2013

Systematic Ideation Effectiveness Study of TRIZ

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*The objective of this paper is to present experimental results of a specific ideation method TRIZ (an abbreviation of a Russian acronym of "**T**eoriya **R**esheniya **I**zobretatelskikh **Z**adatch" meaning theory of inventive problem solving) as compared to ad hoc methods used by students. It is critical to understand how and why TRIZ works as it can lead to improvements on how to teach this method, and also how to analyze ideation methods in general. Our hypothesis is that TRIZ improves the creativity level of subjects using it as observed in the produced design outcomes. The experiments were conducted simultaneously at two institutions: University of Texas at El Paso (UTEP) and University of Maryland (UMD). The results were analyzed as part of an existing research partnership with Pennsylvania State University (PSU). The ideation task present here has been used in all three institutions; it is the redesign of a traffic light that uses light-emitting diodes (LED) instead of incandescent bulbs leading to snow build-up on the lights in certain climates as LED's generate less heat to melt the snow. UTEP and UMD student groups were tasked with redesigning the LED traffic lights to resolve this issue. The assessment was performed on the outcome (i.e., ideas generated) using quantity, novelty and variety as metrics. Numerical results of these metrics are shown along with conclusions based on observations of the experimental process. Data presented in this paper conclude that TRIZ does improve the ideation effectiveness metrics Novelty and Variety while slightly reducing Quantity when compared to a control group using ad hoc ideation methods.*
[DOI: 10.1115/1.4024976]

Keywords: TRIZ, analogies, creativity experiments

1 Introduction

Engineering innovation is a key economic development engine for any nation in a rapidly changing technology-oriented world. As part of the innovation process, design engineers must use their creativity to generate ideas; hence, creativity can be considered as an essential skill for any engineer [1,2]. Given the increased competitive pressures, perhaps it is not surprising that industrial employers point to deficiencies in graduating engineers' key design synthesis capabilities such as: problem solving, generation of alternatives, evaluation and decision-making [3]. Engineering schools, aware of these issues, are developing approaches to address this problem and promote creativity and innovation as part of their curricula. Approaches range from revamping the engineering curricula to improving courses with more design content and more open-ended design problems. Although some of these approaches generate valuable skills for the students, creativity and innovation development remain elusive goals [4].

Engineers are routinely trained to solve difficult problems; this demands a certain level of creativity. The challenges of contemporary society (e.g., those in environmental preservation or meeting healthcare needs) demand increasingly creative solutions making better use of the science, engineering and math knowledge. Since engineers face more difficult problems that demand higher levels of creativity they must improve their design creativity skills. These skills can only be taught upon a foundation of design analysis knowledge and design process methods. The design process provides an overall strategy to achieve a solution while the design tools and methodologies help at each step of the process. One of the key steps in creative design is the ideation process; at this step, designers use ideation methods to promote creativity. Thus, engineering design students must learn effective ideation methods to enhance their creativity levels.

Methods to improve the creative process in engineering are seldom taught in undergraduate courses. Highlighting this fact, Kazerounian [5] published a study at a top engineering school noting the absence of critical attitudes and training required to promote creativity in students; background research for that study concluded that students needed to be trained in creative problem solving methods. Supporting this conclusion is a study done on engineering design teams from the University of Texas in Austin and the U.S. Air Force Academy in which students using a suite of concept generation methods were found to increase the quantity of solutions generated and perceptions of their own creativity [6].

The focus of this paper is a rigorously designed, classroom-based, experimental study of TRIZ. Rigorous experimentation on design methods is challenging for two major reasons: (1) a subject can never approach the same design task in the same way and (2) no two subjects are alike. In this set of experiments we dealt with the problem of subject differences by either using students with the same general background (e.g., students from the same courses taught by the same instructor using the same material as done in the UTEP experiments) or by structuring the experiments as repeated tasks done by the same students, as done in the UMD experiments. Each scenario has different impacts as discussed in the paper.

The research question studied in this paper is as follows: **Can TRIZ Improve the Ideation Performance of Engineering Students?**

It is hypothesized that the training of students in the TRIZ ideation method will improve students' ability to generate innovative concepts.

TRIZ is an innovative problem solving method that is based on the systematic search of solution principles derived from the study

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Contributed by the Design Education Committee of ASME for publication in the Journal of Mechanical Design. Manuscript received May 1, 2012; final manuscript received June 23, 2013; published online September 11, 2013. Assoc. Editor: Janis Terpenny.

of patents. TRIZ is often taught only at graduate level courses, and it is regarded as an effective ideation method.

Earlier work reported on results on piloting of this study at Penn State University and University of Texas-El Paso [7]. Students were tasked with designing a biomass oven that reduced harmful emissions for use in rural areas of developing countries. The pilot results indicated that the TRIZ ideation process resulted in some improvement in the ideation metrics of novelty and variety as defined by Shah et al. [8] but further alignment of the experimental protocols and investigation of design task effects was needed before conclusions could be drawn. Armed with the unified experimentation methodology, we have conducted experiments using the same design task across three settings; in this paper, we present the results. Although UMD, UTEP and PSU are partners in this experimental study on TRIZ, only results from UMD and UTEP are reported here. PSU team-based experiments will be presented separately.

2 Background

To ideate is to imagine or conceive[1]. Ideation occurs at the beginning of conceptual design when the notion of a concept is identified. Ideation is the topic of new studies in engineering, usually in the context of comparing the benefits of new design methods. We deem TRIZ to be inherently relevant to analogies as they are used in ideation processes; accordingly, below we first discuss the relation of analogies to ideation and then further focus the discussion on prior works studying TRIZ.

2.1 Studying Analogies to Improve the Ideation Process. Synectics is one of the first formal ideation methods based specifically on the use of analogies [9]. The Synectics creativity methodology was developed by the Cambridge Research Group in the 1940s; this group was searching for a way to access the psychological mechanisms in the inventor that improve his or her creativity. Knowing how to use the four different types of analogies differentiated in Synectics is valuable for anyone wishing to generate ideas about an existing problem. Synectics trains the user in accessing four types of analogy: (1) direct analogy, (2) fantasy analogy, (3) personal analogy, and (4) symbolic analogy.

Howard et al. [10] discuss the integration of design process models with cognitive psychology research on creativity. Prominent among recent ideation studies are methods that present analogies to designers as a way to encourage production of innovative concepts. A few, recent and representative studies are described here. These selected studies examined both the impact of providing certain information about other designs to study subjects and the method of conveying the information.

Chan et al. [11] measured the impact analogies have on the ideation performance of 153 senior engineering students (95% mechanical) tasked with designing a low-cost, portable device to harvest energy from human motion. Subjects were given analogies in the form of either patent figures or patent descriptions at prescribed times during their individual design sessions. Over 1000 generated concepts were assessed for the degree of solution transfer, quantity, breadth of search and quality of concepts. Concepts developed from far-field analogies (those that were from different domains than the design task) were more likely to share the analogy's features and earn higher novelty scores. These benefits came at the cost of a lower number of concepts generated, a higher variability in quality scores, and a lower overall quality than those of concepts generated without using analogies.

Lopez et al. [12] conducted a more focused study on sixteen senior-year and one graduate mechanical engineering students ($N = 17$) using analogies to create peanut shelling devices that worked without electricity. The goal was to test two theories concerning the impact of the domain distance between given analogies and the design task at hand on designer performance and preference in the use of analogies. Results supported the theories tested: (1) analogies from distant domains increased the number of ideas generated, at least to a point and (2) the subjects (mistakenly) believed that analogies from distant domains were not as useful in stimulating ideas as those from closer domains.

Taking a different approach, Ahmed and Christensen [13] performed a protocol study on twelve practicing design engineers, six with less than 2 yr of experience, while they completed their assigned tasks in the mechanical/aerospace industry. Half the tasks were conceptual designs, the others were detailed designs. Results indicated that more (self-selected) analogies were used during conceptual design than detailed design. Novices used the analogies more for direct transfer of knowledge, whereas the experienced designers used analogies as examples for reasoning about the task at hand.

Ideation methods based on analogies exist for groups as well as individuals. Linsey et al. [14] used a factorial experiment design with four, group-based ideation methods (brainsketching, C-sketch, 6-3-5 method, and phase 1 of the gallery method) to determine the influence of two factors: (1) how ideas were shared with group members (i.e., one-set-at-a-time rotation versus an all-at-once, gallery-style) and (2) how ideas are represented (i.e., words, sketches, or both). The ideation methods vary in the type of communication used to initially represent a concept and the way the concepts are viewed by others in the group. The study participants were twelve, five-person, mechanical engineering senior design teams from The University of Texas at Austin ($N = 60$). The teams developed concepts for a machine to quickly shell peanuts without an electrical energy supply. The results were rated using metrics of Shah et al. [8] with some modifications. The major findings from the study were as follows: (1) the variety and quality of the proposed solutions were consistent across the ideation methods but the quantity increased when the sketching and written words combination were used in communication; (2) the form of the representation had a significant impact on the quantity of solutions but not on other metrics; and (3) the sketching-only representation condition created more instances of high-quality solutions (i.e., max score, although the averages were the same).

Although we only provide a few examples from recent design creativity research focusing on ideation methods, their count is indeed growing due to the increasing importance of creativity and innovation. While we refer the readers to relevant review studies for a more thorough documentation (e.g., Ref. [10]), below we focus on TRIZ.

2.2 TRIZ: Analogy-Based Ideation Method. TRIZ is a prescriptive approach to the generation of innovative designs to seemingly intractable problems [15–17]. Genrich Altshuller rejected the notion that psychological factors were the key to improving creativity and sought to find a more concrete basis for a method. Altshuller developed TRIZ by identifying patterns of innovation in existing concepts and repeated design principles in author certificates, the then Soviet Union's equivalent of patents. Altshuller used his insight into how past design challenges were overcome to create a set of steps for rerepresenting the challenges as technical contradictions in an existing design that may be resolved by the application of selected innovation principles. The TRIZ examples are continually being updated by researchers worldwide. Figure 1 shows an overview of the steps and flows of information in TRIZ (adapted from Ref. [15]). One of the probable reasons for the wide acceptance of TRIZ may be that it tries to solve problems from past, proven experiences (i.e., patents); this makes sense to practicing design engineers especially when comparing to other methods which rely mainly on intuition (e.g., brainstorming, method 6-3-5, etc.).

Success stories of TRIZ involving established companies exist (e.g., see Ref. [18,25] for comprehensive studies of TRIZ usage at Ford and Hewlett Packard). In a relevant study done by Okudan

[1]Word English Dictionary, accessed online at dictionary.reference.com

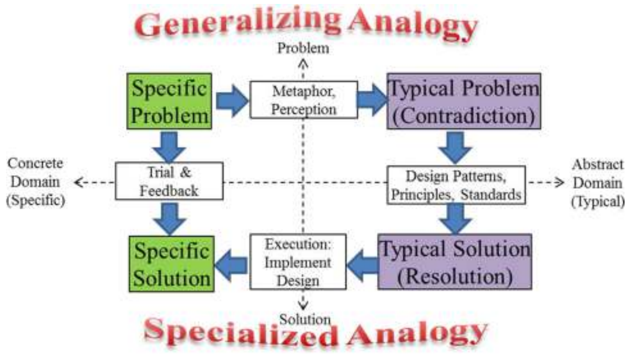


Fig. 1 Overview of TRIZ steps and information flows (Adapted from Ref. [13])

et al. [19], the ideation effectiveness of TRIZ and brainstorming used together was compared to using brainstorming alone. Outcomes were measured by three ideation metrics: quantity, variety, and novelty as described by Shah et al. [8]. The design problem students solved was focused on air velocity control for fumehoods, and was presented by an industry sponsor. Results indicated significant gains in ideation metrics when TRIZ is used with brainstorming. One significant drawback of the study was that it only included team-level analysis of the design outcomes, and the comparisons were made using design reports, and hence, allotted time for ideation was not closely monitored.

TRIZ has also been customized for particular applications and modified to create derived methods. For example, Pham and Liu [20] combined TRIZ principles with I-Ching, an ancient Chinese Philosophy, and provided an example for the layout of seats in an aircraft cabin. Based on the TRIZ principles, Osborn [21] created the **S**ubstitute, **C**ombine, **A**dapt, **M**agnify/**M**odify, **P**ut-to-another-use, **E**liminate, **R**e-arrange/**R**everse model, which simplifies the 40 TRIZ principles to only nine. Furthering this approach, Nakagawa [22] simplified the principles to only five.

Researchers in the UK found that introducing analogical stimuli in the form of TRIZ innovative principles supported the rate of idea generation during brainstorming sessions and lead to less obvious ideas [23].The same lexical study found that the dichotomous stimulus (like that presented in the TRIZ method) led to concepts that were judged by raters to be more novel than other concepts.

Although preliminary evidence exists for TRIZ's potential as an effective ideation tool, its performance has not been conclusively demonstrated. The goal of this work is to provide results from a structured experiment on the effectiveness of TRIZ at improving the ideation process in the engineering classroom. As mentioned previously, prior literature reporting on the effectiveness of TRIZ either focuses on industrial case studies (see Ref. [25] for a review) or provides results at team-level analysis (e.g., Ref. [19]). During idea generation at a team setting, in addition to the ideation tool, several other factors might impact the ideation productivity (e.g., discourse on the design task by members potentially prompting new/additional ideas). Thus, isolation of TRIZ as a factor of significant impact is challenging. The study here addresses this issue by an analysis of the ideation results pertaining to the same design task at the individual level.

3 Research Methodology

This experimental study investigates the ability of TRIZ to improve student creativity. The experimental format limited the length of time for the TRIZ training. Subjects were only introduced to the use of the TRIZ Contradiction Matrix. Using the matrix to identify innovative principles to overcome technical contradictions is the most accessible form of TRIZ for untrained students and is the most widely used. Subjects are not TRIZ experts after the experiment but they are able to use this popular form of TRIZ.

The experimental design is intended to be a rigorous collection of quantitative data to answer the following research question on TRIZ: ***Can TRIZ improve the ideation performance of engineering students?*** The experiments have the objective of comparing students using TRIZ versus students not using it, along with comparisons of preparation levels (e.g., lower classmen to graduate students) for a given design problem. Before conducting the full experiment, the authors ran a pilot study to learn about the variables involved. The experience from the pilot experimentation aided decision-making on conducting the TRIZ training, anticipating students' questions, and refining the experimentation sequence.

3.1 Overview of Experimental Methodology. The general experimental process followed by the participating universities is summarized in a diagram in Fig. 2. The common hypothesis is as follows: *the training of students in the TRIZ ideation method will improve students' ability to generate innovative concepts.* Thus, the main factor identified is the TRIZ intervention with two levels: presence and absence. The responses chosen to measure the effect of the factor are based on Shah et al. [8] effectiveness metrics: quantity, novelty and variety. Experimentation is replicated at UTEP and UMD. One run was assigned for the TRIZ intervention group and another run was defined as the control group (i.e., no TRIZ training). The data collected were the ideas generated by both groups. Judges were trained to assess the ideas using the effectiveness metrics approach based in Shah et al. [8].

After the data collection, the numerical results from the creativity metrics assessment were analyzed to identify statistical significance; this was done using T-tests. Based on the numerical results from the assessment and the T-tests, conclusions were drawn, first for the independent results at each university, and then across institutions. Qualitative conclusions were derived from observations.

This experimental methodology served as the blueprint to develop the replications in the participating universities. Since the exact experimental set up in two different places is nearly impossible,

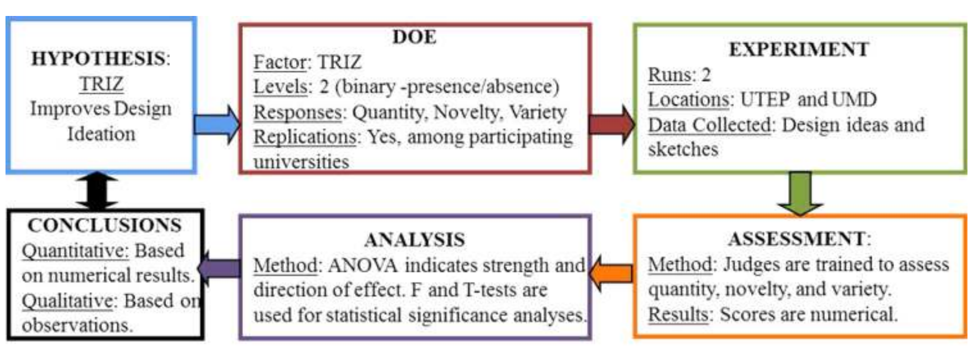


Fig. 2 Experimentation methodology applied across institutions

Table 1 Participating subjects

University	Participating courses (Fall 2010)	Unit of analysis	Student level
UTEP	MECH 4364 (20 in 1 section)—control group MECH 4466 (9 in 1 section)—TRIZ group	Individual	Senior
UMD	ENME600 (20 in 1 section)—control and TRIZ group	Individual	Graduate

relative flexibility on minor details of the experimental procedure was allowed between institutions. The following subsections provide details on the subjects, TRIZ intervention, ideation task, experimentation sequence, assessment method, results and analysis.

3.2 Subjects. All students at the two universities have the following characteristics in common: (1) engineering students, (2) no previous TRIZ experience, and (3) enrolled in a design-related course. UTEP students belong to the Mechanical Design (MECH 4466) or Senior Design Project (MECH 4466) course. MECH 4466 is a prerequisite for MECH 4466 and all ME major students must take these two courses. Maryland students were part of the graduate ENME 600 course; a total of 20 students participated in the experiment. A summary is presented in Table 1. The authors realized that student motivation might also become an issue. For this reason, course grade (between 2% and 5%) as extra credit, in-class assignment or homework was assigned to students upon completion of the experiment. All subjects participated voluntarily and signed appropriate institutional review board release forms.

3.3 TRIZ Intervention. The experimental design requires that student participants prepare a set of design solutions in response to a predetermined design task with and without the TRIZ training (intervention or treatment). The TRIZ treatment included two 50-min lectures. Training materials on TRIZ and the specialized inventive principles and cataloged examples were developed originally by one of the co-authors (under the CCLI Grant No. DUE 0445944). The same set of study materials and examples were available to students in an online module through course management software. The faculty researchers at the study locations administered the TRIZ training.

3.4 Ideation Task. The ideation task selected for the experiment is a redesign of a Traffic Light. It is provided to students along with a newspaper clipping (shown in Fig. 3). The Traffic Light redesign uses a LED instead of an incandescent bulb creating snow accumulation and hence accidents in colder climates. Ideas generated must address the barred vision due to accumulation of snow as well maintain the energy savings of LEDs. The Traffic Light problem was selected because it has an adequate level of technical complexity, domain familiarity, fertility, etc. Assuming that all subjects were familiar with traffic lights was a safe bet. Subjects were provided with a newspaper clipping (Fig. 3) explaining the reasons and consequence of barred vision in snowy conditions. We also note that based on our prior experience on similar studies [19,27], we were familiar with the importance of potential implications of the design task choice; *post facto*, we deem the air velocity control problem in Ref. [19] to be a bit abstract, and the biomass oven design task was not uniformly familiar to our subjects in Ref. [27].

It is expected that more complex problems might produce different results. Hence, the results and conclusions are limited by the experimental variables selected, including the design problem.

3.5 Experimentation Sequence. The detailed experimental sequences for UTEP and University of Maryland are shown in Table 2. UTEP and UMD applied warm-up activities: an unrelated ideation task and the unusual uses of tin can, respectively. The design task is introduced and clarified; this lasts 10 min. UMD has Ideation Session 1 for 20 min; UTEP does not have Ideation Session 1. It has been noted with UMD subjects in this and earlier runs of the Traffic Light experiment that after 20 min of individually generating ideas more than 50% of the students were waiting for the next instruction. The TRIZ group receives the TRIZ training intervention; the control group continues to next step generating ideas with no required method. Students generate ideas for Ideation Session 2. After this, students are asked to continue generating ideas for the next few days with a 2-h involvement limit.

Both institutions followed the same basic experimentation outline; the differences in the details of the experimentation sequence across institutions can provide slight variations on the same experiment. We considered the possibility of cross effects, nevertheless we had a desire to measure the same population before and after the TRIZ intervention; this was the case of UMD experimental setup. To enrich the results and to counteract cross effects, UTEP used two different groups for Control and TRIZ; this takes care of the cross effects, but introduces the possibility of unequal variances. This was addressed using an F-test.

3.6 Assessment Method. The data collected (Ideation Homework in Table 2) were assessed using the ideation effectiveness metrics of Quantity, Novelty and Variety developed by Shah et al. [8]. The numerical results were analyzed using the average (μ) to indicate the direction of the effects (e.g., TRIZ improves or worsens novelty of ideas generated). F-tests were applied to UTEP data to evaluate the variance of the groups (i.e., two samples with equal or unequal variance), and T-tests were used to investigate the statistical significance of the numerical results.

3.6.1 Characterization of Ideas through the Genealogy Tree (GT). The metrics system developed by Shah et al. [8] is based on the GT, a diagram that describes the origin of an idea as shown in Fig. 4. As defined by Pahl and Beitz [24], a function ($F1$, $F2$,…, FX) can be performed through one or more physical principles (PP). A physical principle can be applied through one or more working principles (WP). A working principle can be implemented as one or more Ideas. It is possible to evaluate multiple functions in an idea; each function will have its GT and an importance defined by a relative weight (e.g., $F1 = 50\%$, $F2 = 30\%$, $F3 = 20\%$).

A GT represents a group of ideas. For the experiment, one GT can be defined initially for the TRIZ group and another one for the control group. If the TRIZ and control group are to be compared (as is expected here), the groups' trees need to be merged. The merging process requires having common terms used for the branches; after this, each group can have its own GT based on the aligned definitions of the merged PPs and WPs. A GT for a given group is always created by at least two judges through dialog. When two GTs from different groups are merged, the judges must agree on the terms and concepts; in most cases agreement is easily reached, but in some cases, the judges must go through multiple iterations to arrive at an agreement. The merging also happens across universities; at the end, all three institutions share the same merged tree for assessing all experimental groups.

The **Quantity** of ideas was calculated by adding all the idea counts from each WP branch in a GT for a given group and then dividing this total by the number of subjects in the group. This provides an average quantity of ideas per subject.

Novelty is a characteristic of a single idea based on the frequency with which it appears in a GT. Novelty is calculated using the following formula (Note that the following formula is modified from the original from Shat et al.'s [8] as a problem with the http://abcnews.go.com/US/wirestory?id=9345450&page=2 Page

October 25, 2010
Ideation Exercise

ENME600/648E
Article at right
The Associated Press

By DINESH RAMDE Associated Press Writer
MILWAUKEE December 15, 2009 (AP)

In this photo provided by the Oswego Police, was taken after a fatal crash in Oswego, Ill, on April 6, 2009, Oswego police Detective Rob Sherwood said the wind had blown the snow over the red light, causing a driver run the light and hit the vehicle of 34-year-old Lisa Richter, who was making a left turn. She was killed. (AP Photo/Oswego Police)
(AP)

abcNEWS

Energy-Efficient Traffic Lights Can't Melt Snow

Traffic accidents are blamed on energy-efficient traffic lights getting covered with snow

Cities around the country that have installed energy-efficient traffic lights are discovering a hazardous downside: The bulbs don't burn hot enough to melt snow and can become crusted over in a storm -- a problem blamed for dozens of accidents and at least one death.

"I've never had to put up with this in the past," said Duane Kassens, a driver from West Bend who got into a fender-bender recently because he couldn't see the lights. "The police officer told me the new lights weren't melting the snow. How is that safe?"

Many communities have switched to LED bulbs in their traffic lights because they use 90 percent less energy than the old incandescent variety, last far longer and save money. Their great advantage is also their drawback: They do not waste energy by producing heat.

Authorities in several states are testing possible solutions, including installing weather shields, adding heating elements like those used in airport runway lights, or coating the lights with water-repellent substances.

Short of some kind of technological fix, "as far as I'm aware, all that can be done is to have crews clean off the snow by hand," said Green Bay, Wis., police Lt. Jim Runge. "It's a bit labor-intensive."

In St. Paul, Minn., for example, city crews use air compressors to blow snow and ice off blocked lights.

Some communities began installing cool-burning LEDs more than a decade ago, and it wasn't long before drivers started complaining about the problem.

Illinois authorities said that during a storm in April, 34-year-old Lisa Richter could see she had a green light and began making a left turn. A driver coming from the opposite direction did not realize the stoplight was obscured by snow and plowed into Richter's vehicle, killing her.

"Would the accident have occurred if the lights had been clear? I would be willing to bet not," Oswego police Detective Rob Sherwood said.

Authorities said dozens of similar collisions have been reported in other cold-weather states, including Iowa and Minnesota.

Not every storm causes snow to stick to the lights, but when the wind is right and the snow is wet, drivers should beware, said Gary Fox, a traffic engineer for the city of Des Moines, Iowa.

Exactly how much a technological fix will cost is unclear, but it will surely cut into the savings and the energy efficiency many cities are enjoying.

Wisconsin, which has put LED bulbs at hundreds of intersections, saves about $750,000 per year in energy costs, said Dave Vieth of the state Transportation Department. LEDs installed seven years ago are still burning, while most incandescent bulbs have to be replaced every 12 to 18 months, he said.

"With LEDs we have energy savings in excess of 80 percent, and we don't have to have crews replacing them as often," Vieth said. "So it's clear the overall savings are pretty significant."

In Minnesota, authorities are more than halfway to their goal of upgrading the state's 1,300 or so traffic lights to LEDs. The Transportation Department occasionally gets reports of an obstructed light, but often by the time a highway crew arrives, the wind has knocked out the snow and ice, said traffic systems specialist Jerry Kotzenmacher. Minnesota is experimenting with weather shields.

One reason there have been so few deaths is that drivers know they should treat a traffic signal with obstructed lights as a stop sign, traffic experts say.

"It's the same as if the power is out," said Dave Hansen, a traffic engineer with the Green Bay Department of Public Works. "If there's any question, you err on the side of caution."

Associated Press writers Patrick Condon in Minneapolis and Melanie Welte in Des Moines, Iowa, contributed to this report.

This Dec. 2009 image made from video provided by WLUK-TV Green Bay shows a wrecker getting ready to tow away a car that was involved in an accident in Green Bay, Wis. after a recent snow storm. One downside to the energy-saving LED lights many communities are installing to replace older incandescent bulbs is they don't melt snow very well snowing over the yellow and red lights. (AP Photo/WLUK-TV Green Bay) MANDATORY CREDIT (AP)

Fig. 3 Handout developed to introduce the traffic light design task to students (paper from Ref. [26])

metric was identified and the following version was proposed along with proof in Ref. [28])

$$\text{Novelty} = \frac{\left(\dfrac{1}{\text{Total number of ideas at a given WP branch}}\right)}{\text{Number of WP branches in GT}} \quad (1)$$

Following Fig. 4 as an example, the Novelty score for WP1.2.1 is as follows:

$$\text{Novelty}_{\text{WP1.2.1}} = \frac{\left(\dfrac{1}{3}\right)}{4} = 0.083$$

Table 2 Detailed experimentation sequence

	UTEP	UMD
Warm-up	Unrelated ideation task (20 min)	Unusual uses of tin can (10 min)
Introduce design task	Familiarize students with the design task (10 min)	Familiarize students with the design task (10 min)
Ideation Session 1 in-class (no method)	None	Ideas are generated and recorded by students (20 min)
TRIZ training intervention	Common TRIZ PowerPoint presentation lecture, with TRIZ Principles and Contradiction Matrix Handouts (except for UTEP Control Group)	
Ideation Session 2 in-class	Ideas are generated and recorded by students (50 min)	Ideas are generated and recorded by students (30 min)
Ideation Homework (TRIZ)	**Ideas generated with 2-H time limit** due in 1 week	Ideas Generated with 2-h time limit due in 1 week

All ideas for that WP branch will share the same Novelty score. Scores for other GT branches in Fig. 3 are calculated similarly. Notice that ideas from WP branches with more options receive a lower Novelty score when compared to WP branches with fewer ideas. Once each idea receives a Novelty score, it is possible to calculate an average Novelty score per subject.

Variety is a characteristic of a set of ideas and reflects the spectrum of ideas generated with different working and physical principles. Variety is calculated using the following formula:

$$\text{Variety} = \frac{(\text{Number of PP} * \text{Weight for PP} + \text{Number of WP} * \text{Weight for WP})}{\text{Total number of ideas in the GT}} \quad (2)$$

With this formula, the Variety score can be calculated for the group represented in the GT. Following the example in Fig. 4 and assigning a weight of 9 to PP and a weight of 3 to WP

$$\text{Variety} = \frac{(2 * 9 + 4 * 3)}{8} = 3.75$$

Notice that if more branches exist at the WP level, the Variety score would increase.

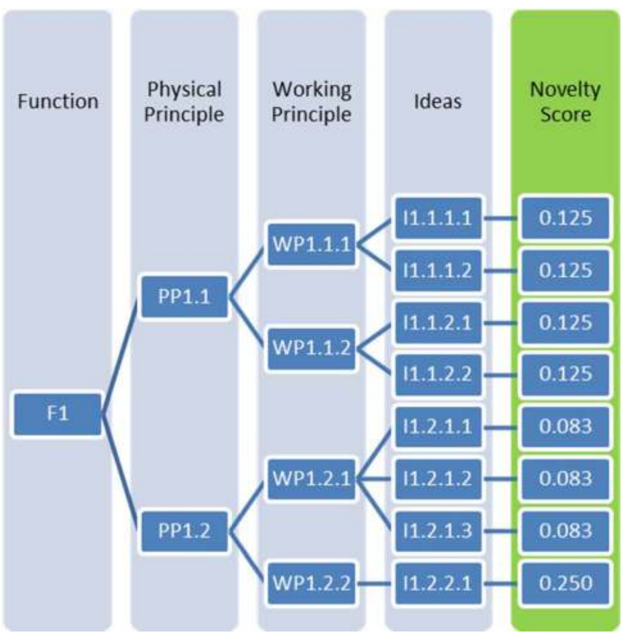


Fig. 4 Sample genealogy tree diagram for function 1

4 Results and Analysis

Figures 5–7 show sample ideas generated at UTEP and UMD using the TRIZ method for the Traffic Light Problem. Figure 5 identifies the principles used while Figs. 6 and 7 present sketches generated using the TRIZ method.

The merged GT for the Traffic Light design task is shown in Fig. 8. The tree was developed jointly by UTEP and UMD with help from Penn State as a first step in the assessment process. The tree is for the main function of the redesigned traffic light: Counter Snow. Figure 8 also includes the data collected from UTEP and UMD. The numbers indicate idea counts at each branch for the Control and TRIZ groups. It is important to clarify that the GT in Fig. 8 is the result of merging UTEP, UMD, and PSU branches; this is evident since Chemical-Heat Generation and Chemical-Combination branches have zero occurrences for UTEP and UMD. We kept this merged tree for future comparison with PSU data and because its effects on metrics calculations are equal for UTEP and UMD. We also note that both at UTEP and UMD data collection was done and reported for individuals.

The numerical results and statistical analysis for Quantity, Novelty, Average Novelty per subject, Maximum Novelty per subject and Variety are shown in Tables 3–6, respectively. The tests compare the Control Group data collected during the in-class, ad hoc design method (Ideation Session 1 for UMD before TRIZ intervention and Ideation Session 2 for UTEP's Control Group) to the TRIZ results submitted as a homework assignment (Ideation Session 2) by the students due in after 7 days for the UTEP and UMD group. The UTEP subjects were different for the Control and TRIZ groups; UMD subjects were the same for Control Group and TRIZ group (before and after TRIZ intervention respectively). Figure 9 below introduces a graphical summary of the numerical results for (a) Average Quantity, (b) Average Novelty, (c) Maximum Novelty, and (d) Variety; each is discussed in detail in the following subsections.

4.1 Average Quantity per Subject (UTEP & UMD). Results in Table 3 for UTEP and UMD indicate that there is no statistically significant difference in the average quantity of ideas generated per subject with the use of TRIZ when compared to the

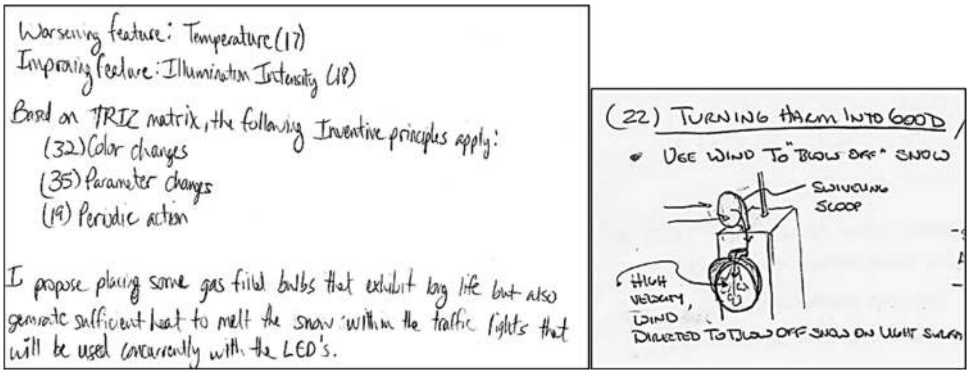


Fig. 5 Sample TRIZ solutions generated at UTEP and UMD that show the use of TRIZ principles

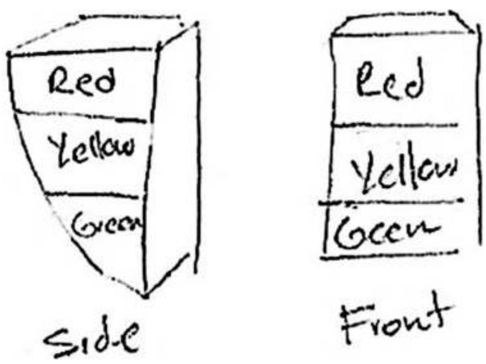


Fig. 6 Sample sketches generated at UTEP with the TRIZ methodology using a change of geometry

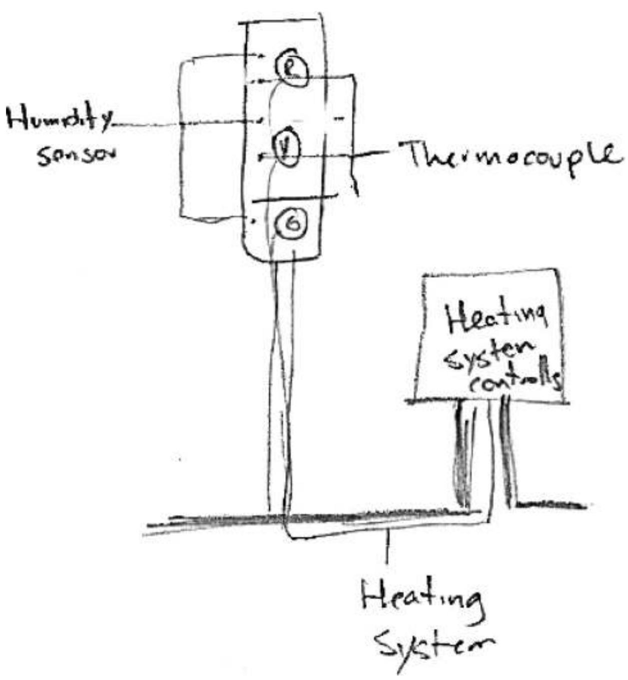


Fig. 7 Sample sketches generated at UTEP with the TRIZ methodology using a heating system

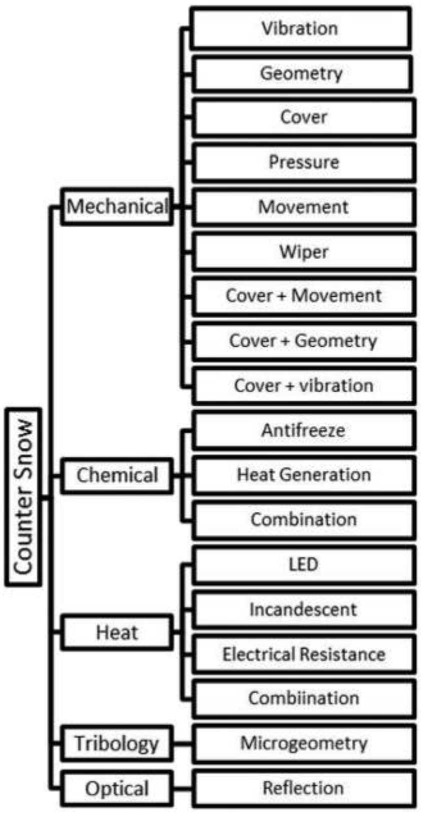
control group. TRIZ requires subjects to follow a specific procedure while the control group doesn't have to follow the formalities of a structured ideation method providing the opportunity to generate more ideas. Data show small decreases in the average quantity of ideas generated using TRIZ; however, the observed decreases are not statistically significant.

4.2 Average and Maximum Novelty per Subject (UTEP & UMD). Results for Average Novelty calculated per subject (Table 4) indicate a statistically significant increase, with p-values of 0.014 and 0.004 for UTEP and UMD, respectively, when TRIZ is compared to the control group. These results indicate that TRIZ produces more GT branches and fewer occurrences at each branch when compared to the control group (i.e., not following a structured ideation method).

The increase in Average Novelty per subject using TRIZ is consistent with positive results from other studies of designers using analogies from distant domains (e.g., Refs. [11,12]). The TRIZ inventive principles are abstractions in domain-neutral language (e.g., segmentation, spheroidality) generalized from many distant domain analogies.

TRIZ increases the Average Novelty of ideas generated per subject as previously mentioned, but the UTEP subjects' standard deviation (σ) also increases from 0.127 to 0.301 with a significance of $P = 0.002$ calculated from the F-test. This means that more subjects increase their average Novelty, but it doesn't account for changes in an individual's best performance. The maximum novelty metric is important since these ideas have better chances to be selected and continue through the design process. The Maximum Novelty results (Table 5) indicate that TRIZ increases the Maximum Novelty at UTEP and UMD. But only the UTEP increase is statistically significant. This TRIZ result of increased variability in personal novelty scores was predicted by a recent analogy study for the distant domain condition [14].

4.3 Variety per Group (UTEP & UMD). Variety results (Table 6) indicate an increase using TRIZ when compared to nonprescribed ideation process (i.e., control group); this pattern is similar both at UTEP and UMD. The Variety calculation takes into consideration the number of branches in the group's own genealogy tree as a way to measure the extent of exploration of the design space; branches at higher (more abstract) levels (e.g., physical principles) have more relative weight than branches at lower (more concrete) levels (e.g., working principles). The experimental numerical results indicate that TRIZ helps subjects to better explore the design space through a search of ideas; this is reflected as more branches in the genealogy tree. Because variety scores are calculated at the group level, statistical comparisons across experimental and control groups were not possible.



Category	Idea	UTEP Control	UTEP TRIZ	UMD Control	UMD TRIZ
Mechanical	Vibration	2	0	6	10
Mechanical	Geometry	5	1	11	5
Mechanical	Cover	7	1	12	13
Mechanical	Pressure	2	2	2	5
Mechanical	Movement	0	1	0	4
Mechanical	Wiper	3	0	13	7
Mechanical	Cover + Movement	0	0	1	2
Mechanical	Cover + Geometry	0	0	0	1
Mechanical	Cover + vibration	0	0	0	1
Chemical	Antifreeze	2	3	3	5
Chemical	Heat Generation	0	0	0	0
Chemical	Combination	0	0	0	0
Heat	LED	2	1	0	2
Heat	Incandescent	1	0	7	5
Heat	Electrical Resistance	14	4	21	14
Heat	Combiination	0	1	0	0
Tribology	Microgeometry	3	1	6	5
Optical	Reflection	0	0	0	2

Fig. 8 Traffic light redesign merged genealogy tree with idea counts for UTEP and UMD

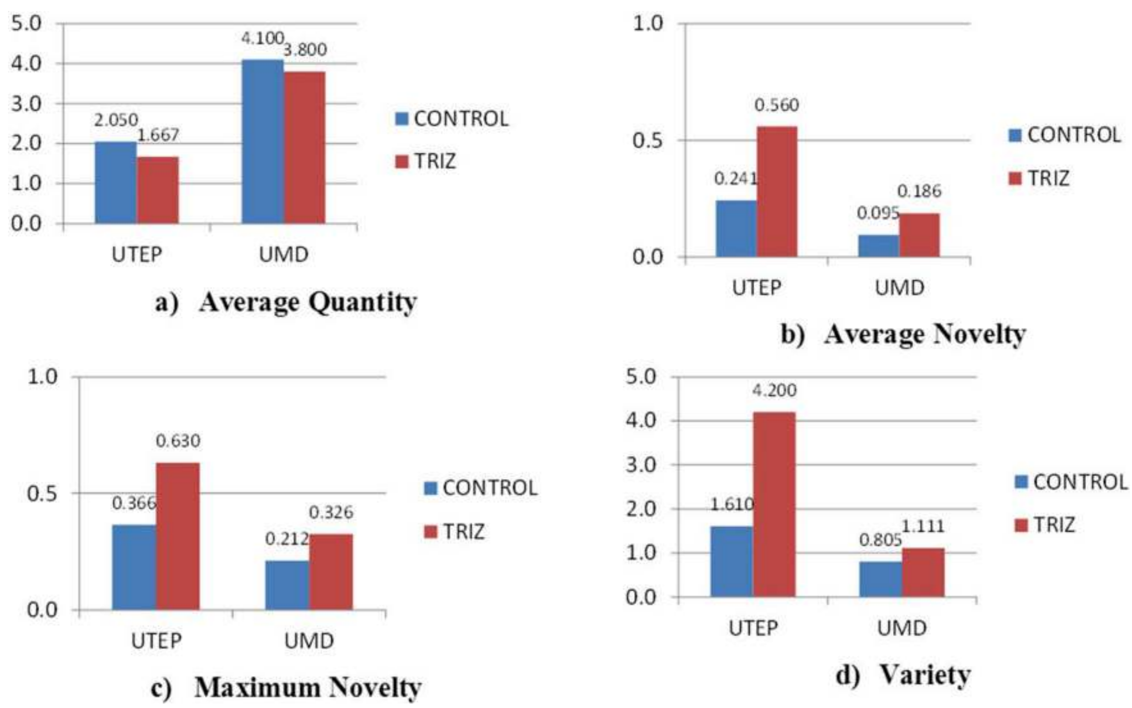


Fig. 9 Graphical summary of results

Table 3 Average quantity numerical results from UTEP and UMD experiments

	Control (μ,σ)	TRIZ (μ,σ)	Set	F-test	T-tests: Type	T-tests: Significance (P-value, 2 tails)
UTEP	(2.050, 0.999) ($N=20$)	(1.667, 0.500) ($N=9$)	Average per subject	0.0510	Two-sample unequal variance	0.181
UMD	(4.100, 1.119) ($N=20$)	(3.800, 2.067) ($N=20$)	Average per subject	0.010	Two-sample unequal variance	0.573

Table 4 Average novelty numerical results from UTEP and UMD experiments

	Control (μ,σ)	TRIZ (μ,σ)	Set	F-test	T-tests: Type	T-tests: Significance (P-value, 2 tails)
UTEP	(0.241, 0.127) ($N=20$)	(0.560, 0.301) ($N=9$)	Average per subject	0.002	Two-sample unequal variance	0.014
UMD	(0.095, 0.079) ($N=20$)	(0.186, 0.104) ($N=20$)	Average per subject	0.243	Two-sample equal variance	0.004

Table 5 Maximum novelty numerical results from UTEP and UMD experiments

	Control (μ,σ)	TRIZ (μ,σ)	Set	F-test	T-tests: Type	T-tests: Significance (P-value, 2 tails)
UTEP	(0.306, 0.166) ($N=20$)	(0.630, 0.359) ($N=9$)	Maximum per subject	0.006	Two-sample unequal variance	0.029
UMD	(0.212, 0.2289) ($N=20$)	(0.326, 0.268) ($N=20$)	Maximum per subject	0.485	Two-sample equal variance	0.156

Table 6 Variety numerical results from UTEP and UMD Experiments

	Control (μ)	TRIZ (μ)
UTEP	1.610 ($N=20$)	4.200 ($N=9$)
UMD	0.805 ($N=20$)	1.111 ($N=20$)

5 Discussion and Conclusions

The goal of this study was to test the effectiveness of a particular ideation method, TRIZ. Data presented in this paper conclude that TRIZ does improve the ideation effectiveness metrics Novelty and Variety while slightly reducing Quantity when compared to a control group using ad hoc ideation methods. Although the statistical significance of the results is limited, the trends indicate a consistent positive impact of TRIZ regardless of institutions, courses, student levels, and other differences in the experimental variables. Variety and Quantity are process variables (i.e., subjects can be asked to generate more and varied ideas) while Novelty is an outcome metric (i.e., cannot be directly controlled); typically, process variables are means to obtain outcome variables. Results indicate that TRIZ improves Variety (Table 6) and average Novelty (Table 4) per subject; the latter result may be more important since it is an outcome metric. TRIZ improved the Maximum Novelty (Table 5) for ideas generated per subject for the UTEP group as well; this is important when effectiveness "spikes" are considered more valuable than an average improvement. It was also found that the application of TRIZ reduces the quantity of ideas generated; this reduction is not statistically significant, and because quantity is a process variable, this is not necessarily counterproductive if other outcome metrics are improved.

The quantitative results for TRIZ, although limited to the design context and the task described in this paper, have wider implications. First, the experimental results match between two institutions (UTEP and UMD), and second, the experimental results match between graduate and undergraduate engineering students.

Work done on ideation by analogies provides insight into the effectiveness of TRIZ. TRIZ is based on analogical reasoning. The inventive principles are abstract principles of strategies to apply to change an existing design into a new one. Thus, TRIZ acts to supply appropriate, distant domain analogies to designers and this strategy has been shown to improve the quality and quantity of concepts in ideation experiments [11,12,14].

The overall results presented in this paper lead us to conclude that TRIZ is an effective method for ideation and can lead to broader sets of solutions than when students address the design task without any formal ideation method. These results are naturally limited in their validity to the selection of experimental variables (i.e., design problem, subjects, interventions, etc.). As future work, the authors would like to address the role of the implementer's personality on the TRIZ ideation process as well as running more experiments to understand how TRIZ can be more easily integrated to the engineering design curricula.

Acknowledgment

The authors gratefully acknowledge the support of the National Science Foundation grant. The project is funded by NSF grant CCLI-II 0920446. The opinions expressed in this paper do not necessarily reflect those of NSF. The authors also acknowledge the student participants in the pilot studies.

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