Drawing and CAD in industrial design

Michael Tovey

Department of Industrial Design, Coventry Polytechnic, Gosford Street, Coventry CV1 5RZ, UK

Drawing is an essential component in the industrial design process, facilitating visual thinking and creativity. It constitutes one type of design model, along with specifications, 3D representations and CAD techniques. The design process involves movement from one model to another, and by using representations of different types and at different levels of detail a fluid and inventive design approach is facilitated. Examples of schematic drawings, ideas sketches and concept drawings demonstrate this in product design and transport design. CAD has proved to be highly effective in evaluative and analytical design development, and in manufacture. It is inherently unsuitable for innovative design, but has potential for contributing to evolutionary design, as is evidenced by its proven effectiveness in engineering optimization. Automotive design is almost always concerned with design evolution, and procedures for car stylists to work productively with CAD are being developed in Coventry Polytechnic's SERC funded research project Computer Aided Vehicle Styling. Vehicle stylist's design thinking is characterized by holistic, right-hemisphere processes informed by tacit knowledge and dependent on visual representation. They have particular difficulties with CAD systems. Nonetheless, design techniques that capitalize on CAD's potential and may be applicable to industrial design are briefly described. CAD drawings and conventional design drawings are compared by using examples from the car industry, and from the research project. Tentative speculations about future design procedures are made.

Keywords: drawing, computer-aided design, automotive design, car styling

All designing of products (not systems) involves representing the device in some form. When an object is designed and made as one process then we call this crafting (examples are craft pottery, craft-made furniture, etc). In design the object is represented and the easiest ways of doing this are by drawing and by 3D modelling. Drawings and 3D models are the physical manifestation of visual thinking, and provide a language for handling design ideas.

The introduction of drawing to the process of designing and manufacturing artefacts was probably the most significant innovation in the history of designing. Some would claim that the introduction of computers to the design process in the last 30 years has been a change of similar or greater importance. CAD is dealt with later in this paper.

In some forms of product design a lot of the designing is done by using 3D representation, such as full-size models, scale models and rigs. For the most part drawing is the preferred method, since it is much quicker and larger products such as transport devices are too big to be easily modelled in any other way.

The activity of drawing design ideas, sometimes called graphic ideation, is important not only as part of the process of producing the design ideas, but also because it is an externalization of the designing, which allows other people to participate. Because they can see what you are doing they can contribute to the design process. This allows the design manager, client, user or other interested party to have more say in the design.

Drawing is probably the quickest way of representing a design idea, so that the route to a solution to the design problem can be fairly short and convenient. The disadvantage of such a technique, is that it assumes that the answer is a certain type of artefact. This can be seen in the examples of design drawings, particularly where they are 'realistic'. This is limiting in that it may reduce the likelihood that alternative types of product are considered, and in some cases that the design solution may not be a product at all, but some rearrangement of the system of which the product is a part. (A re-design of a bus-ticket machine may not be as good a solution as paying for buses out of local taxation and making them free to passengers for example. This kind of idea seldom emerges whilst drawing designs for ticket machines.) As most industrial design is unequivocally concerned with products this is not usually a problem, and drawing and 3D modelling techniques may be used as the best way of initiating and developing design ideas.

VISUAL THINKING

Thinking is the mental activity by which our brains sort through, juxtapose and combine pieces of information. This information has for the most part come to us through our senses as sight, sound, touch, etc. Visual thinking is that thinking which uses visual information. Visual imagination is creative thinking using visual information to form new images, or imagining in its precise and literal sense.

Visual thinking is very widely used, by designers, artists and even scientists: Einstein is reported to have used visual imagery in creating the theory of relativity, and Watson and Crick used visual thinking in devising the double helix model of the DNA molecule. For industrial designers it is impossible to create the physical form of a product, to define it as a 3D object without using visual thinking.

Visual thinking is done by using three kinds of visual imagery:

- the things we see
- the kind we imagine in the mind's eye
- the kind we create by drawing or other means

Seeing involves receiving visual information and interpreting it according to certain codes, conventions and stereotypes. Imagining is an internalized version of seeing, using similar codes and conventions. Drawing is an externalized equivalent of imagining and seeing. The three activities work together complementing each other and encouraging purposeful and productive visual thinking.

Drawings and 3D models are languages for handling design ideas. The actual process of creating design ideas goes on in the mind, and the drawings and 3D models are attempts to reproduce the designer's mental images. The method of drawing or crafting in 3D is one of hand–eye coordination to produce the physical object of either a drawing on paper or a model. Exercising this skill can be mentally relaxing, which in its turn can reduce the inhibitions to the flow of thought. Whilst the designer is drawing there is a mental sifting and sorting of information that can lead to design ideas. As soon as the image has been manifested as a drawing or model it becomes part of the information being handled to produce the next idea. The process is one of interactive generation.

DESIGN MODELS

Drawings are one type of model within the design process. In the visuo-spatial realm drawings are joined by 3D representations as the two most visible modelling languages. Outside it they are complemented by verbal-numerical representations such as specifications and mathematical models, and increasingly by various kinds of CAD models. Indeed the design process may be regarded as the movement from one model to the next, and the models themselves, as representations of the state of play of the design activity.

Within the design of products, drawings are an essential component, particularly in the early stages when they provide cross-sectional snapshots through the design process. They also perform the vital function of facilitating both visual thinking and creativity, through a three-way interaction of seeing, imagining and drawing. Drawings permit a holistic representation of the design idea that is essential in concept design, appearance design and visual innovation, permitting the simultaneous consideration of several elements in the design.

The interaction of seeing, imagining and drawing encourages creativity in part by smoothing the movement from one design model to another within one language-drawing. The existence of drawing permits the designer to consider several alternative design ideas simultaneously. The designer or designers simply pin up their drawings and review all the ideas produced. This allows back-tracking and any design idea drawn can provide a new starting point. This divergent production facilitates creativity by the provision of a wealth of alternative ways for the design to be progressed.

The idea that alternative design proposals modelled within the one modelling language of drawing can facilitate creativity can be extended of course. There is no reason why the design thinking should be restricted to one type of model. Indeed moving from one to another can itself facilitate a creative approach to realising the design. Representing the design idea in words and numbers, for example as a performance specification, can open the way to many alternative ideas for the physical form of the design. Similarly when presented with a physical representation of the design as a 3D model or full-size facsimile many designers resort to sketches to solve the problems that have become apparent in three dimensions[2].

Each of the types of design model can be subdivided into a number of types of representation and for the traditional methods, verbal-numerical and visuo-spatial these can be ranked from undetailed to detailed. This is less easily labelled in CAD, and in any case is not comparably the case.

Each of the verbal-numerical and visuo-spatial models could be said to constitute a frame of reference. Koestler calls the creative collision of frames of reference to yield insights 'bi-sociation', and Davies and Talbot have likened the emergence of new ideas through such collisions to the way in which Moiré patterning occurs when two half-tone screens are angled across each other[3,4].

A number of the models may also be regarded as generators, being by their nature amenable to the production of alternative design forms in the movement from undetailed to detailed model, and across modelling types. Thus:

- a specification can yield many alternative physical forms for one design
- a diagrammatic or abstract representation of the design can yield many alternative proposals for the finished form of the design
- a representation of the package elements can form the basis for alternative configurations for the design

Table 1. Design models

Verbal/numerical		
Design hypothesis		Undetailed
Initial specification		
Performance specification		
Feasibility calculations		
Detail design specification		
Engineering evaluation calculations		Detailed
Visuo-spatial		
2D		
Diagrammatic drawings	: Abstract	Undetailed
	Schematic	
Representational drawings	: Ideas sketches	
	Concept drawings	
Measured drawings	: Package	
	General arrangement	
	Axonometric	
	Part drawings	Detailed
3D		
Sketch model		Undetailed
Scale representation		
Test models and rigs		
Full size exterior		
GtFull size facsimile		
Prototype		Detailed
Computer Aided Design		
2D Elevational line drawings		
Paint box systems		
3D Wire frame	unshaded, shaded	
Surface models	reflective, transparent	
Solid models		
Engineering evaluation		
Finite element, thermal, kinematic, etc.		
Computer Aided Manufacture : NC machines, robots		

The visuo-spatial models are of particular importance in the generation/synthesis phases of the design process. For the design of products these phases are also of particular importance for the industrial design activity.

INDUSTRIAL DESIGN AND DESIGN ENGINEERING

Industrial design is concerned with the design of manufactured products. For less complicated products the industrial designer may take responsibility for the whole of the design, simply handing over to production engineers for the production of the product. For most products the industrial designer works with design engineers, having a relationship with mechanical engineers similar to that enjoyed (if that is the right word) by architects with civil engineers.

Industrial design and engineering design have much in common. They are both concerned with the design of bits of technology. They are both concerned with (as Chris Jones phrases it) 'initiating change in man-made things'[5]. But they are different too; engineering design has been defined by Fielden as 'the use of scientific principles, technical information and imagination in the definition of the mechanical structure, machine or system to perform pre-specified functions with the maximum economy and efficiency'[6]. By contrast industrial design has been defined by Farr as 'the conditioning factor with those parts of the product that come into contact with people'[7].

This definition of industrial design is not particularly helpful apart from its emphasis on the importance of the user interface as part of the design activity. Industrial design has typically worked in design teams alongside engineers of one sort or another and also marketing experts and product planners and so forth. Design teams work together through concept design and design development to the interface with manufacture and in this process the industrial designer has two particular areas of responsibility:

- to represent the market and user requirements and determine the ergonomics and appearance of the product
- to integrate market user and engineering requirements into a whole design solution

These responsibilities may be characterized as a concern with the user interface to the product whether it is in the objective of measurable area of ergonomics or in the subjective area of appearance. Ensuring that these areas are properly considered it is essential that the product be viewed as a whole and from this stems the responsibility of the overall integration of the design solution. In tackling these areas of responsibility the industrial designer has two particular and related functions[8]:

- to visualise the product to concept
- to represent alternative design solutions

This representation of concepts and alternatives is essential as a communication device within the design team. It is also used as a tool of design management, as a method of selling ideas both to management and to marketing. Industrial designers are thus required to be both visual and creative and sometimes regarded as the artists within the design team. Operating in this way the industrial designer calls upon particular skills such as drawing and presentation techniques, and has to have sufficient understanding of engineering and market requirements to ensure that the integrated product design is technically and commercially feasible. The industrial designer will also draw on particular specialized knowledge in ergonomics and appearance design.

Examples of design drawing

Both of the areas of responsibility of the industrial designer and the two functions require the design proposal to be represented, either in 2D or 3D. Drawing is of particular importance for most industrial designers.

The examples of drawings are taken from general product design and from vehicle design. They include drawings of various types fulfilling different functions, including the following.

Schematic and diagrammatic drawings

Schematic and diagrammatic drawings are more abstract representations of the underlying principles of an idea (Figure 1). This can involve different levels of abstraction, indicating for instance different motor positions for a given wheel arrangement, or showing diagrammatically the forces acting on a component in a given situation. At its most abstract it can be simply a representation of, for instance, the sequences of operations of controls. At this level it is quite close to some of the more structured design methods such as the Interaction Net, or matrices. The value of this sort of approach is that the design ideas can be converted into more than one design for a specific object.

Ideas sketches

These are representational drawings that attempt to show what the design ideas look like as physical objects. They are useful for investigating the appearance and visual impact of such ideas. They can be used to investigate geometric configurations, scale and proportion, as well as mechanical and production engineering details. The essence of them is quick execution and consequently most designers use pencils, ball pens and felt pens, on layout pads, or sometimes on a paper roll to allow a continuous sequence. The intention is to produce many ideas in a short time (Figure 2).

Concept drawing

The concept drawing is a form of representational drawing that is of particular importance in the industrial design process. This is a drawing that attempts to show what the design proposal will look like as a finished product. This is essential for the consideration of the appearance and ergonomics of the product. It also serves to focus the design team on the physical form of the emerging design, inducing a solution-led approach to the design process. The initial stages of designing will often involve the consideration of several alternative design concept proposals.

Measured drawing

The measured drawing may be used very closely with the concept drawing to precisely define the limiting boundaries of the design. It is a working version of a technical drawing, and it can often be traced from to produce the finished engineering drawings. It is used to check out the geometry and fit of the design ideas, to see they will work together in a design proposal. This is of course essential in many aspects of the design, particularly the manufacturing technology, but also the anthropometrics, some aspects of regulations and many other areas. Typically such drawings use elevational views.

The full-size tape drawing is a particular development of the measured drawing executed full size and using removable tape for the lines on the drawing, so that they can be easily changed without ruining the drawing. Much used in automotive styling studios, they are very convenient for checking out the elevational geometry of a design, aspects of human factors and scale.

Parallel designing

It is very much easier with design drawings to consider a number of alternative design forms than with any other modelling language. Although the drawings may be produced as a serial process, they can be evaluated in parallel, either as several drawings on a page, or by pinning a number of drawings on a wall. This simple process encourages alternative design directions and a fluidly creative approach. In this respect drawing is markedly different from two of the other modelling languages. Neither 3D representation nor CAD has the same potential for a directly and fluidly creative approach.

To an extent measured drawings, from elevational sketches to technical drawings can be used as part of the same process. But it is less demonstrated by schematic drawings, ideas sketches and concept drawings, each of which is used in various forms in the examples. The movement from undetailed to detailed representation is also shown in the figures.

Innovative and evolutionary design

Not all product design has to be radically original. The design process for some manufactured products is concerned with creativity in respect of the appearance of the product, but little major change otherwise. For others the design involves radical change to fundamental

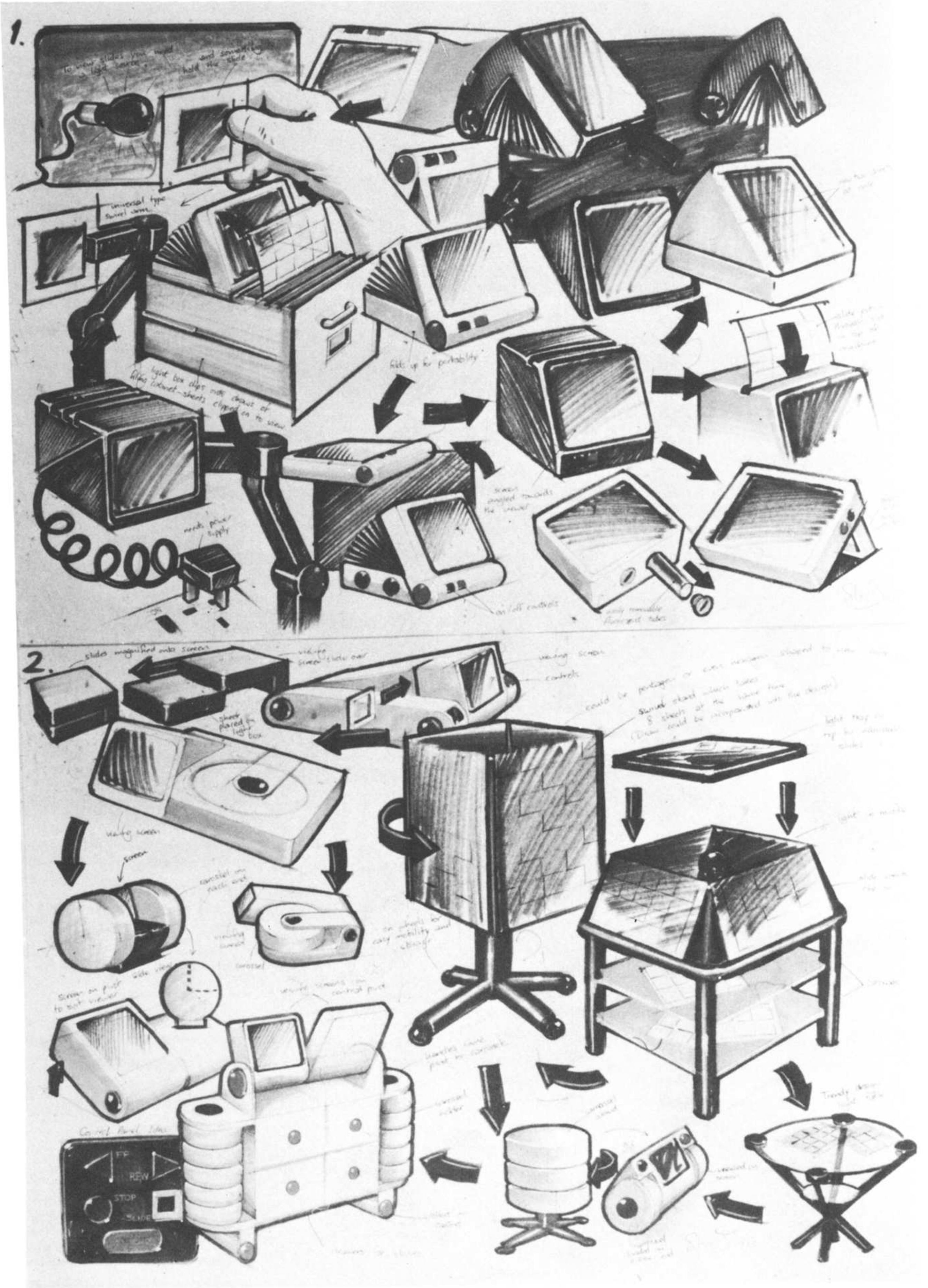

Figure 1. Design sketches: design of a slide storage system by Stephen Lewis

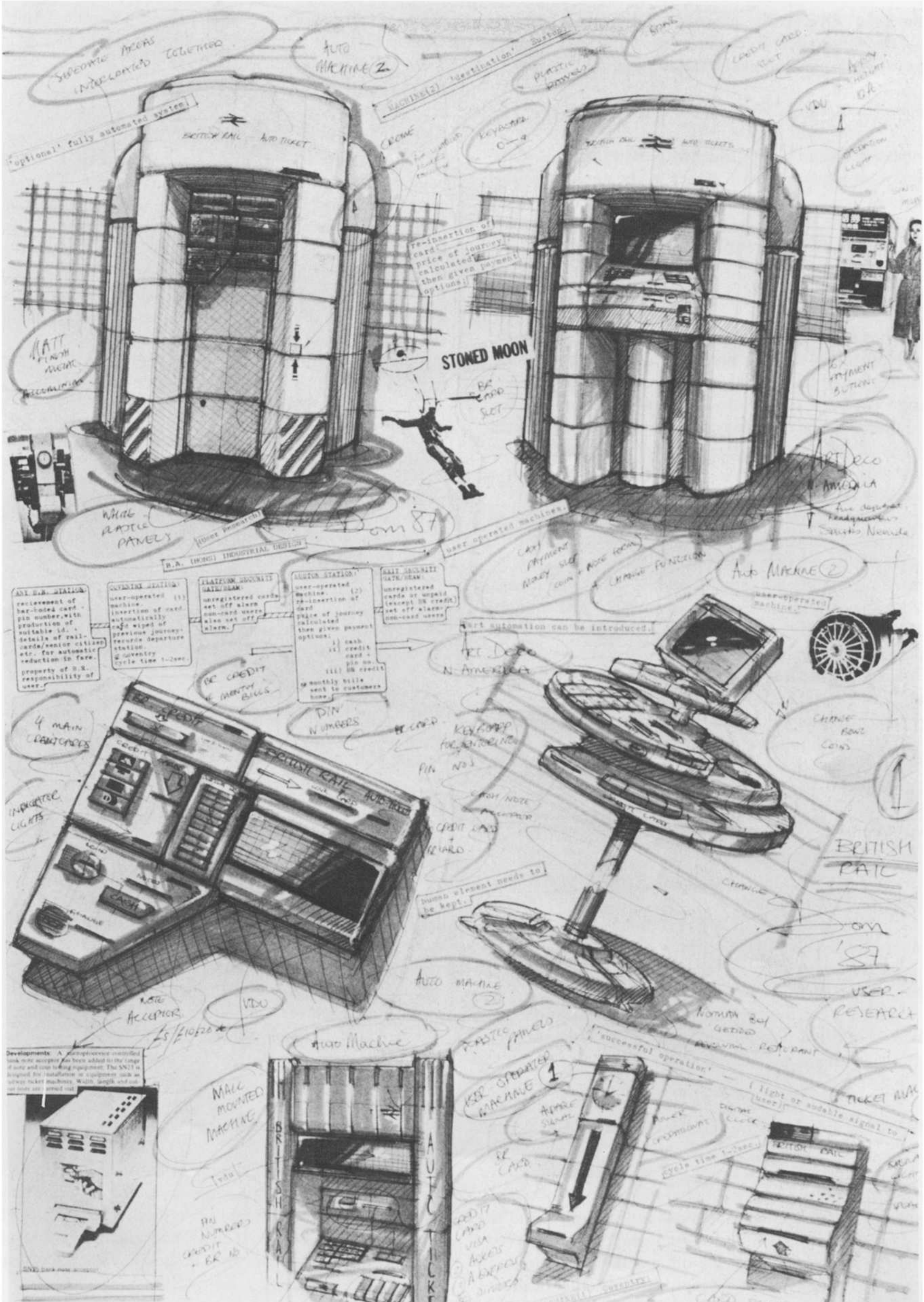

Figure 2. Design sketches and words: design of a railway ticket machine by Dominic Longman

innovation. Overall the process for designing products may be subdivided into those two types of activity: innovative design and evolutionary design.

Innovative design

Innovative design is concerned with radical change in the creation of a new product, either in the area of product function or in technical invention. It is relatively unusual; examples are Sony's creation of the Walkman, or Black and Decker's Strimmer.

Evolutionary design

By contrast evolutionary design is concerned with the development of existing products, with the new design evolving out of the current product. A high proportion of design is of this second type. Indeed all design *becomes* evolutionary after the innovative steps have been taken. Design development is the same whether the starting point is a radically different product idea, or simply a modification of the current one.

Radically innovative design is virtually impossible to computerize, particularly in its early phases, as what the design will consist of is unknown, so a database cannot be created. Evolutionary design on the other hand uses predictable information so it is amenable to computer involvement. Almost all motor car design is evolutionary. Such are the legislative, operational, ergonomic and technical constraints that many elements of an automobile are specified in advance of the designer's doing anything. Automobile design would seem to offer an excellent opportunity for a fully integrated CAD process.

Evolutionary design may itself be divided into two distinct types of activity.

- styling
- engineering optimization

Styling is part of industrial design, and the industrial designer undertaking it will have the concerns and functions listed above. He or she will also be expected to be visually creative, even though the design process as a whole is non-innovative.

Within the car industry engineering optimization, the function of the design engineers, is fully computerized. Styling, for the most part, is not.

COMPUTER AIDED VEHICLE STYLING

A fully integrated CAD process is assumed to have greater flexibility than traditional methods, to have the potential for substantial reductions in lead times, and to have great potential for cost reduction. This has proved to be the case for engineering design. A major question within the car industry at the moment is whether or not it is possible to undertake CAD for styling and if so whether or not it will yield similar advantages.

Coventry Polytechnic's Science and Engineering Research Council funded research project 'Computer Aided Vehicle Styling' is currently tackling this area of CAD.

CAD in the design process

In Principles of Computer-aided Design[9], Rooney and Steadman identify the main contribution of CAD as being to the later stages of the design process. They see such CAD techniques as solid and surface modelling, performance analysis, finite element, thermal and kinematic analysis as being part of the Evaluation stage of the process. Further they locate other CAD techniques such as automated drafting, and the electronic transmission of the final design to NC machines and robots as the last phase of the process, 'Manufacture'.

They comment about the general application of CAD to synthesis and analysis in design.

> One further characteristic of these alternating phases of synthesis and analysis in design is that they tend to move from the general and tentative, to the more specific and definite. At first the designer considers preliminary outline ideas or sketch proposals. The evaluations made here are perhaps of a rather informal and approximate kind; later the preferred design or designs are flushed out in more detail, and analyses of performance and cost are made with greater precision. This fact has important consequences for CAD, since it is extraordinarily difficult to allow for vagueness, sketchiness or ambiguity in a computer program. For this as well as for other reasons, most computer aids produced to date serve the later rather than the earlier stages of the design process.

Within product design these informal and approximate design proposals tend to be the province of the industrial designer.

Car design and styling

Most of the world's cars are manufactured by large companies. They are highly structured organizations and they subdivide the process of creating a new product design between very many specialist groups. These include product planners, exterior designers, interior designers, package engineers, structural engineers, mechanical component engineers, electrical engineers, production engineers, manufacturing system engineers and a whole host of others. The overall process for designing a new car will take 3 to 4 years and the stylists' contribution is a small part of this.

The design process for styling

In the design studios of the major automobile manufacturers the styling process for both the exterior and interior design of an automobile typically passes through the stages listed below. It is a small part of the overall concept to styling approval design and development programme.

- issue of product brief
- issue of mechanical and ergonomic 'package'

- review of competition
- 'brainstorming' discussions
- quick concept or 'theme' development sketching
- package related sketches
- accurate full-size 2D representations
- development of full-size model

The product brief

This is prepared by the planning group and details the complete specification of the intended automobile, including size, model ranges, engine sizes, features, target cost levels and intended launch date.

The package

This is produced by an engineering group, in consultation with the planners and design department representatives; it takes the form of a full-size three-view layout, showing the mechanical, ergonomic and legal parameters of the proposed vehicle. It may well be produced with the aid of a computer-aided drafting system. A copy will be permanently displayed in the design studio for the duration of the programme.

Review of competition

This will take the form of a photographic display, usually A2 or A3 size, of all the significant competitive vehicles, front 3/4, side and rear 3/4 views being shown, plus lists of dimensions; examples of the most important competition will be brought into the design studio for close study.

Brainstorming

A short discussion amongst the studio designers to examine alternative ways of approaching the project, and to generate fresh thinking and enthusiasm.

Concept sketches

These are freehand sketches, possibly started before the issue of the 'package' and may not closely follow the actual dimensional parameters; through experience the designers will have to create the right 'feel' in their sketches. The aim will be to examine alternative aesthetic themes, and to establish if any overall trends are developing. The 'loose' approach facilitates very rapid sketching and freedom of thought, the resulting inaccuracies as exaggerations are well understood and accepted by the designers as a means of communicating visual concepts, particularly as they are mostly for internal discussion; this takes place with all the sketches on display. There may be between 10 and 50 sketches to be reviewed, depending on the number of designers involved. One designer may typically produce 10 or more proposals per day. Various media will be used: ball point, pencil, crayon, marker etc., whatever the designer prefers.

Package related sketching

Following sketches of themes from the previous stage, A2 and sometimes A1 sketches will be produced much more closely related to the package. Sketch-pad size copies of the package may well be used as accurate underlays for this purpose. These sketches will be more elaborate and detailed, usually in colour, shaded, and with artistic interpretations of reflections, to help to show form and surface development. These sketches are, on completion, also displayed simultaneously on boards or panels to be reviewed by management. Further selection then takes place.

Tape drawings

The chosen designs will now be translated accurately into full-size illustrations. The full-size package is mounted on a board or wall, and covered with translucent plastic film. With the chosen sketch for guidance, the designer will interpret the design by using various widths (from 2 mm to 25 mm) of black photographic tape, onto the plastic film, observing all of the requirements imposed by the package. This is a skillful freehand process and involves a considerable element of trial and error, until the designer is satisfied that the desired result has been achieved. The tape drawings can then be shown to management, alterations made and model variants examined. The tape drawings may be rendered to more closely represent an actual vehicle: wiped spirit ink, air brush, spray paint, or varying tones of paper may be used to achieve this.

Modelling

The tape drawing is used as a source of information to begin the full-size clay model. The modellers will make measurements, take templates, or perhaps scan lines, using CAD equipment, from the tape drawing, and reproduce them in three dimensions, under the guidance of the designers. Surfaces not represented in 2D, being developed on the model, once again with an element of trial and error, many changes may take place until a satisfactory result is achieved. Throughout the modelling process, the designers will frequently return to the sketch pad to resolve detail design. It is during the modelling phase that most current CAD systems come into play, enabling the rapid transfer of surface and feasibility data to and from the body engineers.

CAD WITHIN THE AUTOMOBILE INDUSTRY

All major motor car manufacturers use a range of computer systems to perform a varity of tasks. Schuster, Voge and Trippner[10] list the following CAD/CAM tasks which relate to the design and development of the product, where there is actual or potential use:

- new design
- design modifications
- variant programming
- modular 'kit' design
- part digitizing
- drafting
- electrical systems of the vehicle
- analysis
- kinematics
- NC-data (machining, milling, drilling)
- standard parts
- 3D assembly trials

They conclude that no single system is capable of handling all these features, and that what is required in motor car companies is a number of different modular systems that can talk to each other through appropriate interfacing (such as IGES or VDAFS). Such systems must represent the product in a number of ways. The preparation of mechanical components for example requires the representation of wire-frame and 3D surface models, as well as a powerful 2D model system for producing drawings. For these reasons most companies have purchased a number of CAD systems, and many such as Ford and Volkswagen (Figure 3) have developed their own CAD systems to augment the bought-in ones. Joorman and Tennis[11] report that VW uses 14 systems, and that its RD centre alone uses six of them.

- VW SURF handles complete surface geometry
- ICEM Integrated Computer Aided Engineering and Manufacturing
- CADDS Computervision 2D, 3D wire-frames and surfaces
- EUCLID used for solid modelling for NC machining
- CASS Computer Aided Styling Sketches
- ZEISIG electrical circuit diagram drafting

VWSURF, CASS and ZEISIG were developed in-house.

CASS is interesting since it is a relatively unusual example of a system developed for use before the production of the clay model in the styling design process. It was developed in-house because nothing was available off the shelf which would satisfactorily integrate the stylist's design-sketching activity with CAD system. It is described as being a support for the styling department to permit the modification of layouts, and making sketches, to allow the easy creation and manipulation of complex surface models representing the outer surface contours of a car. Although it may fall short of the standard of conventional stylists sketches, it may well offer compensatory advantages that are sufficient for VW to want to develop styling procedures that accommodate their system. In other words their stylists may have learned to live with its disadvantages.

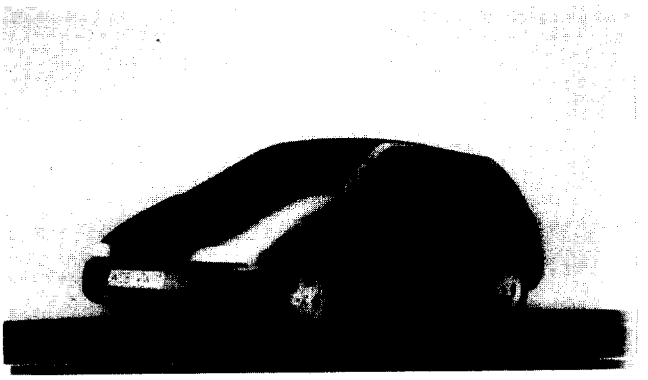

Figure 3. CASS: Computer Aided Styling System used by Volkswagen

Most of the motor car companies are addressing the same issue that VW has tackled with CASS. Some are looking for separate systems for their styling activities, which they can then attempt to integrate with their other established CAD modules. Others are attempting to extend their existing systems so that they can accommodate styling. How this is tackled depends upon which part of the design process is being considered. The obvious advantage of extending an existing system is that it avoids many of the problems experienced in making different systems communicate with each other, by maintaining a single master database.

One approach to this has been demonstrated by MGA Developments in Coventry. Their capabilities include high-speed, multi-axis CNC machining working from a CAD database. They use this to produce a full-size model in a relatively low-cost soft material for styling appraisal. They capitalize on this to bring the full-size representation into an earlier stage in the design process. This is done by tackling the initial stages of that process by using a stylist and CAD engineer sitting together at the computer work station. They work directly on the computer, with vehicle form concepts modelled over the package information. This allows them to identify possible foul conditions with the proposed form and to make modifications. Working in this way there was no need to hold to the level of accuracy required when the form is digitized from a clay model, and this means that an initial surface database can be created in a short lead time. A colour-shaded representation is used only for verification of the design proposal. Such a process makes it possible to move directly to a machined full-size model that the stylists can view and modify. These changes are then scanned and the digitized information transferred to the CAD database. The modified areas are then NC-machined again and re-cut into the styling model. The CAD database is not therefore a close approximation to the model, rather the reverse, the model is a representation of the design stored in the computer[12].

Just as MGA Developments are working to make the 3D model an output of the CAD process, rather than an input, so are Renault. Working closely with Matra Datavision and using its Euclid software, Renault have devised a similar system. Unlike MGA, Renault employ a second system (Raster Technologies visualization system) for post-process imaging to handle the appearance design decisions; reflective surfaces, shadows, colours and so on. But the main part of the process is handled along similar lines to MGA, for which they claim a 50%

reduction in the time it takes to cut a physical model. Overall their engineers estimate that their integrated system will reduce the design cycle of a new Renault car by as much as a year, and cut design costs in half. Nonetheless despite these optimistic projections, and developed capabilities, Renault still use conventional styling procedures for the majority of their design work. Renault seem to find, as do most car companies, that vehicle stylists have difficulty working with CAD systems. The procedures for them to properly master an integrated CAD-based design process seem not to exist[13].

Whether or not the procedures can be developed to permit the stylists to work *productively* directly on the VDU is one of the major questions. It is obviously possible for them to be trained in CAD techniques, and most of the techniques they need for design sketching are theoretically already available in CAD systems. They can draw in perspective, represent curved lines and compute curved surfaces, modify forms and access alternative perspective views and elevational views. In addition they gain techniques that are not available with traditional methods, such as rotated or otherwise animated views, access to package data and the potential for design verification through colour-shaded representation, or machined 3D models, and more rapid engineering involvement. The last offers significant potential for an integrated design process, cutting across the boundaries between styling and engineering.

For all of these reasons the motivation for stylists to find ways of working interactively with CAD is high. There is also a reluctance on the part of car companies to admit that there are difficulties in achieving this because to do so would be bad public relations. Nonetheless it is commonly accepted amongst stylists that there are significant problems, and little effective integration of CAD into the styling process[14].

Some of the difficulties experienced by stylists in using CAD systems are more acute on engineering CAD. Engineering systems such as EUCLID have important advantages: the capacity for driving NC machines to make 3D models is one, the potential for integrating engineering design into the process is another. Both of these areas of advantage stem from the existence of a common database for the design activities, and in as much as this can be achieved at least throughout the design process then it is desirable. Many companies have decided to use more than one system, partly for historical reasons (many systems have only recently developed overlapping capabilities) and partly as a matter of deliberate policy. Where this has been the policy then the possibility of using a system specifically for styling arises. Such systems lack the capacity for driving NC machines, and tackling engineering issues, but they may have better representational characteristics.

In North America General Motors and Ford have devoted considerable resources to this whole issue. Ford use a Dubner paint system to create CAD rendered[15] images with 'air brush effect' colour shading from which the representation of the vehicle is projected full size onto a wall (Figure 4). The life size projection is used both in

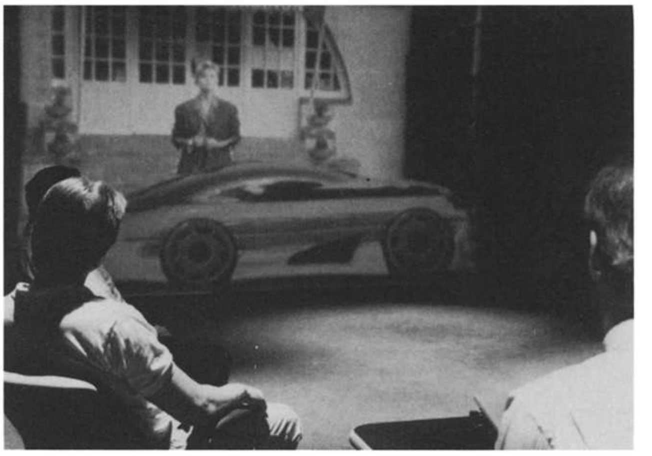

Figure 4. Ford: CAD image projected full size

management presentations and also among engineers. Desired changes can be input through a tablet while the sketches are displayed. Changes are made as people watch. Impressive though this system is, it is of limited application, being used only for presentation purposes. It cannot communicate with their main CAD systems, and it is not used in the sketch design process. For that activity Ford are still closer to the position of most other companies using traditional techniques.

Computer-aided vehicle styling demands new procedures and modelling techniques. If it can be integrated with engineering CAD then the potential savings for car companies are considerable. Despite a number of claims it would seem that no-one has a fully operational interactive system as yet. The considerable interest that the industry is paying to this issue is evidence of how importantly it is regarded.

Computer-aided vehicle styling research project

This research is in the form of a two-part project, the first involving a research assistant, and a Matra Datavision EUCLID CAD system on a DEC VAX 11/GPX Colour Graphics workstation. It is concerned with the information input and the use of conventional styling techniques, which are being used as the basis for defining the styling procedures and evaluative techniques to be used in the second part of the project.

The project is being undertaken in Coventry Polytechnic's Department of Industrial Design in collaboration with: Matra Datavision, Ford, Jaguar, MGA Developments, MIRA, Motor Panels, and Rover Group. I have headed a research team including the research assistant, industrial design graduate David Torr, Automotive Designer Neil Birtley, Computer Scientist Gary Bulmer and CAD interface expert Kay Dekker. The aims of the research are:

- to establish procedures for computer-aided product styling, using as a basis road vehicle design
- to establish the scope and procedures for integrating computer aided styling with both 3D physical models and the CAD/CAM process

The first stage of the project has involved establishing a typical brief for a mid-range car and tackling its design simultaneously by traditional and CAD processes. The necessary information base for the design was assembled and computerized. It included human factors, legislature, technical and vehicle configuration data. These were organized to provide the vehicle design hard points, which were arranged as the CAD equivalent of the package drawing.

THE PROJECT: A MEDIUM RANGE CAR

Vehicle design proposal

The proposed design is for a medium (C′ Class) 4/5 seat 3 and 5 door hatchback, aimed at a highly competitive fleet and family car market, currently dominated in Europe by cars like the Ford Escort and VW Golf. Launch would be in the early 1990s. The car would offer a range of engines from 1 litre to 1.8 litre, transversely mounted, driving the front wheels.

The body design will need to be suitable for base, mid range, luxury and sporting model variants, and the car should incorporate good aerodynamic characteristics, with attention paid to the need for low wind noise. 'Add on' aerodynamic devices are not envisaged. Based on present price levels the range should sell for between £5000 and £9000. A pressed-steel bodyshell is envisaged, with plastic bumpers and body protection. Basic exterior and interior package dimensions are given in Table 2.

This was followed by a head-on attempt to both style the vehicle using design sketches, and on the CAD system. The resulting drawings show the marked differences between the two modelling systems (Figures 5 and 6).

It was apparent from the start that the CAD system

Table 2. Package dimensions (mm)

O/A Length	3870	
O/A Width	1650	
O/A Height	1420	
Wheel base	2500	
Track (front and rear)	1430	
Approach angle (max)	20°	
Departure angle (max)	20°	
Front overhang	750	
Rear overhang	720	
Min. floor to ground	195	
Min. ground clearance	110	
'H' points to ground (95%)	450	
'H' point (front) to wheel c/d	1345	
Interior shoulder width	1350	
Dist. between manikin c/l front	670	
Dist. between manikin c/l rear	650	
Windscreen angle	55°	
Base of screen	900	forward of 'H' point
	890	above ground
Cargo volume (trunk)	1350l	
Fuel tank vol.	50l	
Wheel size	155	SRR 13 DIA 285
Rolling radius	257	

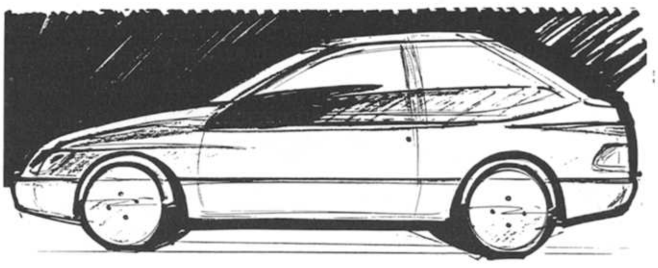

Figure 5. SERC project: vehicle design sketch by Neil Birtley

would not facilitate the kind of fluid-drawing-based designing described earlier in this paper. Nonetheless it was anticipated that alternative procedures with compensatory advantages could be developed. The rapid and easy production of 3D models, using the CAD system to drive an NC machine, was one area. This is particularly straightforward with EUCLID, which has a strong integrated database, and it will feature in the second stage of the project. Another was the quality of the CAD model, which could be animated to provide good colour-shaded perspective views from any desired angle. These are inherently more accurate and reliable than free sketches (Figures 7–9).

Probably the most important potential improvements in the process are a consequence of the integrated evaluation, which becomes possible on CAD. Engineering analysis can be involved much earlier in the process, at the concept design stage, thus shortening the overall timetable and/or making the design more effective. More than with most expansions of CAD use, it became apparent that stylists have a particular antipathy to CAD systems. The root of the problem seemed to be in their fundamental design thinking.

Vehicle stylists' design thinking

The complete designing process involves combinations of analytical evaluative processes and holistic synthetic processes, and during these processes the design is modified in a variety of ways as a specification in words and numbers, as sketches, as measured drawings, as computer representations or as 3D physical representa-

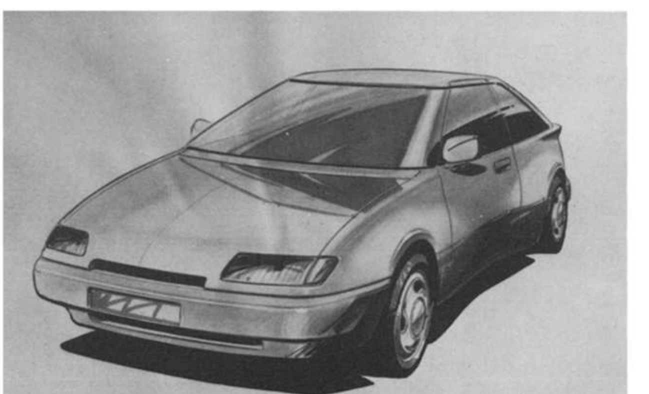

Figure 6. SERC project: vehicle design rendering by Neil Birtley

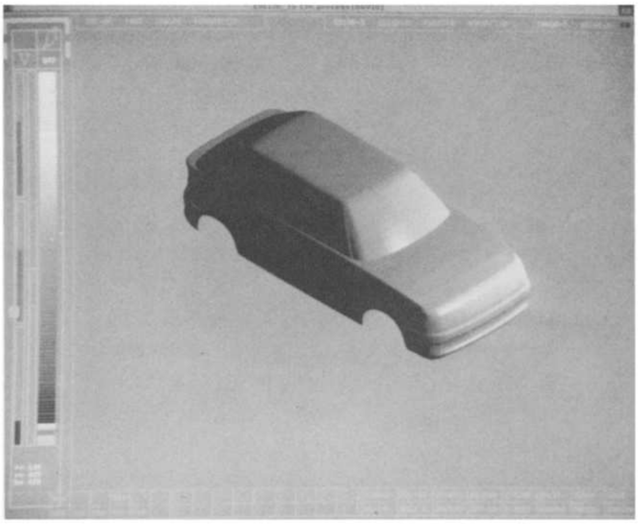

Figure 7. SERC project: vehicle form represented on EUCLID

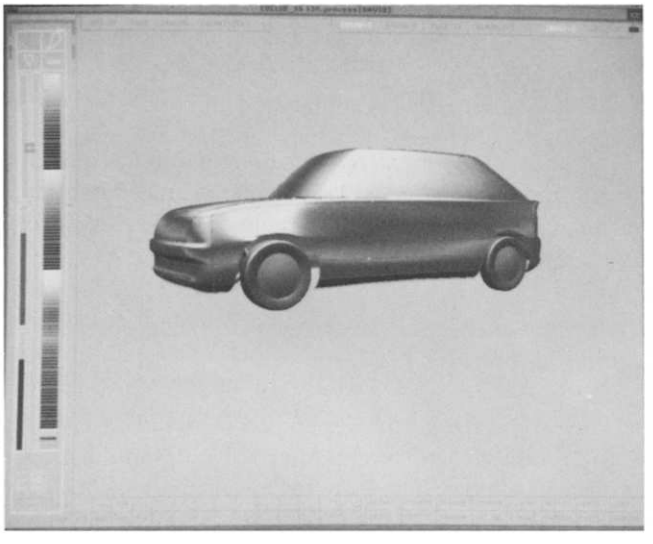

Figure 8. SERC project: vehicle form represented on EUCLID

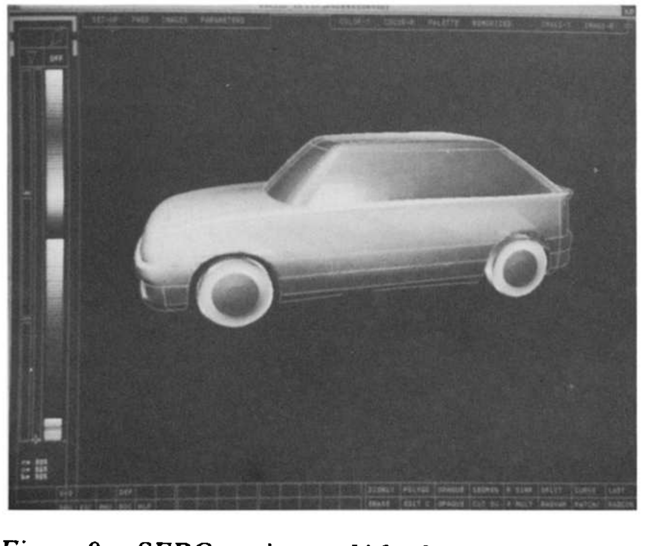

Figure 9. SERC project: vehicle form represented on EUCLID

tions. A complete designer tackling the whole process of creating a product would be involved in the full range of analytical-evaluative activity and in holistic-synthetic activity. Where the design task is large then it is subdivided and specialists take the responsibility for particular parts of the process. The creation of a motor car involves such specialization and it is possible to isolate the particular characteristics and qualities that such specialists must process. None of them is responsible for the whole process, but just for a particular part of it, and typically this involves making use of a particular model of the design. Product planners will work with specifications, and body engineers will be working with computer models. Both of them will be dealing principally with analytical evaluative processes. Stylists will be working with design sketches and dealing principally with holistic-synthetic processes.

Their design thinking could be said to have the following characteristics[2,16]:

- It involves right-hemisphere processes
- It is non-verbal manipulospatial ('thinking with the hands')
- It is holistic and synthetic
- It begins with the whole solution proposal and works into details. It calls on 'unfocused perception' (an important feature of visual creativity): a mental model of the design that contains sufficient ambiguity to permit the development of a new concept
- It involves imaging – the creation of mental images as hazy ideas or mental snapshots, which are externalized as informal sketches
- It needs graphic ideation (although to facilitate the design thinking the drawings can be private, and incomprehensible to others)
- It calls on non-verbal, ineffable knowledge employing a kind of tacit knowing which is difficult to communicate, but which designers recognize amongst themselves
- It deals with judgements of visual appearance, and designers are expected to display visual flair whilst employing a controlled and sophisticated visual language.
- It is visual and concrete; designers dislike abstract, mathematical, symbolic representation
- It is holistic, dealing with the integration of visual relationships

Difficulties stylists experience with CAD

In general the models, procedures and operations of engineering CAD systems are unsympathetic to the processes and techniques employed by stylists in the early stages of the design process. They present particular problems for concept generation and theme development for both exteriors and interiors. They have more potential for assisting the design activity as the design proposal becomes more precisely defined as a physical entity as is the case in the later stages of the styling process.

The following are the main problem areas, as experienced by the research workers, and as reported by the collaborating companies. Problem areas are outlined in the following subsections.

Inputting geometric information is too slow

- Drawing in simple curved lines or complex curved lines is slow
- Constructing flat surfaces is adequately fast, constructing simple curved surfaces and complex curved surfaces is very slow
- Inputting solid forms is from adequately fast to impossible

Geometry is difficult to specify

- Specifying geometry as numerical data understood as algebraic relations presents stylists with problems, as it is abstract and mathematical (not direct, concrete and visual)
- Using a keyboard presents difficulties, thus specification by typed data presents severe problems
- Specification by bit pad is better but presents problems with other than simple planar geometry
- Straight lines specified by point pairs present minor problems but may be tolerable and similarly the development of straight-line wire-frame representations presents problems proportional to the number of lines involved, but this may be tolerable
- Specification of circles and circular arcs presents only minor problems and may be tolerable
- Specification of curved lines by descriptors presents major problems
- Specification of orthogonal flat surfaces presents only minor problems
- Specification of any non-orthogonal geometry presents a range of problems
- Specification of simple curved surfaces presents problems
- Assemblages of curved surfaces presents very minor problems
- Specification of complex curved surfaces by Bezier patches or NURBS presents very major problems
- Specification of simple solids presents minor problems
- Specification of complex machined, solid forms (e.g. engine blocks) presents major problems
- Specification of complex subtle solid forms (similar to vehicle body forms) presents the most extreme problems
- Specifying spatial relationships is very difficult

Representations are too precise

- Early design ideas are represented as 2D and 3D sketches and are vague and imprecise. For all of the reasons listed under difficulties with geometry specification the CAD models by their nature require precise information. Representing early design ideas thus presents very major problems.
- Some designers prefer to allow an intuitively controlled hand movement to produce the design sketch. This is impossible on engineering CAD (It is possible on paint box systems)

Geometry is difficult to modify

- Much of the design process consists of developing the design form by making minor changes to the geometry. This is essentially a process of re-specifying the form. It presents all of the difficulties listed re geometry specification, from minor problems to very very major problems
- Interactive deformation (a potentially desirable modification procedure) is not available for wire-frame, surfaces or solid models
- Templating is possible, but it is subject to all of the problems listed above depending upon the shape and path involved
- Intuitively controlled surface modification by removal of material (sculpting) is extremely difficult. The addition of material to build up a surface is virtually impossible
- This comprehensively inhibits a fluid and responsive interaction between the designers and the model, of the kind that is characteristic of the designer using a conventional sketch representation on paper, or working with a sketch clay model

Reviewing alternative designs is very difficult and an unfamiliar process on CAD

- The early stages of the design process typically involve the production of several alternative design ideas, as design sketches. These are reviewed simultaneously to select between alternatives. This happens several times and previously discarded proposals may be re-introduced. This is difficult with CAD, requires premeditation and involves off-screen photographs or printouts
- Very few design proposals can be displayed easily and conveniently simultaneously on screen. Comparison of alternatives is difficult
- The system often takes as long as 15 minutes to display a wire-frame representation, and even longer to display representational images with colour shading etc. This is intolerably slow, and not cost effective

Visual display quality is too poor for evaluation

- The assessment of the appearance of a design proposal demands a very accurate representation of the physical form. Most VDUs available are too small and have too low a resolution to facilitate this
- Current CAD system software is incapable of generating images of adequate quality
- A choice of visualization methods (e.g. shaded, hidden-line, wire-frame displays) is not always quickly available

General system and interface problems

- Command behaviour is not consistent within the system. There are many areas of inconsistency causing many problems
- The user should be able to distinguish between dead time and when the system has crashed (by a visual indication)
- The quality and quantity of the support documentation is often extremely off-putting, uninformative and disorganized
- Most stylists, like most new users, find the jargon very off-putting, and much of the jargon is unnecessary. That which is necessary is often imprecisely defined
- Stylists find the tactile qualities of the system quite unsatisfactory. The quality of the stylus movement over the bit pad, the resistance or lack of it, and the overall 'feel' compares unfavourably with traditional drawing techniques. A mouse is worse than a bit pad
- The assistance of a computer system Manager is absolutely essential
- There is a large number of user options and they are unstructured and thus difficult to use. They frequently appear to duplicate each other and are thus confusing
- The system provides insufficient on-screen explanation
- The management and organization of much of the system lies outside the normal CAD interface

Speculations on possible procedures and systems

Applications of CAD to the latter stages of the styling process

Most of the difficulties experienced by stylists with CAD are most acute in the early stages of the design process. Whenever the normal modelling method is by means of sketches, or renderings, the engineering CAD systems seem to be slow and unsuitable. Clearly this is an important part of the design process, and possible approaches to solving these problems are discussed later in this section.

However, the sketch and rendering based design activity is only part of the process for stylists. Equally important is the latter part of their activity, which is concerned with design refinement around the agreed design theme. Currently much of this involves tape drawings and clay modelling, and whereas the former is a stylist-controlled activity, the latter entails the stylists working with a clay modeller on a full size representation of the vehicle. Such clay modellers are highly skilled invidual who work with stylists in a similar way to that in which CAD operators work with them in some organizations (such as MGA Developments, or Renault). Our experience leads us to the view that the overall process for the stylist of communicating the design form to a clay modeller is very similar in time, effort and difficulty to that which communicating the design form to CAD operator entails. It is thus possible and quite straightforward to propose that, at this point in the design process, the stylist CAD operator could replace the clay modeller, and that the CAD model could replace the clay model. For systems such as EUCLID with good NC milling capabilities the production of a physical model as an output of such a system is quite straightforward: no post-processor is required and the computer can be plugged directly into the NC machining centre. With careful choice of the materials to be machined this offers the immediate advantage of the rapid production of alternative physical forms from designed in variations to the CAD model. This should have significant advantages over traditional methods, yielding more alternative design forms in 3D, typically full size. This should speed up and refine the process for the designer of selection between alternative proposals, and it permits greater management intervention if required. Such an arrangement is simple to propose although it may present companies with many practical implementation problems. The post processor arrangements for NC machining on some systems are cumbersome for example, and staffing constraints may inhibit others.

The process of tape drawing entails defining design details, typically on full-size elevational package drawings. It is not a fluid or informal process like design sketching. It involves a slower, more measured activity than does sketching, and as such it is in some respects closer to the slower, more stilted and awkward procedures that are typical of interactive CAD. It must be stressed that this is a comparative judgement, for tape drawing is probably closer to the informality of design sketching than it is to CAD. Nonetheless we believe that within the overall process of tape drawing and clay modelling there is considerable potential for CAD systems of the types currently in use (such as our EUCLID system) to replace traditional methods. The use of CAD could be brought forward to encompass the styling processes associated with the production of the package drawing, tape drawing and modelling, and could possibly be involved in the package-related sketching activity.

If the CAD activity were brought into these earlier stages it would yield considerable advantages. The potential for earlier engineering design and evaluation is one such. Other benefits would accrue as a consequence of the nature of the CAD system. One particular feature yields many potential advantages. This is that the CAD system can store all the stages of information input in creating the design form, and all the stages of modification. It is thus possible to return to earlier stages and review the process. This is different from a tape-drawing process in which once the tape is removed and repositioned, its former location is lost. It is also more fundamentally different from the clay modelling process in which it is very difficult to record previous stages of the design form, and thus to compare alternatives. A direct comparison of more than two alternative clay models is expensive and only achieved with prior planning and a deliberate course of action. Conversely on a CAD system it is possible to spontaneously review previous stages and alternative design forms.

The major disadvantage of reviewing design alternatives on CAD is that it is normally a sequential process, in which the alternatives can be viewed only one or two at a time (depending on the number of screens, because of small screen size and loss of definition). A regular and systematic deposition of the design form to a good colour printer, or by photographic means, would allow the designer to accumulate as many alternatives as were desired, and then to review and compare the designs as represented on the printouts or photographs simultaneously. This would offer a major advantage over traditional techniques, serving to open up the design process, both for the designer and for design managers.

Further, these techniques might offer sufficient advantages for them to be considered for use in parallel with or preceding the sketch design stage of the process. This would involve the consideration of alternative package arrangements, possibly with some surfacing proposals as the basis for the sketch designing. This could have particular relevance to the development of the vehicle interior design, which is by its very nature more orthogonally organized, and therefore more amenable to CAD representation.

We believe that overall there is considerable scope for the development of procedures to reduce or overcome the difficulties stylists experience on engineering CAD systems, and that this could have a considerable impact on the design process.

APPLICATION OF CAD TO DESIGN SKETCHING

The sketch modeller

The pencil and sketch pad provides a good intuitively understood medium for the representation of design ideas in which the likely effects of changes can be quickly represented and evaluated. For the maximum advantage to be gained from using a CAD system in styling the representation should be of the 3D form, which should be transferable without loss of fidelity to a CAD/CAM system.

To this end attempting to produce a system that mimics design sketching seems not to be very productive, whereas the metaphor of clay modelling could be quite useful. Its beneficial properties include the accommodation of a changing viewpoint and the effect of simple lighting on surfaces, thus permitting the visual evaluation of form. The computer system should offer further advantages, such as automatically guaranteeing symmetry where it is required.

Unless such a system were responsive in real time it would not succeed. We calculate that conventional high-end workstations could not handle the geometric calculations or re-draw the screen quickly enough. (Flight simulators could draw fast enough but are expensive and may not allow for some of the alternative levels of rendition quality.) A new system with special-purpose hardware to draw the shaded surfaces and remove hidden surfaces, using a set of transputers to perform the geometric calculations, would be powerful enough to perform the sketch modeller task. The basis for such a device already exists, and we believe that it could be produced so as to work as an extra subsystem for an engineering CAD system. Once in, the envisaged modeller forms could be viewed and interactively deformed, allowing evaluation and generation of concepts by the stylists. The resulting geometry would be returned to the CAD system for storage or further processing. Such a device could radically change sketch design and concept generation, providing the basis for totally integrated CAD for evolutionary products.

CONCLUSIONS

Currently CAD

- will not support innovative design
- will support evolutionary design
- cannot match design sketching
- inhibits fluid design thinking
- inhibits fluid design modelling
- can support styling design development
- supports design evaluation
- supports design integration

New systems are possible, which could provide an interactive sketch modeller, and a fully integrated CAD system for evolutionary design.

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