Reshaping the box: creative designing as constraint management

Journal Item

Accepted for *International Journal of Product Development* special issue on "Fostering Out-of-the-box-Creativity in New Product Development" edited by Carmen Kobe, Jannis Faupel and Ina Goller
This paper has not been submitted for publication in English elsewhere.

Reshaping the Box:
Creative designing as constraint management

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Abstract: The nature of novel idea creation in design depends on the nature of the design challenge: how requirements and constraints not only determine what is acceptable but shape thinking. This paper explores how overconstrained and underconstrained problems are tackled in fundamentally different ways, using engineering design, knitwear design and software development as exemplars. Problem framing as well as the iterative reformulation of the design problem is crucial in all fields but is done very differently. However, designers face a variety of types of problem, including problems resembling those typical in other industries; this paper argues that a wider awareness of the creative thinking methods used in other industries would aid designers in many fields to tackle unfamiliar problems.

Keywords: types of design, creativity, cognition, constraint management, overconstrained problems, underconstrained problems, problem framing, requirements specification.

Reference to this paper should be made as follows: Stacey, M.K. and Eckert, C.M. (xxxx) 'Reshaping the Box: Creative designing as constraint management', Int. J. Product Development, Vol. X, No. Y, pp. 000–000.

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1 Introduction

A new shape for a backpack, improving the fuel efficiency of a diesel engine, building a new theatre, planning a range of clothes to fit the fashion trends of the future, adapting a helicopter for new mission profiles, understanding how a software system will be used and misused: these are all examples of problems requiring creative solutions in design.

Dorst and Cross (2001) argue that creativity in design is inherent in the co-evolution of the problem and the design, whereby the designer explores the nature of the problem at the same time as generating tentative solutions; diverse design ideas come together in a "creative event", which designers perceive as the moment when an original thought enables them to develop a coherent and productive idea for the design problem they are working on. Cross (1997) describes this "creative event" as a bridge between the problem space and the solution, which gives the designers a problem frame in which they can solve their problem (see Schön, 1983).

What kinds of creative thoughts a designer can have is determined jointly by the designer's prior knowledge and skills, and by how the designer conceives the design problem (see for instance Darke, 1979); idea generation is most fluent and effective within tight constraints (see for instance Finke, Ward and Smith, 1992). The notion of 'out-of-the-box creativity' is dangerously misleading: creativity is within the box defined by the designer's active construction of a problem to solve, and the key to success is being in the right box. The creative step can lie in defining the box by actively seeking constraints that provide structure for a given ill defined problem, but it can also lie in prioritizing constraints and resolving contradictory constraints to have a problem that is sufficiently constrained, but not overconstrained.

These insights are derived from case studies in single domains, for example architecture in the case of Darke (1979) and Schön (1983) or product design in the case of Dorst and Cross (2001), as well as experimental research on creative thinking. By contrast this paper will take a comparative approach, looking at creativity in a variety of design domains, as discussed in section 2, but grounded in insights from the psychology of creativity in section 3. In section 4 we will discuss different fields of design where standard creativity looks very different, although particular problems can bear a striking resemblance to the standard problems of very different industries;

we discuss this in section 5, and address the relationship between the context of innovation and the contribution it makes to design knowledge in section 6.

2 Methodology: Comparative analysis of design processes

There have been relatively few explicit comparisons between design processes and usually the emphasis has been on identifying the common and fundamental principles of design, according to a single theoretical perspective (for instance Reymen, 2001). Much cognitive research has focused on how all design thinking shares features that differentiate it from non-design thinking; Goel and Pirolli (1989; Goel, 1994) relate these to characteristics of design problems. However, many of the crucial factors that shape design processes are shared across some but by no means all types of designing (see Stacey et al, 2002). Visser (2006a) reviews research on how thinking differs in different design fields, and outlines dimensions of differences in design activities that can be expected to influence design thinking, listing a wide variety of factors.

This paper draws on two types of studies carried out by the authors: case studies of design behaviour, developing a detailed understanding of how particular aspects of designing are handled in individual companies, and a research project specifically on comparisons between different design domains.

Domain	*Interviews*	*Companies*	*Year*	*Focus*
Knitwear	80	25	1992-1998	Communication in teams, inspirations
Engineering	42	2	1999-2003	Engineering change
Engineering	25	2	2000,2005	Planning
Engineering	15	1	2008	Conceptual design
Architecture	13	1	2007	Decision making in design

Table 1 Summary of empirical studies

Table 1 summarizes the empirical case studies, which all followed a similar format of semiformal interviews, which lasted between 30 and 120 minutes. These interviews were as far as possible recorded and transcribed. Otherwise field notes were taken or summaries generated immediately after the interview (early knitwear studies). Detailed analyses of the protocols were carried out by the second author or her colleagues, usually following a combination of grounded theory (Goulding, 2002) and deliberate falsification of current assumptions (Stacey and Eckert, 1999). While creativity was not the direct focus of these studies, it played a significant role in the phenomena studied, most directly in inspiration in knitwear design (Eckert and Stacey, 2001, 2003) and conceptual design in engineering (Wyatt, Eckert and Clarkson, 2009). Creativity was mainly discussed as a cause of disruption or as being needed for fixes to local problems in the context of engineering change (Eckert. Clarkson and Zanker, 2004) and process planning (Flanagan, Eckert and Clarkson, 2007; Eckert and Clarkson, in press). In the studies of communication in knitwear (Eckert, 2001) and decision making in architecture (Jupp, Eckert and Clarkson, 2009) creativity is a recurring theme as a characteristic of individuals responding to the situation under discussion. Details of the methodology of individual studies can be found in the relevant papers. For this paper the existing analyses were revisited to look at creativity.

The Across Design project was set up specifically to compare design processes across domains (see Earl et al., 2005, for a summary of the conclusions). Designers from a variety of fields, see Table 2, were invited to "bear witness" to their design processes and interrogate each other in a series of workshops (see Blackwell et al., 2009, for a methodological discussion). The participants were provided with a list of issues that they were invited to use to guide their presentation, and had about one hour to present and discuss how design works in their domains, focusing on an individual project. The workshops were recorded, transcribed and partially coded according to the initial framework. In addition the participants at the workshops used the framework to make notes. A summary of the key differences can be found in Eckert et al. (in press). In this paper we will concentrate on the role of constraints.

Oct 2002 (UK)	Automotive engineering[e], Software [s], Health, transport and consumer products[a] , Architecture/Urban Planning[aa]
April 2003 (UK)	Civil engineering (structures)[e], Web sites[mm], Automotive styling and consumer products[a], Drugs/pharmaceuticals[ss]
July 2003 (UK)	Graphic media[mm], Aerospace engineering and senior management[e], Documentary film maker[a]
Nov 2003 (UK)	Artistic fashion[a] , Medical devices[s], Food[ss], Packaging[a], Architecture[aa]
Jan 2004(USA)	Architecture[aa], Technical fashion[a], Automotive engineering and senior management[e]
July 2004 (UK)	Electronic products[e], furniture designer[a], software[s], course design[mm]

Table 2 Participants at Across Design project workshops (Key: mm-multimedia, e-engineering, a-artistic/product design, aa-architecture, s-software, ss-science)

3 Building the box

Design thinking is customarily characterized as an iterative cycle of *reformulate the problem – make a change to the design – evaluate the current state of the design – reformulate the problem*, a view usually traced back to Asimow (1962). Although a lot of problem analysis usually precedes serious attempts to develop a design, observations of moment to moment creative design thinking show that designers jump around between problem analysis, creation and evaluation in ways that depend on the skill of the designer (Ahmed, Wallace and Blessing, 2003), as well as on the nature of the problem and the state of the design (see Chusilp and Jin, 2006; Jin and Chusilp, 2006).

3.1 Creative thinking in design

Creativity is customarily associated with the act of *making* a novel design, or component for a design. But Boden (1990), drawing on artificial intelligence conceptions of generative systems, defines creativity as the generation of ideas that cannot be produced by the same set of generative rules as other, familiar ideas. These creative ideas can be in constructing problems and constructing evaluations of design proposals, as well as in constructing design elements, or in the interaction between these operations. As Boden points out, novel, creative results emerge from the application of existing mental operations – for elaborating the problem, elaborating the design, and assessing the current state of the design – to new mental representations. A central part of creative thinking, whether in design or in our thinking and speaking in everyday life, is the creation of novel mental structures through the combination of elements of different mental spaces (sets of objects and relationships), a process so ubiquitous and so rapid that it is largely invisible. Although Koestler (1964) proposed that bisociation – the integration of two previously separate mental spaces – is the mental operation underlying creative acts, Fauconnier and Turner (1998, 2002; Fauconnier, 1997) have shown that it is a central part of all everyday thinking, as central to human cognition as reasoning by consciously making inferences, which is also a cognitive operation essential to creative thinking. Although the mechanisms are not yet understood, research on analogical reasoning and conceptual combination indicates that the construction of coherent mental representations is guided by the satisfaction of multiple constraints imposed by the different elements on each other and by the purpose driving the conceptual combination (Holyoak and Thagard, 1995; Thagard, 1989, 2000).

Research on creative idea generation, such as Finke's (1990) work on pre-inventive forms – getting people to imagine particular shapes, and then use them in creative tasks – indicates that tasks requiring imagination (but soluble in a wide variety of ways) are made easier by tight constraints that supply elements of solutions to be combined and adapted, and reduce the spaces of possible solutions (see Finke, Ward and Smith, 1992). What these studies of human cognitive capacities imply is that problems requiring creativity are made tractable by the possession of mental representations of the problem and possible elements of the solution that enable the retrieval or construction of candidate solution elements by close analogical matches, and the production of a coherent mental model integrating the solution elements and the constraints.

Developing any new design involves the construction of new and more elaborate mental representations of both the design and the context into which it fits (cf Visser, 2006b). The development of the designers' mental representations is usually tightly coupled to the development of external representations of the design and the potential to reinterpret them. Goldschmidt (1991) discusses architects' creative sketching in terms of a dialectical alternation between *seeing as* and *seeing that*: by interpreting their own sketches as combinations of design elements and making conscious inferences about the implications of what they show, architects and other designers reconstruct their problems in terms of the affordances the sketches suggest, and come up with creative new ideas (see Purcell and Gero, 1998, for a review of sketching in design.).

3.2 Creative problem framing

Although the co-evolution of problem and solution is a central aspect of how designing happens, in this paper we are concerned primarily with *problem framing* – how various kinds of designers actively construct their problems, at the beginning or when they reach an impasse, not only to facilitate creative acts but to get the creative acts to yield the results they really want. This has been observed to be a crucial part of the design process in a variety of industries, notably in architecture (Darke, 1979, Schön, 1983; Lloyd and Scott, 1995; see Cross, 2004). Cross (2003) found that what the three outstanding designers he studied have in common included exploring the problem space from a particular perspective in order to frame the problem in a way that stimulated and pre-structured the emergence of design concepts (Cross, 2004). Another important aspect of problem framing is finding, reducing or reprioritizing constraints. The next section will discuss in detail how designers in some different domains handle constraints, and argue that this is a significant source of differences between different design domains.

4 Varieties of design problems

Although design problems can differ in many ways (see Visser, 2006a), this paper concentrates on how different types of constraints shape design problems by requiring different kinds of creative thinking to create a problem frame in which they can be solved. Design problems can be made challenging by having too many possibly irreconcilable constraints, or too few to guide the designer in a clear direction, or by needing imaginative thinking to uncover constraints or translate them into a form in which they can be used to guide designing.

The role of constraints provided a parsimonious explanation of many of the differences commented on and observed in the Across Design project. Engineering designers consistently spoke about the challenges of handling overconstrained problems, while artistic designers described their design processes as narrowing wide design spaces by introducing constraints. In this section we will use knitwear design as an example of artistic design, as we have studied the role of sources of inspiration in knitwear in detail. The software and web designers spoke in terms of analysing and meeting requirements, i.e. constraint analysis.

4.1 Overconstrained problems

Despite the design methodologies that advocate a breadth-first generation of alternative design concepts (see Cross, 2008), much engineering is done by modifying previous designs to meet different specifications, and is therefore constrained by the parts of the earlier design which need to be retained. In reliability-critical industries such as aerospace, innovation is unappealing to customers who want confidence in the long-term performance of the product, as it entails risk of late delivery or later product failure. Many engineering companies try to limit the amount of “newness” a product has in terms of new components or new uses for existing components. Newness at the conceptual design stage is often compelled by performance demands, especially changes to legal regulations, but many of the situations requiring innovation and creative thinking appear later in the design process, as solutions to local problems, in particular unexpected knock-on effects of other decisions. Emergency innovation late in the design process to rescue otherwise conservative projects can be a real driver of technical progress (Eckert, Keller and Clarkson, 2007). Emergency innovation is often very low key: as the emergency was not meant to happen, the innovation is not heralded. Intentional creativity in conceptual design is more likely to be highlighted and shared, and thus contribute to the body of knowledge built up in the profession.

Engineering problems are typically overconstrained, requiring designers to meet a multitude of often conflicting requirements, both during conceptual design and when resolving problems. Developing an understanding of the problem involves exploring the contradictions: many conflicting constraints are not pairwise in contradiction, but have complex interactions. The importance of conflicting constraints to creativity in engineering is widely recognized; for instance Pahl, Newnes and McMahon (2007) presented a model of creative design as resolving a sequence of contradictions (an engineering-centric view).

Meeting conflicting requirements as well as possible involves two distinct but integrated operations, relaxing constraints and finding solutions. Weak constraints can be relaxed to allow less ideal but feasible designs; conflicting strong constraints, that *must* be met, may make the problem impossible. Design problems are constrained both by explicitly formulated requirements and constraints, and by implicit assumptions about the form of the solution. However, designers often have a choice in how they go about solving a given design problem. For example the development of a new vehicle might include targets for the percentage of components to be reused, but designers have a choice which components they will try to keep and which they change.

Engineers are systematically trained to be aware of the possible solutions to particular classes of problems, so they can recognize problem classes, retrieve matching mechanisms, and then refine the details to fit a specific case. However, the problem representations that trigger the recall of these semi-abstract solution classes will include inappropriate assumptions, and designers may fixate on recent or salient solution types even when they know they are inappropriate (cf Purcell and Gero, 1996). What is often needed is to reformulate the requirements and constraints in a more abstract and general form, to eliminate assumptions implicit in the designer’s initial concrete formulation of the problem. Cross and Clayburn Cross (1998; see Cross, 2004) have argued that creative expert designers deliberately define tasks so that they are problematic – that is, deliberately treat them as ill-defined, and therefore harder than the problems seen by novice designers in the same situation (thus shaking up their assumptions about what a solution will look like).

The methods for creative design thinking used in mechanical engineering provide scaffolding both for relaxing constraints and for generating solution proposals. Several engineering design methodologies focus on this. TRIZ (see Altshuller, 1984, 1997) provides designers with procedures for making abstractions so as to classify the constraints and the contradictions between them into a finite set of categories; these can then be mapped to a set of principles for how to change the design defined by TRIZ, which the designer then uses as abstract templates for reasoning about alternative designs. Another approach to conceptual design intended to broaden the scope of solutions is reformulating the problem and the outline of a solution in purely functional terms as a sequence of transformations that need to be performed – this can be specified formally as a bond graph (see for instance Blundell, 1982); then alternative ways to perform the transformations can be explored. The Contact and Channel Model (C&CM, see Matthiesen, 2002) links functions to their physical location in the product and enables the designer to formulate the design of a mechanism in a relatively abstract way, as a sequence of interactions between working surfaces. Axiomatic design (Suh, 2001) provides designers with a way to generate formal specifications of their problems in functional terms. By developing the level of detail of the functional description and the physical description at the same time, engineers using axiomatic design are forced to break away from the reuse of existing solutions, with their uneven level of specification, and take a fresh look at their problem in an abstract form. However many engineers find thinking about design problems using functional formalisms unintuitive and difficult – there is a wide range of individual difference – and find it more natural to reason about engineering problems in terms of shapes, movements and pieces of mechanism. They need to be able to think in these more concrete terms to go beyond formulating problems to creating designs, but the trouble they face is that mental representations of shapes, movements and mechanisms are likely to be tightly linked in memory to pieces of designs that may be inappropriate. TRIZ provides a way around this in the form of a deterministic mapping to solution principles, which designers can use to limit their imaginative thinking about possible designs to concrete embodiments of those principles. The various functional representation approaches enable engineers to decompose their problems into alternative sets of simple subproblems, for which they can remember or look up possible types of solutions in terms of types of mechanism for performing particular functions or further decompositions into more subproblems; these candidate mechanisms then provide building blocks for imagining possible designs.

4.2 Underconstrained problems

By contrast artistic design processes are often ones of active constraint finding. The problems have very few explicit constraints stated in the design brief at the beginning, and the designers must start by trying to identify the implicit constraints on the problem. This section will draw mainly on our analysis of knitwear design, as an example of an artistic process. Knitwear design is more constrained than other artistic design processes, such as graphic design, by both fashion and manufacturing constraints. In knitwear design research to understand and make explicit the constraints is usually carried out for collections of garments that the designers plan to produce, but in some fields research is carried out for a particular product. For instance, a graphic designer who took part in the Across Design project employed a process of progressively narrowing the range of possibilities by making decisions that constrain her later work, including fixing the colour scheme, the fonts and the images she worked with. None of her decisions once taken were in principle irreversible, but she treated them in this way. She makes her choices based on her understanding of the intended users and the context of other graphic designs. Looking for and articulating implicit constraints is not always enough: many designers actively set semi-arbitrary constraints to make their problems narrow enough and concrete enough to be tractable, by picking elements to include or adapt; for example knitwear designers pick their colour ways at the beginning of the process, as did the graphic designer we studied, and rarely ever add more colours later on.

In knitwear design, the research stage is a routine activity that happens at defined points during the year. Understanding a fashion context is essentially a constraint *finding* process, while searching for inspirations – that can trigger and guide design synthesis – is a constraint *setting* process. Knitwear designers employ systematic strategies for using sources of inspiration for both purposes (Eckert and Stacey, 2003).

In knitwear design relatively few technical or anatomical constraints restrict the space of possible designs. However, the spaces of *acceptable* garments, that the customers will buy, are far narrower, and only partly defined by explicit requirements and structural characteristics. Artistic designs are usually subject to fashion, so that the ranges of acceptable or desirable possibilities changes with time, as does the cultural meaning of particular designs. Designers need to find ways to distinguish their own designs from others in the marketplace, yet not be too dissimilar from their competitors. They understand the context of fashion largely in terms of tacitly learned visuospatial categories that influence their perceptions of what looks 'right' or 'appropriate' in ways that are very difficult to analyse (see Eckert and Stacey, 2001; Stacey, 2006); styles are as much about balance and proportion as about the presence or absence of identifiable features.

For fashion and knitwear designers creativity lies at least as much in their constantly evolving understanding of fashion – and therefore their ability to recognize the merit of an existing idea in a new context – as in the synthesis of new designs. Our research on sources of inspiration has shown that creative breakthroughs come from forming different abstractions of the designs within a fashion, or by identifying different starting points for adaptations, that enable the creation of new types of designs that are outside the space of designs that can be generated within other designers' categories, yet perceived as within the style by buyers and consumers (Eckert and Stacey, 2003).

In fashion or knitwear design the spaces of possible design elements are too large for designers to know or generate all the possible solutions to local needs, so the designers constantly equip themselves with sources of new design elements which they use to constrain their imaginative thinking – not just other designs but all sorts of images and objects suggesting shapes and colour combinations. Designers formulate needs for sources of inspiration with specific characteristics and look for them, either to serve as foundations for designs with particular characteristics, or to solve local detail design problems. Many individual designers work out personal strategies with which they can find design ideas to meet specific needs. Therein also lies the great danger for artistic designers: they easily become formulaic. By following the same process too tightly, they produce designs that start to look very similar. The designers go stale, by not rethinking the relationship between their own designs and those that the market demands. This is a significant problem for knitwear designers (Stacey, Eckert and Wiley, 2002).

4.3 Envisaging use: identifying relevant constraints

The development of different kinds of interactive software systems involves a variety of different creative challenges. Web-based applications can involve a considerable element of artistic design in the look and feel of the web pages. The development of information management systems for complex organizations is a large and critically important branch of software development, for which a number of well-worked-out development methodologies are widely used in industry. It is seldom plagued by conflicting hard constraints. Rather, the challenge in information systems, and to a lesser extent in website design and the development of all sorts of interactive systems, is seeing all the angles.

Achieving a successful design is made problematic by the difficulty of identifying and understanding all the critical user requirements, the security issues, and the implications of the interface design for how the system will be used. It requires envisaging how the system might be used or abused within complex human activities – and knowing what those activities might be – and conceptualizing potential uses and abuses in a way that guides designing. The development of interactive systems involves prioritizing the requirements and balancing them against the need to avoid excessive complexity – crucial both to make development tractable, and avoid user interfaces that are too hard to use because they are over-complicated. Clarity and conceptual simplicity is vital for a usable system – at least for the standard tasks – but this often clashes with complexity stemming from the effort to provide a large number of features or fit the interface into a limited space. This is a primary source of conflicts between requirements. Similar issues affect the design of other interactive systems: the consequences of over-complicated systems are familiar to users of video recorders, mobile phones, camcorders, and the like.

Research on the development of design methodologies and their application in industry has focused on methods for mapping requirements into designs described at varying levels of abstraction, and into well-constructed maintainable code; methods for specifying requirements; and methods for managing the development process. A key approach is scenario-based design. Software engineers are trained to define *use* *cases* (Jacobson, 1992; see Bittner and Spence, 2002): they enumerate possible purposes the users might have in interacting with the system, choose the most important to include in the next release of the software, and for each use case identify all the possible variant situations that might arise and define the sequences of inputs and outputs for each situation. These are abstractions of behaviour, but concrete enough to highlight all the variations – they can be made as concrete and specific as is needed to achieve this. The analysis requires imagination, in particular of the potential unintended uses that are afforded by the system. The constraints are embedded in narratives of use or misuse.

The insights generated by systems analysts and software developers need to be translated into more-or-less formal descriptions. Requirements specification methodologies (see for instance Sommerville and Sawyer, 1997; Hull, Jackson and Dick, 2005) and systems development methodologies such as SSADM (see for instance Goodland with Slater, 1995) and Rational Unified Process (see Jacobson, Booch and Rumbaugh, 1999) specify notations for graphical representations for different types of information as well as sequences of activities in which the information in these representations are used to construct new information described in other representations. The development of notations for different aspects of requirements and designs, and methods for constructing particular types of information, has altered software engineers' need for imagination and creative thinking in turning requirements into products by providing inference rules and templates for design thinking.

5 Varieties of designing within industries: visiting differently shaped boxes

Although many design industries are characterized by particular types of problems and by approaches to creative thinking that fit those problems, much designing involves the interaction of different kinds of problem and different kinds of thinking. The tightness of the constraints varies enormously between problems, and individual products can be very tightly constrained in some ways and loosely in others. Technical problems can be underconstrained where the requirements are weak or are not yet understood; sometimes engineering solutions must meet tacit sociocultural expectations, for instance concerning the aesthetic appearance of purely functional engineering products such as jet engine turbine blades. Similarly artistic designers are often faced with seemingly impossible constraints from the business context or the technical realisation of the product. In knitwear design often novices and outsiders produce innovations pushing the boundaries of what is possible; Stacey, Eckert and Wiley (2002) argued that this is precisely because they don't know the tacit and explicit constraints and therefore dare to push for what seems impossible or not worth the fight to the experts.

Engineers and many other types of designers are trained to solve the types of design problems typical in their industries, and may lack effective strategies for framing problems involving different kinds of constraints. They often also undervalue the skill and creativity of specialists in different kinds of problems requiring unfamiliar constraint management methods, especially artistic designers failing to recognize the creativity in engineering, as can be seen in the sometimes uneasy relationships between engineers and artistic designers in creative teams. Knitwear design is an example of a field with a very sharp division of labour between different participants doing different kinds of designing (see Eckert, 2001): the knitwear designers, responsible for the aesthetic design of garments, do not regard the knitting machine technicians as designers or as doing anything creative at all, although they do a lot of detail designing in the course of developing knitting machine programs, which sometimes involves difficult technical problems with conflicting requirements in devising stitch structures that realize the designers' aesthetic intentions at an acceptable cost.

The static consumer products designed by product designers are heavily influenced by fashion, and their shapes are often underconstrained in the way that garments are, but product designers need not only consider cost and manufacturability but also envisage use; Jordan (2000) advocates a scenario-based methodology for designing products to meet users' attitudes and aspirations – essentially a procedure for articulating requirements.

In engineering the patterns of interaction between different kinds of design thinking are more varied; if a new design is not a variant of a familiar structure, visuospatial imagination and decision-making is needed to specify it to the point where mathematical and computational methods are usable. The conceptual design of complex products has aspects that are similar to design in artistic design domains, in that it can be quite intuitive, involving rapid local changes and immediate evaluations, and drawing on other designs as inspirations. For example, we have studied a diesel engine company where conceptual designs for new engines are developed by an apprenticeship-trained conceptual designer who works like an artistic designer; he can make vital trade-offs between conflicting constraints and requirements in his mind, when others would need to set up mathematical models, by imagining many small changes by analogy to other engines, and predicting the consequences of these changes by mapping aspects of the behaviour of the source engines to the new design.

The methods designers know and apply systematically to their problems, such as use case analysis and fashion research, become routine in these fields, and are not necessarily noted as more or less creative, rather as more or less hard, when a very similar activity in another field might be seen as creative, as it goes beyond the application of established procedures and inferences.

6 Creativity and the contribution to knowledge

The relationship between creativity and the contribution a design makes to the development of new design knowledge depends both on the novelty of the solution that is created and on the circumstances of its creation. Contributions to design knowledge are most conspicuous, and spread most effectively, when they come from the development of clever new concepts to solve novel problems. To take an example from the knitwear industry, machines that can do three-dimensional knitting have now opened up completely new possibilities for knitwear designers. The innovation lay in the engineering solution of holding individual stitches on the knitting machine. One company developed a new mechanism, patented it and presented it proudly at a trade-fair as a feature that gave them a distinct competitive advantage. Their competitors had to catch up or be out of business. Under intense time pressure and strong technical constraints they developed technical alternatives to achieve the same function and found ways to market their solutions as technologically superior to their competitors. As these solution principles established themselves, they become established knowledge. Meanwhile comparably creative solutions in safety critical industries produced to deal with emergent problems are much less well publicized or marketed, because companies don't want to admit to problems they encounter in their processes. The creativity contributing to new solutions needs to be actively recognized to contribute to the canon of design knowledge.

Creative problem solving to produce radically new products in artistic design domains can often be traced back to innovation in the technology of production:

creative solutions are the result of technology pull. For instance the development of three-dimensional machine knitting opened up spaces for designs for which there were no aesthetic or technical precedents. Designs making use of new technical possibilities (in knitwear, often produced by the machine manufacturers' own technicians) contribute to design knowledge by providing features for others to copy and adapt.

Creativity in design often lies in the process of developing an understanding of what should be designed, as both the user analysis of the software engineers and the fashion analysis of the fashion designers illustrates. However drawing new knowledge from creative thinking about requirements is a much harder knowledge management challenge. Individual designers learn effective problem solving procedures from their own experiences, but in artistic design fields these are often seen as tricks that are passed on informally if at all. In software engineering, however, requirements analysis is seen as a serious and difficult problem, so there is concerted effort to systematize and pass on good practice (see for instance Sommerville and Sawyer, 1997; Hull, Jackson and Dick, 2005).

7 Conclusions

Creativity in design is not about stepping out of the box, but finding the right box to step into. This depends on the designers' ability to frame the problem in appropriate terms. Problem framing fundamentally depends on two tightly coupled activities: constructing and finding appropriate constraints, and representing the requirements and constraints in the right form – this includes finding the right abstractions and finding the right analogies to other situations – so that they trigger useful memories and effective synthesis actions. To stick with the metaphor of the box: finding the right shape of box and finding the right materials to build the box.

Conceptual blending and reasoning by analogy are universal human thinking mechanisms, which we all engage in all the time, for example when you use the image of the box in this paper. Where designers differ, both between individuals and between professional communities, is both in knowledge, and in how they actively set up problems they can solve by manipulating the constraints on the solutions.

Handling constraints and requirements consists of four fundamental activities: finding constraints in the problem, constructing constraints by looking outside the problem, translating constraints into different forms and exploring their implications, and resolving contradicting constraints. In this paper we have argued that creative thinking in the three types of design domains we discuss in detail is predominantly characterized by their different patterns of constraints and the methods designers employ to manage these constraints. Creative engineering is about the resolution of contradictory constraints. For artistic design, the challenge is in constructing suitable constraints to define problems tightly enough to make them soluble. Software engineering (for information systems) can require creativity in finding the requirements and constraints for a given problem through envisaging how the system will be used. The methodological strengths and weaknesses of each field are influenced by this: designers are trained to use systematic methods to formulate and manage combinations constraints of the types understood to be important in their industries.

Creativity can sometimes lie in working like designers in other fields who have differently shaped problems. In this sense creativity can arise not by stepping out of the box, but using different tools to build the box. Different industries have developed a variety of constraint management methods for creative thinking: while these cannot be used directly in other fields they indicate how designers, especially in aesthetic design fields, could be taught a wider variety of ways to reconceptualize and rerepresent their problems.

Acknowledgements

This paper draws on research on engineering design processes carried out when Claudia Eckert was at the Engineering Design Centre of the University of Cambridge, supported by grants from the EPSRC, and Cambridge-MIT Institute grant CMI/076/P-NCN for the Across Design project. It has benefited from conversations with many colleagues and designers in industry.

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