1 Introduction

Professional design contains a paradox. While the intended outcome of many areas of design practice is a three-dimensional object, its shape will usually be generated by sketching. The method employed to generate a designed object's *three-dimensional* shape, i.e. its form, therefore, is to manipulate a collection of *two-dimensional* elements intended to represent that form as seen from a number of discrete viewpoints.

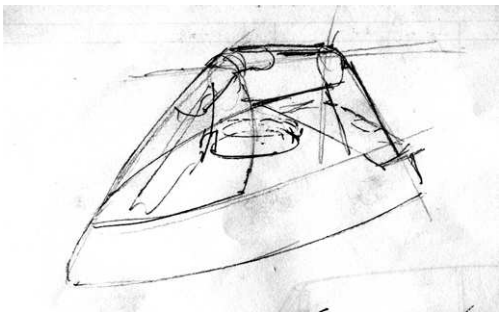

Figure 1-1 a typical design sketch

That sketching should remain at the centre of *contemporary* design practice is more paradoxical still. As designers now have virtual three-dimensional digital design representations available to them, why should they continue to make, what Sutherland (1975) pithily describes as, a collection of dirty marks on a sheet of paper?

Although these dirty marks appear to have many virtues for shape generation (Verstijnen *et al* 1998, Fish 1994, Fish and Scrivener 1990, French 1988), the relationship between the shapes they generate and the forms they purport to describe is not necessarily a direct one. Bordegoni (2004b), for example, notes that transforming two-dimensional sketches into three-dimensional forms can be a difficult and often disappointing experience for designers, while Tovey (2002) observes that these difficulties can come about as sketches may contain distortions which are not apparent until this transition from two dimensions to three is first attempted.

Surprisingly, this uneasy relationship between the two-dimensional shapes generated by sketching and a design proposal's first three-dimensional instantiation remains largely unexamined, despite Simon's (1969) admonition that the 'space' contained in a design

sketch, or inside a designer's head, is very different from that contained in a three-dimensional design representation.

As it is the success of drawing generally, as the 'normal' medium of professional design, may in the past, have masked the contribution made by other forms of external representation to traditional form generation. Indeed, as Pye noted in 'The Nature and Aesthetics of Design' (1978), drawing is not necessarily designing and, furthermore, designing and *making* are so inextricably linked that it is often difficult to say where one ends and the other begins.

Pye's observations are also echoed in the author's first-hand experience of professional design practice. For example, in 1987 he was employed by Foster Associates as one of a team of six model-makers whose sole function within that practice was to turn the architects' design sketches into physical models, i.e. to turn a two-dimensional design representation into its first three-dimensional instantiation. Often, despite the enormous pressure to get work out quickly, more senior members of the design staff would hold up a design proposal until a particular model-maker was free to work on it. The reason for this apparently quixotic behaviour was that, over many years, the work of Foster Associates' in-house model-makers had itself become an integral part of the practice's form generation process. Indeed, the information supplied to the model-makers was often deliberately vague, and individual model-makers were expected to generate much of the form of an initial design proposal themselves. The reason for holding up a project until a particular model-maker was available, therefore, was that that individual's *input* to the form generation process, their particular style was required. Tellingly, model-makers at Foster Associates often earned significantly more than the practice's junior architects. Even now, over twenty years later when all of the practice's architects use three-dimensional computer-aided design tools, the enlarged Foster and Partners (as it is now known) still employs roughly the same ratio of physical model-makers to architects.

Despite this enlightened attitude at Foster and Partners, the lack of research interest in this area may lie in the assumptions that drawings describe three-dimensional form rigorously, so that two-dimensional drawing necessarily deals with three-dimensional form generation, or that physical models, and other three-dimensional representations, are too unambiguous, concrete and depictive in nature to support shape generation effectively

(Tovey 2002, Evans 2005). Yet, if drawing is *essential* to design, how do we account for the plethora of 'designed' objects that stretch from the prehistoric stone hand axe of our earliest ancestors to the beginnings of the industrial revolution?

Both drawing itself and the amount of research effort directed at it now seem somewhat anachronistic in the era of digital design tools. As these have been available to designers for a number of years, and can provide both virtual and *physical* three-dimensional representations of form, it seems timely to assess not only how their incorporation into design practice may have affected spatial reasoning in form generation, but the contribution that might have been made already by existing three-dimensional representations.

1.1 Outline of the research problem

While contemporary design culture, as well as design research, may view creativity in design as being automatically connected to drawing, an alternative thesis, suggested by Pye and the author's experience of professional design, is that drawing (although it is linked with creativity) is only a subset of a much wider range of representation making activities available for form generation. As was alluded to in the example of Foster and Partners, that range of representations has grown over the past twenty years to now include virtual (and physical) digital representations of three-dimensional form.

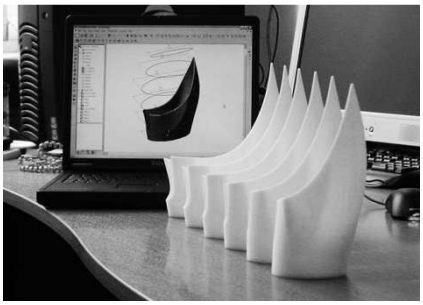

Figure 1-2 digital design representations

The paradox contained in the continued employment of drawing, however, highlights what appears to be a lack of understanding of the role of geometrical representations *generally* in design. Despite these newer virtual digital design representations being originally conceived as replacements for drawings (and other physical design

representations), there is little evidence that drawing itself has been replaced by them in the initial stages of form generation.

As two-dimensional drawings are eventually transformed into three-dimensional objects hundreds, perhaps thousands of times every day in product design studios, architectural practices and engineering design offices across the world, it might be reasonable to assume, despite the author's anecdotal evidence of design practice, that designers' drawings genuinely do describe three-dimensional forms. If this is so then drawing will necessarily include *three-dimensional* form generation within it.

However, accepting this view of form generation uncritically would mean that other representation making activities, those which are not easily classifiable within this paradigm, will tend to be excluded from any further enquiries into form generation that a more comprehensive theory might be derived from. Inevitably, an enquiry which ignores the possibility of using other design representations for form generation will tend only to find further evidence of the power of drawing as a generative medium for design.

Drawing itself has now become such a staple of design practice it is difficult to conceive of professional design without it. Yet the notions of 'professional' design and design through drawing (of which sketching initial proposals for designs is a sub-set) are recent inventions, consequences of the division of labour brought about by the industrial revolution. Indeed it was design through drawing that made professional design as a distinct enterprise in its own right possible, as it separates the necessity to manufacture a finished product (inherent in vernacular design) from the production and distribution of the information required to describe that object's form.

This artificial, and (historically) recent, division between 'designing' and 'making', however, also separates professional design from the body of tacit knowledge accumulated over millennia by vernacular design practices. Initially, when design through drawing was first introduced, it would of course have been used by individuals who also knew how to *make* physical three-dimensional forms. To this first generation of professional designers drawing would therefore have been an *additional* tool, albeit one which was able to greatly extend their perceptual grasp (Jones 1970). In subsequent generations of designers however, with the separation of designing from making implicit in the adoption of design

through drawing, this intimate knowledge of three-dimensional form and the processes required to generate it can no longer be assumed.

The division of labour that created professional design as a separate entity, by separating the creation of descriptions of designed forms from their manufacture, is also mirrored on a smaller scale within the practices of professional design itself. This is often formalised in design theory by neatly compartmentalising the design process into an initial generative phase and a subsequent developmental one:

Generation	Development

Sketching is seen as the primary generative tool, while physical and virtual three-dimensional representations are employed for development. So the character of the generative phase is primarily two-dimensional, while the subsequent developmental phase is three-dimensional:

Generation	Development
Two-dimensional	Three-dimensional

However, the simple division between generation and development, and two-dimensional and three-dimensional representations illustrated here is at odds both with Pye's view of design and the anecdotal evidence from the author's experience of the professional design world. What both these examples suggest is that between generation and development, and two-dimensional and three-dimensional representations, there is an intermediate step which combines elements of each:

Two-dimensional shapes	Form generation	Three-dimensional forms

It is the processes contained in this intermediate step which, by allowing two-dimensional shapes to be transformed into three-dimensional forms, are the subject of this enquiry.

While Dorst and Cross (2001) see design in general as an iterative process, one which alternates between problem statements and solution statements until the most satisfactory fit has been reached, in practice, however, time, funding and physical or mental energy will be exhausted some way short of this ideal point. Given that the resources available to arrive at a design solution are limited, however, it would be beneficial to gauge to what extent each of the representation making activities undertaken by designers contribute to the three-dimensional shape of their designs. If designers' drawing or sketching activity genuinely deals with three-dimensional form then their designs are already as fully realised as practice allows. If the converse is true, and they do not genuinely deal with three-dimensional form, or deal with it only partially, then the potential exists for improvement.

1.2 Research questions

As generating three-dimensional form through drawing entails working in a different space to its intended outcome, and mapping between these spaces (from a representation of lower spatial degree to a higher one) requires *additional* information not contained in the initial two-dimensional representation, where does that additional information come from?

Dorst and Cross' iterative cycle is an obvious source of additional information, but if that additional information is generated in a representation of lower spatial degree from the intended outcome, as happens when designers draw the form of their design proposals, will it then be the kind required to generate a three-dimensional object? If, in turn, the shapes generated by drawing are not necessarily three-dimensionally realisable, is it possible that the information required to map from two dimensions to three is generated in the process of designers making *other* design representations? To paraphrase the Estonian proverb in the frontispiece; will the work (of making representations) teach them how to do it? It was these observations which eventually led to the formulation of the following research questions:

- How three-dimensional *are* the shapes contained in a drawn representation?
- How are the additional shapes required to create three-dimensional form *generated*?

However, the apparent lack of interest in how designers are able to transform their drawings into physical objects (and the resulting lack of knowledge in this area) has meant that this enquiry has necessarily been an exploratory one. It was therefore initially conducted along two separate, but closely related, strands. These were directed toward answering a range of more general questions generated by the literature review, and focussed on two distinct stages of the design process. These examined the position of drawing as the 'normal' medium of design; whether the use of computer-aided design may now take some part in form generation; that if design reasoning could be seen as a form of distributed cognition in sketching, could similar reasoning be identified in making other external representations and, finally, could the tactile qualities of physical representations be used to address the representational poverty of design practice generally, and computational design in particular.

The first strand, investigated through a reverse-engineering task, was concerned with the period in the design process after some form of physical three-dimensional representation has been created. It examined the possibility that the acculturation of digital practices in design, and the increasing fluency of designers with digital design tools, could be used to link these physical representations with their virtual three-dimensional counterparts. The ultimate aim of this line of enquiry, in its initial stages at least, was to enable the transformations made by designers to their physical design representations to be reflected in a related virtual design representation, addressing an apparent breakdown in the flow of information in the existing digital design cycle.

The premise underlying this approach was that, as designers may now regularly use virtual representations, they would also have the constraints and affordances of these representations, and their implicit *structures*, in mind when creating the form of a design proposal.

The second strand, investigated through a series of design protocols, also examined links between representations, but those located at the earliest stages in the creation of a

design instead. Here the area of interest was more concerned with the spatial degree of representations than with their apparent materiality. The purpose of the protocols themselves was to provide empirical evidence of how, when and why experienced designers transform their design proposals from their earliest two-dimensional representations to their first three-dimensional instantiation. In this case; how they generated an initial proposal for the upper body of a domestic clothes iron, employing the range of representations typical of that found in contemporary design practice.

The initial findings from both strands revealed a spatially indeterminate phase when participants moved from two-dimensional to three-dimensional representations, and vice-versa (Paterson *et al* 2007). It was the ambiguity of the degree of the space that design elements are transformed in during this phase, however, which led the enquiry away from its original objective (of addressing the problems of information flow between physical and virtual representations) to analysing how designers manage the transition from two-dimensional to three-dimensional representations instead.

It seems to the author that any discussion about the function of drawing or making in the generation of design proposals may be less than meaningful, in practical terms, before we begin to understand *what* relationship exists between the two-dimensional shapes generated by drawing and the forms generated by making a three-dimensional representation.

Furthermore, while designers are in the process of transforming their designs from two dimensions to three (during the previously mentioned spatially indeterminate phase), do they occupy a two-dimensional perceptual space (and draw two-dimensional shapes), or are they in a three-dimensional perceptual space (and designing three-dimensional forms)? Are they, for example, genuinely responding to the requirements of the three-dimensional form itself, or simply to the two-dimensional forces within a drawn representation?

To answer these questions, rather than retreading unsubstantiated assumptions about the nature and function of different classes of representations in form generation, the author chose instead to concentrate on an in-depth analysis of four of the design protocols already undertaken for the initial research phase of the enquiry.

1.3 Methods

Alexander (1964) states that it is absurd to attempt to separate the study of design from its practice. As the object of this enquiry is to understand an evanescent process (how designers manage the transition from two dimensions to three), and to gauge the relative contributions made by an unconstrained range of representations to that process, a video record was made of each of the participants' protocols.

This video, while it provides a detailed (and indefinitely re-visitable) record of the participants' behaviour during a realistic design task, does not in itself provide data. The exploratory nature of the enquiry, by starting with empirical observation rather than with explicitly stated theories, has meant that the coding schemes required to translate the behaviour observed in each protocol into data have instead been derived from studying the video record and extracting relevant structures from it.

The fundamental unit of structure employed in this enquiry is the design action. Design actions are defined as any modification of a design representation that is bounded by two pauses. The initial pause is that which allows for the assessment of the previous (if any) design action, while the subsequent pause is that which allows for the assessment of the effects of the design action in question.

The generative potential of drawing versus other forms of three-dimensional design representation making activities is assessed by first segregating individual design actions into drawing or making actions, which is achieved by mapping them against Stiny's (2001) algebras of shapes. The relative frequency of two indicators of generative potential is then compared: the nature of the decompositions employed (indefinite or definite) and the nature of the design 'move' (Schön and Wiggins 1992) when mapped against Goel's (2000) lateral and vertical transformations.

While some design activities may involve symbol manipulation and traditional reasoning, shape generation, through representation making, is largely non-symbolic; i.e. it is directly concerned with shape itself rather than with what shapes represent. To reduce this non-symbolic, visual and spatial reasoning to the symbolic form necessary for its description each modification made by the participants to their design representations is regarded here as a production. By laying out design actions in this way the state of the representation at the end of each action can be represented symbolically and

unambiguously; where elements are clearly defined, and the ‘atoms’ of the design *at that moment* can be stated explicitly.

Furthermore, by viewing these interactions (of the participants with their external representations) as a *distributed cognitive system* it is also possible to create a solidly grounded basis for further analysis without becoming entangled in hypotheses about the nature of internal cognition.

Individual design actions are then collected into episodes, an episode initially being defined as any sequence of consecutive design actions performed on a single design representation; whenever a participant changed their choice of representation a new episode commenced.

Although this definition of an episode sufficed when participants were working on two-dimensional representations, during the latter stages of those protocols where they went on to make a three-dimensional representation it was less obviously applicable. Although in these episodes participants would often work on a single instance of a representation for considerable periods of time it was observed that, while the space that the design representation itself occupied was a three-dimensional one, the transformational space of the design elements acted upon by the participants varied during this time and could be divided into more or less distinct episodes. It is here that mapping individual design actions against Stiny’s algebras of shapes provided a way of dividing episodes by the spatial degree of the apparent perceptual space occupied by the participant, rather than strictly by the spatial degree of the representation employed.

The research questions themselves engage with the nature of a designer’s implicit perceptual space versus the explicit transformational space of their chosen media. The data to answer the research questions therefore comes from coding the phenomena observed in the protocols into definite design actions and identifying changes of representation, or the transformational space of design elements within a representation, by arranging these actions into episodes which are defined as: a sequence of actions on a single representation, *or in a single transformational space*.

As the divisions between the three-dimensional episodes are much less clear-cut than in the preceding two-dimensional episodes however, and it is possible that a case may be made for different divisions to those eventually settled upon here, although they have been

retained as an aid to organising, and understanding, the progression of a design proposal from two dimensions to three in the course of the protocol, they have not been used as a basis for statistical analysis.

While measuring variations in the frequency of design actions in an episode between three-dimensional and two-dimensional ones might well create quantitative data, slightly altering the criteria for defining an episode in the use of a single three-dimensional representation can give such widely differing divisions, in number and location, that comparing their frequency in this way would produce results that are meaningless for the purposes of analysis. Their analysis is therefore more qualitative in nature, and is deduced from direct observation how designers employ representations, inferring from that the perceptual space they occupy when transforming those representations.

1.4 Overview of the thesis

This thesis consists of eight chapters, which can be grouped into three major sections. The first, containing chapters one, two and three, provides an executive summary of the research, examines literature relevant to the enquiry and discusses the methodological issues underlying the data collection methods. The second section, containing chapters four, five, six and seven, lays out (and initially analyses) the data collected from four of the design protocols. The final section, chapter eight, presents the conclusions drawn from a further analysis of the findings laid out in the protocol chapters. A summary of the contents of the following chapters is given below.

1.4.1 Chapter 2: Literature review

The literature review identifies areas where an enquiry could make a contribution to the understanding of form generation in design. It looks at the literature that touches on the relationship between professional design practice and the representations it employs when creating shape and form, and is divided into five sections.

Section 2.1 examines the relative positions of drawing and three-dimensional representations in form generation. It introduces the arguments made for sketching as a

creative tool, the position of three-dimensional representations as development tools, and the implicit contradiction between the requirement for ambiguity in the early stages of form creation and the need for greater descriptive rigour in the latter.

Section 2.2 introduces some basic theories of design, and outlines the antecedents of professional design from Homo habilis' stone hand-axe to the beginnings of the industrial revolution. It continues with an outline definition of professional design, as an enterprise which is separate from the manufacture of finished objects and which is undertaken primarily through drawing.

Section 2.3 describes generative mechanisms. Links are made between shape generation, design reasoning, and the iterative nature of these processes in design. Stiny and Gips' shape grammars are then introduced as a means of computationally formalising shape generation.

Section 2.4 discusses the changing nature of design practice in the digital era, and the possibilities and shortcomings of newer virtual and physical digital representations. The discussion initially centres on contrasting information flow in single virtual representations, via haptic interfaces, with information flow in distributed physical and virtual representations. It is then directed toward formulating research questions, by identifying relevant lacunae, and leads to a statement of the initial research questions derived from them.

Section 2.5 closes the literature review with a brief recapitulation of its salient points and a definition of the initial direction of the enquiry.

1.4.2 Chapter 3: Methodology

Chapter 3 describes the development of the data collection methods employed in the enquiry, and the reasoning behind them, in five sections.

Section 3.1 examines issues surrounding the basis for the knowledge of non-verbal phenomena such as visual and spatial reasoning, and why designer's verbalisations are inappropriate for an enquiry which deals with tacit knowledge.

Section 3.2 presents an overview of the two major data collection exercises; the reverse-engineering task and the design protocols, outlines their scope and describes their original purpose.

Section 3.3 discusses how the findings from both of these data collection exercises led to a change of emphasis for the enquiry, from investigating information transfer between physical and virtual representations to a fine-grained analysis of the design protocols instead.

Section 3.4 provides an overview of that analysis, examines how design activity is identified, how it is described, and how the comparison of drawing and making activities in the subsequent protocols can be used to answer the research questions posed in this chapter.

Section 3.5 concludes the methodology chapter with a discussion of how the data collected by the protocols is laid out in the subsequent chapters, and how four of the seven protocols recorded for this enquiry were selected to be described in those chapters.

1.4.3 Chapters 4 – 7: The protocols

The next major section contains **Chapter 4: Lynn's protocol**, **Chapter 5: Miquel's protocol**, **Chapter 6: Andrew's protocol** and **Chapter 7: Peter's protocol**, where the data and initial analyses of the four design protocols examined by this enquiry are laid out.

The sequence they are presented in progresses from a lower to an increasingly higher upper spatial degree of the physical design representation employed: Lynn produces two-dimensional representations; Miquel produces a design that is essentially an extrusion of a two-dimensional shape into three dimensions, while Andrew's protocol results in a three-dimensional object. There is also an implicit progression in the *processes* employed to create them. Lynn drew. Miquel and Andrew combined drawing and making. Peter also drew (both physically and virtually) and made (virtually) but utilised a greater range of Boolean operations than in the preceding protocols.

The later chapters are divided into seven sub-sections, while Lynn's protocol, as it contains drawing actions only, is divided into six.

Section 1 establishes the position of the protocol described in that chapter in relation to the other protocol chapters.

Section 2 gives a brief description of the kind, and number of design actions.

Section 3 describes those actions which took place after the protocol had commenced, but before any shape generation activity as such was observed.

Section 4 lays out a full description of the participants' drawing actions as a series of individual episodes.

Section 5, with the exception of Lynn's protocol, lays out the complementary making actions.

Section 6 completes the description of the protocol by giving an account of a participant's actions after the end of the protocol, i.e., after any observable shape generation activity has ceased.

Section 7 contains an initial analysis of the design actions observed in the protocol. The analysis itself centres on the categorisation of design actions (**7.1**), on mapping categories of design actions against algebras of shapes (**7.2**), the decomposition and embedding of shapes observed in the protocol (**7.3**), on quantifying and comparing design actions (**7.4**), on representational constraints (**7.5**) and to what extent the participant's activities in the protocol could be seen as designing three-dimensional forms as opposed to drawing two-dimensional shapes (**7.6**). These strands are then brought together and summarised in section (**7.7**).

1.4.4 Chapter 8: Conclusions

The final section consists of chapter eight alone, which shows how the analysis of the data collected by the design protocols supplies answers to the research questions set in this chapter.

Section 8.1 revisits the research questions, and describes how they are answered by viewing the detailed examinations of design activity laid out in the preceding protocol chapter from different perspectives.

Section 8.2 draws comparisons between the four protocols, and lays out how their analysis is undertaken by collecting design actions into episodes and mapping them against different aspects of the array of algebras of shapes.

Section 8.3 provides answers to the question of the three-dimensionality of designers' drawings by analysing some of those produced for the protocols. It examines the three-dimensional relations between the shapes produced in different views of the same object and assesses the relevance of the drawn shapes contained in each protocol to the final outcome.

Section 8.4, in turn provides answers to the question of how are the additional shapes required to create three-dimensional form *generated* by examining how shapes generated in the drawn representations are transformed, or supplanted, by those created in subsequent three-dimensional representations.

Section 8.5 brings the analyses from sections 8.2, 8.3 and 8.4 together and summarises their conclusions. The implications of those conclusions for design research in particular and design practice in general are also examined.

Sections 8.6, **8.7**, and **8.8** then discuss, respectively, the enquiry's contribution to knowledge, the potential for further work suggested by its findings, the limits of applicability and generalisation of the conclusions, and a reflection on the success, or otherwise, of the various aspects of the enquiry.

1.5 Endnotes

The ultimate purpose of much design activity is still the creation of physical artefacts, and the end product of many areas of professional design practice will still be some kind of three-dimensional form. Buildings are the end product of architectural design, while the plethora of manufactured objects that surround us, such as toasters, bridges and automobiles (for example) are the equivalent outcomes of industrial, engineering and automotive design. Despite this observation, and despite the wholesale adoption of computer-aided design for form development, form generation itself is still reliant on sketching; i.e. on the use of a two-dimensional, physical medium. Therefore, for many designers digital design remains a hybrid of physical and virtual processes: the early stages of design entail making two-dimensional marks on paper as a way of initially capturing and assessing ideas, while computer-aided design and rapid prototyping are employed for the subsequent three-dimensional development of those ideas.

The range of shape descriptions available to contemporary design, which includes these digital representations, is itself assembled from a motley collection of representational technologies which has been added to piecemeal over the centuries. The adoption of these representations has often been driven by the changing needs of manufacturing or design practice but, ironically, adopting a particular representation has in itself often changed the nature (and therefore the needs) of practice in turn. This circularity of cause and effect in the employment of various design representations has led to some degree of confusion over their nature and efficacy, which can be found in a view sometimes expressed in design research that traditional analogue media are more ‘intuitive’ than newer digital alternatives; a teleological vindication which overlooks the obvious fact that ‘traditional’ media were once the ‘newer’ alternative themselves.

To make the nature of this confusion more readily apparent, and to identify areas where an enquiry could make a contribution to our understanding of form generation in design, the following chapter looks at that research literature which touches on the relationship between professional design practice and the range of representations it employs when creating shape and form.