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A Study of Creativity in Technology and Engineering

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Abstract--**Innovation is the creation of new products, processes and services, and their acceptance in the market. Creativity is central to the innovation process. Creativity has been the subject of intense multi-disciplinary research and a huge volume of academic literature exists on the subject. It has been studied from many perspectives, such as psychology, psychometrics, cognitive science, aesthetics, design research, and management. This study focuses on creativity in technology and engineering and the management thereof.**

In this paper a conceptual framework of creativity is proposed that attempts to unify and synergize much of what is known about creativity. Three case studies of recognized creative engineers were conducted to investigate their creative behaviours. The findings were used to test the theory of creativity and specifically the validity and utility of the proposed conceptual framework in an engineering environment.

It was found that the most important dimensions of creativity in an engineering environment, particularly during product design and development, are technical challenges, a conducive environment for creativity, personnel that is studious and has high self-efficacy and that are able to think both lateral (right-brain) and analytical (left-brain).

This research has value for the management of creativity in technology and engineering. The framework as presented here can be a useful tool to structure and manage creativity in a technology-based organization.

I. INTRODUCTION

Creativity is the ability to bring into existence something new and valuable. It requires a special class of problem solving by means of a thinking process in which original patterns are formed and expressed. Creativity is a universal phenomenon that can be found in all human activities and across all disciplines. Creative professions include not only writing, art, design, theatre, television, radio, motion pictures and related crafts, but also marketing, strategy, architecture, science, technology, design, engineering and many other human endeavours.

Innovation is the creation of new products, processes and services, and their acceptance in the market. Creativity is central to the innovation process. Innovation is the implementation of new ideas - the fruits of creativity. Without creative ideas there cannot be innovation [15]. Innovation, and particularly technological innovation, is recognized as the primary driver of economic growth globally.

Service industries have become the dominant sector in developed and many developing economies. A rapidly expanding service sector is the provision of creative services. It is widely recognized that innovation is the engine driving economic growth in both manufacturing [17] and service industries [13]. The establishment and management of creative environments are therefore extremely important.

Creativity has been the subject of intense multi-disciplinary research and a huge volume of academic literature exists on the subject [33]. It has been studied from many perspectives, such as human evolution [14], brain physiology [7], psychology [9], psychometrics [32], cognitive science [5], art and aesthetics [22], design [41][24], and management [8].

It is not the intention to review this large body of knowledge in this paper. The problem is that there are so many theories, models and methods in this field that the technology manager is at a loss as to what and how to apply it. The focus of this study is therefore on the management of creativity in technology and engineering and the objective is to develop and test a conceptual framework (or model) of creativity that attempts to unify and synergize all that is known about creativity. The goal is to test the validity and utility of the framework in an engineering environment.

II. CONCEPTUAL FRAMEWORK

Extensive research on models of the creative process has been done. In 1926 Wallas [42] created one of the earliest models. Others [43][12][37] proposed that creative ideas emerge from an uncontrollable Darwinian process of random variation and natural selection. Barron (in Appiah & Cronje [6]) placed great emphasis on subconscious and chance processes in his four-phase model and Parnes (in Sternberg, Grigorenko and Singer [39]) proposed a model with six steps. The Directed Creativity Cycle Model of Plsek [31] is a synthesis model that attempts to combine the concepts of various models of creative thinking of the previous 80 years.

A framework that organizes many issues in the study of creativity is the four P's framework; process, product, person and place (or pressure). These are traditionally referred to as the aspects or facets of creativity. This has recently been extended to a six P's framework by adding persuasion and potential [23].

We propose that a simplified conceptual framework of creativity can be formulated that incorporates and synergizes much of what is known on this subject. This framework differs from previous models in as much as it is primarily aimed at technological creativity and the management thereof.

It is proposed that all creative activity can be accounted for in terms of a conceptual framework consisting of five components or 'dimensions'. These dimensions are provisionally titled: 1) Motivation, 2) Deviating thinking, 3) Constraints, 4) Conducive environment and 5) Personality traits. The titles as such do not adequately capture the constructs and therefore each requires further elaboration and clarification. Furthermore, they are not mutually exclusive constructs and should be viewed as five focal points in a continuous force field. This aspect will be highlighted when the interactions between the dimensions are discussed.

A. Motivation for creativity

Creativity is a deliberate act requiring an intelligent creator. Because creativity is non-spontaneous (in the sense of having a cause), it requires some incentive or motivation for it to occur. Motivators could be positive or negative [18]. Positive motivators could be the quest for beauty, perfection, truth, enjoyment and satisfaction [4]. Negative motivators usually relate to real or perceived external threats or challenges [1]. It is proposed that these operate in all disciplines; however, the type and nature of the motivators are domain specific. In art and literature the motivators are often more psychological, whereas in science and technology the motivators are primarily in the physical environment. It is often needs driven, hence the phrase 'necessity is the mother of invention.' In practice, it is usually a combination of both physical and psychological aspects and it is therefore not a matter of one or the other, but rather the relative importance they have in different disciplines.

B. Deviating thinking

Albert Einstein is often quoted as having said that we cannot solve our problems with the same thinking we used when we created them. Creativity requires a thinking process in which original patterns are formed and expressed, in other words it deviates from current patterns, knowledge and paradigms [27]. It is a special or atypical mental process that has been associated with right or forehead brain activity or even specifically with lateral or right-directed thinking. This type of thinking will be called deviating thinking, not in the negative ethical meaning of the word “deviant”, but in the positive meaning of deviation from existing patterns, knowledge and paradigms. It is also often referred to thinking ‘out of the box’.

The neurobiology of creativity has been extensively researched. It appears that highly creative people's capability of deviating thinking is mediated by complex interactions of norepinephrine in the frontal and temporal lobes, dopamine from the limbic system and the cognitive functions of the cerebellum [16].

The role of the subconscious mind seems to be particularly important in deviating thinking and it has been suggested that REM sleep adds to creativity by the forming of associative elements into new combinations.

Many attempts have been made to facilitate, enhance and develop deviating thinking skills. This has resulted in a profusion of creativity techniques, ranging from the psychological-cognitive, such as lateral thinking [38], to the highly-structured, such as Altshuller's Theory of Inventive Problem-Solving [2].

C. Constraints to creativity

The output of creativity that is original but is incomprehensible, unpractical, or has no conceivable purpose or function is considered worthless. The products of creative thought must be both original and appropriate. The products of creativity are ideas capable of expression in some practical or functional form. This need for practical expression places constraints on creativity. Creativity therefore also requires left-directed thinking (representing logical, analytical thought). It also requires specialized knowledge and skills.

Creativity is therefore subject to physical and social constraints such as natural laws, properties of materials, human abilities, social norms and values [40]. These constraints are often perceived rather than real, and creative ideas are often generated when preconceived assumptions are discarded. Nonetheless, it is proposed that there are real constraints to creativity in all disciplines, although they might be very different. In the fine and performing arts the constraints are often restricted to materials, skills and abilities, whereas in science and engineering the constraints are often the properties of materials and laws of nature [36].

D. Conducive environment for creativity

Creativity cannot flourish in an environment that is unreceptive or hostile to new ideas [3]. Within an organizational context, this is a key element of an organizational culture that supports creativity and innovation. Much research has been done on the characteristics of creative environments and how to structure and manage them [29]. Aspects such as encouraging confidence and a willingness to take risks, providing opportunities for choice and discovery, and promoting supportable beliefs about creativity are some of the factors that have been identified [30].

Although this dimension is clearly closely related to the constraints to creativity, it is not the same concept. The distinction is subtle: the expression of a particular creative idea might be inhibited by generally accepted social norms and values (the constraints) but might be well accepted by a particular social group (conducive environment). For example, a scientist is constrained by the laws of physics, but a science-fiction writer is not.

E. Personality traits

Creativity is a deliberate act requiring an intelligent creator with insight and the correct mix of personality traits. A creative personality is imperative to generate original ideas or solutions that are practical and useful.

According to Sánchez-Ruiz et al [35] creativity can be influence by emotion-related personality traits, such as emotional intelligence. Runco [34] suggests that a person with certain personality characteristics, values and attitudes is more likely to perform creatively than when these are absent. Grosul and Feist [19] found that openness to experience and psychoticism can explain variance in scientific creativity. Personality traits function to lower behavioural thresholds and make creative behaviour more likely.

Personality includes intrinsic motivation, openness to experience, and autonomy with a wide interest and independence. Personality can be persuasive which result in influencing and changing the way other people think. Personality effects creative thought and influence the behaviour of a creative person.

F. Interactions

As mentioned before, the above constructs are not mutually exclusive and should be viewed as focal points in a continuous force field. This aspect of the model is shown schematically in figure 1. It is also shown superimposed on Kolb's Experiential Learning Model [25]. Kolb's model was originally conceived as a four-stage learning cycle model [25], but it has also been applied to creative problem solving [20].

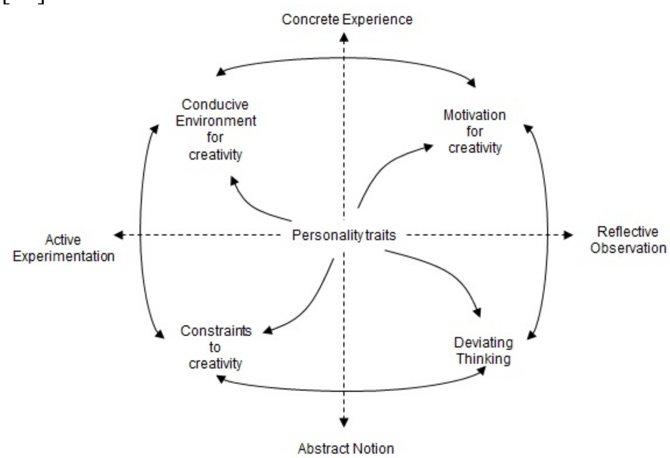

Figure 1: Proposed conceptual framework of creativity

In our conceptual model (Fig. 1), personality traits are at the core because this is an underlying dimension that determines the individual's problem-solving preferences [25]. We have positioned the other dimensions of creativity in the quadrants of Kolb's model as follows: Motivation is the result of reflective observation about concrete reality; deviant thinking is the formation of new ideas or abstract notions based on reflective observation; constraints are encountered when the ideas or abstract notions are subjected the active experimentation; and a conducive environment allows the acceptance of the outcome in the real world of concrete experiences.

III. RESEARCH DESIGN AND METHODOLOGY

This research project is part of a larger research programme on technological creativity. In this study three case studies of recognized creative engineers were conducted to investigate their creative behaviours. The findings were used to test the theory of creativity and specifically the validity and utility of the proposed conceptual framework in an engineering environment. The research design is an explorative multiple case study.

The focus of this research was on creativity in engineering, particularly during product design and development. This activity is highlighted in Fig. 2 that shows the chain of technological innovation sub-systems [11].

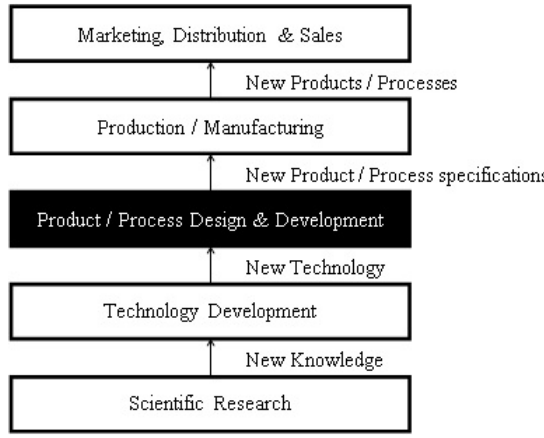

Figure 2: Technological innovation sub-systems

In selecting the subjects for this study, it was decided to investigate the creative behaviour of creative professionals in an engineering environment. The first selection criterion was therefore that the subjects should be employed in innovative companies. Buys [10] has shown that that the local defence related industry is the most innovative sector of the manufacturing industry in South Africa.

Two South African engineering companies were selected for this investigation; a large state-owned company and a medium-size private company. Both companies focus on landward defence systems, products and commercial solutions and are leading suppliers of system, subsystems and products in the defence and commercial market. They have competencies in conceptual designs, software development, power electronics, digital and analogue designs, simulations and computer aided design.

Three suitable candidates were selected from the companies' employees after consultation with senior managers of the companies. The candidates were contacted and their informed consents were obtained for participation in this study. They will be referred to as Participants 1, 2 and 3 in this report. They are all engineers with graduate degrees that have worked in systems design and product development for more than ten years. Their responsibilities include conceptual system designs, the solving of complex technical requirements or problems, product design and development, manufacturing, integration and commissioning of the systems or products. The participant's field of expertise includes the design of complex military combat systems, sub-system designs, finite element analysis, military electronics and commercial designs with graphical user interfaces. Some of their inventions are patented, but the participants do not hold the patents in their personal capacity as the intellectual property is the property of their employers.

The explorative case studies were done by gathering the following sources of evidence for each case:

- Documents, observation and scrutiny of the designs, products and inventions of the participants;

- Information regarding their creative behaviour obtained during formal interviews with their peers, subordinates and superiors;
- Informal unstructured interviews with the participants to gain insight of their background, personalities, behaviour and thinking styles; and
- Formal interviews with the participants using a structured questionnaire.

An important research instrument was a structured questionnaire. The questions were derived from the proposed conceptual framework of creativity. The questionnaire contains 85 questions associated with the five dimensions of the framework as shown in Fig. 3. The participants were required to respond to all the questions using the following 5-point Likert scale: 1 = Strongly disagree, 2 = Disagree, 3 = Neutral – no influence, 4 = Agree, 5 = Strongly agree.

Motivation

1. I am excited to discover new technology
2. I love learning new processes or skills
3. Recognition or rewards motivate me more
4. I always achieve my incentives or set goals
5. I experience joy when my new idea or product is practical for implementation to use
6. I have a natural strong desire for status and power
7. I love to compete with others
8. I am de-motivated by disorganized, unstable and unpredictable working environments
9. I would rather lose my life than losing my reputation or honour
10. I avoid tasks or situations with an negative outcome
11. My work is always of a high quality standard, irrespective of the working environment
12. I love environments/projects with continuous self-learning opportunities to improve my skills
13. I willingly engage in activities or tasks
14. I love challenging work and responsibilities
15. I prefer an environment where my job is secured
16. I have a natural strong desire for social status
17. I have a natural strong desire for social contact
18. I have a natural strong desire for independence
19. I have a natural strong desire for physical activities
20. I have a natural strong desire for acceptance

Deviating thinking

21. New ideas are generated spontaneously
22. I have to sleep over difficult problems before it could be solved
23. New ideas are formed by a combination of existing ideas
24. Complex problems are solved by breaking it down into its various components
25. I can provide many ideas for a solution
26. More ideas are generate after the first one
27. Pressure helps me to solve problems or to come up with a solution
28. Ideas are generated randomly
29. I use mind maps or similar techniques to generate ideas or to solve problems
30. New ideas come to me when I am busy with a design
31. A long time period is needed to get to a solution
32. Ideas are re-iterate before the final solution is produced
33. I have to visualize the problem before a solution can be presented
34. Specific domain knowledge and experience are needed to solve or generate new designs
35. Most suitable solutions are generated in a group discussion
36. Experimentations with trial and error are needed to provide a suitable solution
37. New designs can always instantly be improved when they are presented by someone else
38. I think in pictures to solve complex task, problems or to create new ideas
39. A careful observation is necessary before I can come up with a solution
40. I form association with pervious problems in my memory to generate new ideas or to solve problems
41. I am a logical, analytical thinker
42. I borrow or transfer ideas from totally unrelated domains to generate new ideas or to solve problems in my domain
43. Ideas sometimes come from outside my rational conscious mind
44. These ideas come from my unconscious mind
45. These ideas come from hallucinations
46. These ideas come from a transcendental realm

Environment and Constraints

47. I feel more creative in an environment where there are opportunities for exploration
48. I feel more creative in an environment where I can work independently
49. I feel more creative in an environment where originality is supported and valued
50. I am more creative in an unstructured environment where risks can be taken
51. The unavailability of technology hampers my creativity
52. Negative incidents in the organizational environment enhance my creativity
53. An organizational environment unappreciative to change or open for new ideas influence creativity negatively
54. The climate of the organizational environment influence my creativity, either positively or negatively
55. Creativity leads to positive moods and emotions
56. Positive moods or emotions provides further motivation for creativity
57. The natural laws influence my creative though positively
58. The properties of materials place a strong constrain on my creativity
59. The unavailability of state of the art technological innovation makes me more creative
60. Highly structured environment with traditionalism and working "to the rules" discourage creativity
61. An environment with a certain degree of "chaos" and unconventional behaviour encourage creativity

Personality

62. I am outgoing and sociable
63. I am independent, confident and assertive
64. I possess a definite strong sense of self-efficacy in general
65. I possess a definite strong sense of self-efficacy in my domain of expertise
66. I value tradition, conformity and authority
67. I am most creative when tasks are open ended and not well defined
68. I reject norms, traditions and conservative ideology
69. I am open for new experiences, situations or change
70. I have a wide interest to explore new technology
71. I am curious and imaginative
72. I am comfortable around strangers or large groups of people
73. I am not emotional after a conflict situation
74. I am more creative after a conflict situation
75. I find abstract ideas easy to understand
76. I am more creative in an unstructured environment
77. I am not really interested in other people
78. I do not often have mood swings
79. I am unfriendly towards others
80. I belief that I am better that other people
81. I am persistent, determined and ambitious to reach my goals
82. Tasks and activities are always driven by the pleasure, excitement, the need to discover
83. I am cold, aloof, eccentric, hostile, impulsive, and egocentric
84. I like to set the direction and influence the way other people think
85. My individual drive and ambition is much more important for success than rewards such as money, internal pleasure or recognition.

Figure 3: Structured questionnaire

IV DATA ANALYSIS

A. Creative output of the participants

The case studies were done by firstly gathering relevant documents and by observation and scrutiny of the designs, products and inventions of the participants. Substantial evidence was found of novel and creative contributions by the participants. Some of the innovations where they made important contributions are shown in Table 1. They are turret designs and automatic fire control and monitoring systems for the state-of-the-art Badger infantry combat vehicle, the modernization of the world-renowned 155 mm G6 self-propelled gun-howitzer and the Continuous Rope Monitoring System for the mining industry. One of the participants also contributed to the development of the Pebble Bed Modular Nuclear Reactor.

TABLE 1: INNOVATIONS THAT THE PARTICIPANTS CONTRIBUTED TO

	**Badger Infantry Combat Vehicle** The Badger is a new generation Infantry Combat Vehicle designed to provide soldiers with effective protection and offensive firepower, while enabling them to dismount and interact with civilians during peace-enforcement operations. The Badger is equipped with the locally designed LCT30 turret armed with the GI-30 gun that fires link-less 30 x 173mm ammunition – a world-first for this kind of weapon.
	**G6-52 self-propelled gun-howitzer** The 155mm G6-52 is an advanced development of the G6-45 self-propelled Gun-Howitzer system. The system has a range of 67 km and a rate of fire of eight rounds a minute. Multiple rounds can be fired to simultaneously hit the same target using the AS2000 artillery target engagement system. Automated ammunition handling, fuse handling and ammunition inventory reduce crew workload.
	**Pebble Bed Modular Reactor** The PBMR is a helium-cooled, graphite-moderated High Temperature Nuclear Reactor. The nuclear fuel particles are encased in graphite to form fuel spheres or pebbles. Very high efficiency, passive safety and attractive economics are possible. The South African Pebble Bed Modular Reactor project was terminated in 2010 when it could not secure sufficient investment to continue.
	**Continuous Rope Monitoring System** The CRMS monitors the condition of steel wire ropes used in mine shafts under normal operating conditions. A strong magnetic field is applied to the steel wire rope; this exposes flaws in the rope cross sectional area, broken wires, wire deformation and corrosion, etc. This is the first system that can continuously monitor the condition of steel ropes during normal operation.

B. Interviews with the superiors, peers and subordinates of the participants

The feedback received from the superiors, peers and subordinates of Participant 1 indicated that he has an impressive track record as a creative professional. They experience him as a person that can solve complex problems and generate novel conceptual system designs and indicated the integrated cradle mounted video sight for the Modular Combat Turret as an example. They all agreed that he is an open, self-motivated and independent person with strong leadership qualities.

The superiors, peers and subordinates of Participant 2 all reported that he is highly creative and provided the invention of the Continuous Rope Monitoring System as an example. They all experience him as an open, curious and independent person that regularly comes up with new creative ideas. However, he is a meticulous person that solves complex problems only after protracted detailed investigations. He is seen as more of an individual contributor than a team player.

The superiors, peers and subordinates of Participant 3 all reported that he is creative considering the work that he has done in the past. They experience him as an independent thinker that can generate new ideas for solving complex problems, one example being solutions for the G6-52, an advanced development of the renowned 155 mm G6 self-propelled gun-howitzer. He also contributed to the development of the Pebble Bed Modular Nuclear Reactor.

C. Interviews with the participants

Structured interviews were conducted with the participants to obtain information on their creative behaviour. The following are some of the key observations made during the interviews.

Participant 1

- The breakthrough in solving a complex problem motivates him positively.
- Exceptional breakthroughs need to get recognition over time to motivate him.
- The unavailability or constraints on technology does not hamper his creativity.
- He prefers an environment with freedom and not rules.
- He likes to influence other people.
- He states that complex problem solving starts by thinking in pictures.
- He breaks a complex problem down into sub-problems to be able to find a solution.
- Background knowledge and domain specific experience are critical for creativity.
- When working on a problem he goes to sleep and awakes early in the morning with a totally different insight and realization of what the solution is.
- He often observes a product or process in a different environment that can be used in his working environment to solve a problem.

Participant 2

- He loves an environment with freedom and no rigid rules.
- He has no fixed working hours at the office or at home.
- He likes to influence other people.
- He is open for change.
- He strives to understand how complex systems work.
- He is not an emotional person.
- Recognition and rewards do not motive him. However, an insufficient salary would influence his motivation and creativity negatively.
- He cannot generate new ideas spontaneously. He must simulate and analyses the problem to come up with a new insight.
- Background knowledge and domain specific experience are critical for creativity.
- He thinks in pictures.
- He breaks a complex problem down into sub-problems to be able to find a solution.
- He also awakes in the night realizing how to solve a problem; he will immediately write it down and go back to sleep.

Participant 3

- He believes that teamwork is important for finding creative solutions to complex problems.
- He prefers to work on his own.
- A dynamic environment motivates him.
- Recognition is not important for him.
- He believes in continuous self-improvement and growth.
- Stress and frustration hampers his creativity.
- A relaxing environment enhances his creativity.
- He is open for change.
- He prefers a disciplined environment with freedom and without unnecessary rules.
- He likes to influence other people.
- He draws lines and pictures to visualize a problem and its solution.
- He compares existing systems or building blocks with each other and makes associations to find new solutions.
- He daydreams over complex problems.
- Sometimes solutions just come to him without any deliberate effort to solve it.

The participants all emphasized the importance role that technical knowledge and experience played in their creativity. They indicated that the ‘constraints’ were dealt with creatively by analytical thinking. The importance of analytical thinking in creative problems-solving was emphasized by all the participants.

The above observations made during the interviews are discussed in the following sections.

D. Structured questionnaires

The participants were also asked to complete the structured questionnaire. The first section (questions 1 to 20) dealt with the Motivation dimension. Their responses to the questions are shown in Fig. 4.

The participants all agreed, some strongly, with questions Q1, Q2, Q5, Q11, Q12, Q13 and Q14. There was consensus that the most important motivators for technical creativity are the excitement to discover new technology (Q1), to learn new processes or skills (Q2 & Q12), the joy experienced when a new idea or product is practical for implementation (Q5), achieving high quality standards, irrespective of the working environment (Q12) and challenging work and responsibilities (Q13 & Q14). Two of the questions dealing with the Environment and Constraints dimensions that all the participants strongly agreed with were that creativity leads to positive moods and emotions (Q55) and these provide further motivation for creativity (Q56).

The participants generally disagreed, some strongly, with Q6 – Q10, Q16, Q17 and Q19. These questions deals with personal ambition, such as status and power (Q6), competition with others (Q7), disorganized, unstable and unpredictable working environments (Q8), reputation or honour (Q9), risky tasks or situations (Q10). They also all agreed that rewards such as money or recognition are not important motivators (Q85).

The second section (questions 21 to 46) dealt with the Deviating thinking dimension. Their responses to the questions are shown in Fig. 5.

The participants all agreed, some strongly, with questions Q24, Q25, Q30, Q33, Q35, Q38, Q41 and Q42. These questions deal with analytical (left-brain) problem solving rather than lateral or right-directed thinking. These included breaking down the problem into its various components (Q24), arriving at new ideas while busy with a design (Q30), generating solutions in group discussions (Q35), logical and analytical thinking (Q41).

There was no consensus of opinion on the questions dealing with lateral or right-brain thinking such as the suggestions that new ideas are generated spontaneously (Q21); that you have to sleep over difficult problems before they can be solved (Q22); that ideas are generated randomly (Q28) or through trial and error (Q36); come from outside the rational conscious mind (Q43) or from the unconscious mind (Q44). The participants all disagreed strongly with the suggestions that ideas come from hallucinations (Q45) or from some transcendental realm (Q46). An indication of lateral thinking was their agreement with Q42: “I borrow or transfer ideas from totally unrelated domains to generate new ideas or to solve problems in my domain”.

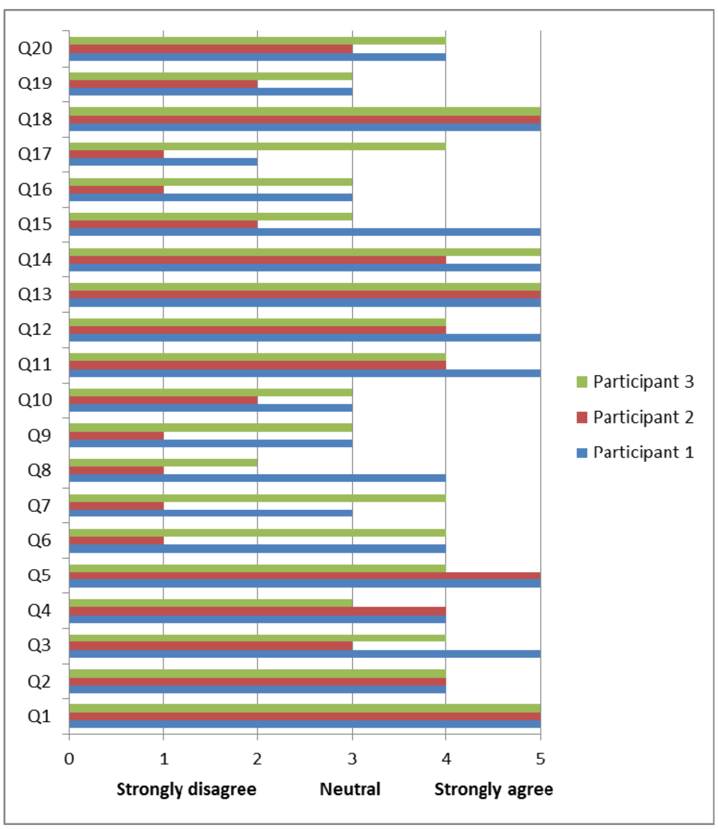

Figure 4: Responses to the questions dealing with the Motivation dimension

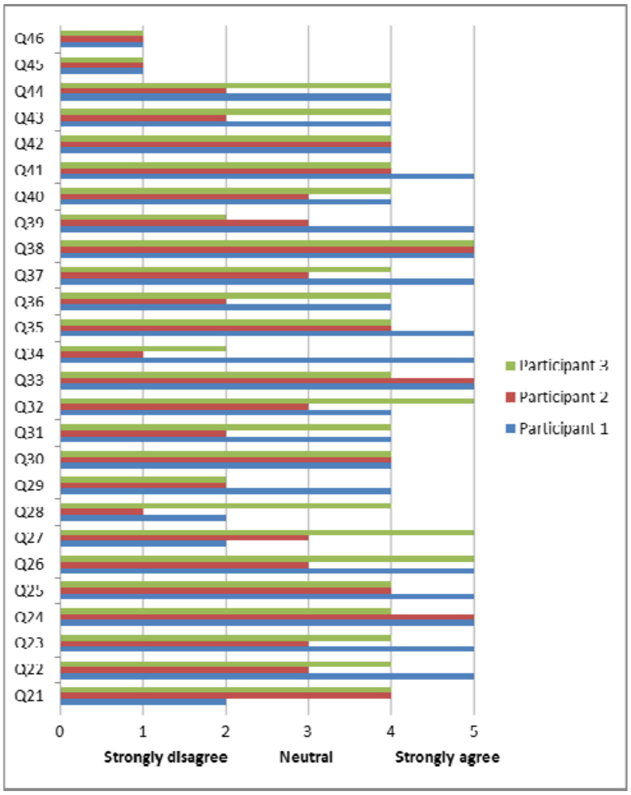

Figure 5: Responses to the questions dealing with the Deviating thinking dimension

The third section (questions 47 to 61) dealt with the Environment and Constraints dimensions. Their responses to the questions are shown in Fig. 6.

The participants all agreed, some strongly, with questions Q47 – Q50, Q55 – Q57, Q60 and Q61. The participants felt more creative in an environment where there are opportunities for exploration (Q47), where they can work independently (Q48) and where originality is supported and valued (Q49). They also agreed that unstructured environments where risks can be taken (Q50) and where there is a certain degree of "chaos" and unconventional behaviour (Q61) are more conducive for creativity, whereas environments with traditionalism and working "to the rules" (Q60) discourage creativity.

There was also no clear consensus in response to the questions regarding organizational climate such as negative incidents in the organizational environment (Q52), an organizational environment unappreciative to change or open for new ideas (Q53) and the climate of the organizational environment (Q54).

There was no clear consensus or strong views in reply to the questions dealing with constraints to creativity, such as the unavailability of technology (Q51, Q59) and the properties of materials (Q58). It was suggested to the participants that natural laws are constraints to technological creativity; however, they all agreed that natural laws are not constraints, but rather influence their creativity positively (Q57).

The last section (questions 62 to 85) dealt with the Personality dimension. Their responses to the questions are shown in Fig. 7.

The participants all agreed, some strongly, with questions Q63, Q65, Q69 – Q71, Q81, Q82 and Q85. The personality profile that emerges are of individuals who are independent, confident and assertive (Q63), possess a strong sense of self-efficacy in their domains of expertise (Q65), are open for new experiences, situations or change (69), have a wide interest to explore new technology (Q70), are curious and imaginative (Q71) and are persistent, determined and ambitious to reach their goals (Q81). They are driven by the pleasure, excitement and the need to discover (Q82). They consider individual drive and ambition more important for success than rewards such as money or recognition (Q85).

The participants all disagreed, some strongly, with suggestions that they are not really interested in other people (Q77), are unfriendly towards others (Q79) and are cold, aloof, eccentric, hostile, impulsive or egocentric (Q83). The participants were neutral or divided on the other questions.

The questionnaire was tested for validity by calculating Cronbach's alpha values. In this case the size of the dataset does not allow for high test reliability. However, as a preliminary indication of validity, the values for the questions dealing with motivation ($\alpha = 0.927$), environment ($\alpha = 0.813$) and deviating thinking ($\alpha = 0.896$) do indicate high validity. The only exception was the questions dealing with personality ($\alpha = 0.413$).

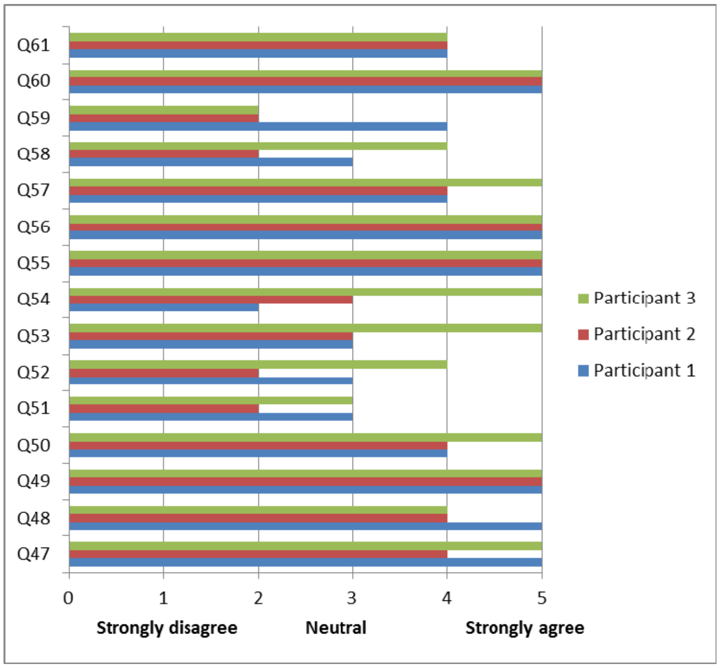

Figure 6: Responses to the questions dealing with the Environment and Constraints dimensions

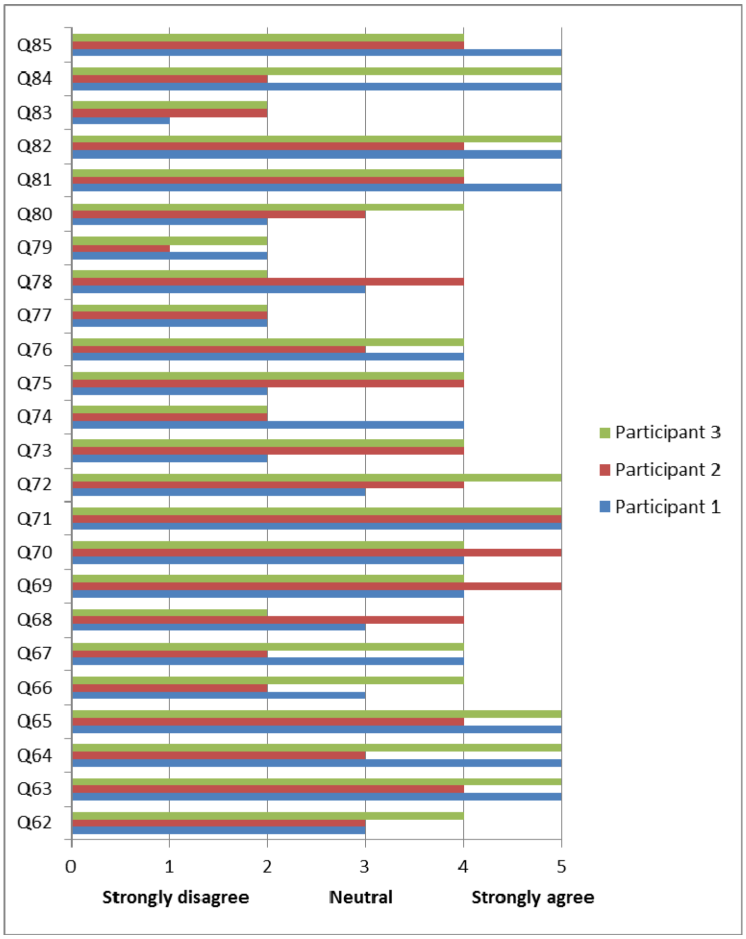

Figure 7: Responses to the questions dealing with the Personality dimension

E. Data analysis

The data analysis was done qualitatively and the specific analytical techniques that were used are pattern matching, explanation building and cross-case synthesis. The development of converging lines of inquiry (convergence of evidence) was done by cross-case data triangulation. The participants were consistent with their interview responses and responses to the questionnaire, and this was supported by the physical evidence and testimony of peers, subordinates and superiors.

The findings, in general, supported the proposed framework as some evidence was found for the validity of all the dimensions of the framework. We have discovered that the original five dimensions of the proposed framework require tailoring for an engineering environment. The qualitative factor analysis identified six dimensions with some sub-dimensions as shown in Table 2.

However, the importance ratings of the sub-dimensions differed. The average scores on the Likert scale for relevant questions were used as a measure of the importance attached to the different sub-dimensions by the participants. This is shown in the radar diagram depicted in Fig. 8.

It is apparent from Fig. 8 that the most important dimensions of creativity in an engineering environment, particularly during product design and development, are technical challenges, a conducive environment for creativity, personnel that are studious and have high self-efficacy and that are able to think both analytical (left-brain) and lateral (right-brain). This analysis shows that there are some dimensions that are of minor importance and can be eliminated from the framework, such as rewards, constraints, asocial and unconventional personalities.

The six important dimensions are technical challenges, conducive environment, analytical thinking, lateral thinking, self-efficacy and studiousness. The proposed conceptual framework of creativity was therefore modified as shown in Figure 9.

TABLE 2: SUB-DIMENSIONS OF THE CONCEPTUAL FRAMEWORK OF CREATIVITY

Dimension	Sub-dimension
Motivation for creativity	Motivation: Challenges Motivation: Rewards
Deviating thinking	Lateral thinking
Analytical thinking	Analytical thinking
Constraints to creativity	Constraints to creativity
Conducive environment for creativity	Conducive environment
Personality traits	Personality: Studious Personality: Asocial Personality: Unconventional Personality: Self-efficacy

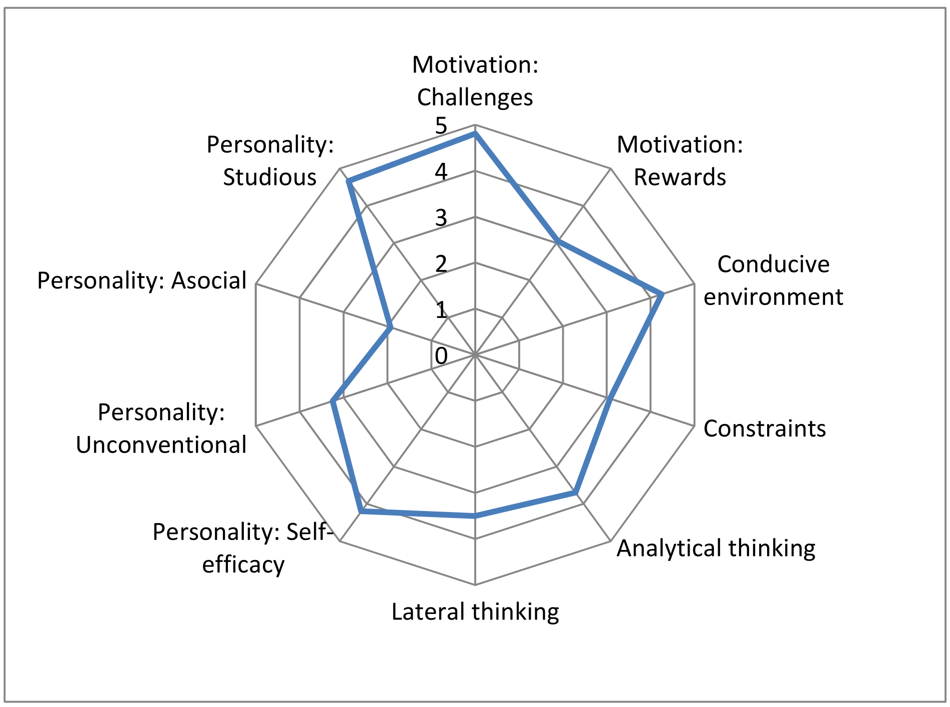

Figure 8: Importance attached to the different dimensions of the conceptual framework of creativity

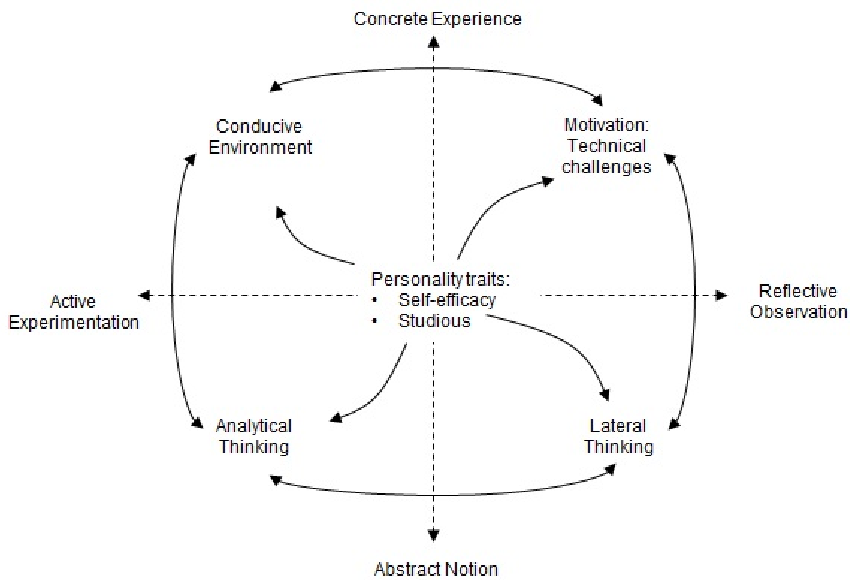

Figure 9: Modified conceptual framework of creativity in an engineering environment

The key findings can be summarized as follows:

- Rewards such as money or recognition are not important motivators for creativity. The dominant motivators are technical challenges and opportunities.
- Both analytical (left-brain) and lateral (right-brain) thinking are important for technological creativity, but there seems to be somewhat more emphasis on analytical thinking.
- Environments where there are opportunities for exploration, where people can work independently with a certain degree of "slack" are more conducive for creativity. Rigid rule-bound environments discourage creativity.
- The unavailability of technology, the properties of materials and natural laws were not perceived as constraints to technological creativity.
- Creative technological innovators are independent, confident and assertive, are curious and eager to learn and are persistent and determined to reach their goals.
- No evidence was found in support of a popular perception that technological inventors are asocial introverts.

This study focused on creativity in engineering, particularly during product design and development as highlighted in Fig. 2. The conclusions are therefore domain-specific and cannot be generalized to other activities in the chain of technological innovation sub-systems. The three case studies were confined to subjects that were predominantly engaged in design and development of high-technology products.

Case studies cannot be representative of the population of all similar cases; therefore generalizations cannot be made to such a population. However, in case study research generalizations can be made to a theory based on cases that represent that theory [44]. The findings will therefore be used to test the validity of the proposed conceptual framework of creativity.

V. CONCLUSIONS AND RECOMMENDATIONS

In this paper a conceptual framework of creativity was proposed that attempts to unify and synergize much of what is known about creativity. It was proposed that all creative activity can be accounted for in terms of this framework consisting of five dimensions; motivation, deviating thinking, constraints, personality traits and an environment conducive for creativity.

Three case studies of recognized creative engineers were conducted to investigate their creative behaviours. The findings were used to test the theory of creativity and specifically the validity and utility of the framework in an engineering environment. In general, good support was found for the framework. However, the dominance of deviating (lateral) thinking in the proposed framework is not supported by this research. Both analytical and lateral thinking is important for technological creativity, with somewhat more emphasis on analytical thinking.

The other dimension in the proposed framework that is not well supported by this research is the constraints to creativity. All the participants see natural laws, properties of materials and unavailability of technology as challenges rather than constraints. This might be a domain-specific phenomenon as the three case studies were confined to subjects that were predominantly engaged in design and development of products and not in scientific research or technology development. It will be interesting to test this finding in these domains.

Technical knowledge and experience played an importance role in the participants' creativity. An engineering degree and extensive experience appear to be requirements for creativity in this field. This is a dimension that should be explored further.

This research dispels the stereotype of the creative personality as being unconventional, eccentric and asocial. It was found that subjects were well-adjusted individuals that enjoyed working with others. However, what was striking was their studiousness and high self-efficacy. They were motivated by technical challenges and opportunities and not by rewards or status. This observation supports Herzberg's two-factor motivation theory [21]. He distinguished between motivators (or satisfiers), such as opportunities for personal development and achievement, and hygiene factors (dissatisfiers), such as working conditions and salaries.

It was found that the most important dimensions of creativity in an engineering environment, particularly during product design and development, are technical challenges, a conducive environment for creativity, personnel that is studious and has high self-efficacy and that are able to think both analytical (left-brain) and lateral (right-brain). The proposed conceptual framework of creativity was therefore modified as shown in Figure 9.

This research has value for the management of creativity in technology and engineering. The framework as presented here can be a useful tool to structure and manage creativity in a technology-based organization. However, as shown in this research, cognizance should be taken of the domain-specific relative importance of the different dimensions of this model.

These research findings are preliminary as it is based on three cases in a particular domain. The validity of the model should be tested with more cases and in other domains.

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