THE ABSENCE OF A CREATIVE FOCUS IN THE CONVENTIONAL ENGINEERING DESIGN PROCESS: IDENTIFYING RESEARCH OPPORTUNITIES TO ADDRESS THIS

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ABSTRACT

This paper synthesises an overview of various models of the engineering design process with an overview of the most relevant theories within the field of creativity studies to conclude that (i) creativity plays a role throughout the engineering design process, and it is possible to incorporate creativity into the engineering design process in a systematic manner; (ii) doing so, at the very least, holds significant potential for economic benefit; and (iii) due to the complex interplay between creativity and the wide range of factors that influence it, organisational climates and management practices cannot simply be assumed to support creativity effectively. It is proposed that organisations be managed proactively to support creativity in engineering design. For this study, a structured literature search protocol was implemented to determine whether there is any evidence in the literature that engineering organisations are being managed proactively with this in mind; none was found. Two opportunities for future research are suggested based on these findings: (i) the development of a framework to guide the proactive management of engineering organisations to support creativity; and (ii) the development of mechanisms for measuring creativity in engineering organisations and engineering design.

OPSOMMING

Hierdie navorsing kombineer 'n oorsig van die verskillende modelle van die ingenieursontwerp-proses met 'n oorsig van die mees relevante teorieë binne die veld van kreatiwiteitstudies en kom tot die gevolgtrekking dat (i) kreatiwiteit deur die volledige gang van die ingenieursontwerp-proses 'n rol speel, en dit moontlik is om kreatiwiteit op 'n sistematiese wyse in die ingenieursontwerp-proses in te lyf; (ii) so 'n benadering minstens die potensiaal vir beduidende ekonomiese voordeel inhou; en (iii) weens die komplekse interaksie tussen kreatiwiteit en die breë stel faktore wat dit beïnvloed, dit onakkuraat is om aan te neem dat organisasies se klimate en bestuurspraktyke noodwendig kreatiwiteit ondersteun. Daar word voorgestel dat organisasies proaktief bestuur behoort te word om kreatiwiteit in ingenieursontwerp te ondersteun. 'n Gestruktureerde protokol word gevolg om vas te stel of daar in die literatuur bewyse is dat ingenieursorganisasies tans so proaktief bestuur word. Geen bewyse word gevind nie. Twee geleenthede vir verdere navorsing word na gelang van hierdie bevindinge voorgestel: (i) die ontwerp van 'n raamwerk om riglyne te bied vir die proaktiewe bestuur van ingenieursorganisasies om kre`atiwiteit te ondersteun; en (ii) die ontwikkeling van meganismes om kreatiwiteit in ingenieursorganisasies en in ingenieursontwerp te meet.

1 INTRODUCTION

The primary skill of the engineering profession is complex problem-solving, which is achieved through the design of a solution. The nature of the problems that are to be solved (and the solutions that are to be designed) varies widely both within the various disciplines of engineering and within different fields of application. Examples of the large variety of problems that could be considered within the engineering discipline include: solutions for airborne travel that range from a spaceship to a drone, solutions for generating and distributing electricity that range from tidal turbines to a bicycle dynamo, and solutions for containing a body of water that range from a dam wall to a bucket.

Creativity plays a vital role in ensuring that the solutions that are generated are of a high quality; solution quality would not only be evaluated in terms of durability or cost-effectiveness, but also in terms of ease of use, ease of maintenance or repair, potential speed of implementation, etc. A classic example of the contribution that creativity can make to engineering design is the case of the microwave oven [1]. It is easy to imagine that, up to the point where the accidental discovery that microwaves melt chocolate was made by an engineer working on an active radar set, designers considering the problem of heating food focused exclusively on different mechanisms for generating heat. These engineers may have generated a great number of ideas for converting various forms of energy into heat (and the generation of a large set of these ideas may have been considered creative), but if they all converged around the topic of heat generation, then no consideration was given to using something other than heat to solve the problem of heating food. This example highlights the significant contribution that creativity in the form of divergent, novel ideas can make to engineering design. It also highlights the importance of accurately measuring or understanding creativity: one divergent, useful idea may hold significantly more value than a large number of convergent ideas.

The literature contains several publications that consider creativity within engineering. The existing research can essentially be divided into:

1. Creativity in engineering education – specifically, how the engineering design process is taught, with suggestions for incorporating a specific mechanism into engineering education that has been proven to increase productivity; and
2. An analysis of the engineering design process, coupled with a suggestion for incorporating a specific method from creativity theory into the engineering design process.

Though models for increasing productivity in the engineering domain are frequently proposed in the literature, very little evidence can be found of mechanisms for measuring creativity in engineering design (especially within the context of engineering organisations). It follows that the literature proposing models for increasing creativity does not contain data proving the efficacy of these models in engineering organisations. This paper takes a different approach, recognising that a large number of different approaches to developing theories of creativity exist, and that creativity is a complex field. Therefore it is the position of this paper that selecting a specific technique for stimulating creativity, and proposing that this should be applied as a mechanism for increasing creativity in the engineering domain, is too narrow an approach. Instead, this paper aims to present a comprehensive yet succinct overview of the most prominent theories of creativity, with the aim of identifying potential areas of research where the application of theories of creativity to the engineering domain can offer benefit. This paper is contextualised through a brief, general overview of the literature in Section 2.

The literature contains several different models of the engineering design process, and Section 3 introduces the concept of engineering design and presents a comparison of the most prominent prescriptive models of the engineering design process. Section 4 provides a high-level overview of research into the field of creativity and the creative process, in order to provide the necessary background for the discussion in Section 5, about whether creativity theory does or should play a role in the engineering design process. Section 6 makes recommendations for further research based on these findings.

2 CONTEXTUALISATION

It is commonly accepted in the literature that problem restructuring (i.e., reaching a novel understanding of or insight into the problem itself) is required when individuals solve problems that require insight [2,3]. Martinsen [2] studied different cognitive styles to determine how this problem restructuring takes place, and how skills are transferred after solving these problems. He identified two cognitive styles that perform well in problems requiring insight:

1. Assimilators – individuals who "give priority to upholding cognitive economy"; and
2. Explorers – individuals who "seek new types of solutions and new ways of solving problems".

Martinsen [2] concludes that creativity plays a key role in both of these cognitive styles, as it "is associated with the ability to handle high task novelty". Referring back to the microwave oven example, it is likely that the design team may have benefitted from employing more rigorous problem restructuring in order to confirm that the problem is not the generation of heat (which will in turn be used to heat food), but rather that the problem is the heating of the food itself.

The microwave oven example illustrates the potential economic benefit that can be associated with a novel idea. In a book that has been cited more than 12,000 times to date, Florida [4] describes creativity as the most important economic resource of this century. Runco [5] agrees that creativity should be viewed as a resource and a form of capital, but cautions that it is important to understand that investing in creative potential involves risk. This risk stems primarily from the novel nature of creative ideas; therefore, investing in creativity implies investing in (the generation or development of) ideas that are untested. This concept is explained more fully by the psycho-economic theory of creativity that is introduced in Section 4. The risk involved offers possible mechanisms for explaining why, despite the close link between proficiency in problem-solving and creativity, and the clear potential for economic benefit associated with creative behaviour, creativity is not generally a trait that is given prominence within the engineering profession.

The topic of creativity within the context of education (from pre-school through to the tertiary level) has been a popular topic of academic discourse in recent years [6-13]. Robinson [7] in particular has argued that creativity is not actively encouraged by organisations that govern education (this statement was made in the UK context), and that creativity has become (inaccurately) stereotyped with only a very narrow set of activities and collection of individuals being viewed as creative. In studies of creativity specifically within engineering education, Berglund and Wennberg [14] found that engineering students had significant creative potential. As mentioned in Section 1, a number of studies have proposed methods for incorporating specific creative methods into engineering education or that seek to understand motivation for creativity in engineering students [15-17].

3 THE ENGINEERING DESIGN PROCESS

In this section, the term 'design' is defined before different models of the engineering design process are compared and analysed.

3.1 Defining design

Dym *et al.* [18] state that engineering design is specifically concerned with problems that are:

1. Ill-structured or ill-defined, which means that the solution cannot be found by applying algorithms or mathematical formulas in a routine or structured manner; and
2. Open-ended, which means that several, divergent, and valid solutions to the problem could exist.

Cross [19] further expands on the characteristics of ill-defined problems by stating that:

1. No definitive formulation of the problem exists;
2. Any formulation of the problem may contain internal inconsistencies that often only become apparent during the solution process; and

3. The process of proposing solutions to the problem is a method of improving the understanding of the problem.

Hubka and Eder [20] make a distinction between the narrower definition of design and the wider definition of design. In the narrower definition, the design process is initiated by a set of demands (requirements, needs, or constraints) on a technical system, and it culminates in some description (e.g., design drawings and specifications) from which the technical system can be manufactured or implemented. For the purposes of this discussion, 'design' according to this narrower definition will be termed 'technical design'. In the wider definition, additional problem-solving activities (for example, product planning) are undertaken before (and sometimes also after) the technical design process.

The term 'design' is used within a broad variety of fields, from fashion to vehicles, and from electronic devices to large structures. Childs [21] gives the following definition of design in a broad context: "Design can be considered to be the process of conceiving, developing, and realising products, artefacts, processes, systems, services, and experiences with the aim of fulfilling identified or perceived needs or desires typically working within defined or negotiated constraints." Engineering is commonly defined as the discipline, art, and profession of acquiring and applying scientific, mathematical, economic, social, and practical knowledge to design and build structures, machines, devices, systems, and processes that safely realise solutions to the needs of society. This definition is representative of definitions of design in the engineering context found in literature. Both the definition of design given by Childs [21] and the commonly used definition of engineering are aligned to the wider definition of design. Kryssanov *et al.* [22] define the discipline of design studies as the "study of the thought process comprising the creation of an artefact in a given (social, technical, economical, etc.) environment".

3.2 The engineering approach to design

No single cross-disciplinary definition of the engineering design process exists; this is not surprising because, as Dym *et al.* [18] state, there is no single engineering design community that transcends the different engineering disciplines. However, the study and documentation of the design process has been a topic of research for several decades, and various authors have proposed maps or models of the process. Cross [19] distinguishes between two types of models: descriptive models that simply attempt to describe the sequence of activities that typically occur in the design process, and prescriptive models that attempt to prescribe a specific sequence of activities that should be employed to arrive at a superior design. Cross [19] then proposes a novel model (defined as an integrative model) that does not attempt to describe or prescribe any specific sequential steps in the design process, but rather attempts to portray the symmetrical relationships between four elements of design: the overall problem, the sub-problems, the sub-solutions, and the overall solution.

It would not be feasible to provide a succinct overview of the various models of the engineering design process here. Rather, in an attempt to provide sufficient background for a discussion of whether creativity plays a role in the engineering design process, the sequential steps described by some prominent linear prescriptive models are compared in Figure 1. Such comparisons are rare in the literature, but the interested reader is referred to Howard *et al.* [23] for a similar comparison of a larger number of less recent models. It is important to note that the intention is not to imply that design is a linear process; all of the models presented in Figure 1 describe an iterative process with several feedback loops both between consecutive steps and between steps that are separated by several intermediate steps. Instead, linear models are selected for presentation, and the feedback loops are not depicted in the comparison because the focus here is solely on identifying and comparing the elements (steps) of the engineering process that are defined by each model. The comparison does not include any generic design process models or any descriptive engineering design process models. These models are generally more basic, and tend not to contain any key elements that are not already described by the prescriptive models that are included in the comparison.

Element identifier	Archer [24]	Total design - core only [25]	Engineering design process [26]	Systematic approach [27]	VDI 2221 model (as given by Cross [19])	Design for six sigma [21]
A	Programming	Market	Recognition of need		Clarify and define task	New product introduction
B	Data collection					Measure customer needs
C	Analysis	Specification		Specification	Determine functions and their structures	Define
D	Synthesis	Conceptual design	Conceptualisation	Concept	Search for solution principles and their combinations	Concept
E			Feasibility assessment			Analysis of conceptual design
F			Work breakdown structure		Divide into realisable modules	
G	Development	Detailed design	Preliminary design	Preliminary layout	Develop layouts of key modules	Technical design
H			Detailed design	Definitive layout	Complete overall layout	
J			Qualification testing			
K	Design communication		Production planning and tooling design	Documentation	Prepare production and operating instructions	
M		Manufacture				Implement
N		Market				Handover

Figure 1: Comparison of the elements defined in various prescriptive models of the engineering design process

With reference to Figure 1, the various prescriptive models show significant variation in the elements that they consider to form part of the engineering design process. In summary, the following elements are defined:

- **Elements A & B**: Identifying and understanding the need;
- **Element C:** Compiling a specification for the design;
- **Element D:** Conceptual design or 'synthesis' (one of only two elements that are included in all the models in Figure 1);
- **Element E:** Evaluating the feasibility of the conceptual design, included only in the models of Ertas and Jones [26] and Childs [21];
- **Element F:** Dividing the design task into a set of smaller design tasks, included only in the models of Ertas and Jones [26] and Cross [19];
- **Elements G & H:** Detail / technical design (the second element that is included in all the models in Figure 1);
- **Element J:** Evaluating the suitability of the detail design, included only in the model of Ertas and Jones [26];
- **Element K:** Documenting the design. According to the majority of the models presented, this is the concluding step of the engineering design process;
- **Element M:** Implementing the solution; and
- **Element N:** Handing the solution over to the market.

The models differ in terms of what they define as the start and end of the design process. For example, the systematic approach [27] focuses solely on the technical design process (or the narrow definition of engineering design), while all of the other models presented here contain at least some description of an initial, exploratory phase (wider definition of design). As mentioned, the majority of the models define design documentation as the last step in the engineering design process; however, both Pugh [25] and Childs [21] do not specifically mention the documentation step, but go beyond documentation to include implementation and handover as forming part of the design process.

When attempting to compare different models of the engineering design process, it is important to take into consideration the notion that models that have been developed in different cultures have different denotations and levels of expressiveness. It is not feasible to take this complexity into consideration in this brief overview. Nevertheless, it is interesting to take note of the language used in describing the various steps. For example, where all of the other models describe the concept design step (Element D) using non-prescriptive language, leaving the user open to interpret the meaning of 'synthesis', 'conceptualisation', 'concept', or 'conceptual design', the VDI 2221 model reduces this step to "search for solution principles and their combinations" [19]. In their analysis of various models of the engineering design process, Howard *et al.* [23] conclude that "engineering design process models are poor with regards [sic] to representing creative processes".

4 CREATIVITY

This section starts with a discussion of the meaning of the term 'creativity', both within a general context and more specifically within an organisational context. This is followed by a brief overview of the most relevant theories within the field of creativity research.

4.1 What is creativity?

A commonly-accepted definition of creativity in organisational theory is the production of novel (or original) and useful ideas within any domain [28,29]. The definition given by Plucker *et al.* [30] has a slightly different approach, which incorporates a focus on the mechanism for the production of a creative idea: "Creativity is the interaction among aptitude, process, and environment by which an individual or group produces a perceptible product that is both novel and useful as defined within a social context". Runco [5] defines originality as the critical contemporary identifier of creativity. According to Kaufman and Sternberg [31], creative ideas have three key characteristics:

1. They are new, different, or innovative;
2. They are of a high quality; and

3. They are appropriate to the purpose for which they were created, or to some redefinition of that purpose.

Creativity is closely associated with:

1. Fluency (i.e., the number of raw ideas that are generated, irrespective of their originality and quality);
2. Originality, which is the degree of novelty of an idea; and
3. Flexibility, which is the degree to which an individual is open to new knowledge [5].

Several authors have proposed definitions of creativity. Gurteen [32] views creativity as the process of generating ideas through divergent thinking, while Cheng [33] defines it as the ability to generate novel ideas. Fernandes *et al.* [34] describe it as a complex phenomenon encompassing four key elements: the creative process, the creative agent, the creative situation, and the creative product.

Amabile *et al.* [28] define innovation as the successful implementation of creative ideas within an organisation. Similarly, Gurteen [32] defines innovation as the sifting, refining, and implementation of creative ideas. From this perspective, creativity (by individuals or teams) is a necessary element for innovation, but creativity alone is not sufficient for successful innovation. A key difference between creativity and innovation is that innovation is directly associated with economic benefit to an organisation, while this is not necessarily the case for creativity.

Rasulzada [35] defines a creative organisation as one that “has the ability and capacity to tap the creative potential of their employees into novel, original and valuable products, services, processes, strategies, or other values”.

4.2 Theories of creativity

The topic of creativity has received widespread research attention over hundreds of years, and there are several distinct theories of creativity. It is not feasible to provide a comprehensive introduction to the field here, but the interested reader is referred to Runco and Albert [36] for such an introduction, and to Kozbelt *et al.* [37] for a review of ten distinct, modern theories of creativity. As an illustration of how theories of creativity differ in their primary assertions, their key concepts, the aspects of creativity that they emphasise (process, product, person, place, persuasion, and potential), and the levels of magnitude that they take into account, Table 1 provides a description of six theories of creativity that were identified by Kozbelt *et al.* [37].

With reference to Table 1, there are similarities in the perspective taken by the economic theory of creativity and the systems theory of creativity. Both employ a holistic view, which takes into consideration the environment or ‘place’ (where environment is defined broadly to incorporate both physical aspects of offices, buildings, and cities, and psychosocial aspects such as organisational culture, management philosophies. and reward structures) within which creative activity takes place, as well as the individual or ‘person’ involved in the creative activity. In contrast to economic and systems theories, the stage and componential process, cognitive, problem-solving and expertise-based, and problem-finding theories employ a narrower focus, and specifically concern themselves with the creative process itself. The processes described by these theories consider different combinations of:

(i) General cognitive processes, which include those based on domain-specific expertise;
(ii) Exploratory behaviours and subjective creative processes, which include divergent thinking and remote association; and
(iii) ideational thought processes, such as metaphorical thinking, problem representation and heuristics, on-line discovery, and other techniques that generate insight.

When considering the presence of creativity in the engineering design process, it is logical that the theories that focus on the creative process should be considered in more detail. However, the engineering design process does not occur in a vacuum. It can therefore be argued that theories incorporating a more holistic approach should also be taken into account, in order to understand the effect of the environment in which the engineering design process functions and of the individual executing the engineering design process.

Table 1: Applicable theories of creativity (excerpted from a table by Kozbelt *et al*. [37])

Theory of creativity	Primary assertion	Key concepts	Emphasised aspect(s) of creativity	Level of magnitude
Economic	Creative ideation and behaviour is influenced by 'market forces' and cost-benefit analyses.	Influence of macro-level factors; Psycho-economic perspective; markets of creativity; and investment decisions.	Person; Place; Product; and Persuasion.	Little-c to Big-C.
Stage and componential process	Creative expression proceeds through a series of stages or components; the process can have linear and recursive elements.	Preparation stages; incubation and insight; verification and evaluation; and component mechanism.	Primarily process.	Mini-c to Big-C.
Cognitive	Ideational thought processes are foundational to creative persons and accomplishments.	Remote association; divergent/convergent thinking; conceptual combination, expansion; metaphorical thinking, imagery; and metacognitive processes.	Person; and Process.	Little-c to Big-C.
Problem-solving and expertise-based	Creative solutions to ill-defined problems result from a rational process that relies on general cognitive processes and domain expertise.	Ill-defined problems; cognitive, computation approach; expertise-based approaches; and problem representation and heuristics.	Person; Process; and Product.	Little-c to Big-C.
Problem finding	Creative people engage proactively in a subjective and exploratory process of identifying problems to be solved.	Subjective creative processes; exploratory behaviours; and on-line discovery.	Process; Person; and Potential.	Primarily mini-c.
Systems	Creativity results from a complex system of interacting and interrelated factors.	Evolving systems; network of enterprises; domain and field; gatekeepers; collaborative creativity; and chaos and complexity.	Varying emphasis across all six aspects.	Little-c to Big-C.

When considering the presence of creativity in an organisational context, it is important to take a holistic approach. This approach recognises that all of the elements of creativity, as defined by Kozbelt *et al*. [37], are present in an organisational context, and must therefore be taken into consideration when attempting to assess whether an organisational environment supports creative activity. As an illustration of some of the dynamics that could influence creativity in an organisational context, the psycho-economic theory of creativity (referred to as the 'economic' theory in Table 1) is singled out for a more in-depth presentation. Inter-disciplinary research in economics and psychology has produced several useful descriptions for understanding the dynamics of various concepts in creativity [5]. It is not feasible to present a comprehensive overview of the psycho-economic perspective on creativity (the interested reader is referred to Runco [5] for a more detailed introduction); instead, some of the most relevant concepts are briefly introduced here [5]:

1. The concept of 'a market for creativity' holds that "social settings can be arranged such that original behaviour has both predictable benefits and minimal costs, [with] the result being a tendency towards creative action".

2. Economic theory is largely devoted to the distribution and allocation of resources. In the creative field, the term 'resources' should be interpreted broadly to include time, psychic energy, money, and physical resources. Psycho-economic theory provides two perspectives on resources in creativity:

   a. Creative potential (whether this be in the form of creative individuals or a work environment that stimulates creativity) as a resource that should be managed appropriately; and
   b. Resources invested in creative work. Specifically, the concept of risk is used to explain why it is often viewed as risky to invest in creative potential (because creativity is associated with that which is novel and therefore untested; this example was given in Section 2). Psycho-economic theory then draws on concepts related to risk tolerance and the minimisation of risk to propose how such a reluctance to invest in creative potential may be overcome.

3. The concept of 'depreciation' is used to explain how an investment in creativity may lead to a reduction in creative potential if it decreases ideational flexibility (in an attempt to reduce the risk of depreciating the value of an existing idea).

In addition to the examples given above, the psycho-economic theory of creativity is also most notably used to explain concepts related to the value of creativity and the relationship between quantity and quality within creativity [5].

When classifying the level of magnitude of creativity, Kozbelt *et al.* [37] make use of the Four C model of creativity proposed by Kaufman and Beghetto [38]:

1. Mini-c: subjective forms of the creativity of everyday life, specifically related to the learning process and the development of creativity;
2. Little-c: objective forms of the creativity of everyday life;
3. Pro-c: professional level creators, in any creative area, who are not or may never become eminent creators; and
4. Big-C, eminent, unambiguous examples of creativity.

A cursory review of these four categories would most likely lead to the conclusion that professional engineers fall into the Pro-c category. Indeed, this paper agrees that Pro-c is the most appropriate category for fully qualified professional engineers.

5 CREATIVITY AND THE ENGINEERING DESIGN PROCESS

This raises two questions: Does creativity play a role in the engineering design process; and if it does, are we (and should we be) proactively managing engineering organisations in such a manner as to ensure that they support creativity in engineering design?

5.1 Does creativity play a role in the engineering design process?

Cox [39] described the relationship between design, creativity, and innovation as follows: "Design is what links creativity and innovation. It shapes ideas to become practical and attractive propositions for users or customers. Design may be described as creativity deployed to a specific end." This description highlights the need for the design process to interact effectively with or incorporate creativity in order successfully to realise the economic benefits associated with innovation.

Creativity (in the form of ideational thought processes such as problem representation) plays an essential role in the problem restructuring that is required when solving complex problems (introduced in Section 2). This problem restructuring phase is represented by the problem definition steps, Elements A, B and C, in Figure 1.

With reference to the iterative nature of the design process, Ertas and Jones [26] note that repeating an earlier step to consider a new alternative becomes increasingly costly as an individual progresses through the process. In addition to the cost element, designers become increasingly less likely to abandon a particular design once it has been chosen as the preferred solution and some effort has been put into developing the design beyond the initial concept phase. Ertas and

Jones [26] also note that any persons involved in a design process tend to lose their objectivity with regard to alternative designs once a particular concept has been chosen. These findings highlight the value of thinking widely early in the design process (for example, in the concept design/synthesis step, which is Element D in Figure 1), in order to generate a large variety of unique, divergent alternatives from which to select.

Creativity does not only add value early in the design process. As engineering design projects progress, more preconditions may emerge that require divergent thinking to address the potential challenges associated with these preconditions.

From the preceding discussion, as well as from the literature accompanying models of the engineering process, it is clear that although models of the engineering process may not explicitly portray creative processes, there is an implicit requirement for creativity throughout the engineering design process.

Several authors have stated that creativity is essentially a systematic process and as such, it can be managed [33,40,34]. From this, it can be concluded that it should be possible to manage the engineering design process proactively so that it supports increased creativity. Incorporating creativity into the engineering design process in a systematic manner could enable the routine generation of higher-quality solutions. Furthermore, from the widely cited work by Florida [4], it is reasonable to conclude that doing so does, at the very least, have the potential to offer significant economic benefit.

5.2 Are we (and should we be) managing for creativity in engineering design?

From the brief overview of the field of creativity in Section 4, it is apparent that, while creativity could be viewed as a systematic process, it would be inaccurate to assume that creative processes are not also influenced by a number of other factors, which include the environment in which they take place and the level of motivation of the individual(s) involved. Against this background, it is proposed that incorporating research on psychosocial approaches that are proven to support creativity within organisations would be a necessary element for enabling increased creativity within engineering organisations. Specifically, it is proposed that an approach that focuses purely on incorporating creativity into the engineering design process without considering factors such as organisational culture, management styles, and reward structures that stifle or encourage creativity within engineering organisations will have limited efficacy.

The overview in Section 4 illustrated that creativity is a complex phenomenon with many different perspectives that need to be taken into account when attempting to understand it fully. It follows that attempting to manage an organisational environment to ensure creativity would be a complex endeavour that requires that the several factors and dynamics that may influence creativity be taken into account. It is reasonable to conclude that organisational climates and practices cannot simply be assumed to be conducive to creativity. Rather, it should be considered that, as with other elements such as the motivation of employees, an organisation must proactively manage if it wants to increase its performance. It is therefore proposed that engineering organisations need to be proactively managed to support creativity in engineering design.

This proposal leads to the final question of this paper: Is there evidence in the literature that engineering organisations are currently being proactively managed to support creativity in engineering design? Appendix A describes a customised search protocol that was conducted to identify the literature on creativity in engineering organisations and discusses the findings in more detail. To summarise, although there is certainly research that considers various aspects of creativity in engineering organisations, there is no evidence in the literature of the existence of a framework, model, or similar defined approach to inform and/or guide management practice to ensure sustained, creative activity in engineering organisations.

6 CONCLUSION

The research produced the following deliverables:

1. It provided a comparison of the elements defined in some prominent models of the engineering design process;

2. It provided a brief introduction to the field of creativity, highlighting aspects that may be relevant to increasing the prominence of creativity in the engineering field;
3. It illustrated that creativity is a complex field, and that it is therefore short-sighted to consider merely one technique for enhancing creativity when researching methods for increasing creative activity within the engineering context;
4. It used findings from the engineering design and creativity literature to hypothesise that (i) creativity does play a role in engineering design; (ii) organisational practices cannot simply be assumed to be conducive to creativity, but rather that engineering organisations should be proactively managed to support creativity in engineering design; and (iii) doing so would (at the very least) hold significant potential for economic benefit; and
5. It concluded that there is no evidence in the literature that engineering organisations are currently being managed proactively to support creativity in engineering design.

It is proposed that the most prudent way of taking these research findings forward would be to develop a framework for managing engineering organisations in a way that actively supports creativity. It is proposed that such a framework should not be overtly onerous to implement (a factor that would most likely render it impractical for managers of engineering organisations). Rather, it should distil the literature on creativity into an understandable set of guidelines that managers could incorporate into their existing operational management practices. Incorporating an understanding of the impact of psychosocial factors into the management of engineering organisations could enable the existing creative potential of these organisations to be unlocked more effectively. Furthermore, developing mechanisms for effecting behavioural change in engineering organisations based on psycho-economic theory could offer solutions to overcome stubborn behavioural problems in these organisations, potentially stretching beyond those affecting creative activity.

Referring back to the lack of measurement techniques for creativity in an engineering context highlighted in Section 1, a second suggested area for future research is the development of appropriate measuring mechanisms. This would enable empirical research on whether interventions to increase creativity in engineering organisations have a measurable impact.

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APPENDIX A: CUSTOMISED LITERATURE SEARCH PROTOCOL

A customised protocol for searching for literature on creativity in engineering organisations was developed and followed in order to ensure a rigorous search of the literature. The following five databases were searched:

- the Scopus database provided by Elsevier;
- the Web of Science database provided by Thomson Reuters;
- the Academic Search Premier database provided by EBSCO Publishing;
- the Taylor and Francis online database provided by Taylor and Francis; and
- the Google Scholar database provided by Google.

Since the search functionality of each of the databases differs, a customised approach was followed during the search of each database. However, all of the searches were aligned to the same basic logic, which was to search for a combination of three terms: 'creativity' AND 'engineering' AND ['organisation' OR 'institution' OR 'company' OR 'firm' OR 'corporation'], in reasonably close proximity to one another, in the title or abstract. The search uncovered 183 research items (mostly articles and conference proceedings) that were investigated to determine whether the literature provides evidence that engineering organisations are being managed proactively to support creativity in engineering design. As stated in Section 5.2, no such evidence was found.

The search did uncover a variety of literature that may be useful when attempting to build on the research presented in this paper. Examples of such literature include the following: Kukushkin and Churlyaeva [41] present an interesting case study, discussing possible reasons for a lack of technological creativity in Russia; Lin [42] presents research on the influence of individuality relatedness and cognitive flexibility on team creativity in an engineering context; Eckert *et al.* [43] use a case study to investigate the effect of an averseness to risk on creativity in engineering design, and concludes that "the emphasis on reliable and repeatable processes causes creativity to be displaced backwards into R&D and forwards into 'emergency innovation' during integration"; Jagodzinski *et al.* [44] use case study research to demonstrate "the adverse effect of organisational and technological change on the creativity of design engineers"; Wang [45] investigates factors influencing the adoption and use of creativity techniques by individuals, specifically in an organisational context, with the aim of informing the use of these techniques in an engineering context; Chakrabarti [46] analyses biographical information of a number of eminent engineering designers to identify the common influences and factors that are likely to have led to their success; and Yilmaz *et al.* [47] present a tool (Design Heuristics) aimed at supporting engineers in considering a larger number of diverse concepts during the idea generation phase of design.

Two publications that are particularly important to note are Menzel *et al.* [48] and Yannou [49]. Menzel *et al.* [48] investigate methods to make engineers active as 'intrapreneurs' in large organisations. Among other questions, the research investigates managerial and organisational factors that assist engineers to function as intrapreneurs. Yannou [49] describes a large research initiative to study "design creativity and innovation from practical perspectives"; the research initiative is specifically aimed at the work of engineers. Although this research initiative has produced a number of roadmaps and frameworks for managing innovation within organisations, no framework focusing on increased creative activity has been proposed.