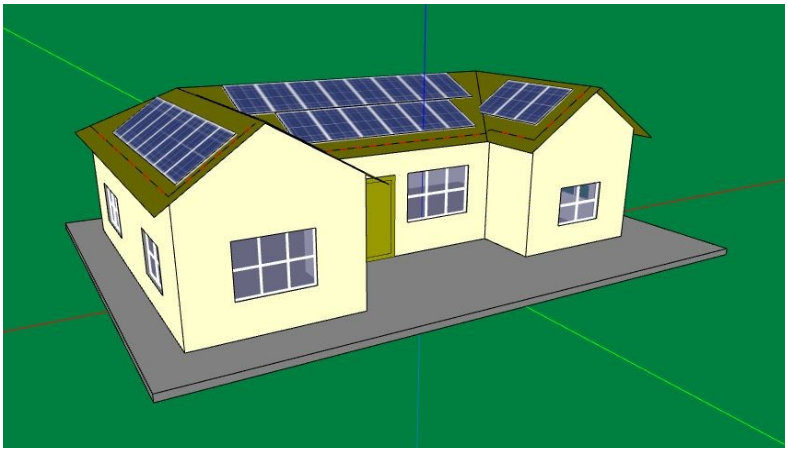

**Figure 1** One of the energy-plus homes designed by a participant in the present study. This design achieved an annual net energy of 6640 kWh with a building cost of $207,289.

Figure 1 shows an example of a solarized energy-plus home that participants built through Energy3D, a computer-aided design program. Energy3D has great utility for conducting design research, and allows for the analysis of engineered systems, scientific simulation, and financial evaluation. The program has built-in tutorials and design examples to help novice designers to learn the software quickly, and offers interactive visualization and simulation tools to allow designers to perform analysis in real time. Additionally, Energy3D has the ability to log all performed actions at fine-grained scale in JSON files, capturing both design actions and the details associated with each of these actions; for example, when a user utilizes a design action to change the efficiency of a solar cell, the new efficiency value for the cell will also be recorded. The following box shows a sample of the design action data that was collected.

*{"Timestamp": "2017-12-04 09:03:52", "File": "EnergyPlusHome.ng3", "Add ShedRoof": {"Type": "ShedRoof", "Building": 2, "ID": 12, "Coordinates": [{"x": 0, "y": 0, "z": 28.5}, {"x": -36.99, "y": 26.99, "z": 28.5}, {"x": 36.99, "y": 26.99, "z": 28.5}]}}*

***Measuring Cognitive Competencies***

***Abbreviated Torrance Test for Adults***

In order to measure participant divergent thinking, the Abbreviated Torrance Test for Adults (ATTA) was administered [31]. This test has roots in the Torrance Test of Creative Thinking (TTCT), first developed by Paul Torrance in the 1960's [37] and then used extensively throughout his long and influential career. Torrance provided ample evidence for the TTCT's validity in measuring creative ability, most famously through a longitudinal study showing a strong positive correlation between high-schoolers scores on the test and their later creative achievements [38]. For many years, the TTCT was the prevailing paradigm for measuring divergent thinking [39, 40]. However, to complete the TTCT takes over an hour, and those scoring it require approximately twenty minutes [27]; thus, the ATTA was later developed by Torrance and Goff as a shortened version that can be completed in under ten minutes, allowing for quick administration and scoring. The ATTA itself has been shown to possess both positive correlations with and predictive reliability for real life creativity [41, 27].

This measure of divergent thinking is widely used and trusted throughout psychology, and thus was chosen for the present study.

The test consists of three activities: one measuring verbal, and two measuring figural divergent thinking. For each activity, participants are timed for three minutes, and are encouraged to, "be creative," a primer that has shown to effect how creative answers can be [43]. In verbal activity, participants were asked to list the problems that would come with the ability to walk on air or fly without being in a vehicle. In the figural activities, they are presented with incomplete geometric figures and are asked to use these figures to complete drawings.

Participant responses were measured across four constructs: *fluency* (the number of generated items per activity), *originality* (how original responses were when compared to the standardized norms), *cognitive flexibility* (the number of distinct domains that were referenced throughout the responses), and *elaboration* (the amount of detail given). To obtain an overall divergent thinking score, answers for each construct were *z*-scored, after which they were averaged together; method similar to that in [44].

***International Cognitive Ability Resource***

Condon and Revelle's [35] International Cognitive Ability Resource (ICAR) test was utilized to capture cognitive ability, a broad term used within psychology to reference reasoning ability that the present study adopts to reference the several different types of reasoning that Frank [16] cites in his model. Though the term lacks a precise definition, it has been used both interchangeably with and alongside intelligence [33, 44]; previous studies have measured the construct through scores in school and on standardized tests [45], along with other measures of intelligence [46]. The ICAR was developed to establish a reliable and validated public domain measure of cognitive ability, that was not only free and easy to obtain, but also quick to administer and score when compared to other measures of the same construct. Because of these reasons, the ICAR was chosen to capture the mappings from Greene and Papalambros' mappings [17] of Frank's model [16] that explicitly reference reasoning ability.

The test is comprised of four item types: *Letter and Number Series*, *Matrix Reasoning*, *Verbal Reasoning*, and *Three-dimensional Rotation*; Table 4 offers a visualization of the types of reasoning that each of the items measure. The first, *Letter and Number Series*, tasks participants to predict the next item in a string of number or letter sequences (ex. "In the following alphanumeric series, what letter comes next? I J L O S"). *Matrix Reasoning* questions present a 3 x 3 display of shapes and ask participants to pick from a pool of 6 additional shapes the one that best completes the array; see Figure 2 for a sample question. *Verbal Reasoning* items challenge participants with general logic questions (ex. "If the day after tomorrow is two days before Thursday, then what day is it today?"). Lastly, *Three-dimensional Rotation* tasks ask participants to correctly choose one of six cubes that is a rotation of an initially presented cube; see Figure 3 for an example of this item type. When scoring, the number of total correct responses is taken as an indication of general cognitive ability.

**Table 4** ICAR item types and the corresponding Cognitive Competencies mappings

| *Item type* | *Cognitive Competencies Mappings* |
|---|---|
| Letter and Number Series | Induction, Analogical thinking, Critical thinking, Logical decision making |
| Matrix Reasoning | Induction, Analogical thinking, Critical thinking, Logical decision making |
| Verbal Reasoning | Induction, Deductive inference, Critical thinking, Logical decision making |
| Three-dimensional Rotation | Analogical thinking, Critical thinking |

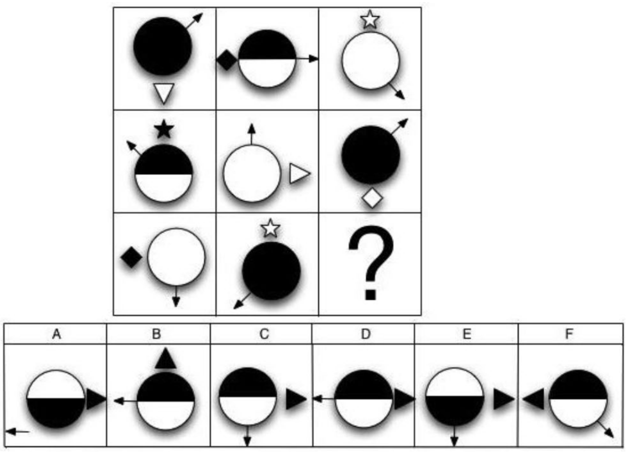


**Figure 2** A Matrix Reasoning item from the ICAR; participants must choose the correct option from the bottom row to complete the pattern shown in the 3 x 3 display.

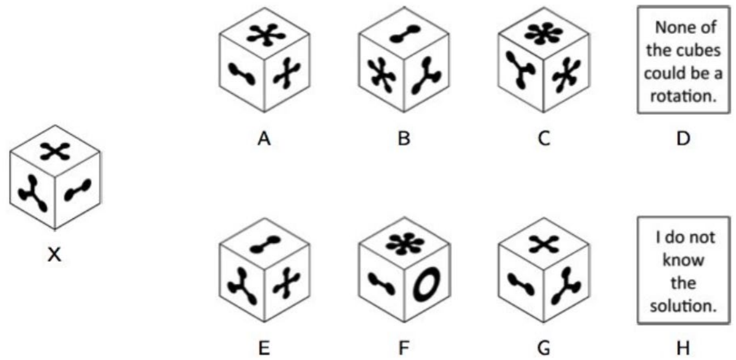


**Figure 3** A Three-dimensional Rotation item from the ICAR; participants are given the instruction to, "Select the choice that represents a rotation of the cube labeled X."

## Results

Performance on the design challenge varied among participants. The average ratio of annual energy output to building cost was 0.083 and ranged from a minimum of 0.016 to a maximum of 0.121. All but two of the participants submitted a design under the $200,000 budget, spending an average of $191,832 per design. The highest annual net energy output achieved was 24,162.66 kWh; the lowest only yielded 5,684.89 kWh, with the average design showing an output of 15,103.57 kWh.

For our first hypothesis, we expected to see significant positive correlations between two psychological measures, the ATTA and the ICAR, and the participant's ratio of annual energy output to building cost in their design. Positive correlations, one of which reached significance, emerged between design performance and the ATTA; however, an insignificant negative correlation was found between design performance and the ICAR. The overall divergent thinking score was positively correlated with design performance, and showed marginal significance ($r = .514$, $p = .087$). The subcomponents also displayed positive correlations: originality was significantly correlated with the design metric ($r = .592$, $p = .0442$), and while fluency ($r = .332$, $p = .291$), flexibility ($r = .486$, $p = .109$), and elaboration ($r = .261$, $p = .412$) all failed to reach significance, they each showed moderate correlations with performance on the design task. There was no significant positive correlation between scores on the ICAR and design performance; instead, an insignificant small negative correlation was found ($r = -.211$, $p = .557$).

The second hypothesis posited that there would be a significant difference in the usefulness of sequential decision making between the participant groups that were created based on their scores on the ATTA and the ICAR. We were particularly interested in the relationship between the second (ATTA score above median, ICAR score below median) and third groups (ATTA score below median, ICAR score above median). Neither prediction was supported. A one-way between subjects ANOVA was conducted to measure the difference in $\delta$ between all groups, and no significant difference was found ($F(3,6) = .515$, $p = .686$).

## Discussion

The research objective of the present study was to explore the relationships between psychological measures used to represent systems thinking and sequential decision making within the engineering systems design context.

To measure systems thinking, six of Greene and Papalambros' mappings [17] of Frank's sixteen cognitive competencies from his CEST model [16] were chosen, based on their relevance to the demands of the design problem. The six chosen competencies can be seen in Table 1. To measure the first competency, the Abbreviated Torrance Test for Adults was administered; for the remaining five, participants were asked to complete the International Cognitive Ability Resource test.

In order to capture sequential decision making, participants were asked to complete an energy-plus home design challenge through the computer-aided design program Energy3D. The challenge was to design a home that, through the utilization of solar energy, resulted in the highest ratio of annual energy output to building cost that participants could achieve; their performance was used to interpret their systems thinking ability and sequential decision making.

The present study had two hypotheses. First, we expected to find positive linear relationships between systems thinking and design thinking; specifically, between the measures of divergent thinking and cognitive ability in comparison to performance on the design challenge. Second, we predicted a significant difference in $\delta$ between the participant groups.

Total divergent thinking and each of the subcomponents showed positive correlations with design performance; only the relationship with participant originality showed significance. Divergent thinking is an essential component of the creative process; without the generation of testable ideas, design would be rendered near impossible.

Cognitive ability displayed a small negative correlation with the performance metric; however, the researchers stress that the high insignificance of the correlation ($p$ = .557) must be considered when interpreting this relationship. The results do not suggest that cognitive ability is detrimental to engineering design, but rather that the ICAR likely does not measure any pertinent psychological constructs.

We found no support towards our second hypothesis. There was no significant difference in $\bar{\delta}$ between participant groups, which has several implications. First, this suggests that there was no benefit to performance in the design challenge through the possession of both high divergent thinking and high cognitive ability. Additionally, these results imply that there is no benefit in showing high ability in only one of these traits, regardless of which the participant was skilled in.

## Limitations

The chief limitations of the presents study reside in the sample that was used. It must first be addressed that our participants were undergraduates, not professional engineers. Thus, the findings are not directly applicable to and do not represent experts and those already in the workforce; it is possible that divergent thinking and cognitive ability play different roles in design when comparing undergraduates and professionals.

Second, the small sample size must be noted. The researchers stress that the results should be taken tentatively, and that any conclusions drawn must be considered in tandem with this limitation. However, as the purpose of the present study was to set a groundwork for future research on this and related topics, we feel it is necessary to document our theoretical and methodological approaches to studying systems thinking and sequential decision making

## Conclusions

The present study set out to build a foundation for the empirical analysis of systems thinking through a psychometric approach, and offered tentative results suggesting which aspects of cognition play a role in engineering design.

Results showed that divergent thinking is closely positively related to performance on the design task, with the originality subconstruct showing significance. Our results also indicate that either cognitive ability played no role in our design task, or that the test used to measure cognitive ability failed to capture any competencies relevant to the design challenge; as the ICAR was employed to measure multiple cognitive competencies, it is difficult to determine how each of the five competencies factor into this relationship. Lastly, analysis did not find a significant difference in sequential decision making based on high ability in either divergent thinking or cognitive ability.

## Future Directions

The present study only looked at the relationship between engineering design and six of the sixteen cognitive competencies given in Frank's model [16]. These six were chosen due to the availability of and convenience of psychological measures for the constructs, and the exploratory nature of the present study; at no point did we believe that these were the only competencies relevant to design. In the future, additional psychological tools measuring different cognitive competencies must be leveraged in order to establish a psychometric approach to systems thinking research.

Additionally, future research should address the limitations that the present study faced. To obtain more sound results, larger samples must be utilized both on undergraduate and professional samples.

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