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CREATIVITY IN THE ENGINEERING DESIGN PROCESS

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ABSTRACT
It is accepted that innovation is key to any company's long term success. Despite this there are few published engineering design processes with the inclusion, mention or consideration of the creative process. With a strong body of research from the social sciences based upon the different creative processes, it is argued that engineering design research should embrace these processes in order to effectively adopt the tools, methods and techniques that have been developed around them.
In this paper it is argued that the design process and the creative process are not synonymous, but it instead will consider creativity as an essential element in designing [1]. Over 100 different design and creative processes have been analysed and considered in total, 42 of which have been tabulated for comparative purposes within this paper. The linear style in which the majority of the process models are presented enabled easy comparison of the terminology. By extracting the key phases from both types of process, a descriptive process model is proposed describing creative process as a cyclical subset of the engineering design process. The overall purpose of this paper is to identify where and when in the process of design does creativity occur.

Keywords: Creative process, design process

1 INTRODUCTION
Creativity is an integral part of the engineering design process, its presence often being the major influence on the impact of a product. Without some element of creativity in design there is no potential for innovation where novel ideas are implemented [2, 3] and transformed into commercial value [4, 5]. To emphasise this importance, recent figures were released from the UK treasury concluding that the top innovating companies produce 75% of revenue from products or services that did not exist 5 years ago [6]. Within industry, creativity does not necessarily equate to success, however, without some form of innovative new product development, long-term failure is a certainty. In order for firms to increase their organisational creativity, thus resulting in enhanced innovation, the creative process of individuals must be considered within the design process [7].
Whilst participating in engineering/social science creativity cluster[1] meetings [8] it was clear that many social scientists could not distinguish between creative and design processes. Furthermore, little differentiation was made between the production and development of ideas and the production and development of a product. Conversely, engineers generally acknowledge that the creative process is different to the design process though are unable to succinctly describe it.
Though the definitions of creativity and design are far from rigid and are used differently throughout research, the following definitions have been constructed from the authors' analysis of the considerable amount of literature reviewed.

- Creative Process: A cognitive process culminating in the generation of an idea.
- Design Process: A labour intensive process culminating in the proposal of a product or process.

This paper will undertake an in-depth study of both the creative process and the engineering design process. The purpose of this paper is to identify where and when in the process of design does creativity occur. Throughout the paper the parallels and contradictions between design literature and creativity literature become apparent.

[1] http://www.creativityindesign.org.uk/

2 THE ENGINEERING DESIGN PROCESS

The understanding of the design process is important for the teaching of design, the improvement of products, and the efficiency of engineering based companies; it is also the foundation on which a lot of design research is conducted. It is thought that understanding this process relative to the creative process may give insight into where and when resources should be focused in order to enhance creative performance and the quality of the product designed.

There are several ways of describing the design process, of which 3 main categories have been identified. Though abstract and non-prescriptive, the most accurate description is the 'knowledge driven' design process, typified by C-K theory [9]. Here, the information contents of the several spaces are filled in a seemingly random order, the process ends when there is sufficient information in each space to terminate or make a design recommendation. Another, and frequently used description, is the divergent-convergent style process, which works along the idea of gaining then evaluating information and, generating then selecting alternatives [10]. However, by far the most common is the linear type design process model. Table 1 contains the various design processes reviewed from the literature. As the models are predominantly of the linear style, column headings were chosen based around broad headings modelled on the Pahl and Beitz systematic design process [11]: 'Need', 'Analysis of Task', 'Conceptual Design', 'Embodiment Design' and 'Detailed Design' in that order. A further column was added to describe post design activities which are often also described by several process models.

This section will draw conclusions from the different engineering design processes described in literature and within Table 1. The findings will provide the reader with an understanding of the different types of engineering design process and the elements that relate to creativity. The subsequent sub-sections deal with the varying characteristics of the different process models, whether prescriptive or descriptive (Section 2.1), generic or specific (Section 2.2), describing outputs or activities (Section 2.3), and whether the process is driven by a market or technology (Section 2.4).

2.1 Prescriptive or Descriptive

There is much literature regarding the formalisation of the design process. These are traditionally split into two categories, the descriptive process models (for example see Figure 1) and the prescriptive process models (for example see Figure 2), both of which are commonly represented by flow diagrams. The descriptive models attempt to replicate the sequence of occurrences throughout design, however, models are said to provide "over simplistic" [12] and "over idealistic" [13] views of the design process. The prescriptive models are then built upon these descriptive models in order to guide the designers more efficiently through the design process.

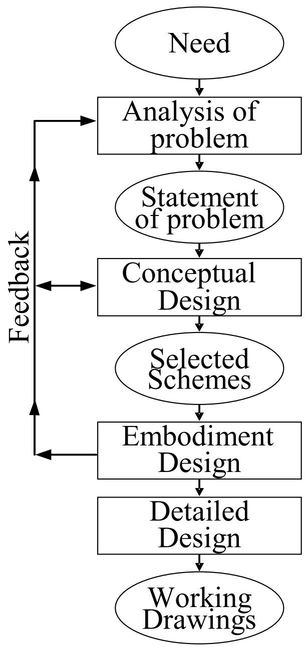

Figure 1 – Descriptive Process Model [19]

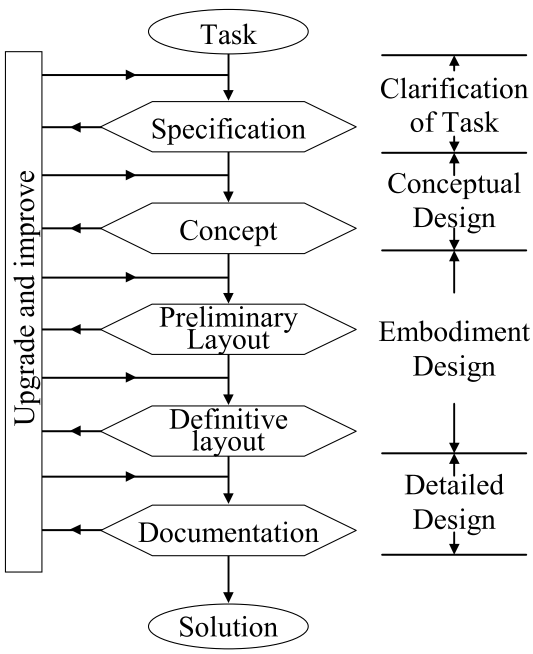

Figure 2 – Prescriptive Process Model [11]

Although the prescriptive models are by definition not natural design practice, many are so generic and well known that they only remain prescriptive to novice design engineers. Perhaps the most famous and commonly quoted of these processes is the Pahl and Beitz systematic design process (Figure 2), now more often used in reference for purposes of descriptive representation. When constructing process models there is always trade-off between how useful or prescriptive it can be, against, how inclusive it is to different projects and how user friendly it is to the designer. This results in very similarly structured process models between descriptive and prescriptive models. Column ‘W’ (in Table 1) shows the breakdown between the Prescriptive (P) and Descriptive (D) models reviewed.

2.2 Generic or Specific

The level of complexity of a design process model is of great importance and has large impact on its value. Simple models generally follow a linear route with fewer, more broadly defined steps leading from the start to finish. These models are easy to apply to the variety of different design projects that may be encountered, making them more user friendly to the designer. Though the field of design research contains a number of these simplistic design process models, very few are adopted by industry as they are considered too generic [14]. Instead of actively guiding the designer these are approaches that are often used as management and documentation tools rather than as actual design aids. It is interesting to note that specific solutions to design processes are more frequently created than they are published. During the planning phase of industrial design projects, it is common to construct gant-charts, timelines and stage gates to map the process ahead. This can be time consuming, particularly when done without the use of a generic guideline. As a solution to this, engineering companies often produce there own generic design processes to suit capabilities, product ranges and customer base, such as the Rolls Royce Derwent Process [15]. These design processes can be particularly effective if constructed on the basis of best known practice and are re-evaluated and updated on a regular basis. An example of a company specific innovation process can be seen at the bottom Table 1[2], labelled IIP (Industrial Innovation Process). The breakdown between the Generic (G) and Specific (S) models reviewed is shown in Column ‘X’ of Table 1.

In both generic and specific design process models, few aid the actual ‘creating’ aspect of design further than suggesting activities, tools or techniques that can be applied, or the deliverables that should be achieved, at each particular stage. Several authors have attempted to fill this gap, though these may be considered to be more exclusive to the difficult conceptual design activities, rather than the rest of the extensive and difficult activities involved in engineering design. These processes neatly span the analysis of task, conceptual design and embodiment design phases as shown in Table 1. A recently introduced tool, PRIZM [16], is a good example of this type of support process. Based around principles from the TRIZ [17] contradiction matrix, the process guides the user though a quest to reach the desired requirements and the ideal final result. Interestingly, here the requirements are placed at the end of the process as aims, rather than functional requirements typically found at the beginning of an engineering design process.

2.3 Output or Activity

Not only do the phases of the design process take on different titles, covering slightly different amounts of the actual design process or viewing it from a slightly different perspective, within the phases authors vary on whether to prescribe or describe the process in terms of outputs or activities. Column ‘Y’ (in Table 1) shows the breakdown between processes describing Outputs (O), Activities (A) or Both (B) from the models reviewed. It becomes evident from this that descriptive models tend to use activities to distinguish the different phases of the design process. Most prescriptive models provide both output and activity; this is also quite typical of flow chart and the stage gate models such as the IIP process (shown in table 1).

Whilst several design activities such as ‘generate’ and ‘evaluate’ can also be found in the creative process, the outputs described are not, as the creative processes tend to only describe activities or cognitive phases. Though the design outputs can also be deemed information inputs to following phases, Black [18] is the only author that donates the input of ‘inspiration’, which is directly linked to the creative process and occurs at a specific point relative to the design process. Interestingly this actually refers to a textile fashion design process rather than an engineering design process.

[2] Reference withheld for confidentiality purposes.

2.4 Market or Technology

The sequence of stages, activities and outputs will be subtly different from project to project. The types of generic design process models try best to encompass these subtle changes through the broad headings of stages, thought there will always be exceptions. In all of the process models evaluated (Table 1), processes proceed in the same direction, moving from a need or analysis of task to conceptual design. For the majority of cases this may be true, where 80% of projects are driven by a realised problem or market space [20]. However there are also cases of design projects driven by the available technology. Though not usually stated in literature, the design process for a technology driven project has a variety of differences, particularly at its starting point. To emphasise this, consider Gero's FBS framework [21] which represents the core elements of Mechanical Engineering Design (Figure 3).

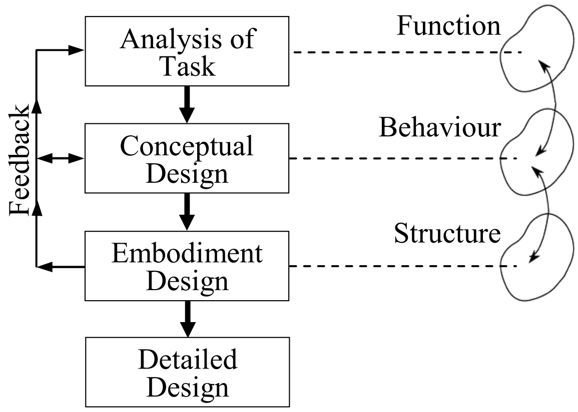

Figure 3 – Relationship between FBS framework and the general design process

The Function (F) of a product will be decided early on in an ideal market driven process (Figure 4); were functional requirements are formed in the 'Analysis of Task Phase'. During the 'Conceptual Design Phase' the designers will produce concepts which have Behaviours (B) that will hopefully satisfy the functional requirements. During the 'Embodiment Design Phase' the physical Structures (S) of these concepts are realised.

In contrast, technology driven projects (Figure 5) are based around the use of behaviours exhibited by other structures. This may be a company trying to exploit one of its patents, or an inventor attempting to make use of an interesting shape or mechanism. Here the projects' begin in the conceptual design phase where the behaviour of a known technology is taken. In a seemingly random sequence, a function is derived from the behaviour to fit a particular market space, whilst a structure is developed by which the behaviour can be embodied. Column 'Z' (in Table 1) shows the breakdown between processes driven by Market (M), Technology (T) or Both (B) from the models reviewed.

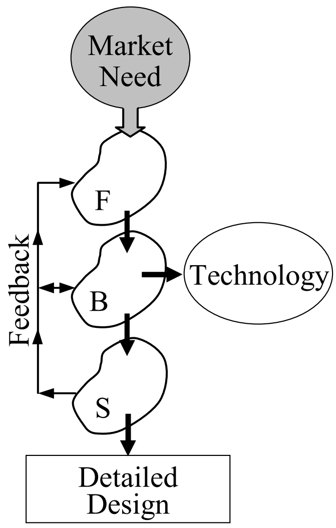

Figure 4 – Market driven process

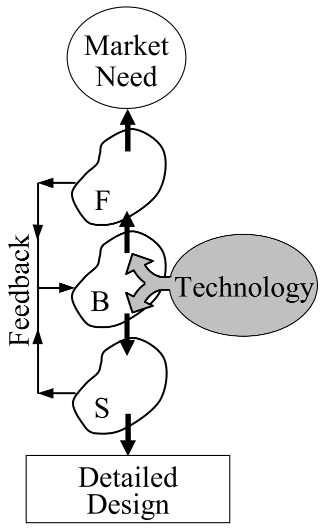

Figure 5 – Technology driven process

Table 1 – Engineering design process models

Models	W	X	Y	Z	Need	Analysis of Task Phase	Conceptual Design Phase	Embodiment Design Phase	Detailed Design Phase	Production, Use, Retirement
1967 [22]	D	G	A	B	X	New Product Strategy Development	Idea Generation; Screening & Evaluation	Business Analysis; Development	Testing	Commercialisation
1968 [23]	P	G	A	B	X	Programming; Data collection	Analysis; Synthesis	Development	Communication	X
1974 [24]	D	G	A	M	Need	X	Concepts	Verification; Decisions	X	Manufacture
1980 [25]	D	G	A	M	Societal Need	Recognize & formalize; FR's & constraints	Ideate and Create	Analyze and/or test	Product, prototype, process	X
1980 [26]	D	G	A	B	Opportunity Identification	Design		Testing		Introduction (Launch); Life Cycle Management
1982 [27]	D	G	O	B	X	Planning	Conceptual Design	Embodiment Design	Detail Design	X
1982 [28]	D	G	A	B	X	X	Conceptual Design	Lay-out Design	Detail Design	X
1984 [29]	D	G	A	B	X	Strategic Planning	Concept Generation	Pretechnical Evaluation	Technical Development	Commercialisation
1984 [11]	P	G	O	M	Task	Clarification of Task	Conceptual Design	Embodiment Design	Detailed Design	X
1985 [19]	D	G	O	M	Need	Analysis of Problem	Conceptual Design	Embodiment of Schemes	Detailing	X
1985 [30]	D	G	B	M	Recognise Problem	Exploration of Problem; Define Problem	Search for Alternative Proposals	Predict Outcome; Test for Feasible Alternatives	Judge Feasible Alternatives; Specify Solution	Implement
1986 [31]	D	G	A	B	Ideation	Preliminary Investigation	Detailed Investigation	Development; Testing & Validation	X	Full Production & Market Launch
1987 [32]	D	G	A	M	Recognition of Need	Investigation of Need	Product Principle	Product Design	Production Preparation	Execution
1991 [33]	D	G	A	M	Market	Specification	Concept Design		Detail Design	Manufacture; Sell
1993 [34]	D	G	B	M	Idea, Need, Proposal, Brief	Task Clarification	Conceptual Design	Embodiment Design	Detail Design	X
1995 [35]	D	G	O	M	Assess innovation opportunity	Possible Products	Possible Concepts	Possible Embodiments	Possible Details	New Product
1995 [36]	D	G	A	M	X	Strategic Planning	Concept Development	System-Level Design	Detail Design	Testing & Refinement; Production Ramp-up
1997 [20]	P	G	A	B	Identify Needs; Plan for the Design Process	Develop Engineering Specifications	Develop Concept	Develop Product		X
1997 [37]	P	G	B	B	Concept	Feasibility	Implementation (or realisation)			Termination
1999 [18]	D	G	B	B	Brief/Concept	Review of 'State of the Art'	Synthesis; Inspiration	Experimentation; Analysis / Reflect	Synthesis; Decisions to constraints	Output; X
2000 [38]	D	G	A	B	X	Exploration	Generation	Evaluation	Communication	X
2006 [10]	D	G	A	B	Discover	Define	Develop		Deliver	X
I.I.P	P	S	B	B	Mission Statement	Market Research	Ideas Phase	Concept Phase	Feasibility Phase	Pre Production

3 THE CREATIVE PROCESS

It may seem that psychologists can be split into two categories as described by Boden, namely as romantics and non-romantics The romantics take a more spiritual view of creativity where it is viewed as a mysterious and subconscious process [39, 40]. This is still quite a common view of the creative process, however, it is of little help to academic research particularly with regards to creativity in engineering design.

Non romantic views of creativity will be the focus of this section and are typically conveyed as flow diagrams or creative process models. Shneiderman [41] offers three different perspectives of non romantic style creativity: situationalist (Section 3.1); structuralist (Section 3.2); and inspirationalist (Section 3.3). The following sections will thus take the reader through these three different views of the creative process with some alternative structures before concluding with a comparative summary of the process models shown in Table 2.

3.1 Situationalist

Situationalists view of creativity moves away from the individual perspective of creativity and views creativity as more of a social process [42, 43]. Its potential realised by Osborn [44] where brainstorming was introduced along with the increased performance of group creativity. This view of creativity is relatively new compared to the view of inspriationalists and structuralists, highlighting more importance on interaction and collaboration with other individuals and the world around us [45].

Due to the relatively new perspective of the situationalists and little research having been performed in the area of social creativity, there are few creative process models showing such a perspective. However, one such model which has been developed to bring a social aspect to the creative process has been developed by [41] who uses fours stages to describe the social creative process: Collect; Relate; Create; and Donate, which can be seen relative to other process models in Table 2.

Although the authors agree that social creativity is one of the most important areas of study in order to enhance creativity within organisations, it is not the focus of this research. For the purpose of the overall research and the proposed hypothesis for idea generation is that, the individual views everything in terms of information. Therefore the social aspect of creativity as it is considered to be a dynamic stream of verbal information amongst peers.

3.2 Structuralist

Structuralists apply a more systematic and methodological approach to creativity [41, 42]. Creative process models in this form have been described by several authors [44, 46, 47] in terms of the exploration and transformation of conceptual spaces.

These models of the creative process are seen as the more modern approach, formulised to move away from the unconscious process of incubation and illumination. Although, this does not necessarily contradict the inspirationalist approach, it just offers a more detailed and structured route to the illumination phase. Koestler [48] describes a conscious idea generation process with deliberate connection of matrices of thought (similar to ideas though association), likened to Amabile's [47] belief, where new ideas are generated through the combination of two or more old, existing ideas.

Amabile [47] attempts to view this phenomenon from an angle known as the componential approach. The three components proposed are: Domain-relevant skills; Creative-relevant skills; and Task motivation. These valid but relatively immeasurable components determine a designer's creative performance in a particular domain, throughout the five-stage process Amabile prescribes. It is a common perception in creative literature that the level of motivation is proportional to creative performance. This is contradictory to the stages of incubation and illumination (described in 3.3) where the conscious motivation is zero as the problem is not being considered. Although the topic of motivation is beyond the scope of this paper, its links to creativity suggest that it is a process that can be managed rather than being totally random.

3.3 Inspirationalist

Inspirationalists focus on the individuals coming up with ideas in a fashion such as the 'eureka' moment – a sudden change in perception giving rise to an idea from the subconscious. Such a creative process model which fits in with this view is Wallas's [49] with his stages of incubation and illumination.

This is the most recognised of all creative process models and detailed a four stage creative process of: Preparation – Incubation – Illumination – Verification. This is a linear process and contains no feedback loops.

Table 2 – The four stage creative process [50]

Preparation:	This regards the information and knowledge inputs into the process, but also the problem structuring and sense making. This is the somewhat overlooked stage of the process that this research hopes to improve. Its relevance is obvious in engineering design as it parallels the common, Problem Definition/Clarification of task stage of the renowned systematic processes.
Incubation:	A relatively unexplained cognitive process where information is left for a period of time to either: remove mental bocks (e.g. writers block) resulting in the assimilation of an adequate association (illumination), and/or, waiting for stimulating information (e.g. waiting for inspiration) to arise and spark an adequate association [51]. This stage of the creative process does not always occur, or may occur but instantaneously. The incubation period may be the difference between producing creative solution and producing routine solutions.
Illumination:	This is not so much a stage of the creative process but rather an output, when a promising idea has been realised. It is associated with a feeling of excitement and accomplishment. This is often referred to as the 'Eureka' or 'Ah ha' moment. In the authors experience this is not always so clear cut. Often the Ah ha feeling can come later when understanding an idea. It is difficult to distinguish between the illumination experience that occurs in a creative process (when something is created i.e. a concept) and the illumination when gaining understanding i.e. when solving a logic puzzle, a maths problem or understanding a problem structure or evaluation method.
Validation:	This is where the solution from the illumination phase is checked for its appropriateness. This phase is less important with regards to this research as it lies after the process of idea generation. The validation, evaluation and testing of idea/concepts is easier and less mystical than the process of producing them.

Table 3 – Creative process models

Models	Analytical Phase	Generation Phase	Evaluation Phase	Communication / Implementation Phase
(1826) [52]	Saturation	Incubation / Illumination	X	X
(1910) [53]	A felt difficulty / Definition and location of difficulty	Develop some possible solutions	Implications of solutions through reasoning	Experience collaboration of conjectural solution
(1926) [50]	Preparation	Incubation / Illumination	Verification	X
(1953) [54]	X	Inspiration	Elaboration	Communication
(1957) [55]	Understanding the Problem / Devising a Plan	Carrying out the Plan	Looking Back	X
(1957) [56]	X	Divergence	Convergence	X
(1960) [57]	Recognition / Definition / Preparation / Analysis	Synthesis	Evaluation	Presentation
(1963) [44]	Fact-finding	Idea-finding	Solution-finding	X
(1967) [58]	Problem, challenge, opportunity / Fact-finding / Problem-finding	Idea-finding	Solution-finding	Acceptance-finding / Action
(1970) [59]	Divergent Search for Data / Understand the Problem	Transformation Pattern finding / Flashes of Insight	Convergent Judgement	X
(1974) [60]	X	Hypothesis formulation	Hypothesis testing	Communication of results
(1981) [61]	Mess Finding / Fact-finding / Problem-finding	Idea-finding	Solution-finding	Acceptance-finding
(1983) [47]	Problem or task presentation / Preparation	Response generation	Response Validation	Outcome
(1981) [39]	X	Conception / Gestation / Parturition	X	Bring up the Baby
(1994) [62]	Constructing Opportunities / Exploring Data / Framing Problem	Generating Ideas	Developing Solutions	Building Acceptance / Appraising Tasks / Designing Process
(1993) [63]	Opportunity, Delineation, Problem Definition / Compiling Information	Generating Ideas	Evaluating, Prioritising Ideas	Developing an Implementation Plan
(2000) [41]	Collect	Create (spanning Generation and Evaluation) Relate (spanning Analytical to Evaluation)		Donate (Communicate)
(2000) [64]	Problem Finding / Fact Finding / Problem Defn.	Idea Finding Diverge – Converge at each stage (spanning all phases)	Evaluate and Select	Plan / Acceptance / Action
(2001) [65]	Functional Requirements / Structural Requirements	Functional Solutions / Analogies, Metaphors	Reinterpretation	X

4 COMPARISON

Paradoxically the confusion between the design process and the creative process is more than understandable given their similarity. The following section will highlight several key crossovers and differences between the two processes, before suggesting how they may fit together forming an integrated descriptive process model (Figure 6).

4.1 Similarities

There are several commonalities between the two processes, in particular the notation or the form that the models are presented. The literature regarding both Creative and Design processes mainly consists of linear type models. This is done in attempt to formalise these quite erratic processes which both contain a substantial cognitive element. Furthermore, the literature regarding both processes also describes two other main types of process model, one involving divergent-convergent processes, the other describing *information spaces* (design) and, *problem and solution spaces* (creativity).

Another notable similarity between the processes is the need for information and its analysis and understanding at the start of the process (analysis of task phase).

4.2 Differences

The embodiment design phase is defined by noticeably different activities and outputs to the equivalent stage of the creative process. Preceding the embodiment phase would be an evaluation and selection of a concept of which to embody, this phase is therefore all about adding the physical form to the concept. This phase of the creative process is simply the evaluation of the idea/solution generated. Following this stage is the detailed design phase which produces formal communication documents for manufacture/implementation, unlike the creative process where this stage does not always exist and involves the less formal externalising of the idea.

It is thus argued that the main difference between the design process and the creative process is seen within the scale and scope of the processes. In the completion of a successful design process, plans of the product or process would be laid out for the user, manufacturer, assembler, etc. Its process steps will consist of logical assumptions, evaluation, decisions and rejected solutions on route the final recommendation. The creative process simply addresses the generation and validation of single ideas.

4.3 Integration

It is clear from the above analysis that the creative process is a vitally important subset of the design process. Figure 6 suggests how the creative process may be integrated into the market driven design process. Here the processes are joined at the common first phase – the 'analysis of task' phase. It is emphasised that the creative process manifests in both the conceptual design phase and the embodiment design phase. Each loop of the creative process within these phases will first generate information as an idea, and then evaluate it which adds to the design information and may re-clarify the task.

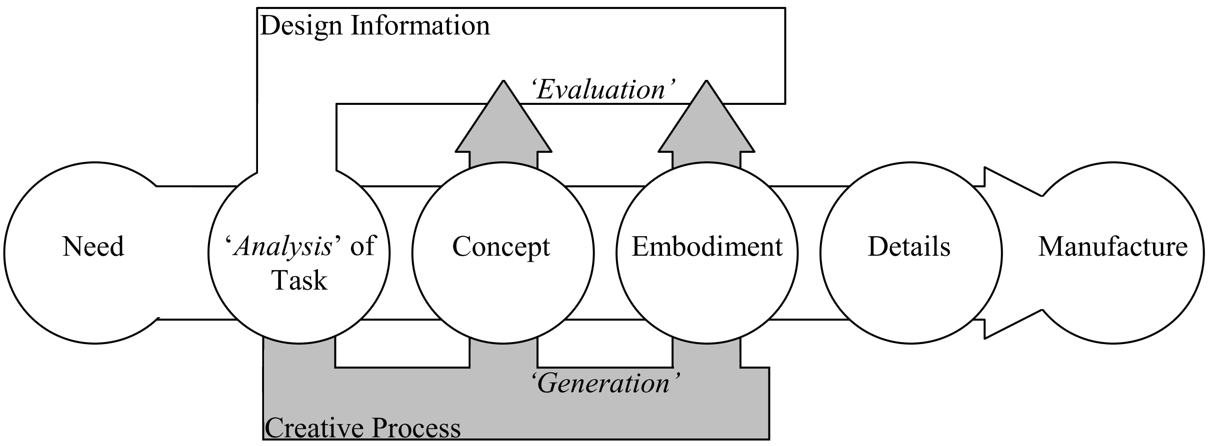

Figure 6 – Integrated Creative-Design Process Model

5 CONCLUDING REMARKS

This paper has analysed and summarised in some detail the key design processes and likewise key ‘creative’ processes. The inconsistencies between the two different processes and approaches are both interesting and challenging, posing the question – what has the engineering design research community to learn from the extensive work undertaken in the social science/physiological communities? Definition is, as usual, a key problem that is unlikely to be resolved completely in the near future. But it is quite clear several creative processes could easily be termed design processes and vice-versa. While design engineers have a broad knowledge of product development and the iterative processes concerned with design, physiologists have much deeper knowledge to the cognitive processes involved in creativity and idea generation. But it can be seen that the ‘creative’ processes could be linked into the engineering design processes with which the engineering design research community is familiar, with potentially considerable benefit. However, cross-disciplinary research and agreement of terminology and process boundaries will be essential in developing effective prescriptive processes to aid creativity throughout the design process.

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