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Analysing creative behaviour in the later stage design process

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Abstract
Creativity is widely seen as an important subject in the study of engineering design. This paper presents a framework and coding scheme for the analysis of creative designer behaviour within the later stage engineering design process, validated through a longitudinal study. By classifying the tasks that designers complete throughout the design process, analysis has demonstrated two different approaches to creative behaviour in later stage design, dependent on the way in which designers identify, develop and use knowledge and design variables. Through such analysis, the understanding required to develop specific and particularly appropriate methods of designer support can be developed, dependent on the stage of the design process and particular approach of the designer.

Keywords: creative design; designer behaviour; engineering design; later stages

Defined as the ability to produce work that is novel, appropriate and unobvious (Howard, Culley, & Dekoninck, 2008; Sternberg & Lubart, 1999), the importance of creativity is well recognised as a topic of interest within design research, and has been extensively studied by researchers from many disciplines, including human-computer interaction, engineering design and architecture (such as Dorst and Cross (2001), Gero (1996), Shneiderman *et al*. (2006), Akin and Akin (1996) and Thompson and Lordan (1999)). However, while research in engineering design has paid particular attention to the earlier conceptual stages, far less has focused on creativity that may be beneficial towards the end of the process.

There are fundamental differences present between early and late stage design when developing product components or systems such as the issue of increasing constraint, as later modules are subject both to the requirements of the design task, and to the design decisions of the earlier modules (Howard, Nair, Culley, & Dekoninck, 2011; McGinnis & Ullman, 1990); the necessary decreasing abstraction and increasing precision of design representations (Visser, 2006) and the issue of changing focus, as the tasks completed in later design stages have a distinct and separate purpose to those at the earlier stage. As an example, early tasks in engineering design typically concern information gathering, understanding, scoping and initial concept generation (amongst others), and later tasks may typically concern material selection, detailed configuration establishing dimensions or design for manufacture (see for example Pahl and Beitz (1984), Pugh (1990) or Hales (1987)).

Due to these differences, it is likely that the later stages of design will show different requirements in the support and improvement of the creative output of designers. For example, the higher focus on design within more highly-developed systems may require a solutions that do not illicit significant change (Eckert, Stacey, Wyatt, & Garthwaite, 2012); and the higher constraint present may require creativity within over-constrained problems (Stacey & Eckert, 2010). Thus there is need to expand understanding of the later stages, in which creative improvement is of benefit and significance, but arguably the influences and needs of the designer have changed.

The purpose of the paper is to present an approach to analyse creative behaviour in the later stages of the design processes. A study is then presented to demonstrate the terms and understanding to be gained from the framework and coding scheme, and to illustrate the research methodology. Some of the early conclusions about this much neglected area of research (creativity in the later stages of the design process) are presented; more rigorous conclusions will be reported in subsequent publications.

1 THE LATER STAGE ENGINEERING DESIGN PROCESS

As demonstrated by the wise body of research, the study of creativity is widespread and extensive. Researchers have undertaken this work in an attempt to unlock the creative potential of designers and engineers, and to support each as they produce both products and systems.

It is the hypothesis of the research that is the basis of this paper that creativity is continually important in the later stages of the design process, during both the embodiment and detail design phases. Within such the designer will be presented with a different design situation to the earlier stages, which may lead to issues such as that of higher constraint (McGinnis & Ullman, 1990) or creativity within incremental or complex design situations (Eckert, et al., 2012).

1.1 TWO PERSPECTIVES OF THE ENGINEERING DESIGN PROCESS

The later stages of design can be classified in two ways. The first takes what can be thought of as a systems approach, where the later stages are not the chronological later stages, but those tasks or activities (See Section 1.3) at a lower systems level, by functional or modular structure (Suh, 1990, pp. 36 - 38; Ulrich & Eppinger, 2012). The system is traditionally broken down using a tree structure, with the primary system or function at the top, and each sub-system or sub-function located beneath it according to their relationship to each other. The design of those systems at the lowest points within the structure (lower system levels) is then considered to be later stage design; occurring following development of the higher systems levels by which they are constrained. The second viewpoint takes a chronological perspective and considers those tasks occurring later in a time-based or gate-based sense, such as those stages that would typically be described as embodiment or detail according to many accepted design process models (Pahl & Beitz, 1984; Pugh, 1990). As such, when taken strictly, the former states that later stage design concerns lower systems levels further down the tree regardless of when they occur; while the latter states that later stage design concerns tasks or activities occurring late in the process, regardless of systems level.

This research recognises that the traditionally chronological design process can appear in part or whole at multiple levels of the design hierarchy (Howard, Culley, & Dekoninck, 2009; Hubka, 1982). As shown in Figure 1, just as a complete design process occurs at the system level (method of transport), so may the sub-system level (drivetrain, a lower level in the system hierarchy) go through the process of concept, embodiment and detail design. It is also possible that the design at this lower level will influence aspects of the higher level design process as its requirements and relationships are clarified and developed. As a complete chronological design process may occur at any system level, the identification of those tasks or activities which occur in the later stages must not rely solely on either of these views.

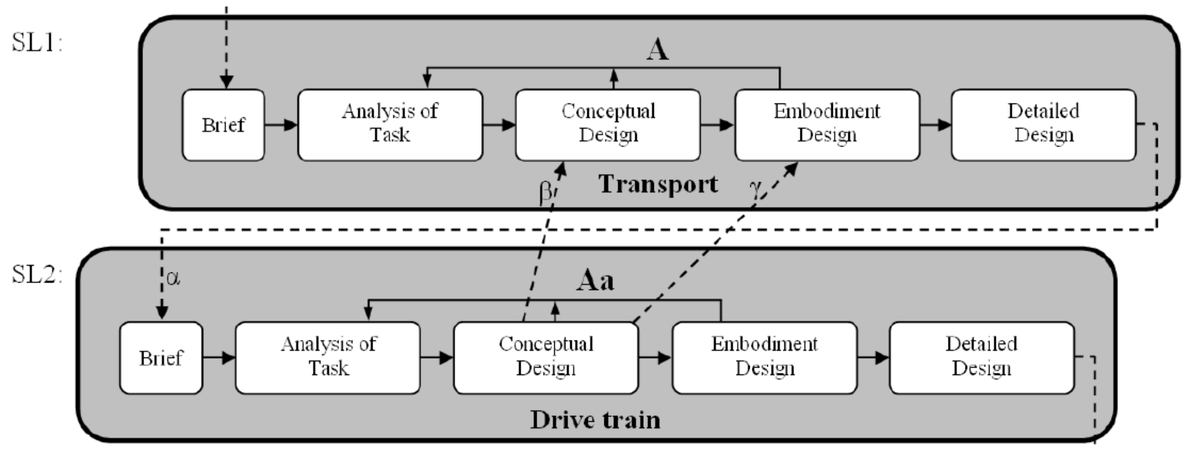


Figure 1: The design process at different system levels (Howard, et al., 2009)

1.2 DETERMINATION OF LATER STAGE DESIGN

One of the real issues is what really constitutes the later stages. The disparity between classification of the later design stages as occurring on a "*lower system level*" or as occurring at a "*later point*" in time creates some difficulty. To study all tasks and activities that concern low system levels will necessarily consider work that would typically be described as conceptual, such as the ideation process for individual sub-systems or components. To study only those tasks that occur at a late point in time creates difficulty in determination of specific point at which the early stages can be said to end and the later begin.

This work defines design stages through the individual purpose of the tasks within each, in which conceptual tasks focus on detailed development of solution principle, embodiment tasks focus on detailed development of system or sub-system behaviour, and detailed tasks focus on detailed development of system structure (Duffey & Dixon, 1990; Gero, 1990; Howard, et al., 2008).

Design Stage	Activity Definition
Analysis	Determine the required and desired functions of the system, for it to complete its purpose.
Concept	Conceive the system functions in detail through preliminary description of system behaviour.
Embodiment	Design detailed system behaviour through preliminary description of system structure.
Detail	Design and finalise system structure, and all other concerned aspects.

Table 1: Definition of the stages of the design process

Typically, research into creativity has occurred in a general sense (such as (Dorst & Cross, 2001; Gero, 1996)) or in the context of the earlier design stages (such as (Nguyen & Shanks, 2009; Shai, Reich, & Rubin, 2009)). The focus of this work is on the less-researched stages defined here as embodiment and detail, and henceforth referred to as later stages.

1.3 ACTIVITIES AND TASKS

The work reported in this paper is part of an overall project to develop an understanding of the behaviour of designers. To do this it is necessary to observe and analyse not only *what* they are doing, but *how* they are doing it. To this end, distinction is needed between those activities that make up the stages of the design process, and the more specific tasks that designers complete.

Within this work, *activities* are defined as individual elements within the design process with a specific goal; while *tasks* are defined as the individual elements of work with a specific focus that are completed by the designer. These definitions are largely taken from Activity Theory (AT) (Kaptelinin, Kuutti, & Bannon, 1995), a highly object-oriented approach within psychology that describes activities as the interaction between agents and objects. A*ctivity* as used here relates to *activity* as used within AT, while *task* as used here relates to *action* as used within AT. Terms have been changed to use vocabulary more familiar within engineering. They are formally defined below, and are illustrated in Table 2.

Activity Concerned with the design process rather than the design itself, this term describes discrete elements within design process stages with a single specific goal, such as determination of design requirements or selection of design layout.

Task Concerned with the production of the design itself by the designer within the design process, this term describes the discrete elements within a specific activity, each with its own specific goal, such as individual calculation, individual application of layouts or gathering information regarding a specific subject.

Although within AT decompositions of these terms exist, these definitions are sufficient within this work to describe the difference between designer tasks and design process stages. Supplementary to these definitions, within this work a designers *approach* is defined as the sequence and nature of tasks that they perform, in order to complete a single or series of design activities.

Activities (Hales, 1986)	Activities (Pahl & Beitz, 1984)	Potential tasks
Select layouts	Select suitable preliminary layouts.	Concept re-design Concept evaluation Functional analysis Morphological analysis
Auxiliary layouts	Develop detailed layouts and form designs for the auxiliary function carriers and complete overall layouts.	Patent searching Part configuration Dimensioning Functional analysis
Optimise form designs	Optimise and complete form designs.	Stress/strain analysis Dimensioning Computer simulation

Table 2: Some examples of activities within the embodiment design stage, and potential tasks within

Using these definitions acknowledges that different designers will complete stages of the design process in different ways. While all will choose a single layout to take forward within the "select layout" activity, different designers may use different types of task in order to develop the information needed to make a decision.

It is through analysis of these tasks that the research reported within this paper identifies differences in the behaviour of designers.

1.4 THE STUDY OF THE CREATIVE PROCESS

The definition of what it is to be creative is a much discussed topic. Many consider that the interpretation of an output or process as creative is based on the judgement of the observer, which is in turn based on their own experience (Boden, 1994). Thus while a single output may be considered highly creative by some, others may describe it as entirely non-creative. Taking into account that experience and interpretation of observers will vary widely, this creates some complexity in the study of creativity. There is no requirement for a single process to exist which will always produce a creative output, nor for an output to exist that will always be interpreted as creative. Indeed, from this perspective there is no need for a process which would typically be interpreted as creative to produce a creative output, or perhaps even for a creative output to stem only from a creative process. However, while such considerations are vital, much research has occurred into common features and patterns seen within elements that are judged to be creative; typically those of the creative person, the creative process, the creative product and the creative press, as presented by Rhodes (1961). Although there is no *requirement* for any properties to be judged as creative, such work considers that there are common characteristics to which a creative judgement may be attributed, and aims to understand creativity through their identification and study.

Although consensus has not been reached, terms and metrics describing the commonly found characteristics of creative outputs can be placed into groups representing the three concepts of novelty, appropriateness and unobviousness (Howard, et al., 2008). However, the understanding of how a creative output is produced requires consideration not only of its features, but also of how the elements presented by Rhodes (1961) contribute to its production and the complex relationship between each.

This wider perspective necessitates a distinction between creative product and creative process. While a creative output must display elements of the above metrics, such terms describe a creative process only when it is considered as a distinct entity in itself, and not the nature of the activities or tasks completed within. A process may be novel and appropriate in that it has not been completed before and produces excellent results, but this does not describe the characteristics and features of the process itself. Much study of the creative design process has been performed (Howard, et al., 2008); such as the classical structure of the creative process (Wallas, 1926), importance of divergent-convergent processes (Guilford, 1956), and co-evolutionary design (Dorst & Cross, 2001; Maher & de Silva Garza, 2008). As discussed in Section 2, it is from such literature that the framework and coding scheme presented in this paper draws.

Although a vital part of creativity research, the purpose of this work is not to study creative output as defined as novel, appropriate and unobvious. This work forms a significant extension to past work (Snider, Dekoninck, & Culley, 2011), and aims to present a framework and coding scheme based on existing creative process literature, from which the creative process followed by designers can be analysed.

1.5 CREATIVITY AND LATER STAGE DESIGN

While much work has studied creativity within the design process, such as its assessment (Sarkar & Chakrabarti, 2011; Shah, Smith, & Vargas-Hernandez, 2003), the process by which it appears (such as Dorst and Cross (2001) and Cross (1997)) and its support or enhancement (Yilmaz & Seifert, 2011), focus has remained heavily on the design process in a general sense, or on the earlier stages.

This work proposes that the manner in which designers are creative may vary throughout the design process. As according to the presented definitions for design stages; while working on early stage tasks, creative behaviour will focus on the understanding and development of system functions and appropriate solution principles, which can then be developed into a product. According to the same definitions, within later stages focus shifts away from methods of functional completion and onto the development of system behaviour and system structure. Creative behaviour in the later stages may then potentially concern different types of task, requiring a different form of support to the early stages. Whereas early stage creativity will provide benefit through alternative and superior solution principles and change fundamental to the function of the product, later stage creativity will provide alternatives related to the way in which the chosen solution principle behaves and is structured; providing, for example, increases in product performance or lower costs or timescales related to manufacture and assembly.

Core is then the designer's approach within the later stages. As designers may perform different tasks to complete later stage design activities, it is important that the approaches followed can be identified and analysed. Although some research into later-stage design has occurred (such as Bender and Blessing (2004), who studied opportunism in an early-embodiment task, and Motte and Bjärnemo (2004), who studied problem solving strategy in later-stage design), the behaviour of the designer within the later stages of the design process in relation to the appearance and role of creativity has remained largely understudied within the literature.

1.6 DEVELOPING UNDERSTANDING OF CREATIVE DESIGN APPROACHES

In order to identify the approaches of designers within the later stage design process, a framework and coding scheme have been developed; capable of categorising the tasks completed by designers throughout the design process, and of highlighting the specific *tasks* in which they are creative. It is this framework and coding scheme that are presented within this paper. These will then form the tools capable of providing the analysis and understanding required to eventually develop creative support methods particularly suited to the later stage design process.

2 ESTABLISHING CREATIVE DESIGN APPROACHES

Within the literature, some approaches classify forms of design by their inherent creativity, separating between non-creative *routine* design (Brinkop, Laudwein, & Maasen, 1995); and two categories of non-routine design: *creative* design (Chakrabarti, 2006) and (in some cases) *innovative* or *variant* design (Dym, 1994; Gero, 2000).

A framework, which will be described later, by which these creative approaches could be identified and studied was developed according to accepted methods (Blessing & Chakrabarti, 2009; Elo & Kyngäs, 2008); primarily through a deductive method from current theory, following which an inductive method using the content analysis of one complete product development record was used to validate and improve coding categories.

It is first necessary to put in place some key considerations and key definitions. As according to Brown (1996), routine design can be described as a reflection of the experience of the designer completing the task. Thus in cases of higher experience a designer will have more knowledge of the design situation, will be able to utilise previous methods, and will be able to complete the design problem in a manner that would be interpreted as routine. Such a definition is therefore similar to the interpretations of Gero (2000) and Dym (1994), stating that *routine* design occurs when a designer knows all required information to produce the final product; all design variables are known at the initial state and are used in a known manner. Implication of this definition is that routine design must lie on a spectrum depending on the amount of relevant knowledge that the designer holds, and that what is a routine task for one designer or community may be quite non-routine for another. Any single task may therefore be completed in either a routine or non-routine manner.

Complexity here exists in the relationship between non-routine and creative design. Within the former, a lack of knowledge of process or variables has led to the lack of a well-formed approach to the solution. Within the latter, by the definitions of Gero (2000) and Dym (1994), the creative design process includes the introduction of new variables or knowledge into the design (termed *creative* by both); or includes either the removal of context which constrains the values that variables can take (thus allowing variables to take unexpected behaviours), or a lack of understanding of how present knowledge should be applied for the design to progress (termed *innovative* and *variant* design respectively). By the definition of non-routine design as the lack of a well-formed approach to solution, these definitions therefore permit creativity in either a routine or non-routine process. A designers approach may be to routinely explore new variables for use in the design (thus *creative* and *routine*) or may be required to introduce new variables as they have no well-formed approach that can complete the design without (thus *creative* and *non-routine*). Non-creative design, however, requires that the designer follows a routine approach in that all knowledge and variables needed for solution are known, and that all are used in a known manner.

As is discussed in Section 3.1, creative design processes in this work are recognised through the act of expansion, using the characteristics of *creative, innovative* and *variant* design of Gero (2000) and Dym (1994). There is no distinction made in these cases of whether the act of creativity is *routine* by the experience and process of the designer, or *non-routine*. Non-creative design processes however do have this definition, in that for a non-creative process to occur, so must all conditions that would determine it to be routine.

It is then proposed within this work that whether a designer follows a *routine, non-creative* process, or a *creative* process of any form can be determined by studying the tasks that they complete and the individual outcome of each. Should a task be *creative*, it will demonstrate characteristics of the addition and manipulation of knowledge or variables and/or their use; should it be *non-creative*/*routine*, it will use previously known knowledge and variables in a known way. It is the collection and sequences of such tasks that forms the designers' processes.

2.1 A FRAMEWORK FOR CREATIVE APPROACHES WITHIN THE DESIGN PROCESS

Whether creative or non-creative, a distinction can be drawn within each of these definitions. In one case, activities or tasks concern the knowledge or variables required to produce the design (*non-creative* when the knowledge or variables to be used are already present at the outset, *creative* when not). In another case, activities or tasks concern how the knowledge or variables are used or applied to the design (*non-creative* when applied in a usual or known manner, *creative* when not). This distinction provides two possible categories for "*types of task*" within the design process, based on their characteristics which may be interpreted as creative.

The outcome of the first type of task concerns the knowledge and variables that are present, and their development for use in the design process. When following a non-creative process, knowledge and variables may be developed, clarified or understood, but categorically new knowledge or variables are not introduced (a creative process). The outcome of the second type of task concerns how the knowledge and variables present are used in the design. When following a non-creative process, each are used in usual or expected ways; when creative, the context surrounding each is removed so that they can follow unexpected behaviours.

The two types of task used in this research, regardless of creativity, are defined as follows:

Information	Any task or activity concerned with the development of knowledge or introduction of variables into the design. Thereby concerned with the knowledge that is present for the design process.
Application	Any task or activity concerned with the actual design output and the use of knowledge or variables within it. Thereby concerned with how the present knowledge is used in the design itself.

To illustrate, an information output task may involve development of knowledge as a resource for the design. An application output task may then explore how that resource would be used within the physical design itself. A further information output task may then analyse the use of that resource in the actual design for the purpose of re-formulation of the problem. A final application output task may then finalise the configuration and dimensions of the design for production. In each case, an information output task is concerned with the development of the knowledge and variables that can be used; and an application output task is concerned with how the knowledge and variables are used within the actual design. The types of task which can fall under these categories are detailed in further sections. Parallels to this distinction can be found within literature, such as that between the set of domain knowledge and requirements to fulfil, against the design description used within MOKA (see (Klein, 2000; Stokes, 2001)).

Within both *information* and *application* task types, there is possibility for a creative or a non-creative approach. When non-creative in either, such an approach is here termed "*standard*". When creative in the *information* type, such an approach is here termed "*astute"*, reflecting that the designer is cleverly and actively seeking new knowledge or variables to use in the design. When creative in the *application* type, such an approach is here termed "*effectuating*", reflecting that the designer is cleverly and actively putting current knowledge or variables into operation within the design. These terms are chosen for each creative approach due to their definitions and positive connotations, not through direct precedent from literature. The terms *regular* and *standard* are therefore largely synonymous with *routine* as used by Gero and Dym; *astute* is largely synonymous with *creative* as used by Gero and Dym; and *effectuating* is largely synonymous with *innovative* or *variant* as used by Gero and Dym respectively. These terms reflect that both *astute* and *effectuating* approaches have potential to demonstrate creativity; and hence have potential to be of equal importance and benefit. The relationships between terms used within this framework are shown in Figure 2.

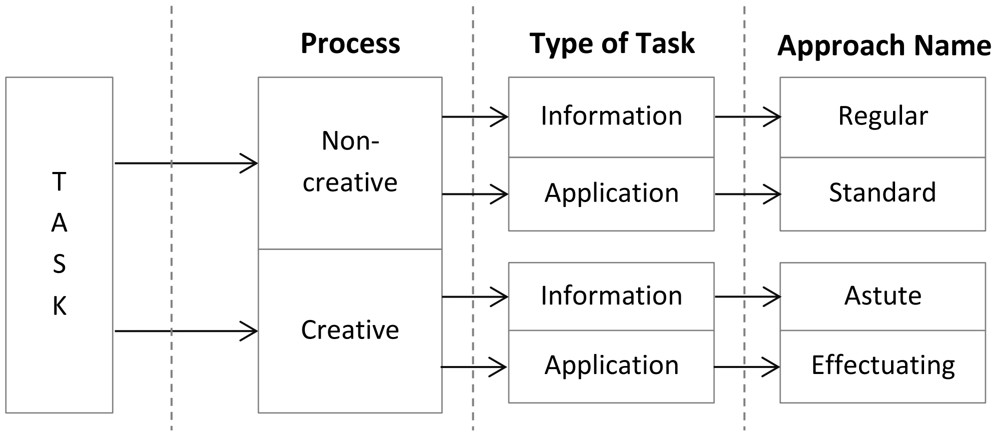


Figure 2: The framework for creative design approaches

3 A CODING SCHEME FOR CREATIVE DESIGN APPROACHES

As the aim of the overall work is to allow analysis of creative behaviour in the later stages of the design processes, it is necessary to have a coding scheme to classify tasks that occur according to the framework. The premise is that undertaking design tasks will lead to outcomes, and the process by which these outcomes were achieved can be usefully classified as being non-creative or creative (Section 2). Furthermore these outcomes have been achieved by designers undertaking tasks concerning either "*information*", developing the knowledge and variables that are present in the design, or "application", developing the way in which knowledge and variables are applied to the design itself.

Within the context of the framework (Figure 2), it is necessary to develop a scheme by which individual tasks can be identified and classified. This is achieved through using the MOKA coding scheme for knowledge based engineering applications (Klein, 2000; Stokes, 2001). Within the use of MOKA, '*entities*' form the inputs and outputs of any task, with the task itself being the transformation between the two. Four discrete standard MOKA entities are used, defined in Table 3. By providing clearly defined *entities* to identify within data, the use of the MOKA framework both increases the rigour of the coding process, and simplifies the process completed by the coder.

Entity	Definition
Knowledge (K)	What is known about the project and what describes it, in terms of background, domain and context.
Function (F)	The purpose of the project, what the product or system must do.
Behaviour (B)	The way that the project completes its function.
Physical (P)	The discrete objects that create the project, either physically or virtually.

Table 3: The four task entities (Klein, 2000; Stokes, 2001)

In Section 2.1 it is argued that designers are completing information or application task types. Another way of considering this is that they are transforming the task entities. Looking at the definitions of each entity, both knowledge and function entities consider the knowledge and variables that are present in the design, hence relating to *information* type tasks; while behaviour and physical entities consider how knowledge and variables are applied to the design, hence relating to *application* type tasks.

From MOKA, there are 4 basic transformations possible; knowledge or function into more knowledge or function (K/F→K/F); knowledge or function into behaviour or physical (K/F→B/P); behaviour or physical into knowledge and function (B/P→K/F); and behaviour or physical into more behaviour or physical (B/P→B/P). Coupled with the option for either a non-creative or creative process eight different task types are then possible, defined in Table 4. It is also shown how the standard, astute and effectuating approaches map on to the task classification.

Creativity of task	MOKA Entity transformation	Approach name	Task type	
Non-creative	K / F → K / F	Regular	Information	Output must be information
	B / P → K / F	Regular	Information	Output must be information
	K / F → B / P	Standard	Application	Output must be application
	B / P → B / P	Standard	Application	Output must be application
Creative	K / F → K / F	Astute	Information	Output must be information
	B / P → K / F	Astute	Information	Output must be information
	K / F → B / P	Effectuating	Application	Output must be application
	B / P → B / P	Effectuating	Application	Output must be application

Table 4: Types of entity transformation

There is clear similarity between the entities used within this scheme and within the FBS model of Gero (1990). The entity transformations, however, are not to be considered synonymous at this time. Although overlap between many of Gero's design processes and the MOKA entity transformations may exist, Gero's design processes are considered at this time to be equivalent to *activities* as defined in Section 1.3. To this end, there may prove to be multiple tasks that occur within a single design process. For example, Gero's *formulation* (a Function to Expected Behaviour process) may include both K/F → K/F and K/F → B/P entity transformations as the designer clarifies the knowledge that they have, and applies it into a preliminary approximation of a solution. Though it is expected that understanding will be gained from comparison of this framework with the FBS model and methodologies, such analysis must be carefully performed in detail and will be the subject of further work.

3.1 IDENTIFYING CREATIVE ACTS THROUGH EXPANSION

As both information type and application type tasks can be either non-creative or creative, it is necessary to develop a way to identify creative acts. A creative act is defined as the element within a task that would often encourage the judgement of the task process as creative.

A creative act within the framework is recognised as and termed an act of *expansion*, in which the designer will attempt to identify new knowledge and variables (*astute* approach), or identify new ways in which present knowledge or variables can be used (*effectuating* approach). Such actions are performed with a goal of promoting a creative result according to definitions within literature; a design that is novel, appropriate and unobvious (Chakrabarti, 2006; Howard, et al., 2008; Sarkar & Chakrabarti, 2011). In this sense a creative act can be tied to the purposeful goal of reducing clarity to the possible solution and understanding of the design decision to take by considering alternatives; a view corroborated by Dym's (1994) interpretation of non-routine design, and the tendency of particularly creative designers to treat problems as ill-defined, regardless of the actual level of definition (Candy & Edmonds, 1997; Cross, 2004).

To relate this interpretation to that of a more classical view, expansion refers to creative behaviour within both the divergent and convergent stages of Guilford (1956). Within divergence, when the purpose of the task is idea generation, creative behaviour is logical. The designer will usually attempt to produce alternative solutions to some extent. Convergence however can also be creative (Cropley, 2006), in that the designer may attempt to form a single solution through alternative combinations of parts and systems, or may evaluate based on alternative criteria such as added functionality beyond the specification. Expansion within this work is then illustrated In Figure 3. As has been stated within Section 1.4, behaviour and outputs that are interpreted as creative may vary according to the judgement of the observer. However, it is through the study of behaviour often found within creative processes, such as that studied within literature, that deeper understanding may be gained.

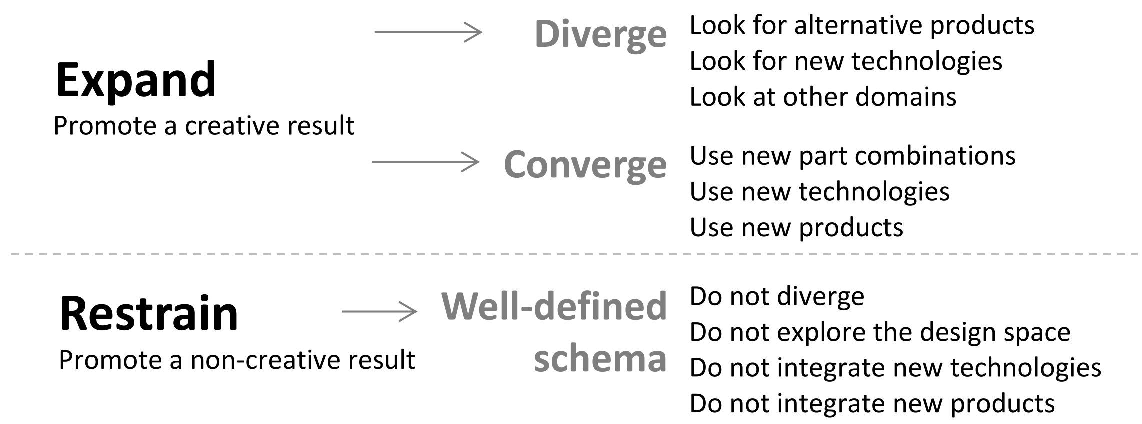


Figure 3: Expanding and restraining as terms describing creative and non-creative

A non-creative act is therefore one that does not attempt to identify options, narrowing the possibilities and increasing clarity to the solution. The term used in this case is *restrain*, and is meant to reflect a task that does not promote a creative result, through the use of a well-defined schema or the lack of exploration of options, and as shown in Figure 3.

3.2 INTERPRETATION OF TASKS DURING THE CODING PROCESS

Each type of transformation can be completed in either a non-creative or a creative manner (Table 4). There are then eight basic task types, under each of which many actual tasks as completed by designers may fall. These are summarised in Table 5.

Creativity of task	MOKA entity transformation	Example
Restrained	K / F → K / F	Refine knowledge of certain materials e.g. database lookup of material properties for specific application.
	B / P → K / F	Perform stress analysis of a component to understand force and performance requirements of system/sub-system.
	K / F → B / P	Configure a layout for components within a sub-system according to past design iterations.
	B / P → B / P	Parametrically alter dimensions for a component to allow interface within a sub-system.
Expansive	K / F → K / F	Search for materials with properties applicable or appropriate to expected solution possibilities.
	B / P → K / F	Perform analysis of components within a sub-system to infer potential redundancy and reduce part count.
	K / F → B / P	Develop a number of potential sub-system configurations based on behavioural and functional requirement.
	B / P → B / P	Explore possible configurations or dimensions of components to reduce material use without compromising performance.

Table 5: Definitions of tasks used to help the coder

In reality, there are many individual tasks which may fall under each entity transformation. As example, under the category of restrained B / P → K / F a designer may perform the task described in Table 5, which would likely be classed as a P → K transformation; may analyse the motion profile of a component to ensure no interference, which would likely be classed as a B → K transformation; or may analyse performance characteristics of a current configuration, which would likely be classed as a B → F transformation. Within the design process the appearance of individual tasks is considered highly contextual, relating to the individual design project and designer. However, by assigning the individual defined entities, any task as completed by the designer can be distinguished and included in analysis.

For the purposes of this work, a distinction in task types is created between those suggesting an astute approach and those suggesting an effectuating approach (Section 2.1). Identification of entities as belonging to either the information type or application type is therefore sufficient in this case. Higher levels of granularity are possible using the coding scheme, but will be the subject of further work.

3.3 ANALYSIS CONSIDERATIONS

The presented framework proposes the notion of information and application based tasks, identified by their output. However, for the purposes of analysis, an alternative distinction is also thought to be useful. Looking at Table 4, there are four tasks with an information output and four with an application output. Tasks can also be separated by the "*type of transformation*" that occurs. In the same table, four tasks begin and end with the same type of entity (information to information or application to application), while four other tasks begin and end with different types of entity (information to application or application to information). The former of these is termed "within entity type" transformation, while the latter is termed a "cross entity type" transformation.

Classification Type		**Definition**
Output	**Information**	A task that produces information entities in any way.
	Application	A task that produces application entities in any way.
Transformation	**Within entity type**	A task that develops the current state of either information or application towards an improved version of itself.
	Cross entity type	A task that uses the current state of either information or application to develop the other.

Table 6: Definitions of task types through the way in which they are classified

It is this scheme to analyse creative behaviour that will be tested in the pilot study described in the next sections of the paper.

3.4 METHODOLOGY OF SCHEME DEVELOPMENT

The framework and coding scheme within this work were primarily generated deductively from existing literature, as recommended by Potter and Levine Donnerstein (1999). Through study of current theory and understanding of tasks and creativity, it has been possible to define each individual element in relation to the past work in which it appears. Such a process is particularly suitable in this case where much appropriate literature exists; where the purpose of the scheme and framework is as extension to theory to consider later stage design (Hsieh & Shannon, 2005); and is typical of cases where latent pattern content is analysed (Potter & Levine Donnerstein, 1999), such as occurs here.

In order to maintain validity in context of the type of data, the scheme was repeatedly applied to several data sets throughout its development. Each of these samples is identical in form to the data used within the following study, but was used only for scheme development. This process is closer to the inductive approach, and ensured that the scheme was capable of coding all data that appeared. At earlier stages this preliminary coding process highlighted many areas for development, all of which were studied and implemented in context of existing literature. As a result, the coding scheme was capable of coding all data without exception, while maintaining a basis in current theory and understanding. More detail of the methodology by which the framework and scheme were developed has been provided in Snider *et al.* (2012).

3.5 SUMMARY

For clarity, Figure 4 places each element of the framework of the coding scheme in context of its source from literature or as a proposal of the work.

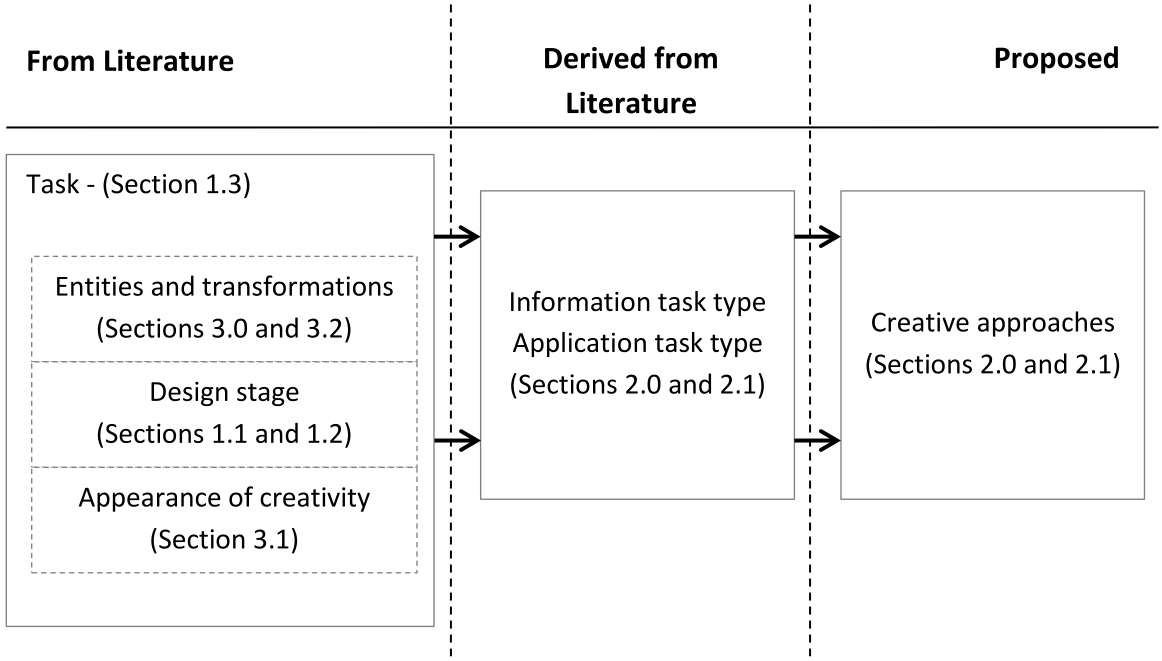


Figure 4: The elements of the framework

All elements within the "From Literature" segment are taken directly from literature with minor terminological changes, and are as defined in their sources. The elements within the "Derived from Literature" segment form the output of the elements from literature and are well supported. Although similarity to prior work exists as referenced, these are described in original terms. The elements within the "proposed" segment are to be verified within the following study. It is from the elements within literature that each task type can be derived, and it is through the interpretation of tasks that creative approaches can be identified.

4 METHODOLOGY

In order to test the validity, reliability and usefulness of the framework and coding scheme, it was applied to the work of seven final-year undergraduate students over the entirety of individual, different 22-week projects. Although not a large sample size, through the detailed analysis of the working process of designers valuable and interesting results have been produced within much research (such as (Ahmed, Wallace, & Blessing, 2003; Akin & Akin, 1996; Dorst & Cross, 2001)). The purpose of the study here presented is to demonstrate usefulness, validity and reliability of the framework and coding scheme, and to present early results and conclusions; a goal that the data gathered is sufficient to achieve. Elaboration and confirmation will occur upon such understanding in further work with a higher number of participants. Each project consisted of a significant part of the design process, from initial task clarification to the construction of a working, proof-of-principle prototype. These projects varied between designers, but all followed the same requirements and structure:

Weeks 1-11	Weeks 12-22
Stage 1 Develop problem understanding	**Stage 4** Develop final concept
Stage 2 Perform background research	**Stage 5** Manufacture proof of principle working prototype
Stage 3 Report research and in-depth specification	**Stage 6** Full report
Assessment	**Assessment**

Table 7: Project structure

Each designer had completed identical higher education and of the seven, three had completed 12 months experience as part of an industrial placement. Each was free to complete the design process according to their own preference, although all had been familiarised with well accepted design approaches such as Pahl and Beitz (1984) and Pugh (1990). Although interesting conclusions have been made on the complex similarities and differences between student and practitioner design processes (Cash, Hicks, & Culley, In Press), such considerations are to be future developments of the work.

4.1 SOURCE OF DATA

Coding occurred through the use of the student's logbooks, which they were instructed to use as a working document and complete record of the design process, and also formed part of the assessment process. As such the logbooks contained a substantial amount of data taking the form of, for example, lists and explorations of requirements and constraints, lists of suppliers, descriptions and analysis of competitive products, sketches of behaviours, configurations and components, brainstorms and mind maps, assembly diagrams and detailed dimensioned drawings of components for production. Within such data there is much evidence of the individual entities defined within Section 3.0, which can then be coded as tasks. For example, a dimensioned component sketch is likely to be coded as a *physical* (P) entity, and a table of material properties is likely to be coded as a *knowledge* (K) entity. Further examples can be seen in Figure 5.

Engineers logbooks are a good record of the process followed, in terms of the chronology of recordings within (McAlpine, Hicks, Huet, & Culley, 2006), and due to the reliance of undergraduates on hand-drawn representations (Sobek, 2002). However, while logbooks capture a large amount of the expansive idea generation process (Currano & Leifer, 2009), they will not necessarily capture all tasks that occur. For example, while initial dimensioning tasks may be drawn, the logbook will not capture any evolution of these dimensions that occurred during any computer-aided design process. When gathering data, seven logbooks were chosen from a sample of seventeen. This was necessary for practical reasons in order to remove logbooks that were illegible, showed little evidence of developing work (thus suggesting a logbook that was written after the design process as a reporting tool rather than as a record of the design process), or with little overall content (suggesting that the designer completed the majority of their work in other media). Although a limitation of this work, this is not thought to significantly affect the results and analysis gathered as evidenced by similar results gained from further study in which such discrimination did not take place (Snider, Cash, Dekoninck, & Culley, 2012).

While alternative methods of data collection such as observational study or protocol analysis (Blessing & Chakrabarti, 2009) may have provided a data set that could be treated as complete with confidence, they were considered impractical in this case due both to the difficulties in capturing reliable data (Gero & Tang, 2001) over the long duration and the limiting effect it may have on the working styles of the undergraduates.

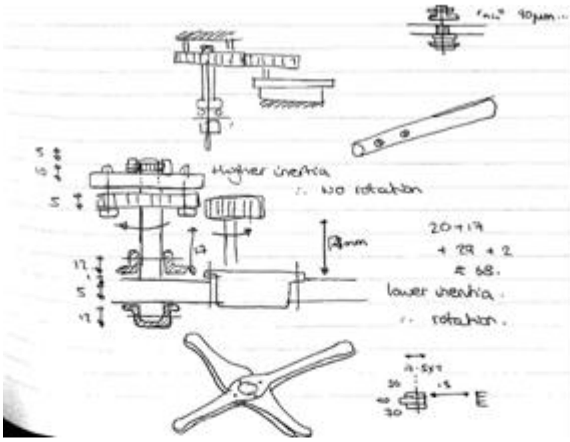
4.2 THE CODING PROCESS

Each logbook was coded in three separate passes; the first to allow separation of individual tasks, the second to identify the input and output entities within each task (*Knowledge, Function, Behaviour and Physical*) and whether the task was expansive or restrained, and the third to identify the appropriate design stage. Task separation was coded according to three criteria; initially by date, with each new date forming the start of a new task; then by purpose, where a change in purpose of a task on a single date indicated a new task; and thirdly by subject matter, where purpose remained the same but the subject of the task changed. Coding within the other two passes occurred according to the descriptions of entities and tasks, expansive or restrained behaviour and design stages set out previously. Coding in these separate passes allowed higher focus on each individual element of the coding scheme.

Additionally, the designers each completed a creative test similar to that of the KAI (Kirton Adaptor-Innovator (Kirton, 1976; Kirton, 1978)) test to determine their creative style, which was used to provide validation of the results of the coding scheme against an external measure. The KAI test predominantly differentiates between creative styles, a goal similar to that of this study, but has also been shown to bear some correlation to overall creative level (Isaksen & Puccio, 1988). As such, it is a highly appropriate measure for comparison.

An *expansive* task performed by designer D, in which the *Function* (Dynamic Head Support) is transformed into a collection of several working principles (examples of suitable *Behaviour*). Hence the appropriate *Entity Transformation* and verb:

F → B; "*Apply*"



A *restrained* task performed by designer B, in which the *Behaviour* (gear/shaft) system) is transformed into a single *Physical Concept* (a structural layout), in a decisive manner without consideration of options. Hence the appropriate *Entity Transformation* and verb:

B → P; "*Structure*"

Figure 5: showing excerpts from the logbooks of two designers, and accompanying coding.

4.3 RELIABILITY OF CODING

It is important to test for reliability of any coding scheme to ensure that the results produced are consistent regardless of coder and data set; usually completed through inter-coder reliability testing (Krippendorff, 1981). A sample of approximately 10% of the total data set was taken (a suitable size for confidence in the results (Potter & Levine Donnerstein, 1999)), randomly sampled in groups from the logbooks of two of the students to ensure that all stages of the design process were assessed. The first logbook was chosen as it was completely new to both coders; the second due to the particularly awkward nature of the recordings within, as judged by the original researcher.

Evaluation and testing occurred using the original researcher and one additional coder who was entirely unfamiliar with the previous work or development of the scheme, although their experience did include knowledge of the engineering design process as described in typical prescriptive models.. Training of the additional coder took place over a week long period during which the coding definitions were reassessed, as recommended by Krippendorff (1981). This evaluation throughout the initial testing process was judged from disagreement in coding between researcher and trainee, and aided a reduction in ambiguity in the rules and hence output. Great care was taken during this process to not introduce rules that may influence the judgement of the coder and invalidate results, an important consideration for latent pattern data such as that within this study (Potter & Levine Donnerstein, 1999). The sample data used during the training and evaluation process (in excess of 400 individual tasks) was not used in the reliability testing process.

Both Cohen's kappa (Cohen, 1960) and Krippendorff's alpha (Hayes & Krippendorff, 2007) were used as measures of reliability, with testing achieving values of 0.770 and 0.768 respectively after three training iterations. These values are below the typically accepted value for testing of 0.8 (Neuendorf, 2002), but are well above the value of 0.7, which is accepted as suitable for research such as that presented here (Blessing & Chakrabarti, 2009; Klenke, 2008). As such the reliability of the coding scheme is suitable.

5 RESULTS AND DISCUSSION

Overall, 1045 individual tasks were analysed. Designers recorded 149 distinct tasks in the 22 week period on average, of which 32.1% were classed as non-applicable to the design process. These included items such as "to do" lists, phone numbers, and other administration or coursework practicalities. All applicable tasks could be coded as either *information* type or *application* type.

5.1 THE STAGES OF DESIGN

As the focus of this study lies with the later stages of the design process, those that are typically considered early (analysis and concept) are grouped together in this analysis. Results then refer to the whole process as including analysis and concept stages (collectively termed early stage design), and the embodiment and detail stages either discussed individually or collectively (termed later stage design). As the designers progressed through the design process, a shift occurred from tasks with an output in information to those with an output in application (analysis and concept 82.9% information, detail 63.4% application). While tasks were often completed in an expansive manner, *application* type tasks maintained a higher proportion of expansive tasks for the majority of the process (information tasks 27.6% expansive during embodiment; application tasks 48.4% expansive during embodiment; Table 8).

Design Stage	Task type (%)	
	Information	Application
Analysis and Concept (early stage)	82.9 (47.2)	17.1 (55.4)
Embodiment	38.9 (27.6)	61.1 (48.4)
Detail	36.6 (12.3)	63.4 (10.9)

Table 8: Proportion of information and application tasks through the design process; in brackets relative proportions of expansive tasks

As the design process continues, it is logical for the focus to switch from those tasks that develop information to those that develop the physical design, hence producing a higher proportion of application tasks. This trend is reflected in the structure of many accepted design process models (Pahl & Beitz, 1984; Pugh, 1990).

5.2 THE ORDER OF DESIGN STAGES

Looking at the order in which tasks occur by their design stage (defined non-chronologically within Section 1.2), frequent switching is evident (Figure 6).

There were no cases for any designer of a rigid, chronological transition from early stage, to embodiment, to detail. All switched between tasks attributed to different stages regularly, creating a pattern similar to that seen for Designer C in Figure 6. Of particular interest when looking at Figure 6 is the speed at which the early stages are completed in comparison to embodiment and detail, which then frequently switch between each other for the remainder of the process; a feature that was common amongst all designers. This frequent stage switching is perhaps an example of opportunism within the design process (Bender & Blessing, 2004; Guindon, 1990; Visser, 1994, 2006), in which the designer will often change focus in their process to alternative sub-systems or tasks when the opportunity appears to them, instead of following a rigid, procedural and hierarchical process in a more systematic manner.

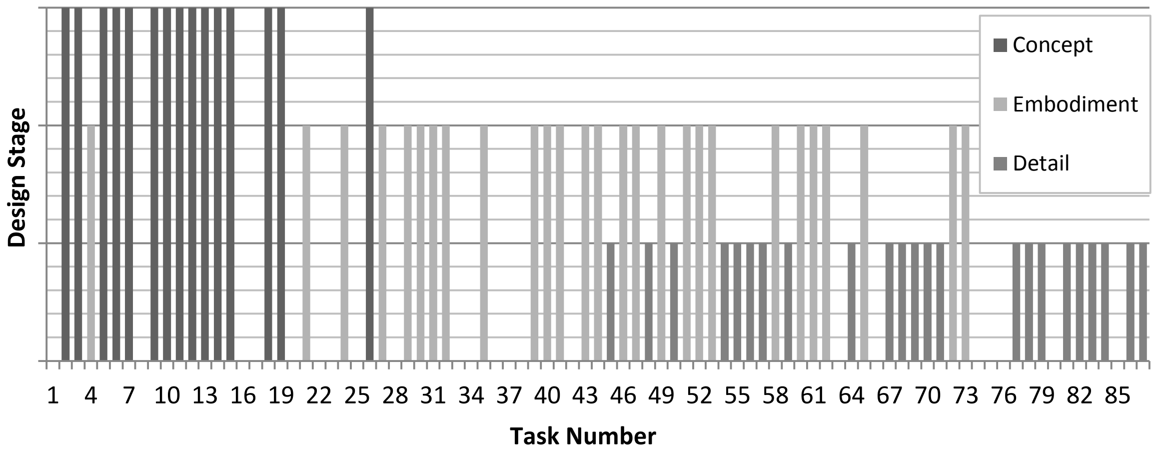


Figure 6: Design stages throughout the process; Designer C

5.3 CREATIVE BEHAVIOUR THROUGH THE PROCESS

Breaking down the data from each individual designer allows determination of their individual creative approaches within the later stages, as well as identification of the typical task types in which they are creative. This data supports a primary proposal of this work; that two creative approaches exist within design, here termed *effectuating* and *astute* as according to Figure 2.

Designer	**Expansive tasks by design stage (%)**		
	Early Stage	**Embodiment**	**Detail**
A	36.7	28.8	0.00
B	64.7	42.9	23.1
C	26.7	29.6	13.0
D	42.9	41.7	3.70
E	48.5	50.0	7.89
F	58.8	49.2	13.2
G	68.0	46.4	13.0
Average	49.5	41.2	10.6

Table 9: Showing percentage of expansive tasks by design stage, extended from Snider *et al.* (2011)

Designers vary in expansive task completion both in terms of the proportion completed as a whole, and in the maintenance of a higher proportion through the stages (such as Designer B, high expansion and high maintenance, 64.7%/42.9%/23.1% early/embodiment/detail; Table 9); both factors which suggest the potential for an inherent ability for some designers to be more creative than others in a general sense, and in the specific design situation that the later stages present.

5.4 CREATIVE DESIGN APPROACHES

Looking at the proportions of tasks completed in a restrained manner and expansive manner in *information* type and *application* type tasks, creative approaches can be identified. Table 10 shows the relevant proportions for the later stages of the design process (the area of focus within this work).

Designer	Information Tasks		Application Tasks		Primary approach
		Expansive Proportion (astute)		Expansive Proportion (effectuating)	
A	45.2	24.2	54.8	17.5	Astute
B	48.8	25.0	51.2	47.6	Effectuating
C	30.0	26.7	70.0	20.0	Astute
D	15.4	0.00	84.6	18.2	Effectuating
E	32.1	40.7	67.9	26.3	Astute
F	42.9	14.6	57.1	45.3	Effectuating
G	43.0	23.5	57.0	46.7	Effectuating
Average	36.8	22.1	63.2	31.7	

Table 6: Later stage information and application tasks, and their relative expansive proportions

Expansive proportion here refers to proportion of either information or application tasks completed in an expansive manner. The primary approach refers to the higher proportion; for example, if a designer completed a higher proportion of information tasks expansively than they did application tasks, their primary approach is considered *astute*. In the later stages, most designers show a higher proportion of application based tasks (average 63.2%; Table 6). The proportion completed expansively also varies greatly, both in terms of the quantity that focus on information (highest 40.7% of 32.1% completed, Designer E; lowest 0.00% Designer D), and those that focus on application (highest 47.6%, lowest 17.5%). Here, a distinction exists between those who primarily follow an *astute* approach, and those who follow an *effectuating* approach, where primary designer approaches are identified by the relative proportions of each. The *astute* designers (A, C and E) each completed a higher proportion of information tasks expansively (e.g. Designer A: 24.2% astute, 17.5% effectuating, see Table 10); while the *effectuating* designers (B, D, F, and G) each completed a higher proportion of application tasks expansively (e.g. Designer B: 25.0% astute, 47.6% effectuating, see Table 10).

5.5 WITHIN AND CROSS ENTITY TYPE TASK CATEGORISATION

Instead of categorising tasks as *information* type or *application* type, it is possible to classify those that focus on only on entity type (*within entity type* according to Table 6), and those that transfer between two (*cross entity type)*.

Designer	Within Entity Type Tasks		Cross Entity Type Tasks	
		Expansive Proportion		Expansive Proportion
A	39.7	13.8	60.3	25.0
B	31.7	26.9	68.3	41.1
C	46.0	8.70	54.0	33.3
D	74.4	17.2	25.6	10.0
E	63.1	18.9	36.9	51.6
F	39.3	22.7	60.7	38.2
G	40.5	31.3	59.5	40.4
Average	47.8	19.9	52.2	34.2

Table 11: Within entity type and cross entity type tasks within the later stages, and their expansive proportions

With the exception of Designer D, all completed a higher proportion of cross entity type tasks expansively (such as Designer B, 41.1% expansive cross entity type, 26.9% expansive within entity type, Table 11). Most designers are therefore creative when completing cross entity type tasks. These represent the transition from an information input to an application output or vice versa, and so the result perhaps suggests that designers are typically more creative in the later stages when either applying the information they have gathered into a concept, or when they are studying the concept to look for information. This suggests that it may be a trait of creativity in the later stages, highlighting the type of task (cross entity type) that designers are most consistently able to perform in a creative manner.

5.6 EXTERNAL DATA AND CORRELATIONS

To ensure that the framework and coding scheme produce results that are applicable to the underlying theory on which they are built, it is necessary to perform correlation analysis with an external measure.

Comparison of the results produced by the coding scheme against those of an external measure for creativity allows scheme validation. In this case, a test for creative style similar to that of the KAI test was completed by each designer (Kirton, 1976; Kirton, 1978). Those classed as *adaptors* according to Kirton's measure are characterised by working within given structures, precision and conformity. Those classed as *innovators* are characterised by approaching tasks from unexpected angles and not being limited by problem boundaries (Isaksen & Puccio, 1988). Scores are placed on a spectrum from *adaptor* to *innovator* following a normal distribution with median 96. Those who are *adaptors* are then less likely to expand within tasks, instead remaining within the constraints of the problem, while those who are *innovators* are more likely to search for alternative angles and expand beyond task boundaries. Correlation against this metric will then show validity in the results of the scheme as measuring some element of creativity.

Designer	Overall expansive proportion (%)	Later Stage expansive proportion (%)	Design Approach	Creative Test Score
A	25.2	20.5	Astute	89
B	44.8	36.6	Effectuating	95
C	23.1	22.0	Astute	97
D	25.0	15.4	Effectuating	74
E	35.9	31.0	Astute	105
F	38.4	32.1	Effectuating	113
G	44.2	36.7	Effectuating	110

Table 12: Showing comparisons of coded and external measures for each designer

First Variable	Second Variable	Correlation	Significance (P<…)
Creative test score	Cross Entity Type task expansion	0.834	0.0098
	Later stage expansion	0.790	0.0172

Table 13: Correlations between variables

There are strong, significant correlations between the creative test score and expansion (P<0.0098 against cross entity type tasks; P<0.0172 against later stage expansion; Table 13). These show that people who are identified according to Kirton (1976) as innovators (a characteristic that has been linked with higher levels of creativity (Goldsmith & Matherly, 1987; Isaksen & Puccio, 1988)) will complete a higher proportion of the later stages in a more expansive way, particularly within cross entity type tasks. Therefore it is highly likely (within the bounds of this sample size) that expansion is suitable as an indicator of creative behaviour and so that the coding scheme is identifying that which it was designed to identify, creative behaviour within the later stages of the design process.

6 GENERAL DISCUSSION

The purpose of this pilot study was to assess the validity, reliability and usefulness of the proposed framework and consequent coding scheme. To achieve this it must demonstrate that the framework and coding scheme analyse the proposed aspects of creativity identified within the literature, that they do so in a consistent manner, and that the results produced improved understanding of creative designer behaviour (particularly within the later stages of the engineering design process).

6.1 VALIDITY

As the framework has been developed deductively from existing literature and existing knowledge it can be said to be valid in terms of its underlying theory. However, it is also important to demonstrate that the results gained from the coding process represent this underlying theory, and are not skewed by the coding process or the opinions of the coder (Potter & Levine Donnerstein, 1999). This is achieved in this case by correlating the relevant results within the scheme with an external measure, a creative style test similar to the Kirton Adaption-innovation test (Kirton, 1976). That significant correlation exists (Table 13) between the measure of creativity within this framework (*expansion*) and the creative style test score shows validity in the scheme as measuring that for which it was designed. Described as those who are more likely to approach tasks from unsuspected angles and manipulate problems (Kirton, 1976), and also identified by some as those with a higher creative level (Isaksen & Puccio, 1988); that *innovators* correlated significantly with *expansion* scores suggests that the scheme is indeed measuring creativity appropriately.

As the scheme has been built from accepted theory and correlates appropriately with alternative, external measures, it can be said to be of appropriate validity.

6.2 RELIABILITY

Through inter-coder reliability testing according to the training and testing process set by Krippendorff (1981), the coding scheme achieved a value of Krippendorff's alpha (Hayes & Krippendorff, 2007) of 0.768. This is a suitable score for more exploratory study (Blessing & Chakrabarti, 2009) that will be improved within further work. Hence the coding scheme is of appropriate reliability.

6.3 USEFULNESS

To demonstrate usefulness, the coding scheme and framework must first produce results confirming the assertions on which it was built, and second must produce results with implications useful to the original purpose of the research.

6.3.1 INFORMATION AND APPLICATION TYPE TASKS

The proposal that design tasks can be separated into *information* type and *application* type depending on whether they develop the knowledge and variables present (*information*) or the way in which knowledge and variables are used (*application*) is supported by the coding process. All tasks concerning the design and its development were consistently identified by the coders, with tasks that are not directly related to the design or its development being classed as non-applicable.

This basic classification also demonstrated trends expected from literature. The transfer from an information type majority to an application type (Table 8) mirrors the theories and design procedures proposed by many researchers, such as Pahl and Beitz (1984), Cross (2000) and Pugh (1990).

6.3.2 ASTUTE AND EFFECTUATING DESIGN APPROACHES

Another primary assertion is the identification of two alternative *creative approaches* (termed the *astute* approach and the *effectuating* approach (Figure 2)) that were developed from the literature. As shown in (Table 10), each designer completed multiple tasks according to each of these approaches throughout the design process, with a variation between designers who are primarily *astute* and who are primarily *effectuating* within later design stages. This is despite of the fact that a higher number of *application* type tasks occurred within later stages, providing higher potential for the *effectuating* type tasks to occur.

6.3.3 IMPLICATIONS FOR LATER STAGE CREATIVE SUPPORT

As the eventual aim of this research is to produce the knowledge required to support designers within the specific situation of the later stage engineering design process, the framework and coding scheme must produce results relevant to this perspective.

Following the results demonstrating that the later stages are different to the early in terms of focus (*application* type rather than *information* type tasks) (Table 8), and in terms of the occurrence of creative behaviour (Table 9), it can be stated that the later stages present a different design situation for the designer. This supports an original premise of the work (Section 1). Furthermore, this supports the notion that the later stages of the design process may require alternative methods of support, particular to their content, focus and situation.

Further results presented by the scheme then create some suggestions of the form that these specific methods of support may take. The unclear boundaries between design stages and frequent jumping between tasks (Figure 6) bear similarity to opportunism within processes (Guindon, 1990) and theories of co-evolutionary design (Dorst & Cross, 2001); perhaps suggesting the importance of allowing designers freedom within their design process and the importance of iteration. The fact that different designers demonstrate different creative approaches (Table 10) provides multiple opportunities for support. By encouraging designers to follow one approach or another at differing stages of the design process it may be possible to provide support tailored to their design situation and to their own personal creative style. This support could be in varying forms, for example increasing the proportion of tasks that they complete creatively, or improving the efficiency with which they reach a solution. That all designers were more creative when completing cross-entity tasks (Table 11) suggests one way in which all designers can be supported independent of their own style or the design process. If cross-entity tasks (in which designers switch focus from one type of task to the other) can be directly stimulated and the higher proportion maintained, all designers can be encouraged to be more creative.

Results such as these demonstrate the use of the framework and coding scheme as a research tool to develop understanding of designer support within the later stages. From such research, further work can then allow the development of specific methods of support.

6.4 DETAIL DESIGN WITHIN THIS STUDY

Due to the nature of the project and experience level of the designers, acknowledgement must be made of the contrast formed against practice in an industrial context by professional designers.

Particularly in cases of highly-detailed design, some parts of the design process as (required in an industrial context) were beyond the scope of the projects completed within this study, thereby limiting the results. For example, considerations beyond the need of a single working proof-of-principle prototype (such as ability to mass produce or aesthetic concerns) were superfluous to the needs of the student designers and their project, but are important steps in many industrial product development projects.

However, as the projects studied within this work included a significant proportion of the design process, the work presented in this study is representative of the majority of tasks completed by designers at multiple stages of the design process and hence provides a strong basis on which to further understanding of designer behaviour in the later stages.

6.5 FURTHER WORK

The understanding allowed by this research suggests much scope for future work. Initially, through development and refinement of the scheme it is possible to achieve far more detailed analysis of the individual design processes of designers. Distinction between information type and application type tasks is suitable at this point to demonstrate the use and validity of the scheme. Through extension of the study to include further division and study of individual entities and detailed comparison of the FBS model (Gero, 1990), more detailed understanding of the individual behaviour of designers and of the creative approaches employed can be gained. Further, there is benefit to be had by extending the research to study additional participants in high detail. While the number of participants used is sufficient for some statistical analysis and to provide validation of the coding scheme, a higher number would allow further correlations and patterns to be analysed.

There is a focus within this work on the process followed by the person, as they create the product. This then relates to three of the four pillars of creativity (Rhodes, 1961), currently excluding the influence of the creative environment. There are two areas of creativity research to which this scheme can be extended. First, by explicit consideration of the environment in which the designer is working understanding can be gained of how their approach is influenced by their surroundings; in terms of, for example, inter-personal interaction and process constraints such as time and budget. There is also much scope for comparison between the results gained by the scheme and those products, processes and characteristics independently judged as creative by observers. Second, it is well accepted that the description of an object as creative is heavily dependent on the interpretation of such by an observer. While the results produced this scheme recognise creativity by characteristics typically described within literature, further comparison against independent judgement of the same by external observers is expected to produce interesting and valuable results.

7 CONCLUSIONS

Through study of existing literature, this work has proposed and validated a framework and coding scheme designed to study creative designer behaviour within the engineering design process. This framework is based on the distinction between tasks and activities that focus on the knowledge and variables present within the design (*information* type); and tasks and activities that focus on how the present knowledge and variables are used (*application* type).

Tasks are identified using a coding scheme derived from MOKA, an existing scheme used in the management of engineering knowledge. By classifying tasks according to their input and output *entities* (as per the MOKA methodology), tasks can be assigned to either the *information* or *application* type. Then identified according to the extent of expansion, a term derived from existing literature on creativity, each task completed by a designer can be classed as following a restrained or expansive process; with those that are expansive classified as either *astute* (when of the *information* type) or *effectuating* (when of the *application* type).

Validity and reliability of the framework and scheme are ensured through significant correlation with an external measure (similar to the Kirton Adaption-Innovation test) and inter-coder reliability analysis, which achieved an acceptable value.

Through identification of each type of task, and a varying predominance of the creative type of task completed by each designer, the data has demonstrated the existence of both the *effectuating* and *astute* creative approaches, dependent on the creative style of the designer.

Results of this work have implication in the support of designers and understanding of creativity within the engineering design process. By highlighting the variation in creative behaviour of designers throughout the design process, the results suggest the importance of supporting in designers in a manner that is specifically suitable their personal style and to the stage of the design process at which the designer is working. Furthermore, the results suggest more effective ways of supporting designers in the later stages of the design process, such as encouraging the use of *cross-entity* type tasks.

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