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The Creativity Model for Fostering Greater Synergy between Engineering Classroom and Industrial Activities for Advancement of Students' Creativity and Innovation*

TEBOHO PITSO
Centre for Innovation and Entrepreneurship, Vaal University of Technology, Private Bag X021, Vanderbijlpark, Andries Potgieter Blvrd ~ 1900, South Africa. E-mail: biki@vut.ac.za

This article describes the TRIZ-based Creativity model whose prototype was iteratively tested for efficacy in closing the transactional space between undergraduate classroom activities and industrial processes with the purpose of advancing undergraduates' creativity and innovation. The testing of this creativity model included presentations in two conferences of the International Multi-Conference on Engineering and Technological Innovation (IMETI) organised under the auspices of the International Institute of Informatics and Systematics (IIIS) and received excellent reviews (an average of 85%). The effectiveness of this creativity model in developing students' creative abilities was also tested on twenty-four, final-year Process Instrumentation undergraduates after two iterative pilot studies. The pre- and post-test results derived from evaluating students' creative abilities through the standardised Torrance's Tests of Creative Thinking (TTCT) show significance as measured through the t-test. Given the establishment of statistical significance in this study, it can reasonably be inferred that the TRIZ-based Creativity model with its leveraging of the university-industry nexus had a positive effect on increasing undergraduates' creative abilities and sets conducive conditions for students' innovativeness. The design and testing of this creativity model needs to be understood within the framework of the emerging synergistic connection among universities, industry and government which seeks to drive greater innovation and technological advancements for which the university-industry nexus was accentuated in this study.

Keywords: TRIZ; creativity, innovation, TTCT; Engineering Education

1. Introduction

In more recent times, engineering education has embraced a new vision that attempts to connect undergraduate engineering studies with creativity and innovation. This new engineering education vision suggests that creativity and innovation occur in a collaborative manner that involves greater interaction between classroom activities and industry processes within the open innovation systems [1–4]. At the more theoretical level, this new engineering education vision is guided by the advent of the knowledge-based society in the 21st Century which marks the coming of age of universities as equal in status with government and industry in respect of driving economic and social development [5]. Whereas in the past, universities tended to play a more secondary and supportive role to government and industry as two primary drivers of societal development, today the interaction among universities, industry and government has become equally distributed and is the source of innovativeness and development of incubators, innovation hubs, interdisciplinary research and venture capital in any of the three spheres of society—private, public and social. There are today sufficient grounds to link technological advances with the greater synergistic cooperation among universities, industry and government [5]. In order to explore this new way of generating and using knowledge within the open innovative systems and understanding better how greater interaction between engineering undergraduate classroom activities and industrial processes, as aspects of the university-industry nexus, could unleash a new creative energy that could contribute in the development of innovative products and services for betterment of society, I invited twenty-four, final-year Process Instrumentation undergraduates to participate in a semester-long study.

This study focused on testing the viability of the TRIZ-based Creativity Model that attempted to close the transactional space between classroom activities and industrial processes within the framework of allowing students to search for the ideality and higher designs of operating industrial technologies. This study was preceded by two pilot studies and two international conferences whose findings and reviews were fed into improving the creativity model. The creative abilities of the students were pre- and post-tested using the standardised Torrance's Tests of Creative Thinking (TTCT) which measure the number of ideas each student generated per given time (fluency), the variety of the generated ideas (flexibility) and the unusualness of the generated ideas (originality). The purpose of the pre- and post-test measures was to determine the extent to

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which students' creative abilities increased as the result of exposure to the TRIZ-based Creativity Model so that the students' TTCT scores were tested for significance through use of the t-test. The t-test results show significance and thus confirm the viability of the TRIZ-based Creativity Model in facilitating students' creativity through closer interaction between university-industry nexus. The students' innovativeness was evaluated through determining the extent to which the results of their case studies attempted to be disruptive of existing sets of benefits for a particular context.

2. Teaching-learning methodology

2.1 The TRIZ-based creativity model

This creativity model is based on TRIZ theory. TRIZ is derived from the Russian phrase "*Teoriya Resheniya Izobretatelskikh Zadatch*" which translates into "*The theory of inventive problem-solving*" [6, 1]. TRIZ is a heuristic problem-solving theory that was developed by the Russian, Genrich Saulovich Altshuller, in 1946 and by the late fifties had become a powerful methodology for creative problem-solving in engineering. The uniqueness of TRIZ resides in the use of a relatively small number of concepts, heuristics and effective knowledge databases to solve non-routine problems of any of the classes of problems ranging from the improvement of quality or/and quantity to the search for and prevention of shortcomings through creation of fundamentally new techniques to fit new needs [7, ii]. TRIZ is also a model-based technology for generating innovative ideas and solutions thus becomes compatible with another type of creativity called innovation. TRIZ, unlike other problem-solving techniques such as brainstorming which derives from random ideas generation, aims for systematic and scientific approach to the invention of new systems and the refinement of existing ones [7, 4–7]. TRIZ has proved to be effective in problem formulation, system analysis, system failure analysis and patterns of system evolution [8–12].

According to Rantanen and Domb [6], TRIZ supports most of the features of good solutions because it ensures that contradictions in the system or technology are resolved through finding relevant information to eliminate these contradictions. TRIZ tends to focus on the use of idle resources thus pitching it closer to the sustainable development discourses with its emphasis on bridling the use of natural resources. TRIZ is also recognized for its reorganization of creative activities. This allows for the transition from the existing ways of conventional problem-solving where contradictions of the technologies or systems are hidden leading potentially to use of additional resources in problem-solving to new ways of systematic and creative problem-solving where contradictions are clarified, idle resources are used and ideal outcomes are illuminated early on to guide the solution space. The features of a good solution that underpin TRIZ are represented schematically in Fig. 1.

According to Rantanen and Domb [6]), these features of a good solution came into being as a consideration of McGregor's theories X and Y [13]. The hard model of problem-solving as described through McGregor's Theory X has largely been discredited because of its emphasis on control. The solutions under the hard model are mediated through budgets and time limits in an atmosphere of some asphyxiating management control. The underlying assumption under this problem-solving conditions is that people need to be controlled and directed tightly so that the end-result of this approach to problem-solving has been minor improvements but seldom produced great, qualitatively new ideas [6, 6). Rantanen and Domb [6, 7] suggest a problem-solving approach that fits McGregor's Theory Y where people naturally have imagination and creativity in solving problems. This creative problem-solving approach encourages free ideas generation but lacks the rigour often associated with hard models of pro-

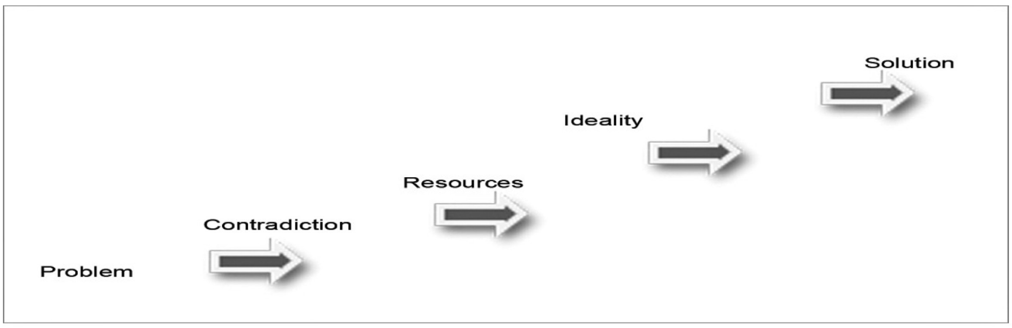


Fig. 1. Features of good solutions [6, 7].

blem-solving. TRIZ solves the problems encountered in both these approaches to problem-solving through pursuing the understanding of the problem, modeling the contradictions, checking the patterns of evolution in the problem, removing these contradictions through using idle resources and improving the ideality of the technology or system. Ideality refers to the pursuit and achievement of a higher design of the technology [6, 7].

TRIZ problem-solving relies on the knowledge of the technology or system that needs improvement and the knowledge of the systematic method for improvement as its focus is not on whether people are creative or not but focuses on whether the ideas that are being generated to find a solution are good or bad so that good ones can be elaborated on. TRIZ method insists on knowledge and good information to resolve difficulties in the technology or system and thus thrives on research and management of various pieces of information. Hence, TRIZ calls for people to manage complexity.

The following principles and elements of TRIZ Theory were gleaned to inform the study's creativity model:

- The use of as few as possible concepts in positing the theory. I believe that creative problem-solving is sufficiently difficult without being obfuscated by a complicated model.
- Its focus on both technical and non-technical problem-solving. I am aware that most of the methods for solving technical problems in engineering are unique to each specialized area of engineering [7] and are thus very limiting. TRIZ problem-solving heuristics, on the other hand, increases the scope of creative problem-solving as it works well both with engineering and non-technical problems. A creativity model that transcends the confines of the technical is more likely to affect the personal lives of users in more profound ways.
- The use of systematic and scientific approaches to problem-solving. I have reason to believe that a research-based approach almost always has a growth focus as users are more likely to generate new insights or information to guide decisions towards solutions.
- Its ideality-driven approach. One of the most important aspects of TRIZ is that it seeks the higher designs of existing technologies which is hugely relevant to the study. First and for the study's purpose, all technologies that are driven by depleting natural resources are irredeemably flawed and require improvement.

Water, coal-based energy and forestation-driven paper production technologies need urgent attention either by way of significantly reducing unfettered use or turning to alternative sources. I provided extended opportunities to students in the study to pursue the higher designs (ideality) of these technologies. I further allowed students to systematically investigate these resources to seek their ideality which brings into sharper focus the six classes of inventive problems [7]. Every effort on ideality status of the existing technologies has, over many years, revealed the consistent emergence of any of these inventive problems [7, 6]. These six classes are divided in terms of whether they first, *require an entirely new solution or change in the existing techniques*. Second, on *Improvement or/ and perfection in both quality and quantity of product or service* which focus on reducing contradictions in an existing system or technique. The s*earch for and prevention of shortcomings* attempts to diagnose weaknesses, contradictions and flaws in a system or technique before they actually occur and move towards proactiveness. *Cost reduction of existing technique*, as the fourth class, attempts to trim or significantly reduce existing inputs (capital, human and physical resources) without compromising outputs (products or service). Its primary focus is on productivity of an entity. *New use of known processes and systems* is analogous to trying out new ways by sensing limits and creating new insights that transform existing processes and systems into more effective instruments. Sixth, focus is on *Generation of new "mixtures" or hybrids of already existing elements* which synthesizes these elements in ways that foreground new thinking, new insights and new ways of doing things.

I have put these classes of inventive problems at the heart of our creativity model together with the search for ideality of existing technologies. TRIZ use of idle resources is in line with general thinking in the 21st Century on environmental sustainability and issues related to recyclability. I believe that by insisting on credible knowledge and good information, TRIZ resonates strongly with the view that creative problem-solving is essentially research-driven. Hence, the study's educational efforts on creating learning conditions that are conducive to research-driven learning were deemed vital. I also labour under the impression that our efforts in the study may contribute to the development of a socially relevant curriculum and set out educational settings that keep students socially engaged and conscious of environmental sustainability for posterity. Based on these key principles of TRIZ, I set out to design our own creativity model.

The first critical step in our model relates to the meaning and current ideality status of the technology with the questions focusing on demystifying the technology and checking whether the technology is operating at near-perfect. Given that almost all

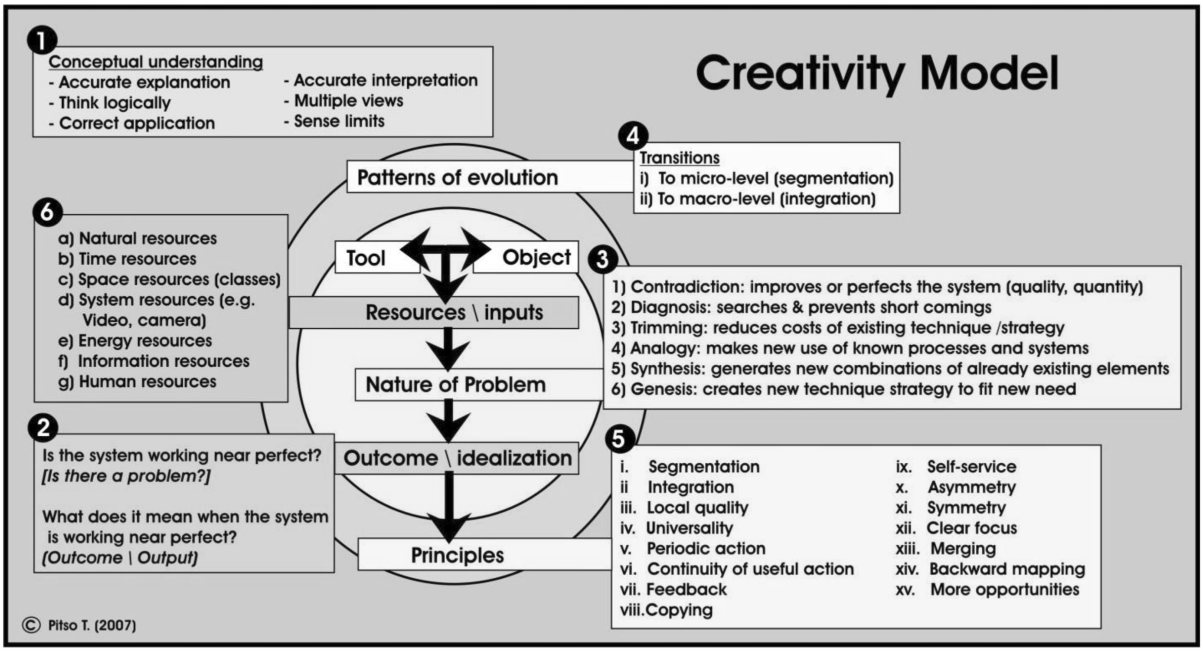


Fig. 2. The Creativity Model developed, showing its six steps.

technologies that were designed during the industrial age were premised on unfettered use of natural resources [14, 15], I took it for granted that most existing technologies would require rethinking and possible redesign to cater for the new dwindling status of natural resources. In the actual study I provided some evidence of the environmental challenges of the technologies related to water, coal-based energy and paper. Students were expected to investigate the issues further.

The second step related to the causes or constraints that prevent the technology from operate at near-perfect. As I suggested earlier, I also expected students to add to this list of possible causes or constraints as and when their own systematic investigation points to a different set of causation or constraints.

Step three entailed deciding on the transition that may need to occur in order to resolve identified causes or constraints and in the fourth step, decisions relate to the pattern of evolution that may be required to achieve the higher design of the chosen technology even at a level of gaining insight. In step five, I thought it wise to include the principles that may lead to the resolution of the identified cause(s) or constraints in the chosen technology.

Step six involved identifying and estimating the resources that may be required in order to achieve the higher design of the chosen technology. It is important to note that each of these steps required more than mastery of existing knowledge in the textbooks and thus compelled students to undertake fieldtrips which involved observing and interviewing personnel where these technologies were operated with focus beyond current technology operations. The model is illustrated in Fig. 2.

The conceptual framework of this model was given credence by its presentation at conferences and in peer-reviewed journals. It was first presented at the International Conference on Learning held in Johannesburg, South Africa in 2007 [16] and accepted for publication in the a peer-reviewed International Journal of Learning, Volume 14, Number 8 [16]. In 2008 and 2009, the model was presented at the peer-reviewed conferences entitled 'International Multi-Conference on Engineering and Technological Innovation'' held in Orlando, Florida (USA) and the overall rating of the paper was 9/10 as judged by three blind reviewers [17, 18]. Prior to using the model in the study, the model was twice piloted on 53 Power Engineering undergraduates and was rated, during two focus group interviews, as user-friendly by the participants. I, however, was under no illusions that the model would yield results immediately. I understand that to be sufficiently skillful in TRIZ and models underpinned by TRIZ considerable time is needed and our current engineering undergraduate educational settings struggle to provide time in the existing curricular conditions that continue to be mediated mainly through packed syllabus, full of science and maths and technical subjects [1].

2.2 *Testing the creativity model*

In order to determine the effectiveness of the TRIZ-based Creativity model, twenty-four final-year Process Instrumentation undergraduates were invited to participate in the study that took six months. The study was conducted at the same venue where the Process Instrumentation classes usually take place to ensure as minimal disruption as possible of the naturalistic settings which is the precondition of the Design-Based Research (DBR) methodology that was used in the study. DBR, as a mode of inquiry, draws on multiple theoretical perspectives and research paradigms with the express purpose of building and establishing understandings of the nature and conditions of learning. In the case of this study, these understandings around the nature and conditions of learning relate to finding appropriate learning conditions that can result in the development of undergraduates' creative abilities. DBR is intended to develop evidence-based claims from naturalistic investigations that can result in knowledge about how people generally learn [19]. DBR work thus involves the development of learning conditions with a view to achieving clearly stated outcomes which, in the case of this study, entail improved undergraduates' creative abilities and advancing a learning theory that can be used in engineering education to understand and support learning conditions that can lead to the development of creativity within the undergraduate curriculum. The fundamental essence of DBR is that knowing and context are ''*irreducibly co-constituted and cannot be treated as isolated entities or processes*'' [19, 2]. DBR methodological approaches are closer to quasi-experimental design as it requires no control group.

The first contact session with the students involved testing their creative abilities through the standardized Torrance's Tests of Creative Thinking (TTCT) which have proved to be culture neutral except the use of the US-Dollar which was converted into South African Rand. In this session, students were explicitly trained on the TRIZ-based Creativity model and were further informed about resources that were made available to them in order to tackle the tasks at hand which included special internet and library access, telephones and transport. Students were also divided into three intermediate teams and were given three case studies of which each team selected what was comfortable for the team. The case studies involved water purification and distribution technologies, energy generation, transmission and distribution technologies as well as paper production and recycling technologies.

The second session involved sharing the climate change and carbon footprint information and statistics with students. The main purpose of this exercise was to provide disconfirmation data with the agenda of creating a learning anxiety that could facilitate the change process and provide sufficient motivation to students to undertake tasks with high levels of complexity, uncertainty and even more importantly, undertake tasks that are epiphantic, that is, tasks whose exact outcomes could not be laid in advance.

Session three was more about student teams presenting their Plans of Action and the progress each team has made on the plans. Each team indicated how it planned to tackle the better understanding of the technology at hand which involved literature review (textbooks, articles, and relevant industrial websites) and actual visits to the cognate industry to aid problem identification and refinement.

In session four, teams presented how they were going to tackle the problems they themselves figured out. Team A focused on energy efficiency and the relatively under-explored solar energy that remained under-exploited in South Africa. The team estimated, based on its investigation, that more than 3,850, 000 exajoules were being absorbed by the earth's atmosphere, oceans and land masses so that there was more energy in an hour than the world used in a year. This information motivated the team to further investigate solar technologies because of their potential to reduce dependence on coal as the source of energy generation.

This team visited two sites were solar technologies were produced to inform itself on its operations and costs of installation. Team B focused on students' residences of its university in respect of water usage. The motivation was based on the fact that post-apartheid, the students population in these residences increased from 189 to 15 000. In its argument, the team indicated that the water supply pressure must have been affected by the increase in students' population. The team visited Rand Water Board that supplies water to the entire country to gain insights on water supply in the students; residences. The team also reported on the anomaly it discovered when calculating water usage in the students' residences. The team compared water usage when students were in residence and when students were on recess. The team discovered that water usage substantially increased when students were on recess. Team C paid attention to paper recycling technologies and visited Mondi Paper-Producing Plant.

Sessions five to eight involved teams reporting on progress on solutions and challenges including on the principles and patterns of evolution that held better prospects of resolving the problems at hand. Team B inquiry is more interesting as it found that the increased students' population worked to ease the burden on the aging water infrastructure in this particular residence. According to the team, when students were present in the residences less pressure was put on the supplying pipes and when the students' population decreased during recesses and less water was being used, the supplying pipes came under extreme pressure and thus leaks developed which accounted for the increase in water usage costs. This team is now investigating the possibility of developing household water leak detectors for commercialization and the alternative sealant to the obsolete bitumen which the team found to be compromising the quality of water which it tested with Rand Water Board. Sessions nine and ten were used to run post-tests with each team.

3. Main results

This section presents the TTCT and t-test results.

3.1 TTCT Results

3.1.1 Fluency results

As shown in Fig. 3, the number of students who got higher marks post-intervention as compared to prior intervention increased and shifted to higher values as the number of those who received lower marks prior to intervention also decreased to account for shift towards higher marks. While the peak value of the pre-intervention marks is located at the range of marks 41–50, the post-intervention marks peak at the range of marks 51–60 which indicate a shift of the graph toward the right. Prior to intervention, the number of ideas students generated ended at the range of marks 61–70 whereas post-intervention students range of marks went up to 110–120 although only one reached the highest marks.

3.1.2 Flexibility results

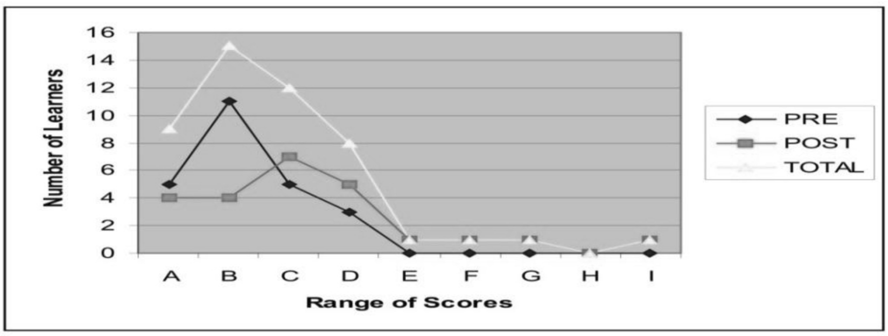
Figure 4 shows the right-inclined distribution of the curve of post-intervention flexibility marks of the students. The variety of ideas students produced post-intervention spread over the peak value of the curve calibrating pre-intervention students' marks which are located at the range of marks 51–60. However, none of the students achieve the highest mark as comparable with the fluency marks.

3.1.3 Originality results

In Fig. 5, the number of students that received higher marks post-intervention peaks at higher level of 51–60 as compared to the peak value curve of prior intervention which is located at the range of marks 41-50. Student' marks are even at the highest scores of range 71–80 and only one student achieves such higher marks. In both fluency and flexibility, students' scores have been able to reach the 100 marks point whereas the originality scores could only reach the 80 marks point.

3.2 The t-test results

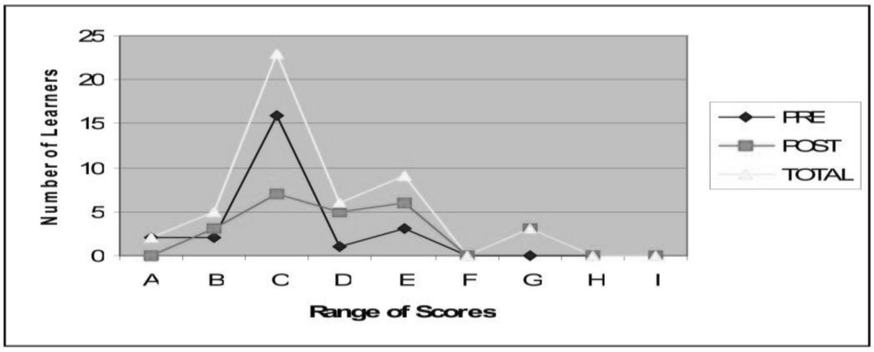
The findings in table 1 indicate that two of the three metric variables that measured students' creativity show significant improvement on students' generation of a variety of ideas (p = 0.003) and the unusualness of the generated ideas (p = 0.001). The mean scores of all three metric variables of the TTCT increased when the pre- and post-test scores of students are compared which indicates the general improvement of students' creativity performance post-intervention. The t-test also shows statistical significance between the TTCT metric variables which indicates that students' scores on



Scores of learners' thinking fluency

Number of learners	Range of scores	A 31-40	B 41-50	C 51-60	D 61-70	E 71-80	F 81-90	G 91-100	H 101-110	I 110-120
	Pre-test	5	11	5	3	0	0	0	0	0
	Post-test	4	4	7	5	1	1	1	0	1
	Total	9	15	12	8	1	1	1	0	1

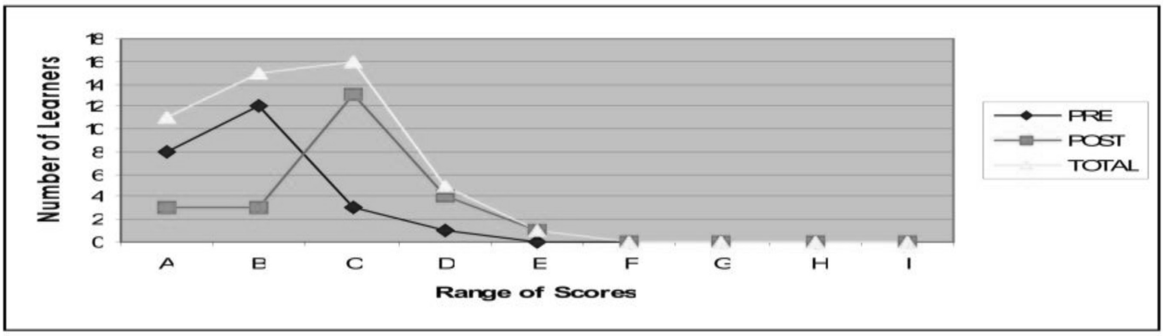
Fig. 3. Fluency Scores.



Scores of learners' thinking flexibility

Number of learners	Range of scores	A 31-40	B 41-50	C 51-60	D 61-70	E 71-80	F 81-90	G 91-100	H 101-110	I 110-120
	Pre-test	2	2	16	1	3	0	0	0	0
	Post-test	0	3	7	5	6	0	3	0	0
	Total	2	5	23	6	9	0	3	0	0

Fig. 4. Flexibility Scores.



Scores of learners' thinking originality

Number of learners	Range of scores	A 31-40	B 41-50	C 51-60	D 61-70	E 71-80	F 81-90	G 91-100	H 101-110	I 110-120
	Pre-test	8	12	3	1	0	0	0	0	0
	Post-test	3	3	13	4	1	0	0	0	0
	Total	11	15	16	5	1	0	0	0	0

Fig. 5. Originality Scores.

Table 1. t-test scores

	Pre-test		Post-test			
	Mean	**Standard deviation**	**Mean**	**Standard Deviation**	**t-test**	**p-value**
Fluency	47.83	8.65	58.25	20.32	–2.614	0.016
Flexibility	36.33	9.49	45.46	14.59	–3.291	0.003
Originality	24.08	7.57	33.71	12.18	–3.975	0.001

fluency, flexibility and originality increased post-intervention although with varying degrees. The standard deviation increased post-intervention as the result of two students making no progress at all during the intervention.

3.3 Conclusions

These findings provide solid evidence that the TRIZ-based Creativity Model that leveraged university-industry nexus in developing students' creativity was effective. The t-test scores show significance which is further proof of the effectiveness of the TRIZ-based Creativity Model. While the results of students' fluency, flexibility and originality increased after exposure to the TRIZ-based Creativity Model, this happened in variation with originality scores noting modest increase as compared to the fluency and flexibility scores. It can thus be concluded that the ability of students to develop unusual and innovative ideas may require more than the six months that the study took but this, in no way, vitiates the effectiveness of the TRIZ-based Creativity Model in developing students' creative abilities only indicating the need for more time.

4. The emerging contours of the university-industry nexus

Through students' presentations and discussions during their problem-solving exercises, I was able to glean out the following issues as relevant in further investigating the university-industry nexus. As students presented and shared their experiences of these industrial visits, the contours of greater contact between engineering-in-academia and engineering-in-industry began to appear and take the shape of five key factors that become necessary conditions for the success of university-industry nexus. *Diversity* as measured in terms of variation in understanding (differing perspectives), focus and agency, *boundary maintenance* which mediates nature and appropriation of knowledge (formal, non-formal, informal), *degree and nature of interaction and integration* which speaks to what each of these domains of knowledge are prepared to make publicly available and what to keep private and, *areas of collaboration* which illuminate issues of trust, mutual expectations and cooperation.

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Teboho Pitso serves as the Senior Project Manager in the Centre for Academic Development, Vaal University of Technology, South Africa and holds a PhD in Engineering Education from the University of the Witwatersrand which focused on developing pedagogies and curricula that were likely to promote students' creative and innovative abilities especially at engineering undergraduate level. My colleague and I, Malefane Lebusa (PhD), are establishing the Centre for Innovation and Entrepreneurship (CIE) which focuses on fostering technological innovation and developing enterprising individuals. The underlying theory of the CIE is the Triple Helix Model that places universities, industry and government at the heart of technological innovation as well as economic and social development.