

2 Literature review

This chapter reviews literature relevant to understanding how shape and form are generated through making representations, and how those representations of shape and form are typically employed in design practice. It identifies areas where contributions remain to be made in both areas and is divided into five main sections.

The first section examines the relative positions of drawing and three-dimensional representations in form creation. The arguments for sketching as a creative tool and three-dimensional representations as development tools are laid out, and the requirement for ambiguity in the early stages of form creation is contrasted against the need for greater descriptive rigour in the latter.

The second section reviews theories of design and outlines the antecedents of professional design from the earliest stone hand-axe to the beginnings of the industrial revolution. It continues with an outline of professional design, as an enterprise separate from the manufacture of finished objects and undertaken primarily through drawing.

The third section describes generative mechanisms, and links are made between shape generation, design reasoning, and the iterative nature of design. Stiny and Gips' shape grammars are introduced as a means of computationally formalising shape generation.

The fourth section discusses the changing nature of design practice in the digital era, and the possibilities offered by virtual and physical digital representations. This discussion initially contrasts information flow in single virtual representations, via haptic interfaces, with information flow in distributed physical and virtual representations. It then formulates the initial research questions by identifying relevant lacunae in the literature.

The fifth and final section closes this chapter by recapitulating its salient points and laying out the definition of the initial direction of the enquiry.

2.1 Introduction

There are many forms of design representation available to contemporary designers, some two-dimensional, some three-dimensional, some physical and some virtual. Among the most popular of these, at least in the earliest stages of generating a design's shape, is

still the designer's sketch. As Stappers and Hennessey (1999) observe, despite the availability of sophisticated and flexible digital alternatives, many designers still prefer to sketch their initial design proposals.

While drawing has apparently been enormously successful in professional design it is possible that it might be inadvertently limiting designers. We may not be aware of these limitations because the culture of design practice *itself* has not encouraged the use of other representations in the earliest stages of creative activity.

There appears, both in design practice and in design research, to be an uncritical acceptance of the efficacy of drawing as a design tool beyond that which has definitely been proven. There are recent signs, however, that this acceptance is beginning to be questioned. Bilda and Gero (2008), and Jonson (2005), for example have undertaken studies which suggest that drawing may not be as essential to experienced practitioners as was once thought, while Rogers (1996) reminds us that the cognitive value of any graphical representation (*including* a designer's sketch) remains uncertain.

While the ambiguity inherent in a designer's sketch is thought to afford the generation of unforeseen possibilities, through perceptual processes such as visual emergence (Soufi and Edmonds 1996), and while Bordegoni (2004a) stresses that design is a opportunistic process, this same ambiguity can also mean that drawings may lack rigour in their description of form (Tovey 2002). Although digital representations are eminently capable of supplying this descriptive rigour, they in turn are criticised for requiring explicit structures which Sutherland (1975), Kalay (2006) and Stiny (2006) see as conflicting with the dynamic nature of creative design practice. Anticipating which particular explicit structure will be required, at the outset of creating a digital design proposal, is where the problem appears to lie (Hernandez 2006).

Reading the literature on design theory generally, and looking for research on form generation in particular, can be a frustrating activity. Twenty-five years ago Cross (1984) reported that due to the fragmented nature of design research, and the lack of basic textbooks on design, there was no easy way for neophytes to become familiar with it as a subject of study. In the intervening years little seems to have changed. Indeed, the body of literature produced since then seems to have become wider and more fragmented still.

Other aspects of the literature have changed though. The prescriptive role of design theory from the earliest period of design research may now be seen as overambitious in its aims, and the models of the design process proposed in it as inadequate and oversimplified. Viewing design as a problem solving exercise is one example. Simon (1969) proposes that the key to answering design problems lies in choosing a suitable representation, while Alexander (1964) in turn sees form as the 'solution' to the 'problem' of context, thereby allowing form to be defined by functional requirements. Alexander even goes on to suggest that the apparently complicated nature of many design problems can be tackled by breaking them down into a series of sub-problems, and by solving these sub-problems individually and independently.

This early phase of design research, with its emphasis on efficient management and control of the whole design process, is difficult to relate to an enquiry (such as this) which focuses on aspects of design practice which are more personal, and situated activities instead. An overview of the whole design process is unlikely to contain details of the actions of a designer creating the form of a body of a domestic clothes iron, for example.

Many researchers however, from the earliest period of design research such as Simon (1969) and Alexander (1964), and onwards to more recent examples such as Steino (2006) recognise that understanding and manipulating form remains at the heart of many design activities. Despite this recognition of the centrality of three-dimensional form in design our understanding of how it is created is still less than complete.

This lack of understanding in design research may in itself be due to a lack of understanding in design practice. For many designers, the transition from a two-dimensional drawing to a three-dimensional object remains a difficult, and sometimes disappointing, experience. Bordegoni (2004b) for example stresses that this transition requires a large degree of effort, skill and experience to negotiate it successfully. Part of the problem may lie in Tovey's (2002) observation that designers' drawings themselves often contain distortions that are not apparent until the first attempt is made to convert them into a three-dimensional form.

While many digital tools, such as computer aided design (CAD) and rapid-prototyping (RP), have been incorporated into contemporary design practice to address this

representational shortcoming, their application, according to Broek *et al* (2000) has been confined almost exclusively to the development of form rather than its generation.

Indeed, during the short history of professional design, the separation of two-dimensional generation and three-dimensional development has become part of design practice canon. In the author's experience (of working in some of the larger design firms) these activities are now quite often undertaken by entirely separate groups, each consisting of designers who, as part of the development of their careers, have specialized in these roles. This might not appear to be a cause for concern in itself, as many professions thrive on specialisation within their ranks. However, because of the differing constraints and affordances of the design representations available to designers, form *creation* (when it is divided up into generation and development by different groups in this way) will inevitably be undertaken in quite different design 'spaces'. Form *generation* is confined to the smaller design space of two-dimensional shapes, while form *development* takes place within the larger one of three-dimensional forms.

Although the subject of this enquiry is an apparently overlooked (or perhaps unfruitful from the point of view of research) part of the design process, successful form generation remains highly significant to the design process as a *whole*. Decisions made about the three-dimensional form of a design during the initial conceptual stages can have large effects on its subsequent development and engineering phases. Tovey (2002), for example, concludes that being able to fully define the form of a design earlier in the process would be a significant contribution to design practice, while Roemer *et al* (2001) estimate that as much as 70% of a product's costs are determined in the first 20% of the design process.

To this end physical models are still seen as an essential aid to defining three-dimensional form. Broek *et al* (2000) posit that they allow designers to experience the tactile and visual properties of their designs in the round, or as a Gestalt whole, while Eckert *et al* (2004) have alluded to their wider social function in communicating these properties to others. Yet despite this recognition of their importance there is still very little information available on the use of physical models in the early stages of design (Broek *et al* 2000). In those studies that *do* investigate the use of three-dimensional representations (Bordegoni 2004a and 2004b, Cugini 2004, Evans *et al* 2005, Giraudi and Bordegoni 2005,

Prieto *et al* 2003, Simondetti 2002) there is no examination of *how* designers are able to transform their paper drawings into virtual geometry, or into physical models.

For many designers digital design itself remains an essentially two-dimensional enterprise. Drawing is a staple of contemporary design practice, while the earliest stages of design still entail making marks on paper as a way of initially capturing and assessing ideas. Although virtual three-dimensional representations *may* be employed for the subsequent development of those ideas, they will most often still be presented to the designer, either on-screen or on paper, through some form of two-dimensional medium.

Rapid-prototyping, as it can supply physical instantiations of virtual digital geometry, does however have the potential (when used in combination with reverse engineering) to link physical design representations with the virtual three-dimensional solution spaces available through CAD. This raises the possibility of bringing the malleability of digital representations to the physical domain. Unfortunately physical models are, as yet, incapable of being incorporated iteratively with digital design representations in the earliest stages of design (Simondetti 2002). In contemporary design practice therefore three-dimensional design representations are employed, for the most part, as a final verification of the shapes generated by two-dimensional design rather than taking an active role in the generation of three-dimensional form.

2.2 Design

Simon's famous, or perhaps *infamous*, statement that: 'Everyone designs who devises courses of action aimed at changing existing situations into preferred ones.' (Simon 1969) is an old chestnut that is often criticised as being, not so much a definition of design itself but of any kind of human endeavour.

Archer's (1991) contention that 'Design is always seen as setting in train the production, and the introduction into the world, of some real thing or system' can be seen as a clarification of Simon's definition, but one that now includes the production of *artefacts* as one of its distinguishing features. In the same text Archer further defines design by identifying its pertinent qualities. Design is useful, productive, intentional, integrative, inventive and expedient. Usefulness and integration deal with the position of design in the

wider social context but productiveness, intentionality, expediency and inventiveness are directly relevant to a discussion of form generation.

Productiveness, of course, is already subsumed under the definition of design given by Archer in the previous paragraph. It does, however, place design squarely in the world of action. Intentionality is also linked to the world of action and, according to Archer, includes a designer's ability to make judgments in a world of incomplete and imperfect information. He posits that designers actively create solutions to design problems rather than relying on chance or serendipity. Expediency in turn draws a distinction between design and the sciences. Design, Archer states, is judged by the success of its results, by the artefacts it produces rather than by the rigour of its methods.

Inventiveness, however, is identified by Archer as one of the most distinctive features of the design process. The forms of invention that he sees as applicable to design range from functional inventiveness; such as performing an operation or service that had not been offered before, operational inventiveness; where a design may function in a more efficient or convenient way, technical inventiveness; where a design may embody a novel mechanism or construction and finally, and perhaps most importantly for a consideration of form generation in design, to inventiveness in the aesthetic outcomes of design.

As outlined earlier, Simon (1969) views design problems as ones that can be solved if one can find the right representation. However Rorick (1975) and Smithers (2001) note that this assumes a definable problem, and that many design problems are beyond objective definition. In a similar vein Alexander and Poyner (1984) observe that in the field of architectural design, even if the function of a building is clearly defined its geometry will still largely be the result of a designer's intuition. Tjalve (1979) notes that in engineering and product design often only very small areas of a design consist of 'functional surfaces', that is to say those parts of the design whose particular shape is essential to, and can therefore be driven by, their function.

Dorst and Cross (2001) also talk about creativity in design in terms of problems and solutions but, rather than seeing the design problem as something that can be initially stated, see it and its solution as equal partners in the creative process instead. Each resides in notional design 'spaces', respectively termed the problem space and the solution space.

Each refines and develops the other through an ongoing iterative process of analysis, synthesis and evaluation where they co-evolve by exchanging information between them.

Archer and Roberts (1992) stress that, in the context of design, ‘problem’ means the current state of the design rather than an initial statement of requirements for the design to fulfil. Similarly, the term ‘solution’ in this context also refers to a temporary state rather than the final outcome of the design process. Both problem and solution according to Archer and Roberts (and as described in Dorst and Cross’ example) exist in a state of flux in which they constantly redefine each other.

On a less abstract level, Rorick (1975) states that the ability of designers to directly apprehend what is in front of them, even if that apprehension cannot be put into words, is a vital asset in design as ‘...the real-world manipulation of an environment over time is always richer than the fantasy-bound creation of the designer’. Schön and Wiggins (1992) also emphasise this engagement with the phenomenal world when they stress the importance of recognising that designers work in a medium. They also state, in the same text, that research that concentrates on abstract concepts of design alone ‘...are bound to miss crucially important features of the design process, whatever else they may capture’.

Design, no matter how abstract its conceptual foundations, inevitably entails some degree of engagement with, and modification of, the physical world.

A large part of designers’ modification of their physical surroundings consists of creating design representations. They use a variety of non-verbal media such as sketches, drawings and constructions which are typified by Cross (1982) as part of the ‘third culture’ of design.

2.2.1 Vernacular design

Booker (1963) sees drawing as a primary tool of design, but physical form has of course been generated for millennia before the adoption of drawing as a design representation. For example Baynes and Pugh (1981) observe that in ship design, throughout most of its long history, the process of *building* ships has been undertaken without reference to drawings.

‘Designed’ objects have of course been in existence for millennia before even as ancient an activity as shipbuilding came about. The common ancestor of all designed objects, and

the earliest known example of human artefact production, is the stone hand-axe. This first appeared approximately two million years ago and has been ascribed to *Homo habilis* (McKie 2000), our first and oldest direct ancestor.

Bronowski (1973) describes the hand-axe's invention as a fundamental innovation, not only because it is the first human manufactured tool but, by requiring our ancestors to set aside particular stones to make it, it also required a *purposeful* action. This ability of even our most ancient ancestors to foresee a situation in the indefinite future, to imagine a change to that situation and to put in place ahead of time the means of bringing that change about is, of course, also the same ability as that defined in Simon's famous quote and included in Archer's 'intentionality'.

Tool use is not of course unique to us or our ancestors. Some animals do employ simple tools as well, but what is unique about human tool use is this forethought implied in the details of their manufacture. We may also use tools to make *other* objects, indirectly, rather than through a direct and unmediated manipulation of our environment. The significance of *Homo habilis*' stone hand axe therefore lies in its *fabricatory depth*, both in the number of layers of tools or processes required to make it *and* in the degree of planning implied by that depth.

This link between design and artefact production, now begins to suggest why Simon's definition of design could not avoid the accusation of being, not so much a definition of design itself but of any kind of human endeavour instead. As some evidence of artefact production, some evidence of 'technology' is required before any putative ancestor of the human race can be incorporated into the genus 'Homo', it would be difficult for any truly comprehensive definition of design to be otherwise.

However, until the beginnings of the industrial revolution the design of an object and its manufacture were often the same thing. *Homo habilis*' stone hand-axe, for example, was produced without the creation of any intermediate representation. Its form is generated by chipping it directly out of the final material. Indeed, rather than seeing it as the earliest example of modern product design, it is more akin perhaps to one of the products of traditional 'vernacular' design.

2.2.2 Professional design

Vernacular design, or design by making as it might be termed, is often conflated with technology. To further define design Archer (1991) describes it as 'envisaging-what', differentiating it from the 'knowing-how' of technology. By separating design from technology, Archer now makes it possible to distinguish 'professional' design from other human activities, and representation-use to distinguish designers from other professionals.

It is designers' ability, desire, or tendency to model their 'envisaging-what' externally through drawings, models and now other less tangible media such as CAD representations that differentiates the restricted usage of the word design, in the sense that it is commonly understood, from other more mundane planning activities. Design in this definition is of course once again linked to making artefacts, but the artefacts are now abstract (and often graphical) representations of an object rather than the object itself.

Drawing, one such example of a graphical representation, was adopted as the 'normal' medium of design at the outset of the industrial revolution (Baynes and Pugh 1981). One of the consequences of the division of labour brought about by the industrial revolution was the need for systematic production control (Baynes and Pugh 1981), with its concomitant requirement for precision (Brett 1986) and the explicit description of the form of designed objects at a component level. It was the necessity to provide an unambiguous and more easily disseminable description of form that led to the adoption of drawing as the most convenient tool for this purpose (Baynes and Pugh 1981).

With design by drawing it is possible for designers, divorced as they now are from manufacturing the finished object, to produce and distribute only the information required to describe its form instead (Brett 1986, Baynes and Pugh 1981). The notion of the professional designer therefore, as the individual responsible for initiating a design (and who could describe its form unambiguously enough so that third parties would be able to undertake its manufacture) appears at this point.

Form creation is now divided up into generation and development. Generation is the responsibility of the designer who produces sketches, drawings and, occasionally, simple models. Development is the responsibility of junior designers, perhaps a specialized model maker or rendering artist and, finally, the toolmaker, the person who has to turn these representations into hardware that could actually produce the finished object. The process

based representations of vernacular design are now, in theory at least, replaced by the state based representations of design by drawing.

Although this division between generation and development looks neat on paper, in practice, those who were tasked with turning the generative documents (two-dimensional drawings) into development artefacts (three-dimensional objects) would still have to generate further design solutions of their own, and would almost certainly have to add their own input (albeit tacitly) to the design process as a whole. Much of the detail of how components were manufactured would still have been left to traditional methods (Booker 1963).

This distribution of form creation, both between individuals and between differing media, has long been part of artefact production and drawing, as part of the design process, does of course predate the Industrial Revolution in both architecture and shipbuilding (Brett 1986). A precursor of design through drawing can even be found in the earlier practice of laying out scale elevations and plans of buildings (and the full-sized shapes of the components of ships) onto the floor of 'moulding lofts' (Baynes and Pugh 1981, Porter 1979).

Drawing itself, as a design aid, would originally have arisen in both these fields as part of the constructional practices of carpenters, stonemasons and shipwrights. These individuals, rather than drawing complete designs onto paper, or on the other kinds of prepared surfaces employed in moulding lofts, would have made their marks directly onto their constructional materials instead (Baynes and Pugh 1981, Brett 1986). The purpose of these marks would simply have been to act as a guide for the subsequent shaping of individual components, however.

In time this practice of marking directly onto materials would have led to the use of templates, i.e., more permanent guides made out of a material separate from that intended for the finished component. The original purpose of templates would have been to aid the construction of parts that were especially arduous to lay out, or that were intended to be made in large numbers of nearly identical copies.

The particular significance of the employment of templates in the antecedents of professional design is that they are an externalisation (and a non-symbolic abstraction) of design knowledge. As such they allow shape to be considered in its own right in the design

of functional objects, as something which can be stored, re-used and disseminated entirely separately from that object.

The separation of the description of the shape of an object from the processes required to make it also facilitated the pre-planning, or pre-visualisation required for larger structures (Baynes and Pugh 1981, Booker 1963). It can be seen as a precursor of the sophisticated geometrical methods used to represent three-dimensional form in two dimensions in the industrial revolution and, ultimately, to control the distributed construction process brought about by the division of labour.

It is this creation of intermediate representations, the separating of creation of descriptions of form from the manufacture of that form, which distinguishes professional design from its antecedents.

With the invention of professional design the fabricatory depth of designed objects now has to include graphical design representations in its enumeration, and the definition of 'tool' is taken to an abstract and much more malleable state. Drawing can therefore be thought of as a tool, but one which now enables reasoning about shape in an abstract and exploratory sense.

2.3 Shape generation

Jones (1970) has noted that the employment of drawing in design has extended a designer's 'perceptual span'. Brett (1986) in turn sees drawing as a form of thinking, and Smithers (2001) suggests that early design sketches are elements of the language of thought employed in design, rather than being representational devices as such.

Drawing, as a way of thinking, appears to be highly appropriate to the needs of designers as some (though by no means all) design problems can be seen as 'wicked' ones. It has already been noted that design problems are not always well defined (Rorick 1975, Smithers 2001) and a wicked problem, unlike a well-formed one, is itself initially indefinable. The solution of a wicked problem and its definition are so intimately bound up together that to understand the problem itself it is necessary to envisage possible solutions to it, without as yet fully understanding it (Rittel and Webber 1984). Schön (1998) also

echoes this dichotomy when he states that designers, at the outset of working on a design proposal, must attempt to make sense out of situations which initially make no sense.

Design drawings, as they can be seen to contain statements of both problems *and* solutions, fulfil the apparently contradictory requirements for solving wicked problems. When a designer sketches a representation of a design proposal, each mark added to it can be seen to function both as a statement of a possible design solution *and* as the statement of a new design problem. In this way each new mark (or group of marks), as well documenting the present state of the design, can also provide a stimulus for further design solutions. Although Simon's view that solving design problems is largely one of choosing the right representation was criticised on the grounds that it assumed a well-defined problem (Rorick 1975, Smithers 2001), Simon (1969) himself addresses this shortcoming when he states that: 'A paradoxical, but perhaps realistic view of design goals is that their function is to motivate activity which will in turn generate new goals.'

2.3.1 Sketching

Sketching activity, with its two-way interaction between design problem spaces and design solution spaces, also resembles Dorst and Cross' (2001) model of design as an iterative cycle. This two-way interaction is also modelled in Schön and Wiggins' (1992) *see – move – see* cycle, where they see designing both as '...an interaction of making and seeing, doing and discovering.' and as a '...conversation with materials conducted in the medium of drawing' where the process of making representations generates new conditions.

The *see – move – see* cycle, as the name suggests, is comprised of two elements: seeing and moving. Shape generation itself can be seen as reiterating this basic unit, moving the developing design idea back and forth between internal and external representations (Schön and Wiggins 1992, Roemer *et al* 2001) and all the while moving from the descriptive, abstract and categorical to the depictive, concrete and spatially specific (Fish and Scrivener 1990).

Seeing, according to Schön and Wiggins (1992) is a crucial part of this conversation (with materials) and consists of several types: 'The basic local unit of the design process,

which we call a move experiment, involves several kinds of seeing, all dependent on visual apprehension, or literal seeing....'. The design 'moves' themselves consist of transforming features of the representation in response to these various kinds of seeing where, as the same quote continues: '...the construction of figures or gestalts ...determine the things and relations in terms of which the designer thinks; appreciation of the qualities in terms of which intentions are formed, problems are set, and solutions are judged'

Furthermore, an important feature of the *see – move – see* cycle, is that judging these solutions (generated by sketching activity), as the quote concludes, also allows for '...the recognition of both intended and *unintended* consequences of moves' or, in other words, emergence.

Emergence in design, according to Antonsson and Cagan (2001), is the appearance of features, behaviours or geometries that were not stated, or anticipated at the outset of the design process. Generative systems can also be described as emergent ones (McCormack *et al* 2004), and Evans (2005) notes the importance of emergence for the generation of designs, often as a result of the uncertainty and ambiguity contained in designers' sketches.

Soufi and Edmonds (1996) also note the importance of visual representations for designers as generative tools. Rather than features or behaviours, they stress instead that emergent *shapes* can be generated through interacting with visual representations of designs, and that these shapes arise not only through designers' perceptions actively constructing a model of the phenomenal world, but also *through* the transformations they make to the physical world underlying it. They note that their model of emergence in design also coincides with one of Boden's general models of creativity (creativity as a transformation of conceptual spaces), and use this as evidence in support of the role of emergence as an important source of creativity in design.

2.3.2 Modelling spatial reasoning

It is possible to model spatial reasoning in design by adopting Simon's (1969) suggestion that Post production systems, as the basis of his *generate – test* model, could be used to model human cognition in design more generally.

Post production systems are, as Simon observes, reminiscent of the $S \rightarrow R$ pairs of stimulus – response psychology. Each production in the system (of which there can be arbitrarily many) consists of two parts: a series of tests or conditions, and a set of actions. Whenever the tests (or conditions) are satisfied the requisite action is carried out. With regards to the details and description of this process Simon notes that productions ‘...are usually represented by the notation: Condition \rightarrow Action’, and that each production acts in independence of the others. To make this relationship between $S \rightarrow R$ pairs and Post production systems clearer they have been mapped against each other in the following table:

$S \rightarrow R$ pairs	Stimulus	\rightarrow	Response
Post production systems	Test/condition	\rightarrow	Action

The *generate – test* model itself, when mapped by function against Post production systems and $S \rightarrow R$ pairs, appears to commence at the point where they finish:

$S \rightarrow R$ pairs	Stimulus	\rightarrow	Response
Post production systems	Test/condition	\rightarrow	Action
Simon’s model			Generate \rightarrow Test

It is here that Schön and Wiggins’ *see – move – see* cycle, as their fundamental unit of a predominantly visual and situated design process, can be used to resolve this apparent mismatch. By mapping $S \rightarrow R$ pairs, Post production systems and the *generate – test* model against the *see – move – see* cycle it can be seen that Post production systems and $S \rightarrow R$ pairs make up the first two-thirds of the cycle, and that the *generate-test* model overlaps them to make up the latter two-thirds:

$S \rightarrow R$ pairs	Stimulus	\rightarrow	Response
Post production systems	Test/condition	\rightarrow	Action
Simon’s model			Generate \rightarrow Test
Schön & Wiggins’ model	See	\rightarrow	Move \rightarrow See

The *see – move – see* cycle can therefore be seen as equivalent to *test – generate – test*:

Simon’s model	Test	\rightarrow	Generate	\rightarrow	Test
Schön & Wiggins’ model	See	\rightarrow	Move	\rightarrow	See

This has interesting implications as Smithers (2001) has criticised Simon's *generate - test* model on the grounds that it ignores the situated nature of many design activities. Part of Smithers' objection to Simon's model is that Smithers sees designers' use of their design representations as a form of working memory, as opposed to what he sees as Simon's view of design, as a cognitive process that occurs in short term memory alone. What mapping the *generate - test* model against the *see - move - see* cycle shows is that it is possible to recognise the *generate - test* model at work within a situated, and predominantly visual design activity. Simon himself, when outlining possible systems for modelling human cognition (1969), does allow for productions in which conditions are tests of the outside world. This *stimulus* driven production system, whose behaviour is governed by perceptual productions, would allow the shape generation process to be driven in an incremental fashion by the current state of the design representation as well. The *see - move - see* cycle, as a fundamental unit of visual design 'reasoning' now allows *qualitative*, rather than functional, judgements to be brought in to drive shape generation. Elements of the representation can be assessed qualitatively (i.e. too big, too small, too sharp, too curved) and then transformed in response to these qualitative judgements.

2.3.3 Formalising shape generation in design

Shape grammars, as a form of production system that supports geometric representation, reasoning and emergent shapes (Antonsson and Cagan 2001), can be used to formalise predominantly visual generative processes. McCullough (1996) however reminds us that the shapes contained in design drawings, unlike other more familiar symbol schemes such as alphabets, are not finitely differentiable. Shapes, as they are employed by designers in shape generation, are not uniquely reducible to symbols.

March (2001), echoes this when he states that design is more than combinatorial search, and that shape grammars represent part of the paradigmatic break from symbolic representation and combinatorial search that typified earlier approaches to design theory.

The key concept behind these statements is that the shape decompositions that designers typically employ, and which are modelled in those shape grammars which support

emergent shapes, are indefinite rather than combinatorial, are dynamic, can be applied retrospectively and need not be defined in advance (March 2001).

Shape grammars themselves were initially developed to formalise the processes required to generate abstract geometrical paintings and (in theory at least) sculpture (Stiny and Gips 1972). Shape grammars function through the application of shape rules to shapes. Stiny and Gips (1978) define the procedure as follows:

1/ Find a subshape of the given shape that is geometrically similar to the left side of a shape rule.

2/ Find the Euclidean transformations (translation, rotation, scale, mirror image) that make the left side of the shape rule identical to the corresponding subshape of the given shape.

3/ Apply these transformations to the right side of the shape rule.

4/ Substitute the resulting shape for the occurrence of the subshape in the given shape.

The left hand side of a shape rule, when mapped against the previously discussed models of shape generation, sits in the same left hand column that contains the stimulus of an $S \rightarrow R$ pair, the test/condition of a Post production system and the initial *see* of the *see – move – see* cycle. The right hand side of a shape rule, the rule itself, sits in the centre column under the response of an $S \rightarrow R$ pair, the action of a Post production system, the *generate* section of the *generate – test* model and the *move* of the *see – move – see* cycle:

$S \rightarrow R$ pairs	Stimulus	→	Response	
Post production systems	Test/condition	→	Action	
Simon's model			Generate	→ Test
Schön & Wiggins' model	See	→	Move	→ See
Shape grammars	Shape	→	Rule	

In design itself the shape grammar formalism has found its greatest application in generating architectural plans. Perhaps this is because architects, of the pre-digital era, would often generate floor plans through a process of shape matching and shape replacement directly analogous to that employed by a shape grammar. Stiny himself recently remarked (2007) that the way in which architects used to employ 'yellow trace' (in the pre-digital era) was a useful analogy for explaining how shape grammars worked, and regretted that many younger practitioners, and younger researchers, had not been exposed to it. Fortunately, as the author's earliest experiences in design consisted of working in Norman Foster and Terry Farrell's architectural practices from 1987 to 1992, he is in a position to explain this procedure directly from his first-hand experience of it.

Yellow trace, as the name suggests, is a form of tracing paper. Perhaps the reason for its employment in this process was the particular nature of its opacity which, when laid on top of a design sketch, would render the underlying design visible enough to allow it to be traced through, but opaque enough not to let the underlying sketch overpower any shapes subsequently traced over them.

The process of generating a floor plan simply involved tracing elements of designs onto a loose sheet of this material, and then moving these tracings over the existing drawing. The loose nature of the sheet of yellow trace, which could be slid about over a fixed underlying drawing or grid at will, meant that architects were able to physically manipulate abstracted elements from their designs in relation to the rest of the drawing, and to search for correlations between the traced elements and the underlying drawing. When an especially pleasing, or simply intriguing correlation was found a further sheet of yellow trace would be placed over both the existing sketch plan and the traced element, and this newly perceived correlation embodied on the new sheet as a drawing of a new, and complete, third shape. This is, in essence, what shape grammar implementations do.

2.4 Discussion

The picture of design practice in the digital era painted by design research is still fragmented and often contradictory. In the change from traditional to digital design tools, Roemer *et al* (2001) claim that there is a mismatch between the cognitive abilities of

designers and the affordances of newer digital tools. Stappers and Hennessey (1999), when assessing why computer-supported tools were not being used during the conceptual phase of design, imply that it is because the digital alternatives available were not exactly like pencil and paper in their function and affordances.

Even Sutherland (1975), despite his seminal role in creating CAD, note that CAD is not a suitable replacement for sketching in design. He states that the unstructured nature of conventional drawings, which are instantiated simply as a series of dirty marks on paper, allows designers to concentrate on a drawing solely as a representation of an evolving design. This is in direct contrast to the topological and geometrical structure of a CAD representation which, because it has to be built up explicitly, is in addition to and entirely separate from the rest of a CAD representation's function as a representation of the evolving design.

Since Sutherland's observation, however, there has been an entirely new generation of designers who have grown up in a world that has always contained personal computers and digital design software. These designers are more comfortable with, and aware of the constraints and affordances of this newer medium in a way that more seasoned designers may never be. Jabi (2004), for example, has observed that a facility with CAD is now an accepted part of the standard arsenal of skills found among more recently qualified designers.

2.4.1 The changing culture of design practice

While sketching would appear from this to still be an essential design tool, it may not be as important to conceptual design as was once thought. A recent study of practice by Jonson (2005) found that sketching had only been employed to initiate designs in 10% of the cases he examined.

Jonson's findings in this study also generally challenge the view that computers and CAD are unsuitable for conceptual design. Perhaps an argument can be made here that the perceived unsuitability of CAD for conceptualization arises not because the new tool of CAD is not properly adapted to previous practices, but instead that the use of traditional tools in previous practices has not been properly understood (Kalay 2006).

In design practice, as well as design theory, it seems that two-dimensional shape generation has often been confused with three-dimensional form generation. While sketching does have qualities that can be seen to enable shape generation, through ambiguity and emergence, it also has distinct shortcomings when used to generate three-dimensional form. An example of this is given below (in Figure 2-1) where, even in the hands of a skilled practitioner, the use of sketching to describe this particular form would be unlikely to predict the changing intersection between its two main elements. In this example the diameter of the conical element has been varied in increments that are practically imperceptible in the accompanying orthogonal view yet, as can readily be seen, has still created major changes in the shape of the intersection between the two elements:

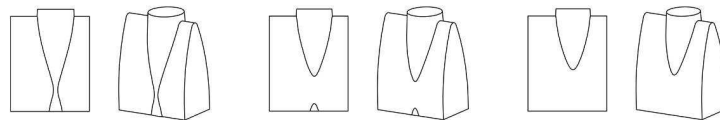


Figure 2-1 some properties of form are difficult to predict by sketching

While physical modelling would address this representational shortcoming, there are obstacles that remain when trying to integrate physical models into a digital design process.

Evans (2005), although he stresses the importance of emergence for the generation of designs through the uncertainty and ambiguity contained in sketches, also allows for the possibility of emergence through similar uncertainty and ambiguity in hand-made sketch models. He notes however that the rigorous CAD modelling necessary to create rapid-prototyped representations makes this ambiguity practically impossible to reproduce.

Prieto *et al* (2003), while also upholding the view that sketching on paper is preferred to computing, also observes that many designers still prefer generating form by sculpting physical (often foam) models directly, rather than using CAD.

While feedback from handling physical objects could be used to give a truer sense of form, it would be advantageous to include them in a matrix of representations that included both traditional and virtual geometry. Stappers and Hennessey (1999) observe that computer generated physical objects can have a place in the early stages of the design process, and Simondetti (2002) remarks that their utility to design would be enhanced if they could be used recursively, rather than just as a final verification.

There are of course precedents for physical computing in form generation which can be found in the work of Frei Otto, Antoni Gaudi, and Hans Isler, but Kilian (2006) notes that their use in these cases is confined to structural optimisation rather than for aesthetic exploration.

Although there has been a change in the culture of design practice, brought about through the adoption of digital design representations, McCullough (1996) notes that there is often a lag between the adoption of a new tool and the adoption of new ways of thinking that might be brought about by that tool: 'Usually a new tool is used to do things pretty much as they always had been done; usually a new task is done for quite some time by means of adapting existing tools'. This lag can be seen in those digital modelling programs, often derived from earlier two-dimensional CAD packages, which are essentially electronic paper. They continue to work within the design through drawing paradigm.

Pacey (1999) suggests that another (implicit) paradigm in engineering, which has its roots in the industrial revolution, might also be at the root of the confusion and suspicion over the function of digital technology in creativity. As the most profitable inventions of the industrial revolution were those of self-acting machinery, which led to the redundancy or de-skilling of labourers, the natural goal of any invention or technology came to be seen as simply that of greater automation. However Pacey asserts that CAD, like the spinning jenny of an earlier era, rather than being a technology to assist the automation of skills can be seen instead as a skill-enhancing invention. He also sees computerisation in design as being no different in its nature from any previous (non-digital) technology. Instead, like all prior human technologies, he sees using computers as 'self-revealing inventions' that allow us to learn about our human '...impulses, purposes, abilities and potential'

CAD and computers can be viewed as tools of the contemporary designers' trade, and tools are not neutral agents. Once tools are employed to change the desired state of the world their constraints and affordances begin to change not only the changes that can be envisaged, but eventually the changes that come to be desired themselves. In other words, tools begin to shape us as well as allowing us to shape our environment. Indeed, using stone hand-axes led to the literal, as well as the psychological, reshaping of our human ancestors: Bronowski (1973) observes that, as well as the implied neurological changes which resulted

in greater dexterity in our ancestors, *the physical shape of their hands* also changed, over a number of generations, with the employment of the hand-axe.

2.4.2 The possibilities inherent in digital media

There are however new possibilities inherent in employing digital representations of three-dimensional form in design. McCullough (1996) suggests that adopting solid modelling changes sculptural geometry, which previously had no notation, to one that is now describable and therefore susceptible to generative constructions. He employs Goodman's distinction between autographic and allographic media in the arts to make this clearer. Goodman (1969) defines autographic media as those in which '...the distinction between original and forgery of it is significant; or better, if and only if even the most exact duplication of it does not thereby count as genuine.' Painting therefore, before the invention of reproduction technologies such as the camera, was an autographic art, while music, as it can be described in notation and be reproduced indefinitely from that notation, has been an allographic art for centuries.

Autographic media can also be seen as state-based, and allographic media in turn as process-based. Simon (1969) notes that the graphical representations employed in design, as state descriptions, describe the world as it is sensed. Process descriptions, on the other hand, describe the world as it is acted upon and give the means for generating objects instead.

Rather than being defined by the state-based static descriptions of drawing, shape can now be described by the rules used to generate it. Three-dimensional geometry, for example, can now be described by collections of interconnected surfaces which are in turn generated by a profile (or profiles) moving along a generatrix (or generatrices).

The iterative process by which designers create form can now be modelled by generative formalisms. An implication of this is that process-based representations allow designers to reason about their designs in terms of the processes used to create them, which would lead to a yet further level of abstraction beyond that noted previously in the adoption of graphical design representations.

Process based representations of form, such as the feature-based parametric solid modelling approach illustrated in Figure 2-2, offer an alternative approach to form generation that is more akin to design through making rather than design through drawing. Programs such as SolidWorks or Pro/Engineer, used throughout professional practice, approach form development in a way that is closer to traditional craft practice, by using the digital equivalents of the kind of marking out and shaping practices to be found in physical making.

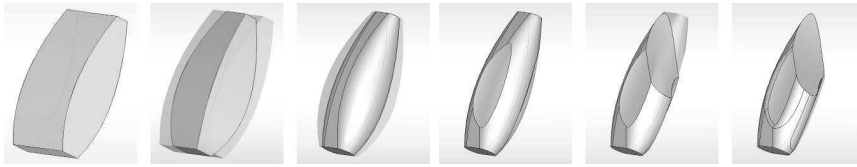


Figure 2-2 feature based modelling

Furthermore, the malleability of virtual representations affords greater opportunities for experimentation, as any action performed on a representation can just as easily be undone. Virtual representations can be seen to behave as two-way functions, while physical representations remain, more often than not, as one-way ones.

Representational technologies, as tools employed to shape our environment, are also not neutral. They stand between an idea and its presentation (Kalay 2006). To some extent they determine what is communicable, or what is 'knowable', about a form described by them. The different affordances of each design medium, therefore, affect how designs can be reasoned about. As an example, Halasz (1979) observes that architects working from two-dimensional drawings alone produce designs that are less three-dimensionally expressive than those produced with the aid of physical models. Another, and perhaps more empirically verifiable, example of the effects of representational constraints can be seen in the shape of product designs themselves in the pre-digital era. The need to communicate the form of a design proposal from the designer to a third party, to colleagues, clients, toolmakers or even, at a later date back to the designer themselves often constrained the form of these designs to those which could be readily (re)produced. Both on the drawing board, and in manufacture, they tended to contain only such shapes as could be made up

from collections of straight line segments and connecting radii. As Pipes (1990) notes 'It was not so much 'form follows function' as form follows drawing style'.

2.4.3 Information flow in a single virtual representation

Dorst and Cross note that there is a flow of information between problem and solution spaces (2001), and it was noted previously that designers' drawings can be seen to contain both the problem space *and* the solution space of an evolving design proposal. However, the three-dimensional virtual geometry available in CAD, in addition to the problem and solution spaces of two-dimensional shapes that are already available to drawn design proposals, *also* contains the problem and solution spaces of three-dimensional forms. The potential reversibility of every design action available to virtual representations, when combined with the three-dimensional geometry available in many CAD packages therefore makes them potentially very attractive as design tools.

Putting the previously listed objections to CAD as a generative tool aside temporarily, there is a sizable body of literature on haptic interfaces that takes a different approach to addressing its apparent unsuitability for form generation.

This line of investigation, rather than viewing the objection to CAD as one of having to define the geometry of a potential design solution rigidly in the early stages of design, argues instead that it is cognitive dissonance, the perceptual distance that digital tools place between designers and their ideas, that is the source of the trouble. As tactile assessment has been identified in many studies as an important part of the evaluation and development of design proposals it is worth turning aside to study this argument. Indeed, as Evans *et al* (2005) have suggested that physical interaction with design representations has the potential to direct the process of design itself, the argument in favour of adding tangible control of form to digital design tools is a seductive one.

It is this desire for the direct manipulation of a virtual representation that has fuelled the development of a number of bespoke haptic interfaces. Their champions often make bold claims about the 'intuitive' nature of these devices in general, and their desirability as more suitable interfaces for digital designing in particular. However, the appeal to intuition generally, and in interface design in particular, is not as convincing as it might at first seem.

What is regarded as an intuitive interface by designers who may have been trained in pre-digital design practices may prove to be unnecessarily limiting to those who follow them.

Kalay (2006) enlarges on this when she observes that the perceived mismatch between computational and traditional practices in architecture has also occurred in other technologies. New technologies, she states, are often viewed through the paradigm of the old, and she cites the example of the introduction of the motor car which was originally known as the 'horseless carriage'. To extend this metaphor a little further, if the interface design of modern cars had followed the allegedly intuitive path they would all now be equipped with reins, a whip and a simulated view of the rear end of a horse. Would this interface, given the divergent evolution of the horseless-carriage away from the nature of horse transport into the modern motor car, still be considered appropriate?

I suspect that the intuitive argument, as used by the proponents of haptic interfaces, is obscuring the possibility that these devices are more likely to be a case of a technological tail wagging a practical dog. When a technologically impressive 'solution' has been invented, it seems its creators may then go in search of a problem to 'solve' with it. The application of haptic devices to form generation would appear to be just this.

The *Sensible* interface, as used by Sener *et al* (2002), in their research on the application of haptic interfaces to product design, can serve as an example. This device, rather than allowing product designers to realize the form of their designs by carving and sanding (as they would do when modelling proposals in blue foam), due to the constraints of the technology employed, simulates the action of sculpting clay with a stylus instead.

The application of force feed-back in this and many other haptic solutions is also distinctly punctual (used here in the sense of acting at a point), and users are reduced to assessing the form of their designs by prodding them with a stylus. Bordegoni (2004b) predicts that palpation, that is assessing form through whole hand contact with a surface, will not be within the capabilities of any foreseeable haptic device based on presently available technologies.

Bordegoni (2004b) has however suggested a solution with a variation on the haptic approach. She suggests that, as a greater or lesser part of form assessment may be mediated through a tool moving over the surface of that form during the process of shaping it, it would be beneficial to replicate the kinds of workshop tools and practices that are already

used by designers. To this end she has developed haptically enabled digital equivalents of rasps and scrapers, which mimic the physical qualities of the analogue, real-world objects that they are intended to replace.

However, as Evans *et al* (2005) have noted in their studies of existing haptic interfaces, when precise control of form is required, which is one of the strongest reasons for employing CAD in the first place, it is often more effective to use the digital form shaping tools already available in CAD through the standard mouse and keyboard interface instead.

2.4.4 Information flow in distributed physical *and* virtual representations

Although the haptic interfaces described in the previous section attempt to address the apparent immateriality of virtual representations, both the internal representation of a design (in the designer's imagination) and its external representation, whether physical or virtual, are part of its materiality, i.e. that knowledge of it which is available to the designer's senses. This materiality exists whether or not this sensory input comes from physical or from virtual sources (Peacock 2004).

Yet, while the digital means for representing and manipulating form have been incorporated and, to a large extent, acculturated across a number of design domains we all, designers included, continue to live in a material culture, and to draw on the knowledge that is encapsulated in physical objects to inspire and guide the creation of new forms (Cross 1982). As well as the virtual digital representations that drive the haptic interfaces described in the previous section there are now also physical, or material, manifestations of that virtual digital geometry available to designers through the technologies of rapid prototyping.

Rapid prototyped objects, as physical instances of digital representations which straddle the physical and virtual divide, can be used to assess those tactile and functional qualities of proposed design solutions which are unavailable from on-screen representations. An alternative approach to the question of information flow between problem and solution spaces therefore is, rather than employing a single (virtual) representation of a digital design's geometry, is to split that geometrical representation between physical and virtual representations instead.



Figure 2-3 tactile assessment of physical representations

Sass and Oxman (2006) have proposed that the physical objects produced by rapid prototyping can be part of the creative process of form generation, and have amplified the observations of demographic change in design made by Jabi (2004) when they note an increase in the adoption of technologies such as rapid prototyping in design practice. They suggest that, by incorporating rapid prototyping into the earlier stages of design, three-dimensional modelling could become equivalent to sketching in design creation. They note, however, that to do this would require a paradigm shift in methodology and software application, but that this shift could potentially lead to a ‘third way’ of working, a hybrid of digital and physical. They go on to posit the concept of ‘Digital Design Fabrication’ as a possible way of combining generative computing with rapid prototyping and computer aided design/computer aided manufacture.

A practical example of this possible ‘third way’ has been described by Burry (2002), where digital modelling has been employed as a cost-effective aid to the continuing construction work on Gaudi’s Sagrada Familia. Because this building’s geometry is so organic and complex it has been difficult to model it in CAD. The nature of its form also makes it difficult in turn for contractors (and others involved in its construction) to understand the on-screen wire-frame representations of those CAD models that have been made of it. To get around both of these problems the design and construction teams have developed a solution in their own form of hand-mediated rapid prototyping.

However, while this approach has led to significant savings in design costs as the precision required by digital representations is not necessary with this hand-mediated approach, the information flow in it is only one-way, and is driven primarily by the constructability constraints of the final object.

Further attempts to enable the iterative flow of information between virtual and physical digital representations can be found in the contrasting approaches of Broek *et al* (2000), at TUDelft, Simondetti (2002) at the Hong Kong Polytechnic University, and Prieto *et al* (2003) and Qin *et al* (2006) at Brunel.

Broek *et al* focus on giving physical models a longer useful life by only replacing those elements of a physical model that have been modified in work on the accompanying virtual representation. To do this they employ modular physical representations, carved from foam by bespoke hardware driven by the virtual digital representation, and use laser scanning, and other forms of reverse engineering, to transfer modifications made to the physical model back into the virtual representation. However, no working system has been demonstrated as yet.

While Simondetti has undertaken a series of studies covering furniture design, architectural massing and product design, which utilises similar technologies to Broek *et al*, his emphasis is on ergonomic and functional assessment rather than initial form generation.

Prieto *et al*, in contrast to Broek *et al* and Simondetti, and more in keeping with Burry, have taken a hand-mediated rather than a wholly technological approach to this problem. By creating rapid-prototyped models, with the three-dimensional equivalent of graph paper embedded in them, they have been able to use image mapping techniques to transfer modifications made to a physical rapid-prototyped representation back to the original virtual representation. This is done by photographing the physically modified rapid prototyped model, and using that photograph as a guide (loaded as a backdrop in a digital modelling program) to modify the NURBS curves defining the virtual representation.

Continuing work at Brunel by Qin *et al* has now removed the need for either an initial CAD model, or a specialized rapid-prototyped representation, using a system of parallel lines projected externally onto the physical representation to provide the required curves instead. These however still enforce a particular, and predetermined rather than dynamic, decomposition on the curves that can be extracted from the physical representation

Although both haptic research, and the work on combining physical and virtual representations, have both generated large amounts of lab-based research neither has as yet been accepted in design practice on any scale.

Haptic devices in particular, as they have been implemented so far, appear to be a solution to a different, and unspecified, problem rather than any faced by designers when working with digital representations of form.

Furthermore the argument for employing haptic interfaces also rests on the assumption that the designer already has a virtual representation of the form of their proposed design to drive the haptic, as well as the visual interface in the first place. If Sutherland (1975) and Stiny (2006) are right about the unsuitability of CAD for form generation, because of the structured nature of its representations, then the problem of using digital representations in form generation is situated at a much earlier stage in the design process than any that a haptic device would encounter.

While the attempts to link physical with virtual representations of form described here have shown some promise, all have fallen down on this question of structure when attempting to return useful design information from the physical to the virtual representation.

2.4.5 Towards research questions

Somewhere between five hundred years ago when drawing began to be adopted for engineering and architectural design (Ferguson 1993), and two hundred years ago when it became the normal medium (Baynes and Pugh 1981) for what we would now call product design, the value of making of three-dimensional artefacts in design has been discounted to the point where Cross (1994) can claim that there is a definite distinction between it and the act of 'designing'.

As a consequence what research has been undertaken into the use of these other design representations, rather than attempting to uncover any evidence of possible generative mechanisms in their employment in design practice, has concentrated instead on their function as tools for developing design proposals. To date there is little knowledge available on the possible role that traditional physical representations might have played, and may continue to play in form generation, and on how the newer virtual and *physical* digital, three-dimensional representations now available to design practice might yet be used to augment it.

Schön and Wiggins show that design solutions co-evolve with design representations such as sketches as a result of the process of drawing, rather than drawing functioning merely as a way to externalize an already complete internal representation. This see-move-see cycle also externalizes part of the normally hidden process of cognition, as the interaction of designers with their representations can be seen as a form of distributed cognition.

However, drawing and sketching have only been the ‘normal’ medium of design since the industrial revolution. The nature of form generation, from Homo Habilis’ stone hand-axes up until the beginning of the industrial revolution, has been almost exclusively process-based instead. Drawing as a two-dimensional state based representation, when viewed against the long history of three-dimensional process based physical form generation, could be seen as a temporary aberration in the course of human development.

The position of the hand-drawn sketch as the inevitable choice for form generation therefore is not as definite as it once seemed. Conversely, CAD, for example, with its three-dimensional representations, may now have become so acculturated in design practice that it may take some part in form generation.

If the design reasoning required to generate shape in drawing can be seen as a form of distributed cognition, it is possible that similar forms of distributed cognition could also be at work in other external design representations. Are there alternative generative processes, specific to physical or virtual three-dimensional representations, similar to that illustrated below, derived from the author’s experience of design practice?

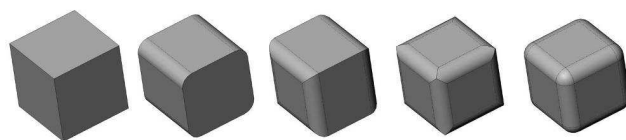


Figure 2-4 an example of transitional emergence in process-based design

This particular example is reminiscent of Schön and Wiggins (1992) description of emergence, in a sketch based design protocol, through ‘...appreciation of an intermediate design product...’ Here the intermediate products are generated by the process of rounding off the corners of a solid block: radii have been applied to the corners along each spatial axis in sequence, each axis having all the corners that lie along that axis radiused before

moving onto the next which, rather than generating a smoothly radiused block automatically generates an unanticipated three-cornered figure in the penultimate step.

While enquiries such as those undertaken by Giraudi and Bordegoni (2005) or Evans *et al* (2005), which *have* begun to look at how physical design representations are created, have so far been driven by the desire to emulate hand making processes. Both argue that it is the cognitive load imposed by digital interfaces that keeps digital tools from being effectively integrated in the early design process. An alternative thesis might be that it is the inflexibility of the structuring of digital representations, the difficulty of changing their structure in response to emergent design solutions generated by the fluid nature of the early design process, which is the cause of their not being successfully employed in design practice at this point.

McCullough notes (1996) that, in general, there is a lag between adopting new tools and adapting practices to them. There is also a specific lag between design practice itself and the understanding of the implications of that practice in design research where, as Cross (1982) observes: 'the world of 'doing and making' is usually ahead of the world of understanding...' Digital design in particular, as a form in its own right, is still largely misunderstood (Oxman 2006).

The role of physical objects themselves in generating and developing form in design is still not clearly understood. Even in the era of digital design there is still a perceived need for more research into how traditional non-digital design tools have functioned in the design process so far (Roemer *et al* 2001). For many years their function in the design process has been at the level of tacit, or 'taken for granted', knowledge. However, as digital representations of form were intended to supplant physical objects and processes, and physical objects and processes are still being used alongside them, it would seem that our knowledge of the function of these physical objects and processes in design is incomplete

It seems that any enquiry directed toward discovering more appropriate ways of using existing digital design tools might be better aimed at gaining a fuller understanding of this critical initial phase of the design process. Indeed Dorst and Cross (2001) have called for more studies of designers' practices to gain a better understanding of how creative design occurs.

So, as CAD may have become acculturated amongst newer designers and physical, craft based processes are still being employed in digital design, it seems that a re-assessment of how physical representations are being used alongside virtual representations is now required.

2.4.6 Lacunae

Sketches, the informal drawings that are often a designer's first attempt to represent the shape of a design proposal, are thought to provide a malleable and flexible medium that is well suited to generating design proposals. There has been a substantial amount of research into the use of sketching in design, under the rubric of graphonomics, but Bordegoni (2004a) states that there has been no complementary work on the use of three-dimensional representations as a means of generating form. Broek *et al* (2000) also remark that very little literature is available on how physical models are used in the early stages of design. There is, it appears, an unwritten assumption in design research that designers' sketches necessarily deal with three-dimensional form, so that research into sketching will, by definition, automatically deal with three-dimensional form generation as well.

Emergence has been identified as playing a critical role in the creative design process but most research has so far been limited to the field of two-dimensional pictorial representations.

While the use of multiple representations is felt to be beneficial for emergence (Soufi and Edmonds 1996), and switching between representations has been identified by Akin (2001) as a feature of the design process, with the exception of Kilian (2006) who concentrates on non-geometrical representations in his research, there is little evidence of this area as a topic in the literature.

If we accept that representation switching is inevitable, or even desirable due to the different constraints and affordances of each representation (as we can only reason about shape and form so far in each), then the ability to remain in the virtual domain, as haptic interfaces allow, does not seem so compelling. Employing physical models of digital design proposals, instead of the haptic augmentation of virtual representations, would also allow

designers to experience the tactile and visual properties of their designs unimpeded and in the round.

When Schön and Wiggins describe design as a process of ‘see – move – see’ they of course emphasise the visual aspect of designing. However this emphasis on the visual may be constraining the design reasoning possible to that which engages with visual qualities only. Stiny and Gips allude to the place of tactile assessment in both their seminal paper on shape grammars (1972), and subsequent book *Algorithmic Aesthetics* (1978), when they refer to painting *and* sculpture as applications of shape grammars. Despite this, the subsequent representational poverty of shape grammar implementations can be seen in its application in architecture where it is confined to two-dimensional plans, composed of straight lines, and often arranged as more or less rectangular elements.

The implementation of shape grammars in areas such as product design, which deal with solid volumes which may be bounded by free-form ‘organically’ curved surfaces, have often merely extended the rectangular, straight line, two-dimensional paradigm of architectural grammars. One example of an implementation which steps a little way out of this mould however, Agarwal and Cagan’s coffee maker grammar (1998), seems to be more concerned with the parametric variation of pre-existing forms rather than generating those forms per se. Stiny himself has recently (2006) reiterated the potential for shape grammars to incorporate tactile assessment yet, although haptic research shows that there is an interest in employing tactile assessment in design, shape grammar research has so far not engaged with this area.

2.4.7 Initial research questions

Perhaps this representational poverty arises unintentionally because the terms shape and form are, to some extent, used indiscriminately and interchangeably. This may be of little importance in everyday speech, but the distinctions between them are implicit in any activity that is directed toward creating physical three-dimensional form. This is hinted at when Simon (1969) observes that: ‘...it should be clear that “space” inside the head of the designer or the memory of a computer may have very different properties from a picture on paper or a three-dimensional model’. This observation, in the context of this literature

review begins to beg the question of how three-dimensional *is* the design proposal that is contained within a design sketch?

Although drawing can be seen as an active form of design reasoning, rather than the passive creation of representations, it may not always be synonymous with form generation. Conversely, given the lack of research into the use of three-dimensional representations, and the contradictory evidence of millennia of vernacular design, questions also begin to arise about the generative potential of three-dimensional representations.

Could physical and virtual three-dimensional design representations also display similar evidence of an ability to function in form generation as an active form of design reasoning? Rather than viewing them as competitors to drawing are they instead part of a larger matrix of generative design representations? If multiple representations are beneficial for emergence, how does the way that designers jump between design representations affect the way that they transform, or ‘move’ within, their design representations? The initial questions raised by this review of the literature therefore can be précised as:

- Is drawing still the ‘normal’ medium of design?
- Has the use of CAD become so acculturated in designers’ practice that it may now take some part in form generation?
- If design reasoning takes place as a form of distributed cognition in drawing, can similar reasoning be identified in making other external representations?
- If this is so, could the tactile as well as the visual qualities of physical representations be used to address the representational poverty of design practice generally, and computational design in particular?

2.5 Endnotes

As was noted earlier, physical models have been used in the generation and development of form throughout recorded history (Baynes and Pugh 1981). Before the adoption of drawing as a design tool in other fields, large scale traditional structures such as ships and cathedrals would have been designed through the use of scale models in addition to drawings (Porter 1979).

Although sketching and drawing began to take a greater part in form generation with the advent of design as a profession, three-dimensional physical objects have continued to be used in it as design aids (Baynes and Pugh 1981). Three-dimensional physical objects as design aids do have a number of shortcomings however. They are essentially parochial in nature; there will always be a limit to the number of people who can have direct knowledge of, or interact directly with them (Sterling 2005), and they are neither as flexible nor as disseminable as digital representations of form.

Digital tools, such as CAD, can be both flexible, when applied to form development, and restrictive, when applied to form generation. In developing a three-dimensional form they afford the possibility of practically unlimited manipulation, but only after that form has had a definite geometric structure imposed on it. Although the speed and flexibility of CAD, digital modelling and rapid-prototyping have been beneficial to the later stages of design, their use has so far been confined to the development of three-dimensional form rather than its generation.

Form generation itself is contingent, evanescent, iterative and ill-defined. However the iterative nature of design in general, and shape generation in drawing in particular, breaks down when designers begin to employ physical and virtual three-dimensional representations. To examine this breakdown the author undertook two closely related data gathering exercises; a series of design protocols and a reverse-engineering task. The details of their employment and their role in developing the research questions further are covered in the following chapter.