# Chapter 20

# Computer aided ergonomics and workspace design

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## *Man\*-modelling CAD systems*

Computer aided design (CAD) methods are becoming very popular with engineers as they provide considerably more flexibility than conventional techniques. Although they are now commonplace in manufacturing industries the great majority of CAD systems completely ignore the most important component of the human-machine system being designed-humans them- selves.

The importance of an ergonomics input to a design is now recognized by many industries as being essential. The increasing complexity of modern systems and the social, economic and legislative pressures for good design have led to the demand for the ergonomics input to be made available as early as possible in the design programme, starting preferably at the concept stage. Traditionally, ergonomists have had to wait until the mock-up stage before being able to perform a detailed evaluation of a prototype design. This delay has several consequences, which will be discussed later in this chapter, all of which are detrimental to the design process.

Clearly, the optimum solution is to provide a means of supplying the ergonomics input in a complementary fashion to the engineering input; the logical conclusion being to develop CAD systems with facilities to model both equipment and people. Recognizing the potential of this solution, in some cases as early as the late 1960s, several research teams have developed man-modelling CAD systems. These have met with varying degrees of success but, essentially, they are design tools which enable evaluations of postural comfort and the assessment of clearances, reach and vision to be conducted on the earliest designs, and even

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'Man' is used in this chapter as a generic term in preference to human or people in the context of modelling systems, since this is the terminology employed in the area.

from sketches. In order to achieve these predictions, the systems need: three-dimensional modelling of equipment and workplaces which can be displayed on a computer graphics screen; three- dimensional man models (representations of the human form which can be varied in size, shape and posture for a variety of populations); evaluative techniques, based around the man model, to assess reach, vision, fit and posture; and a highly interactive user interface which allows the user to tailor design evaluations to their own requirements.

**Existing systems**

Existing man-modelling CAD systems show considerable differences in the extent to which the above facilities have been developed, and the breadth of their potential applications. Brief descriptions of the most established, or most recently developed man-modelling systems are given below:

ANYBODY
This is a three-dimensional ergonomics template or stencil of the human form which is used in conjunction with the CADKEY workplace modelling system which can be run on an IBM AT (see Figure 20.1). The system is believed to have been developed originally as 'OSCAR' by the Hungarian Design Council in Budapest, but in its current form is marketed by IST GmbH in Germany. The templates are available for men and women in a variety of sizes (females: 5th and 50th percentiles; males 50th and 95th percentiles), and shapes (ectomorph,
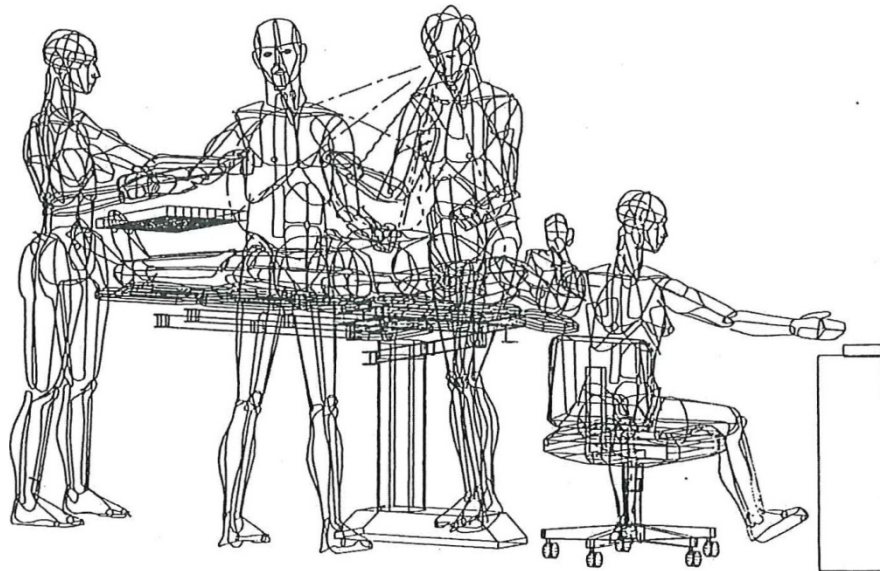


Figure 20.1. ANYBODY (sourced from 1ST GmbH, Germany)

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mesomorph and endomorph). The anthropometric data are taken from DIN 33402 part 2 which presents information for the German public, although 50th percentile models are available for other data bases such as those presented in *Bodyspace* (Pheasant, 1986). The developers suggest that these templates can be linearly scaled to represent other body dimensions. More recently IST have released a system called ANTHROPOS (apparently a development of ANYBODY) which includes some animation features. No published studies on the development or application of either system have been found to date.

APOLIN

Stands for APproximation by Ovals and LINes (APOLIN) technique, which uses parameter based, universal geometrical elements for modelling of human body segments (see Figure 20.2). The basic concept of the system is similar to that of SAMMIE (Grobelny *et al.,* 1992). The system is based upon primitive objects developed using the constructive solid geometry (CSG) method and is capable of using objects generated externally (e.g., AutoCAD or RoboSolid) using DXF file format. The man-model has 15 links with 14 joints, the anthropometry covers 1st to 99th percentile adults and joint constraints can be actively modified. Vision, posture and reach can be evaluated in a 3D environment which allows the building of models in complex structural hierarchies. At the time of writing the commercial availability of this system is unclear.
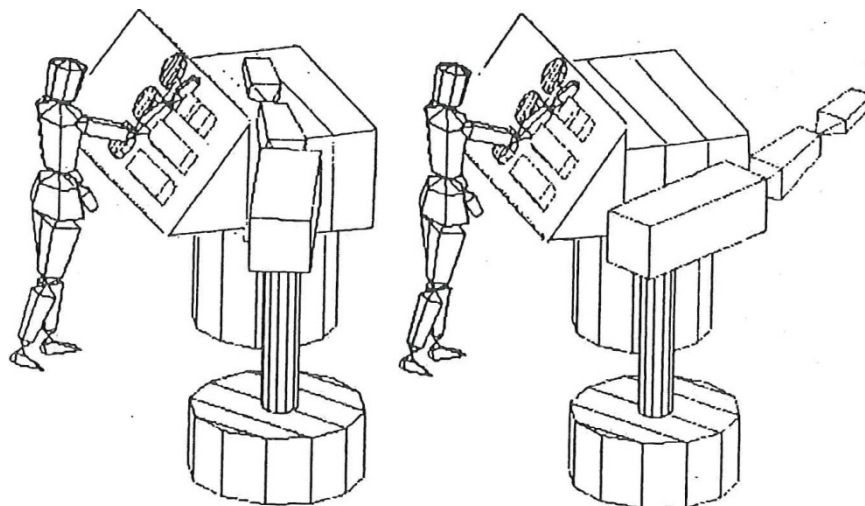


Figure 20.2. Design of robotic workstation using APOLIN (reproduced from Grobelny *et al.,* 1992)

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BOEMAN

Developed by the Boeing Corporation, Washington in 1969 for use in checking cockpit layout (see Figure 20.3), the system was complex to use and it was not designed for interactive use as graphics terminals were not commonly in use at that time.


BUFORD

Developed by Rockwell International, California (see Figure 20.4), it offers a simple model of an astronaut, with or without a space suit. Body segments can be selected separately and assembled to construct any desired model, although these segments must be moved individually to simulate working postures. The model does not predict reach but a reach envelope of two- handed functional reach can be defined and displayed around the arms. It is not generally available.


CAR (*C*rew *A*ssessment of *R*each)

Developed by Boeing Aerospace Corporation for use by the Naval Air Development Centre in the USA, the system is designed to estimate the percentage of users (i.e., aircrew) who will be able to be accommodated physically in a particular workstation. The analysis is purely mathematical and the system has no graphical display. It is only available for in-house assessment of reach in aircraft crew stations.
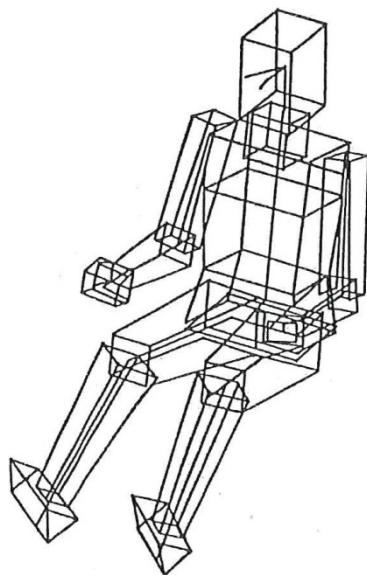
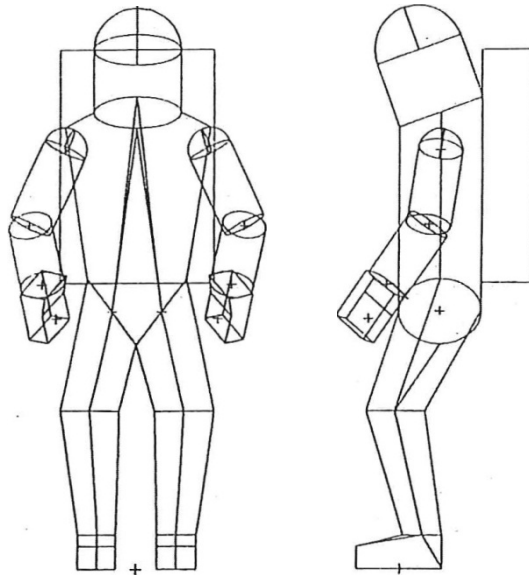Figure 20.3. BOEMAN (reproduced from Dooley, 1982)

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Figure 20.4. BUFORD (reproduced from Dooley, 1982)

COMBIMAN (*Com*puterized *Bi*omechanical *Man* Model)

Developed by the Armstrong Aerospace Medical Research Laboratory to evaluate the physical accommodation of pilots in aircraft crewstations, the pilot model is constructed using an array of interconnected triangles which can be reduced to just a profile view (as in Figure 20.5) from any viewing angle. COMBIMAN can produce pilot visibility plots to meet military standards, reach tests can be conducted for various types of control taking account of the clothing and harnessing being used. Strength predictions cart be made for seated pilots based upon empirical data. COMBIMAN has been distributed to the major aerospace industries since 1978.

CREW CHIEF

This is a three-dimensional model of a maintenance technician and was developed by the Armstrong Aerospace Medical Research Laboratory and the Human Resources Laboratory (see Figure 20.6). Much of CREW CHIEF's functionality is based upon that incorporated in COMBIMAN. The system can generate 10 sizes of model (five male and five female) with four types of clothing and 12 initial postures. It can usefully be used to assess physical access for reaching into confined spaces as well as visual accessibility and strength analysis. CREW CHIEF has been generally available since 1988.

CYBERMAN (*Cyber*netic *Man* Model)

Developed by the Chrysler Corporation in 1974 for use in design studies of car interiors (see Figure 20.7). There are no constraints on the choice of joint angles
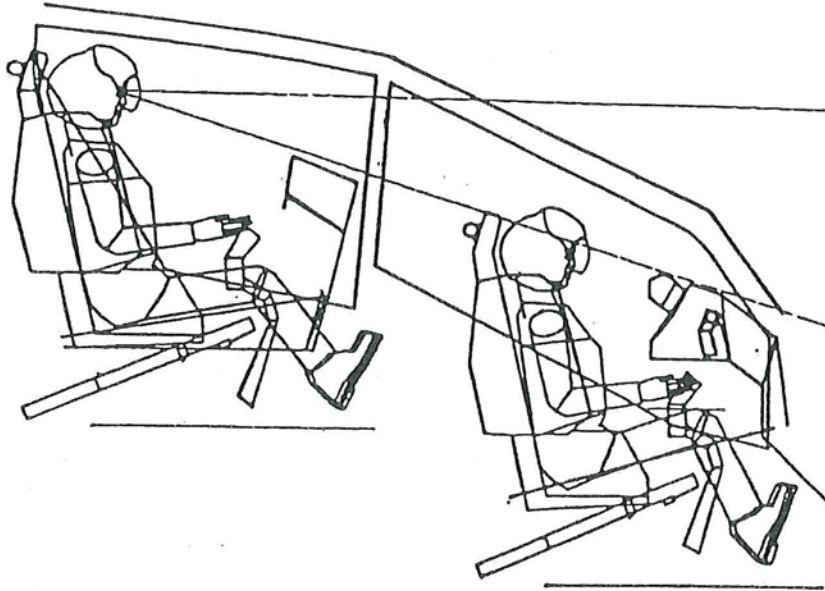
Figure 20.5. COMBIMAN. The plot shows a side view of a Helicopter crewstation (reproduced from McDaniel, 1990)
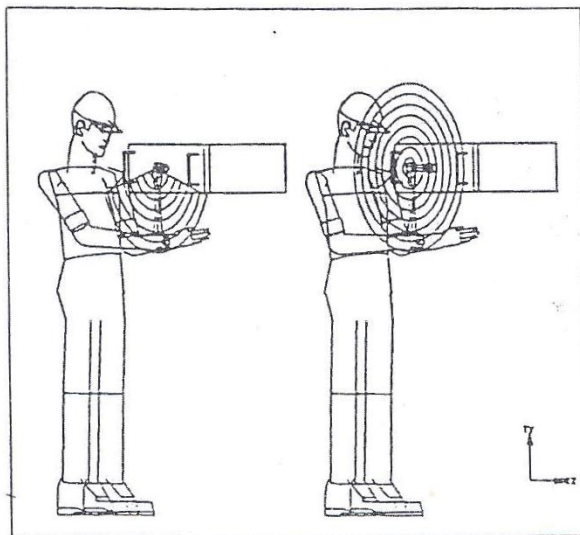


Figure 20.6. CREW CHIEF: Rotation of ratchet wrench is limited by handles on the box (left plot). The use of an extension rod between the ratchet and socket results in unobstructed rotation (right plot) (reproduced from McDaniel, 1990)
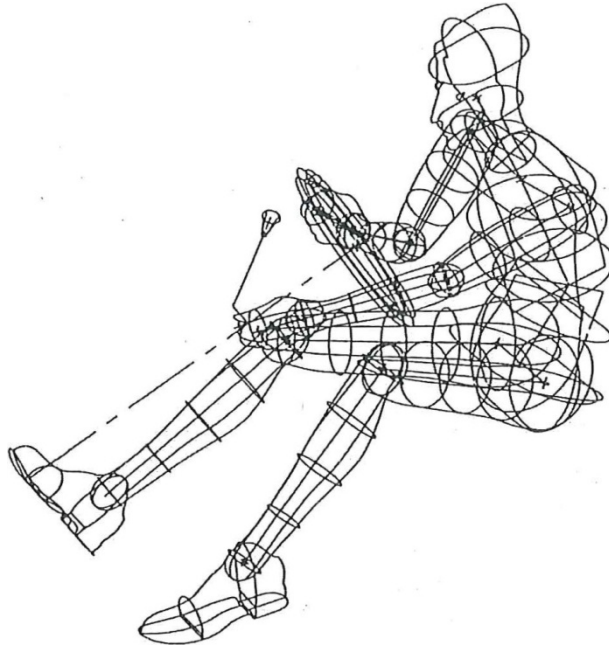
Figure: 20.7. CYBERMAN (reproduced from Dooley, 1982)

so the man-model's usefulness for in-depth ergonomics evaluations is rather limited. This system is also not generally available. ·

ERGOMAN

A relatively new man-modelling facility forms a constituent part of the ERGODATA system (see Figure 20.8). It is based upon the ELUCID CAD system software. The man-model has a 20 link body segment architecture, with 22 joints. Anthropometry is mainly controlled by varying body segment link length joint to joint distance) with some ability to define depths and circumferences. The main man-modelling functions include: choice of morphotypes, joint angle limits, simulation of zero gravity, clothing simulation, upper limb reach areas, fields of vision, tool handling, motion and collision detection. Included with the ERGODATA system are a number of data bases covering anthropometry, biomechanics, strength, a computerized human movement catalogue and a general ergonomics bibliography. For more details see Coblentz *et al.* (1991).

ERGOSHAPE

This system developed at the Institute of Occupational Health in Helsinki offers a two-dimensional manikin which runs within the AutoCAD system (see Figure 20.9). The models can be viewed from four viewpoints (left, right, top and front). The manikin can be constructed from up to nine segments, a set of basic
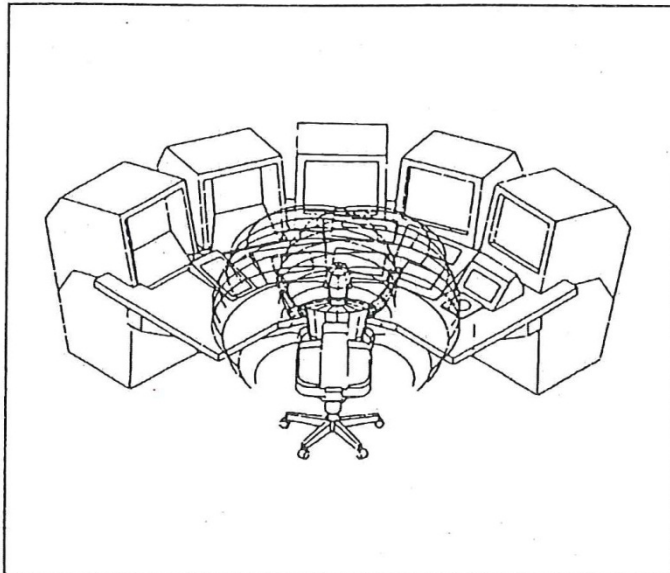
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Figure 20.8. ERGOMAN. Reach capability assessment from the maximal reach areas for upper arms (reproduced from Mollard e*t al.,* 1992)
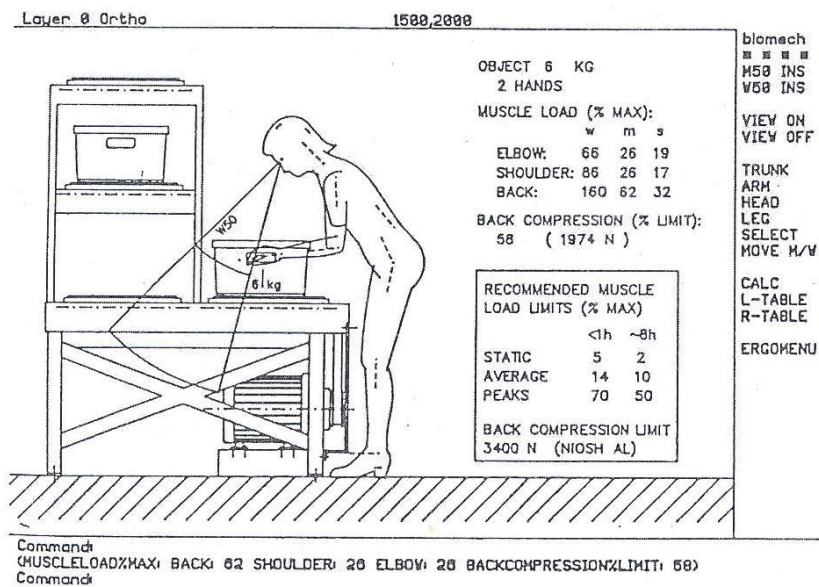


Figure 20.9. ErgiSHAPE. The figure shows the screen of the AutoCAD system when the biomechanical calculation of the ErgoSHAPE system is used (reproduced from Launis and Lehtela, 1992)

postures is provided, although they can be user defined, and the manikins are available in male and female, 5th, 50th and 95th percentiles, or a user specified size. The anthropometric database includes Finnish, North European and North American populations although the manikins can be linearly scaled as required. In addition to two-dimensional reach and vision evaluation the system also permits the evaluation of postural stress resulting from vertical loads and provides recommendation charts giving guidance in various design areas.

ERGOSPACE

This is a three-dimensional man-model with its own workplace modelling facilities (see Figure 20.10). The system was developed within the restrictions imposed by microcomputers and therefore the graphic presentations of the man-model and the workplace are greatly simplified. The man-model has 17 joints and, in order to attain a reasonable response time, a stick model (i.e., the man-model's link structure) representation is used for moving the model. The model can subsequently be enfleshed using an ellipsoidal wire frame.
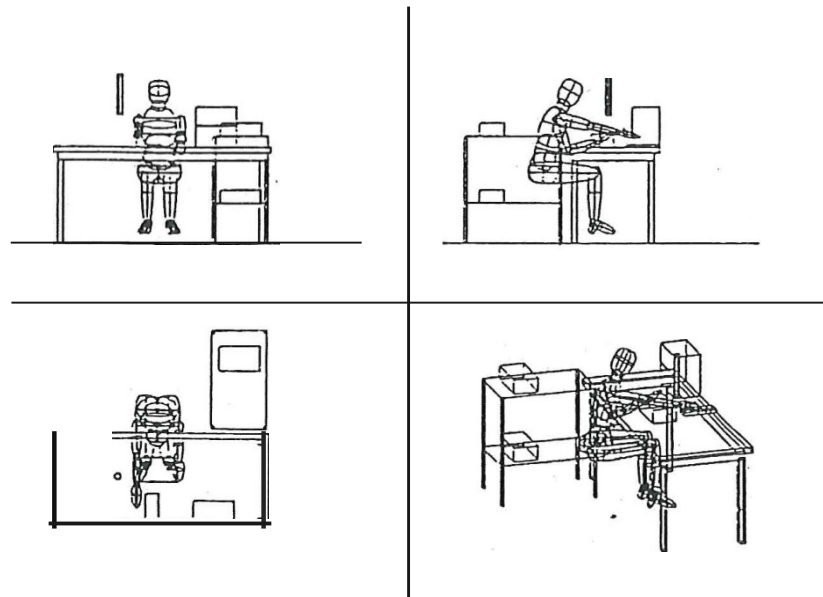


Figure 20.10. ErgoSPACE. Four views (front, plan, side and perspective) of a workstation evaluation (reproduced from Launis and Lehtela, 1990)

FRANKY

Developed by Gesellschaft für Ingenieur-Tecnick (GIT) mbH in Essen (see Figure 20.11), it has a very similar (and comprehensive) suite of facilities to SAMMIE (which is described below). However FRANKY is not presently commercially available following the closure of GIT in 1987.

JACK

Developed by the University of Pennsylvania with extensive funding from NASA and the US Army Research Office, amongst others (see Figure 20.12). This man-model has 71 segments and 70 joints, including a 17-vertebrae spine and fully articulated hands. The default human figure is based upon data from the Society of Automotive Engineers for the 50th percentile male, although anthropometric data from a variety of populations can be entered and manipulated through the Spread Sheet Anthropometric Scaling System (SASS). Physical dimensions, joint limits, moments of inertia, centres of mass and strength data can be entered. The complexity of the man-model's flesh shape and structure can be controlled by the user. The system enables the evaluation of reach, fit, vision, posture, and torque load on joints and has been used to simulate human performance in the Apache Helicopter and the US Space Station. The system also allows the creation of human-like motion via an animation package, and includes rendering facilities enabling colour surface shading, reflections, shadows and textures (for clothing portrayal). Its availability is currently limited to Silicon Graphics workstation computers. For more information see Badler (1990).
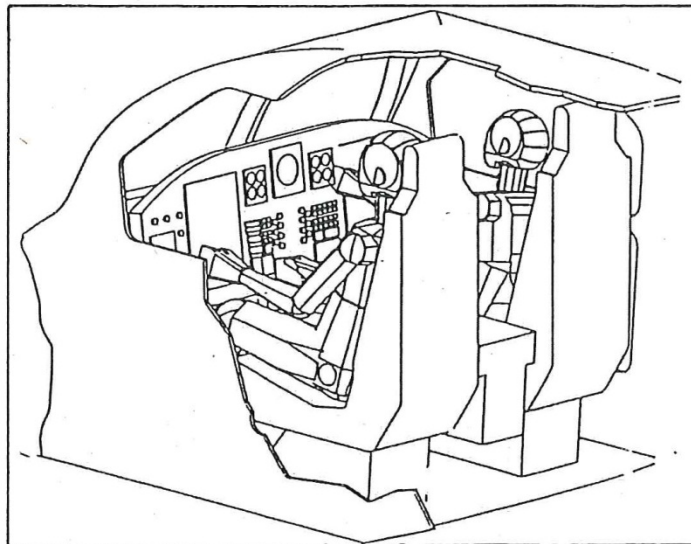


Figure 20.11. FRANKY. An aircraft cockpit model (reproduced from Elias and Lux, 1986)
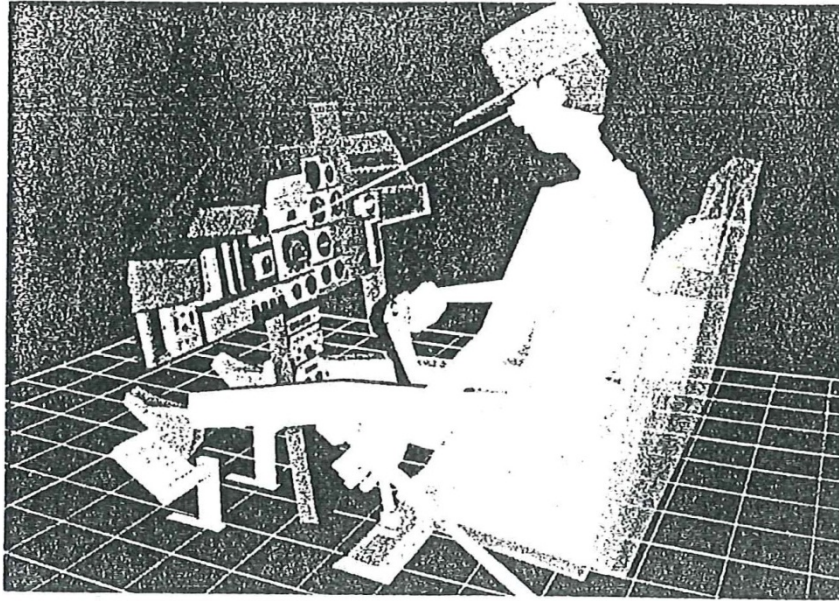
Figure 20.12. JACK. Colour shaded image of a cockpit model
JACK. Colour shaded image of an office reception area

MANNEQUIN

A recent PC based man-model from HUMANCAD, which, although it includes a basic workplace modeller, is primarily designed to be used with other graphics software, such as AutoCAD. Workplace models created in other CAD systems can be imported for ergonomics evaluations or Mannequin man-models can be exported as simple 'people pictures' for use in other CAD drawing systems. The man-model has 16 major body segments as well as articulated fingers and toes, has constrained joints and comes in 5 different body sizes from 2·5th to 97·5th percentile, created from a data base of 10 nationalities (see Figure 20.13). Posture can be controlled by use of a range of standard whole body or hand postures or by manipulation of individual limbs. Reach volumes can be shown, as can sight paths and views from the man-model. Various joint torques can be calculated and a limited amount of animation is possible. Being PC based the system has limitations in terms of graphics speed and modelling complexity. There appears to be little in the way of published papers detailing principal exploitation of the system as an ergonomics design tool.

MINTAC

*M*an Machine *INT*er*AC*tion was developed in 1984-5 by the Kuopio Regional Institute of Occupational Health and the University of Oulu (see Figure 20.14) for the Computervision CAD/CAM system. The three-dimensional man-model is

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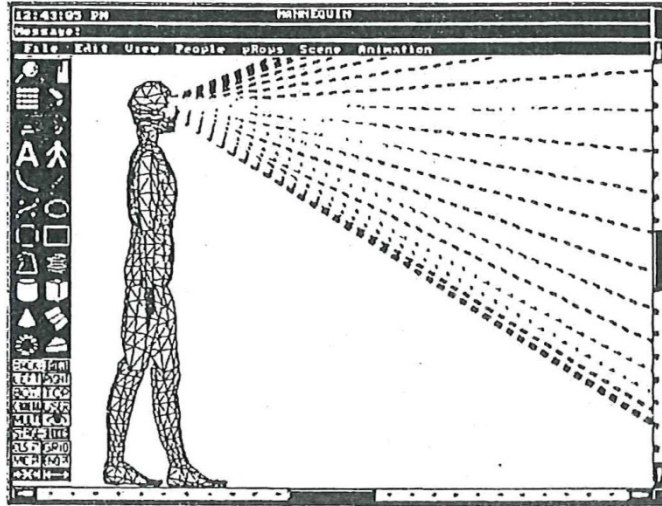
Figure 20.13. MANNEQUIN. A screen image showing field of view analysis and the system's iconic interface (sourced from HUMANCAD, 1991)
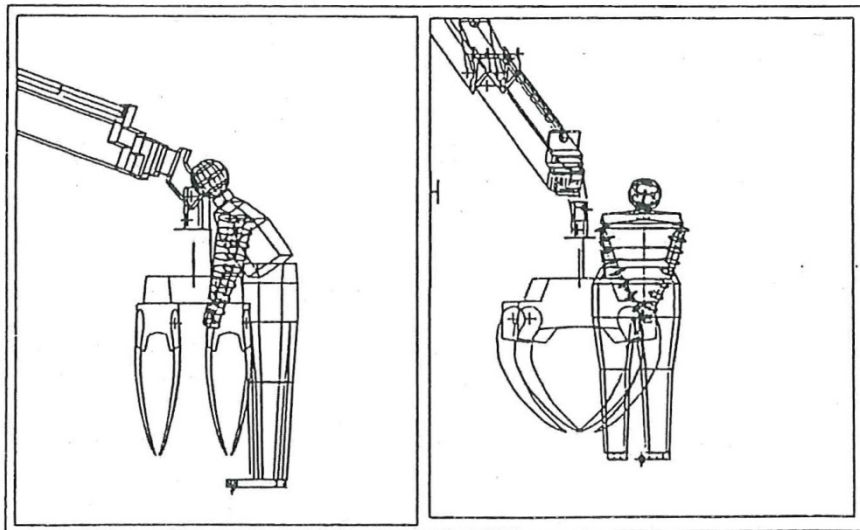


Figure 20.14. MINTAC. An operator is shown lubricating grease nipples of a tractor's grabbing mechanism (reproduced from Kuusisto and Mattila, 1990)

based upon the anthropometric data base published by Dreyfuss (1967) for the American civilian population, although the model is adjusted to simulate the wearing of winter clothes in order to evaluate difficult working postures encountered in Finnish agriculture and forestry.

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The simple man-model contains six links: lower links (one rigid block which can be selected in a choice of 13 postures), back, upper arms and forearms. The man-model was designed to be compatible with the OWAS working posture analysis system (Karhu *et* al., 1977, and see chapter 23 of this book) although it is considered that MINTAC is not appropriate for widespread use because of its simplified posture, and is suitable only for the analysis of heavy work. Further details of this, and some other Finnish systems, are given in Kuusisto and Mattila (1990).

SAMMIE

*S*ystem for *A*iding *M*an-*M*achine *I*nteraction *E*valuation was originally developed at Nottingham University and subsequently at Loughborough University with funding generated by commercial consultancy (see Figure 20.15). SAMMIE has been used extensively by its developers since the mid-1970s and SAMMIE CAD Ltd currently market their software world-wide. This system is described in considerable detail later in this chapter but, briefly, it is a versatile three-dimensional system comprising a man-model of completely variable anthropometry, with comfortable and maximal joint angle constraints for each of its joints, together with its own workplace modeller. The general purpose nature of the system makes it suitable for a wide range of applications and special or logical relationships between model components can be defined allowing the models to be functional, for example, the operational movements and limitations of pedals, doors, seats or levers can easily be specified and executed. SAMMIE provides sophisticated ergonomics facilities and a powerful workplace modelling system, across a range of different computer systems (e.g., SUN, Silicon



Figure 20.15. SAMMIE. An adjustable computer workstation model

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Graphics, HP/ Apollo). Recent descriptions of the SAMMIE system include Case *et al.* (1990a), Case *et al.* (1990b) and Porter *et al.* (1990).

TADAPS

*T*wente *A*nthropometric *D*esign *A*ssessment *P*rogram *S*ystem was developed by the University of Twente in The Netherlands to run on VAX computers (see Figure 20.16). The system is based upon ADAPS, developed by Delft University for the POP-11 computer in the late 1970s (see Post and Smeets, 1981). The basic man-
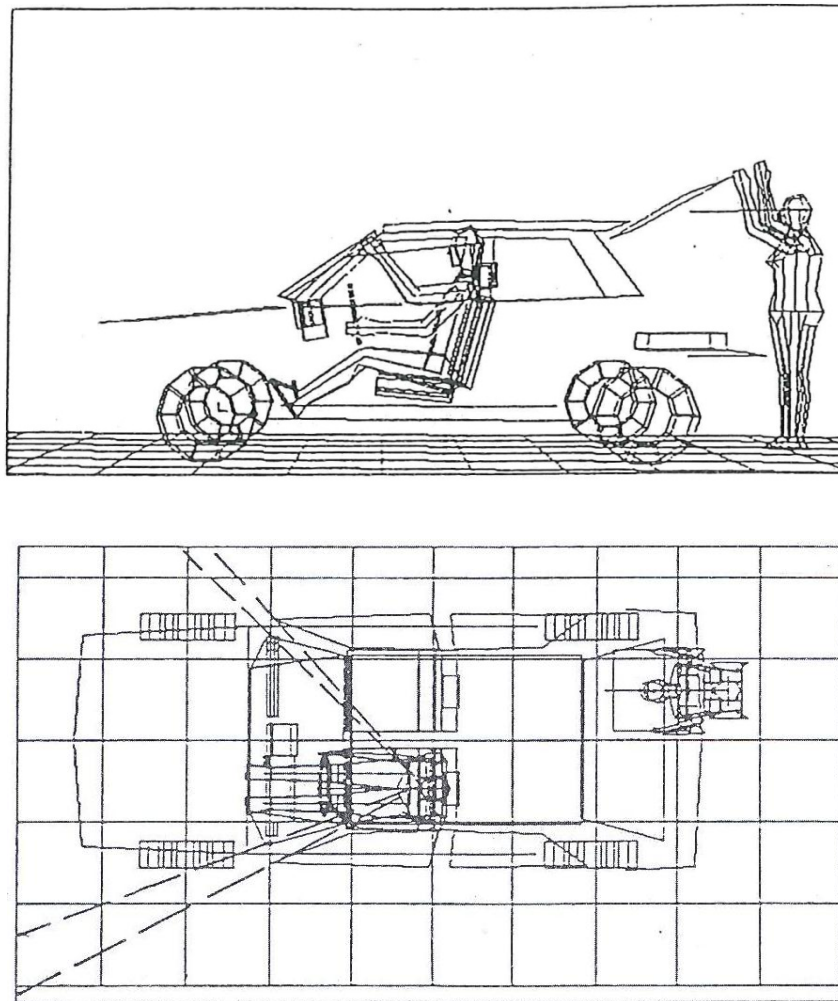


Figure 20.16. TADAPS. The two views show an analysis of reach (top) and vision (bottom) (reproduced from Westernik *et al.,* 1990)

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model consists of 24 segments although the amount can be reduced or extended to suit the intended application. The system includes its own workplace modeller. The anthropometric data base comprises Dutch men, women and 4-year-old boys as well as American pilots and it is relatively easy to create models of other populations. All percentiles can be chosen although the man-model is linearly scaled from the 50th percentile proportions and it is not clear whether individual body segments can be set to different percentile values. TADAPS offers a prediction of the compression and shear force of the inter-vertebral disc L5-S1 for various postures and external loads.

WERNER

Developed at the Institute of Occupational Health at the University of Dortmund and implemented on the Astari ST personal computer (see Figure 20.17), the three-dimensional man-model consists of 19 segments, each of which is defined by simple solids most of which are ellipsoids. A convex hull is constructed over these solids to define a silhouette of the man-model. The model's anthropometry appears to be based on the German National Standard DIN 43116. WERNER communicates with AutoCAD to provide its three- dimensional workspace modelling features.
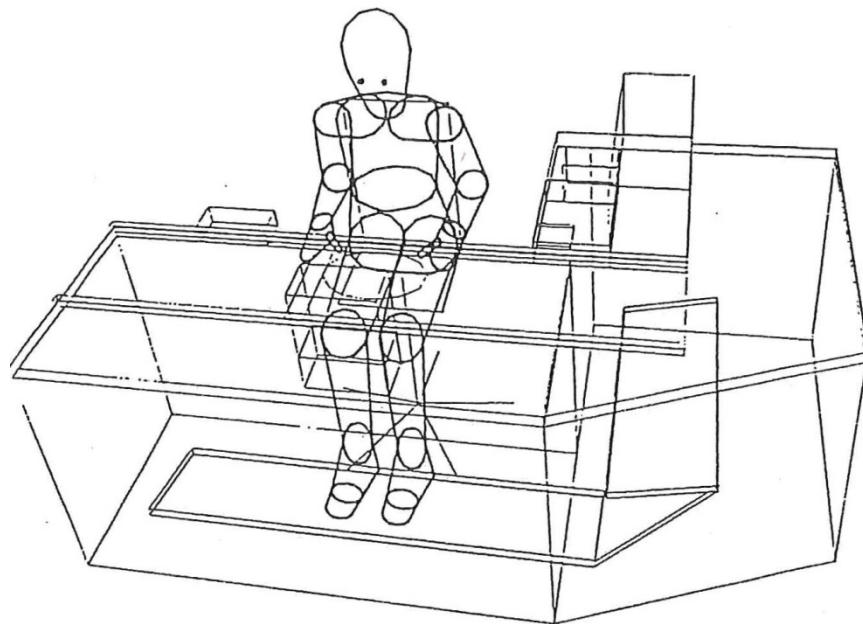


Figure 20.17. WERNER. An evaluation of a cash desk workstation (reproduced from Kloke, 1990)

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**Further information**

Dooley (1982) and Rothwell (1985) and more recently Porter *et al.* (1993) present surveys of man-modelling systems, including many of the above sys-tems. Other sources include: Elias and Lux (1986) (FRANKY); Lippmann (1986) (OSCAR); McDaniel (1976) (COMBIMAN); Porter (1992) and Porter and Freer (1987) (SAMMIE).

## *A man-modelling CAD system*

The SAMMIE system will now be described in more detail to demonstrate how a man-modelling CAD system can be used as an effective ergonomics tool; the facilities discussed are indicative of what is possible with such methods.

### Equipment and workplace modelling

The workplace modelling system is used to generate full-size 3D geometric representations of a working environment and specific items of equipment. A boundary representation form of solid modelling is used to enable the system to be highly interactive whilst maintaining a sufficiently accurate 3D model. This method requires that solid shapes are constructed from a description of the location of their vertices, a knowledge of which vertices are joined together to form edges and which edges form plane polygon faces.

Models of considerable complexity can be built quickly from a range of parametrically defined primitive shapes such as cuboids, polyprisms, and cones (see Figure 20.18). These are constructed interactively from a primitives menu, requiring very brief specification, such as object name, depth, width, etc. Complex
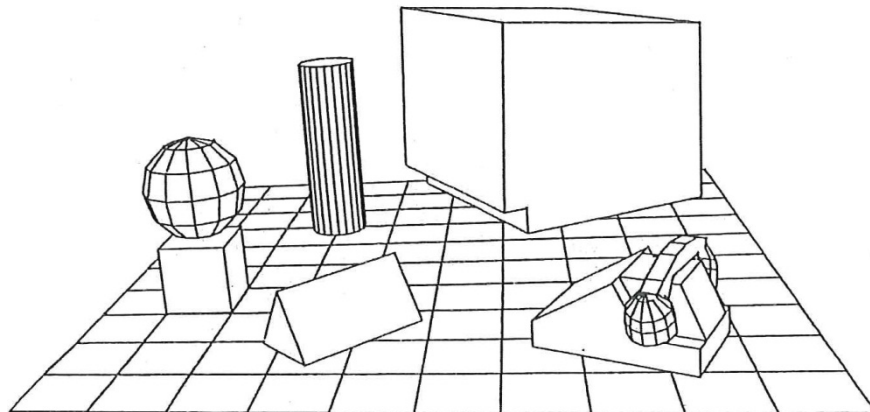


Figure 20.18. Examples of simple model types available in the SAMMIE system. The telephone is an example of how models are formed from these basic types

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non-regular solids can be developed by describing vertex locations together with edge and face definitions and solids of revolution can be created by defining an axis of revolution and the desired profile both can be carried out interactively. Although truly curved surfaces cannot be built this is rarely a cause for concern as sufficient accuracy can be obtained from a suitably configured faceted model (see Figure 20.19). A reflection facility is also available so that mirror images of solids can be constructed automatically; for example, only one side of a car needs to be defined manually.

Specification of logical or functional relationships between items in the model is achieved using a hierarchical data structure, an example of which is shown in Figure 20.20. This hierarchy allows the designer to move the whole car as one unit or to open individual doors or the boot (see Figure 20.21), to rotate the steering wheel or to adjust the tilt of the driver's seat cushion. To achieve this selectivity, users need to travel across and up or down the data structure until they reach the level which will control the particular item(s) to be adjusted.

The data describing the 30 workplace model can be taken directly from engineering drawings or sketches and entered via the interactive 'primitive' modelling menu, modelled off-line in data definition format, or it can be imported via IGES format files from other CAD systems (see Figure 20.22). Another important feature of the system is the interactive geometric editing facility which allows model modifications in ways relevant to various design situations. Importantly the structural validity of the model is maintained during
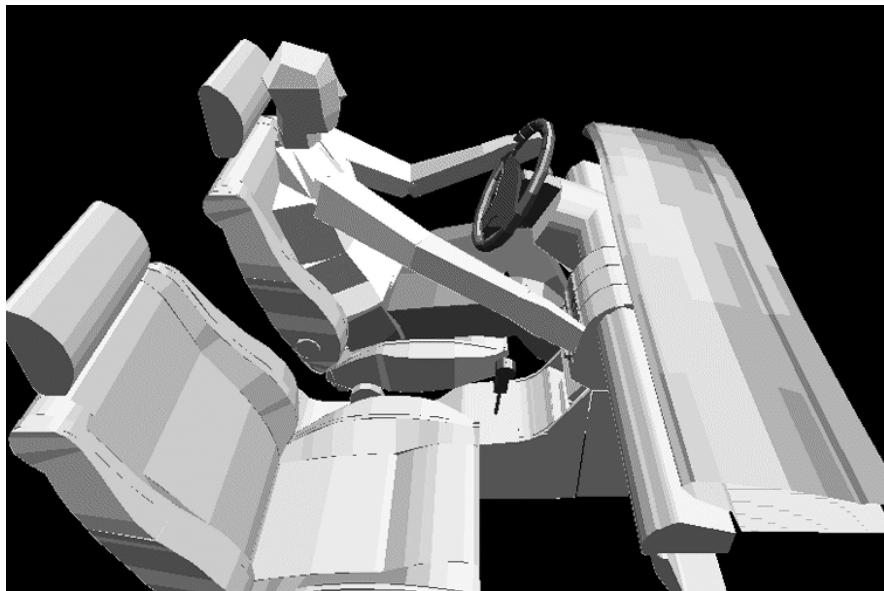


Figure 20.19. A wide angle perspective view of a car interior showing complex surface detail using 'faceted' objects to imitate curves ·
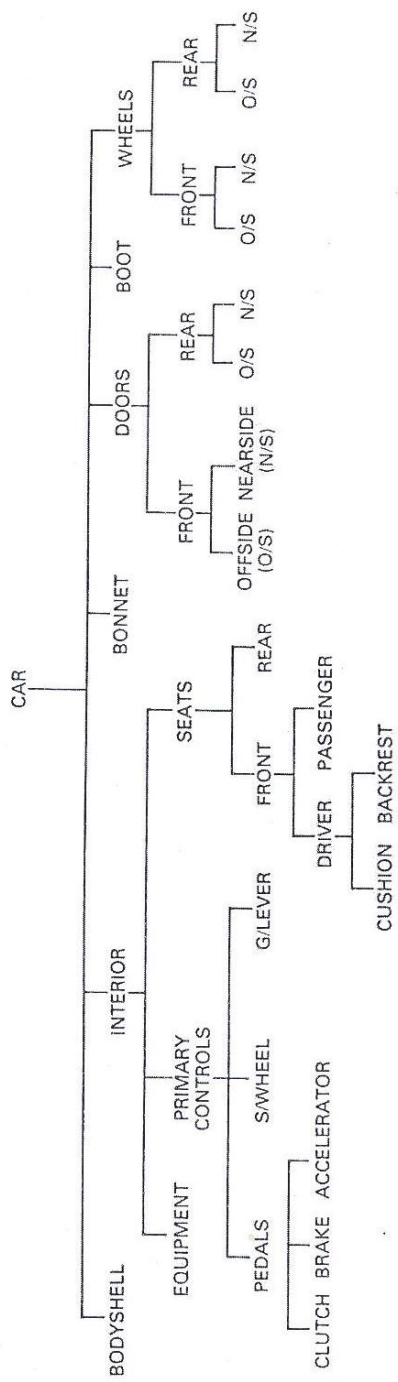
Figure 20.20. An example of the hierarchical data structure which allows the model to be functional as shown in Figure 20.21
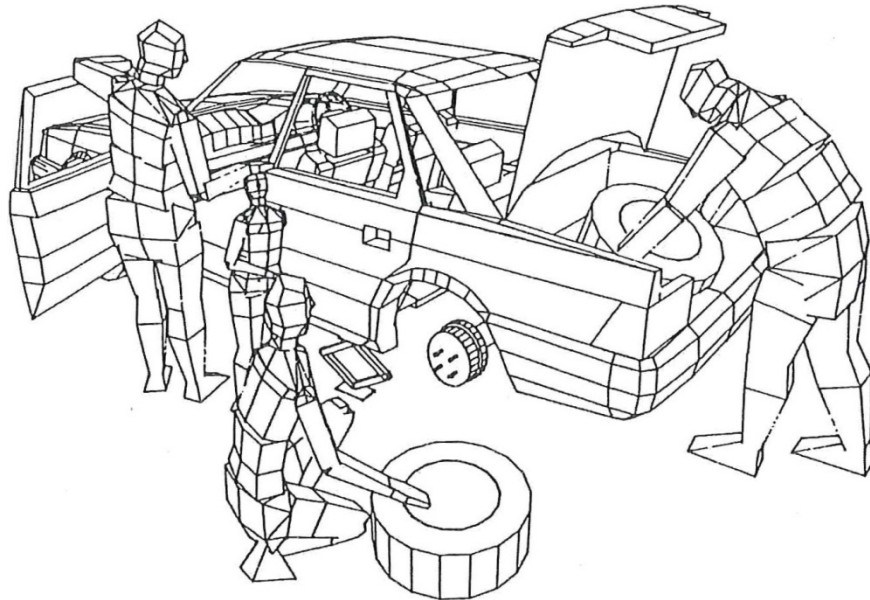
Figure 20.21. A complex car model. A hierarchical data structure enables functional as well as geometric relationships to be modelled, thus all moving parts of the model can be made to function. For example the car's doors, bonnet and boot can be nude to open and close. Imide the car it is possible to adjust the seat and steering wheel within the design specification

modifications, for example, if a table was modelled as a top and four legs, then increasing the width of the table would automatically reposition the legs to maintain a valid model.

**Man-modelling**

The man model is a 30 representation of the human body with articulation at all the major body joints. Limits to joint movement can be specified and the dimensions and body shape of the man-model can be varied to reflect the ranges of size and shape in the relevant national and/or occupational populations (see Figure 20.22).

The man-model has a set of 18 joints and 21 straight rigid links structured hierarchically to represent the major points of articulation and the body segment dimensions (see Figure 20.23). Optional hands can be introduced consisting of 16 links with 18 joints (see Figure 20.24). The hierarchical structure is similar to that shown for the car, so that when the man-model's right upper arm is raised, then the right forearm and hand follow accordingly. By dropping down the hierarchy users can control just the forearm and hand together or just the hand, at their discretion.

The size, shape and range of postures permitted are a function of the
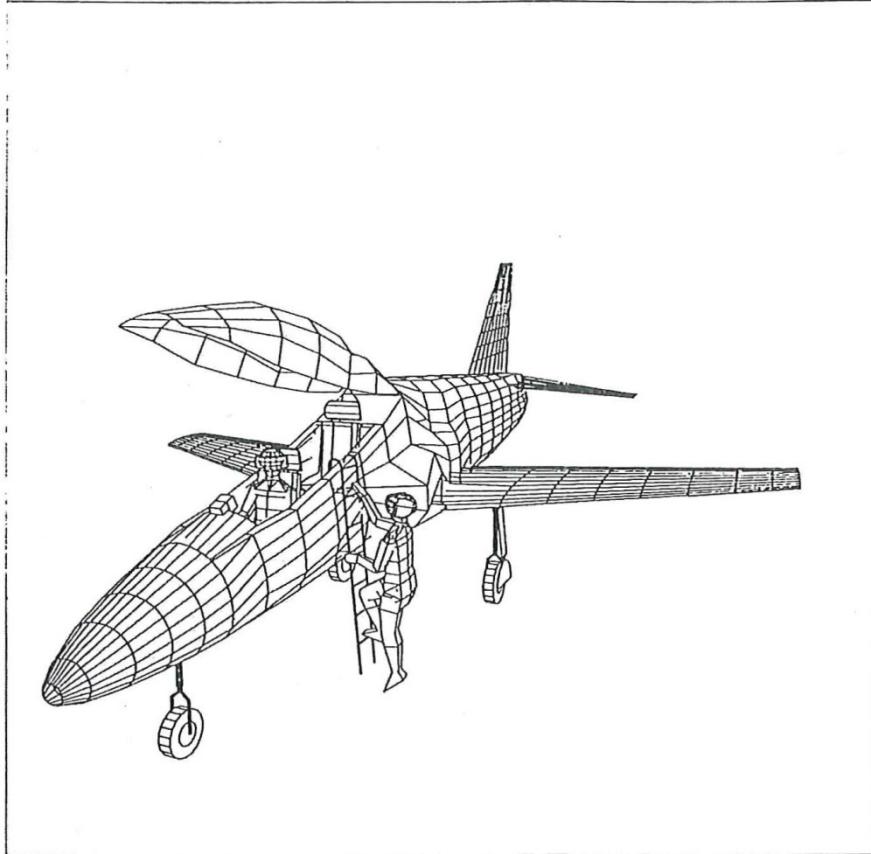
Figure 20.22. An aircraft model imported to SAMMIE from the UNIRAS system

anthropometric and biomechanical data bases chosen by the user. The data required consist of the linear dimensions between adjacent joints (e.g., from elbow to wrist), the body segment parameters of weight and centre of gravity, and the absolute and 'normal' limits for each joint in each of the three degrees of freedom (i.e., flexion-extension, abduction-adduction and medial-lateral rotation).

The limb length data can be stored as either a set of mean dimensions together with standard deviations, or as a set of dimensions explicitly defining the anthropometry of an individual. The displayed man-model can be interactively amended by changing the overall body percentile, individual link percentile, explicit link dimension and the use of correlation equations to relate internal link dimensions to external anthropometric dimensions.

The anthropometric data base provided varies according to need, and users can incorporate any anthropometric data base suitable for their chosen application, to either define a population data set or to build a specific individual.

The flesh shape is controlled by a classification system known as somatotyping

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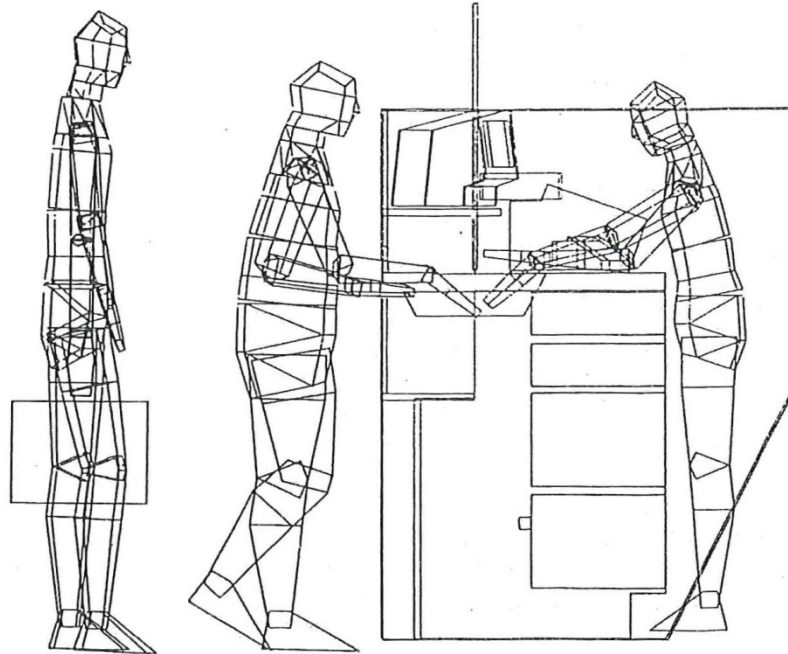
Figure 20.23. Shown, from left to right, are male models of 95th, 50th and 5th percentile stature from a chosen population . The system also enables changes to be made to individual limbs allowing representation of specific user or groups of users. The shape of the models' flesh envelope can be varied in accordance with somatotypes providing a useful evaluative technique for situations involving work in confined spaces
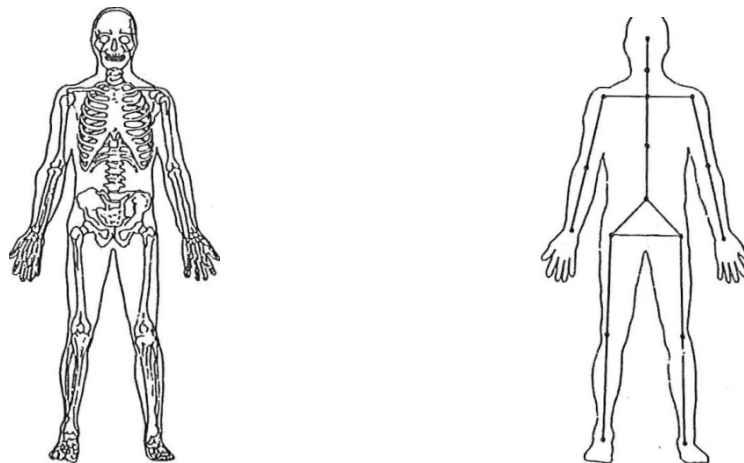


Figure 20.24. The link structure of the nun model is a simplification of the human skeletal frame, with pin-joints suitably constrained to simulate human movement capabilities. The rigid links between the joint centres arc defined by use of anthropometric data and arc usually displayed with 3D flesh shapes

(Sheldon, 1940) which enables the extent of endomorphy, (plumpness), mesomorphy (muscularity) and ectomorphy (leanness) to be specified; the somatotype number and the height and weight enables 17 body dimensions to be obtained from Sheldon's experimental data.

The joint constraints prevent the man-model being positioned in an unattainable posture. For example, it is impossible to abduct the elbow. The system indicates whether a selected joint angle is within the 'nomal' range of movement, within the maximum range, or infeasible. The limb dimensions and somatotype can be interactively altered to construct 3D man-models to the user's unique specification if desired. Additionally, the joint constraints can be actively edited by the user to suit particular design situations, for example, joint movement range might be limited to represent disability, joint angle comfort ranges, the effects of bulky clothing or unusual working conditions, for example, where high gravity forces may severely limit arm movement.

Variable anthropometry allows the evaluation of body clearances (fit) and reach. In addition, the 'man's view' facility allows the user to display the man-model's field of view on the graphics screen. These facilities allow the user to predict the likely work postures that a given design will enforce. For example, a tall and fat model of a driver might be shown to adopt a slouched posture to gain sufficient headroom with arms at full stretch to the steering wheel under which the thighs are trapped. The view to the main driving displays may be obscured by the steering wheel, causing the driver to slouch to an even greater extent. This posture can be visualized by the designer and specified in terms of joint angles which can be compared with recommended angles in the literature (e.g., Rebiffe, 1966 for the driving task). The ergonomist would be able to comment upon such a posture saying that tall drivers of that particular car would suffer considerable discomfort in the neck, shoulders, lower back and thighs. Furthermore, the design can then be interactively modified by lowering the seat or raising the roof-line, and re-positioning or providing adjustment to the steering wheel.

## Ergonomics facilities

The system has several facilities to help the user assess the ergonomics of a particular design.

### A clasher routine

This facility automatically detects whether two solids are intersecting and, if this is the case, it flashes the appropriate items to attract the user's attention. This feature can be used to check clearances with the man-model set to an appropriate size and shape, say 99th percentile limb lengths and an extreme endomorph. Alternatively, visual inspection from a variety of angles will achieve the same result.

*Reach algorithms*

Reach can be assessed simply by positioning the arms or legs so that the hands or feet either contact, or fail to contact, a specified control or point in space (see Figure 20.22). This method could become tedious for a large number of controls so an algorithm has been developed which predicts a feasible posture for the arms or legs given a specified model item or co- ordinates to be reached. Generally, there will be a large number of feasible postures for any successful reach attempt. The algorithm selects the limb posture to be displayed by attempting to minimize the extension of the joints away from their neutral positions and by preferring the greater extension of distal links to those that are more proximal. This feature does not ensure that the displayed limb posture is the likely posture adopted by a human, but it does confirm whether or not the reach attempt will be successful. If a reach attempt fails, the system displays this fact together with the distance by which it failed.

There are two other automated methods to define reach: reach areas and reach volumes. Both methods are especially suited to concept design as they are generated without specifying control locations or co-ordinates. The first method enables envelopes of reach areas to be overbid on any surface of the design as an aid to assessing suitable positions for control locations. The second method is an extension of this whereby reach is assessed over a number of imaginary surfaces parallel to either the frontal, sagittal or transverse planes of the man-model. An example of a reach volume in the transverse plane is shown in Figure 20.25; such information is particularly useful for locating controls above head height. A major study was conducted using this facility to determine both hand and foot reach zones for drivers of agricultural tractors (Reid *et al.,* 1985).

*Vision tests*

The view 'seen' by the man-model (man's view) is under the full control of the user (see Figure 20.26). For example, one can select left, right or a mean eye position, 60 or 120° cone of vision and specify the angle of vision using the eyes and/ or head as appropriate. Constraints limit the maximum angles of vision from the eyes. As with reach, the testing of vision can be achieved manually by directing the head and eyes or else the user can specify the model item or co-ordinates to be viewed; the resulting view, together with the visual angle and viewing distance, will be displayed automatically. Sight lines can be attached to the man-model to show preferred, acceptable or maximal visual angles and distances based on any set of recommendations appropriate to a particular design scenario.

Vision can further be evaluated by using 20 visibility plots showing vision across a given surface (e.g., checking vision of the facia in a vehicle and, in particular, through the steering wheel) and 30 visibility maps which enable the

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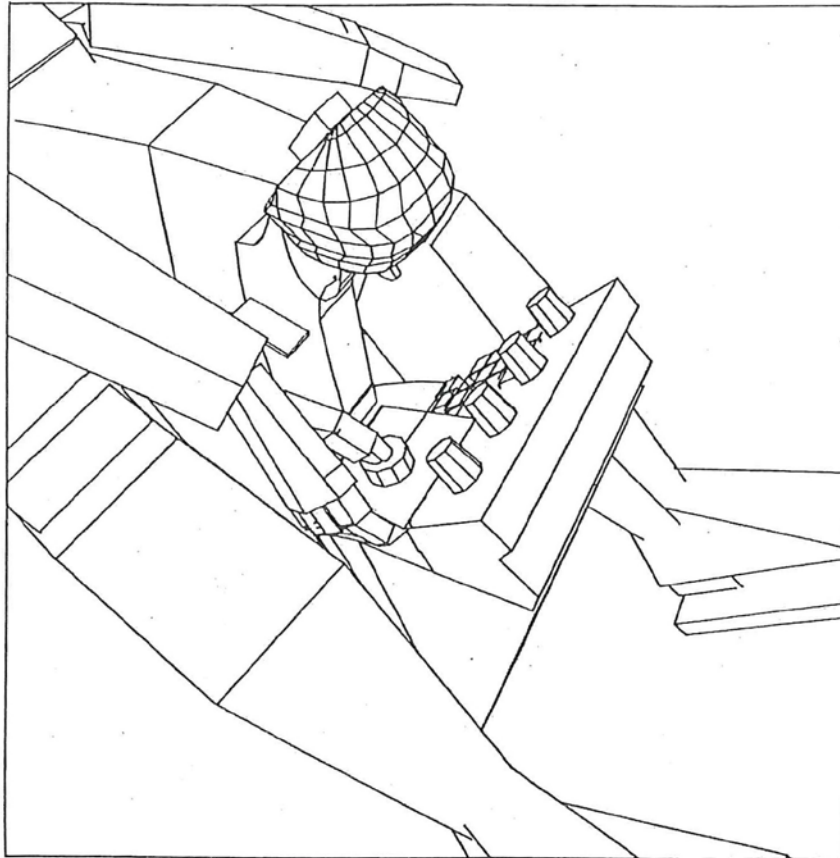
Figure 20.25. A close up view of cockpit model showing the pilot's pedestal controls and joystick. A functional hand model is being used to demonstrate alternative postures for operating a push button control

visual field to be described in terms of areas or volumes that are obscured from view by workplace structures (e.g., checking external visibility from a vehicle through the windows). Simple calculations allow one to determine the maximal visibility in any plane (vertical or horizontal) so, for example, the user can check whether a tall car driver would be able to see signposts without leaning forward or whether a train driver can see track side signals without having to move out of his seat. Aitoff equal area projections can be taken giving a full 360° field of view from a single view point (see Figure 20.27), particularly useful in aircraft and helicopter evaluation where clear fields of view need to be described in terms of visual angles.

25

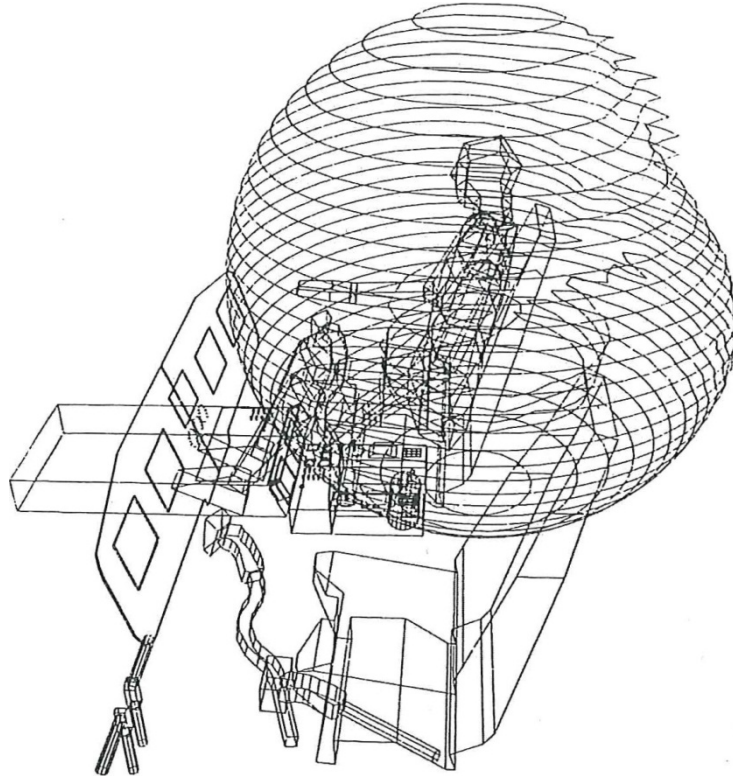Figure 20.26. This plot illustrates volumetric reach facility (available for both hands and feet). In this example the right hand reach for a 50th percentile male helicopter pilot is being assessed

## *Mirrors and reflections*

The mirror modelling facility can be used to design mirrors for vehicles (see Figure 20.26) or to determine whether reflections will be a problem in windscreens or computer screens. The mirror parameters of focal length, convexity/concavity, size and orientation are all variable and can be interactively adjusted to provide the required field of view displayed on the mirror surface, as seen by the man-model.

## *Saving postures*

Having selected an appropriate size and shape of man-model and adjusted his/her posture to suit the task demands and physical constraints of the workplace, it is important that this posture can be stored and recalled at a later date. This facility exists and it enables the user to run through a sequence of typical work postures in rapid succession, for example driving forwards, depressing the clutch and engaging first gear, depressing the clutch, engaging reverse gear and looking rearwards (see Figure 20.28).
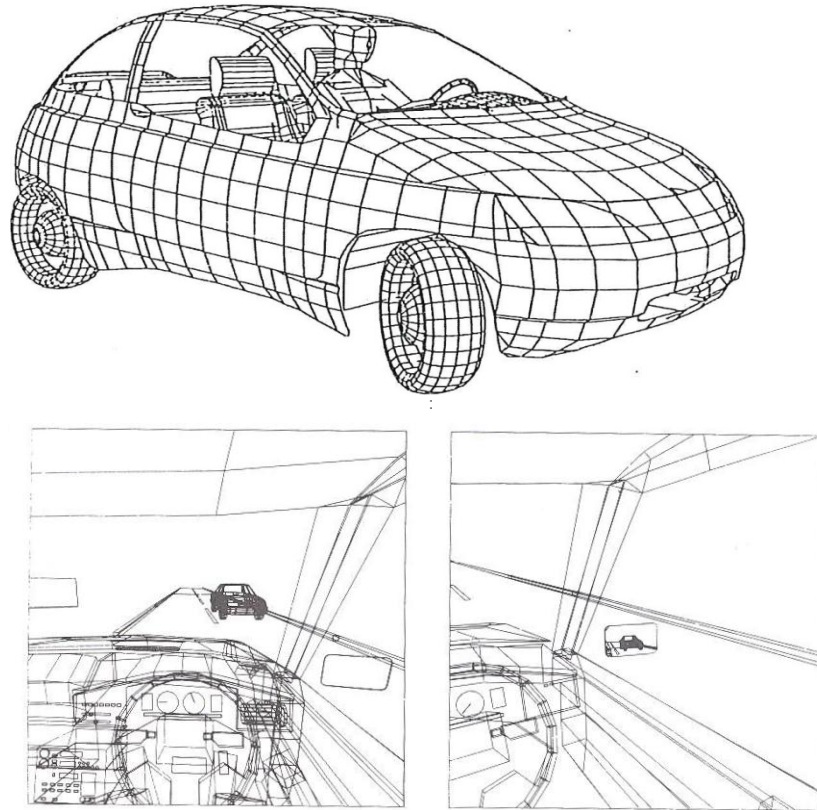
Figure 20.27. SAMMIE's viewing facilities enable the evaluation of the visual field for the full range of operator sizes. Left shows a 95th percentile male driver's view of the car controls and displays and the road through the windscreen. Right shows a 95th percentile male driver's view in his off-side exterior mirror. Reflections in the windscreen at night due to unshielded illuminated displays can also be identified at an early stage in the design .

**User dialogue**

The system is highly interactive and allows designers to proceed through the design process in a manner determined by their own requirements rather than in a predetermined manner. The system is operated via an easy to use, graphical, menu based dialogue using either a mouse driven cursor to select menu options, by direct entry of command abbreviations from the keyboard or by using a MACRO command processor (described later). Each menu, of which there are nearly 40, contains logically named commands grouped according to their functions. A brief description of some of the mam menus is given below:

*View menu*

The status of the graphics display is governed by four main parameters. The first is the centre of interest, basically what the user is looking at, either directly or
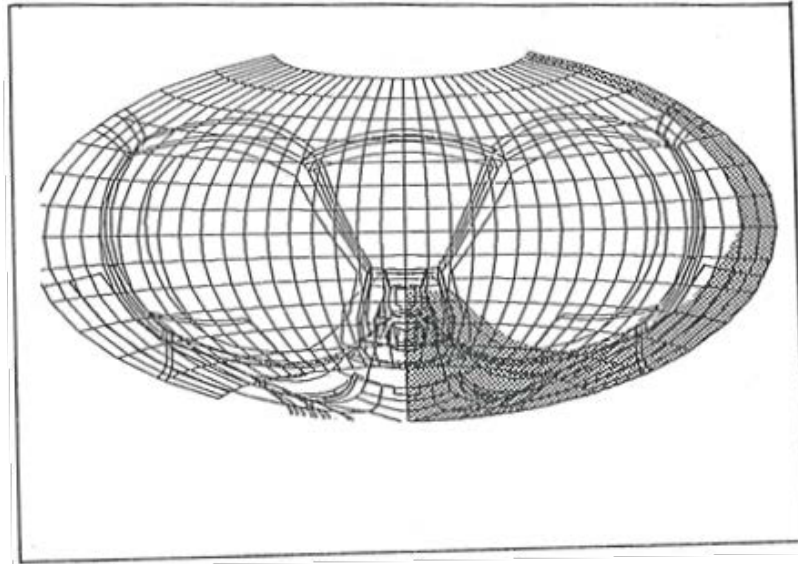
Figur20.28. An Aitoiff Equal Area projection showing 360° field of view from the rear seat in a tandem aircraft cockpit. The shaded area is part of an overlay indicating the legislative clear field of view requirements for this particular aircraft type (note that the non-shaded area is the clear field of vision)

through the man's view. The second is the viewing point, which can be set at the man-model's eyes or any other point in 3D space around or inside the models that have been constructed. The third parameter is the choice between displaying view in plane parallel projection (e.g., engineering drawing style) or in perspective and the fourth is the size of the displayed model, which is set by the scale factor in plane parallel projection and by the acceptance angle (i.e., the viewing angle) in perspective. The 'view menu' contains a variety of ways of interactively changing these parameters and it also provides a director of 'saved views' which the user has set up for future use.

### Workplace menu

These commands allow the interactive positioning of models or component parts of models in the workplace. Items can be shifted or rotated about either their own (local) axis system or the global axis system. An example of this important dimension is illustrated in Figure 20.29.

A commonly used alternative to specifying the shift distance in millimetres is to 'drag' the chosen item(s) to a desired location on the screen using the light pen, keyboard cursor keys or mouse. This method can be faster because the location can be changed in two axes simultaneously and the accuracy can be maintained by increasing the scale of the model.

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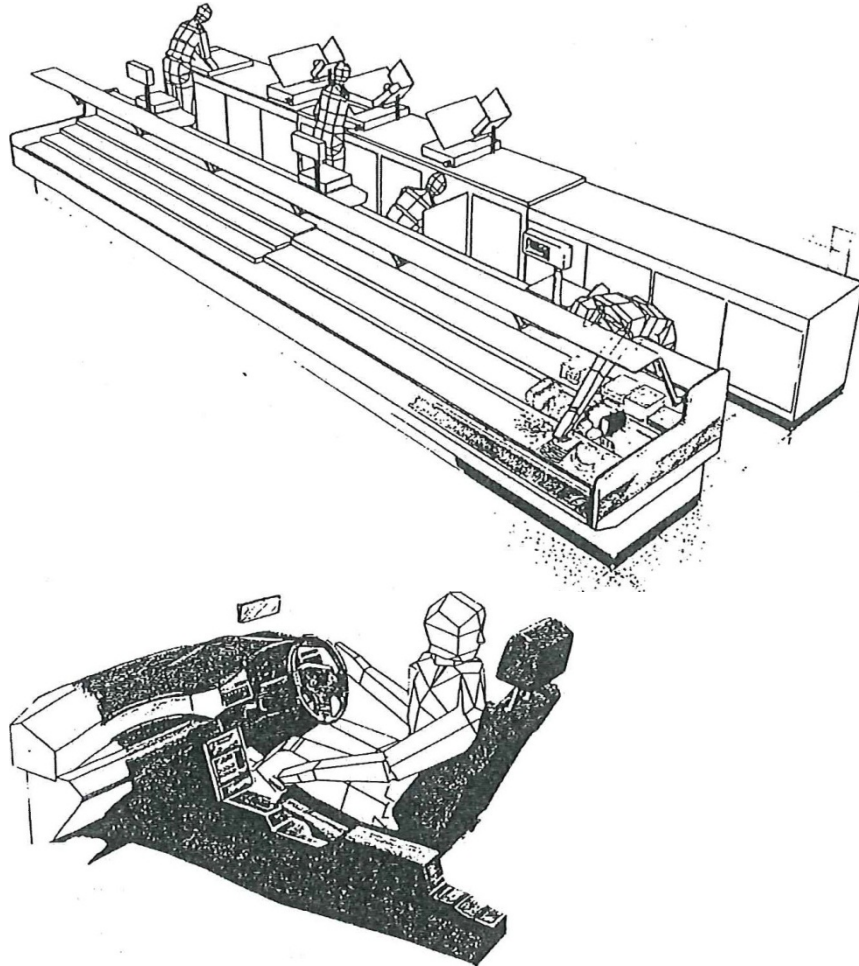
Figure 20.29. SAMMIE can be used to evaluate fit, postural comfort (by reference to joint angle data) and reach to controls or other important workplace items, in a delicatessen, for example (top) or in a car (bottom). As well as the appraisal of static reach and comfort it is also possible to consider sequences

*Display menu*

Complex models take longer to be drawn on the graphics screen and sometimes these models appear confusing. The 'display menu' allows the user to select which items need to be displayed as required.

*Man menu*

This menu contains a variety of sub-menus including the 'anthropometry menu' for changing the anthropometry of the man-model, the 'joint movement menu' for postural changes, the 'man's view menu' for displaying the view seen by the man-model and the 'reach menu' for producing reach areas and reach volumes.

*Workplace editor menu*

When evaluating a design it is useful to be able to change the size or shape of model items. Objects and group entities can be modified by scaling, shearing, extruding and re-dimensioning along a variety of axis systems. Additionally model shapes can be interactively changed by using the cursor to 'drag' vertices, edges or faces of objects on the screen. This feature is invaluable at the concept stage in design since it allows simple models to be constructed initially which can then be modified to model an increasing level of complexity as the design progresses. A wrap around console, for example, can begin life as a number of simple cuboids roughly arranged as needed and subsequently shapes can be interactively 'dragged' to form neat angled corner joints (see Figure 20.30).

Additionally the hierarchical data structure can be edited to allow the user to redefine logical relationships between model items as the need arises. The man-model can, for example, be attached to a seat such that he/she moves with the seat throughout its range of adjustment, or equipment such as helmets, boots, back packs, etc., can be attached to various parts of the man-model such that they move and remain logically related to him/her as posture is changed.

*Hidden lines menu*

Models are usually displayed on the graphics screen in wire frame form (see Figure 20.25) so that all the edges of the model are visible, even though some in reality would be totally or partially obscured by solid objects. For extra clarity or presentations, the 'hidden lines' can be automatically removed (e.g., Figures 20.18, 20.22 and 20.28).

*Plot menu*

The end result of a design and/ or evaluation will usually be in the form of a variety of views taken of the model. These are output in a wide variety of plot formats which can be sent to a wide variety of output devices, or to graphics packages for further manipulation or rendering, etc.
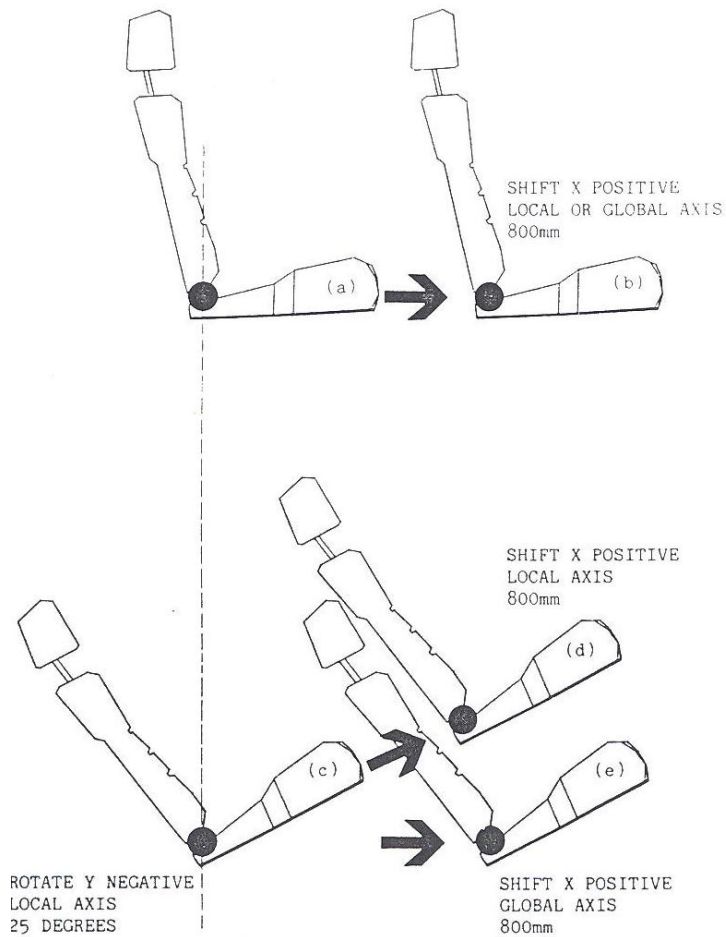
Figure 20.30. An example of the use of the local and global axis system; available in the SAMMIE system. In some orientations these axis systems are identical, as shown in (a) and (b) where the seat is shifted 800 mm along the global or local X axis. In (c) the car seat has been rotated about its local Y axis to produce seat tilt. (If it had been rotated about the global Y axis then it would have pivoted around the centre of the· available workspace.) Examples (d) and (e) show how a subsequent 800 mm shift along the local and global axis systems, respectively, can produce different results. If the intended movement is to simulate fore and aft adjustment of the seat, then only (e) is appropriate

*Macro command processor*

A MACRO command processor enables users to generate files of commands outside of SAMMIE (using any appropriate text editor). In their simplest form these files would contain sequences of commands in a form identical that which could be entered through the normal user interface, usefully allowing users to construct and retain sets of commands which suit their needs in particular situations. A more powerful aspect of the command processor is the ability it has

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to include variables and programming logic to control the issuing of commands thus providing users with a mechanism with which to customize their usage. Another important use of command files is the development of evaluation programs. A command file could contain a defined set of reach and vision tests, for example, which could be automatically applied while also varying the size and shape of the man-model, in effect processing a large number of different users through the design. In this way an assessment of the percentage of the target population accommodated by a design can be conducted with minimal effort. The range of user sizes could include the modelling of all the individuals recorded in a relevant anthropometric survey, using the command file to run them all through the test set, identifying all individuals who fail to complete any test successfully. Alternatively, where the full survey data is not available, the Monte Carlo method (see Churchill, 1978) might be used to generate a wide range of users from a knowledge of means, standard deviations and correlation coefficients for the survey data. Lastly, the command files are used to generate sets of standard ergonomics evaluations that can be applied to different designs. Thus a standard set of evaluations could be defined that would commonly be applicable to cockpit models, for example, where issues such as vision to specific displays, reach to joystick, knee room, etc., are common concerns.

## *Case studies using SAMMIE*

Two short projects carried out using SAMMIE are described here, to give the reader an insight into the way in which such systems are used.

### Computer workstation design

The aim of this project was to design an integrated workstation to be used in the computer aided design of printed circuit boards. The original workstation was purely a grouping together of the hardware needed to perform the required functions, which resulted in a three-sided configuration, comprising an alphanumeric VDT on the left, an AO digitizer board in the centre and a graphics VDT on the right. Not unexpectedly, this arrangement was far from satisfactory with a high incidence of physical discomfort reported by the users. The manufacturers then designed two prototype integrated workstations where the graphics VDT and a much reduced digitizer, which was sunk into the worksurface, were placed directly in front of the user. However, both these designs were found to cause problems for the user for several reasons, including lack of thigh clearance, forward leaning over the worksurface, difficult reach to the keyboard and an excessive viewing distance to the graphics VDT. The manufacturers were both surprised and disappointed when these problems came to light within the first few days of testing, as they had invested considerable time and expense to produce

the prototypes. However, most of their attention had been directed at the engineering problems and the interface design had suffered as a consequence.

Following initial discussions with the manufacturers, it was decided to develop three alternative designs using SAMMIE, covering a range of manufacturing costs. These designs are illustrated in Figure 20.31 and arc now briefly described:

(a) This was the cheapest design with all the components free standing on the fixed height worksurface. Whilst this option may appear satisfactory as a paper specification, the visualization of the workstation clearly shows its shortcomings, such as the lack of space for paperwork, the likely wrist and arm discomfort arising from the raised digitizer board, and the generally clumsy layout.

(b) This was the most expensive design as it offered both worksurface height and tilt adjustment. The digitizer was sunk into the worksurface and the workstation could be set up for either left- or right-handed use as it was divided into two modules; this feature also made it considerably more port- able.
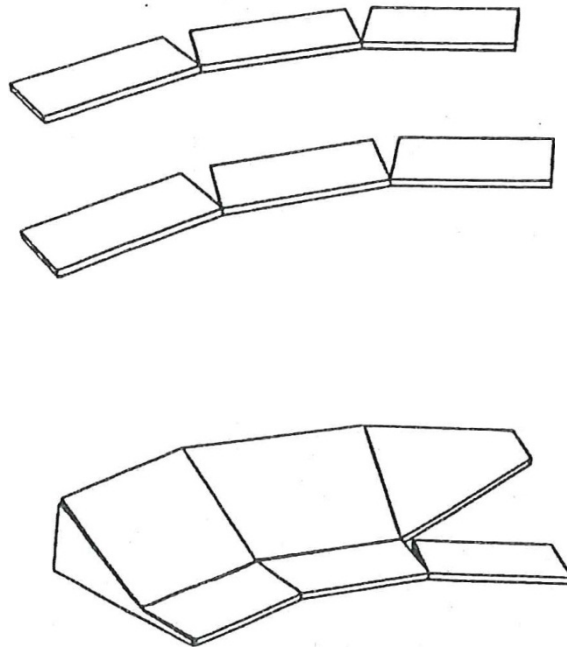


Figure 20.31. A group of six simple cuboid primitives (top) are shown laid out horizontally in the approximate form of a console. By interactively 'dragging' the corners and edges of the cuboids a wrap-around console can be quickly built (bottom). Note that the right hand side of the console is shown partially completed

(c) This was the medium cost design which had all of the features of (b) above except the adjustable tile angle. The VDTs were adjustable.

These designs were presented to the manufacturers in the form of slides, as reproduced here. The plots were visually enhanced by an industrial designer who was closely involved in the project. The manufacturers were able to visualize accurately the concept workstations knowing that the system had been used to evaluate the designs in terms of fit, reach, vision and posture. The chosen design was (c) because of several factors, namely its aesthetic appeal, ease of manufacture, cost and sound ergonomics. This workstation was manufactured successfully and the product was nominated for a design award the following year. Further details of this project can be found in Porter (1981).


**Tram driver's workstation**

This project was conducted by SAMMIE CAD Ltd. in co-operation with Design Triangle of Cambridge and concerned the design of the STIB Tramway 2000 in Brussels. SAMMIE was used to investigate and propose design solutions to a number of human factors problem areas identified from an initial assessment of the proposed tram cab design. The cab design was complicated by the need for a wraparound console providing sufficient surface area, within a limited cab space, for the required controls and displays which would allow the driver to sit comfortably facing forward when driving, and also swivel around to face back down the tram when selling tickets to passengers. Furthermore, the placement of an electrical equipment cupboard in the rear wall bulkhead placed severe width restrictions upon the driver's cab entrance space.

A full functional model was built of the entire tram from engineering drawings (see Figure 20.32). STIB provided anthropometric data which were used to generate a range of man-models for the drivers, with passengers being derived from European data from Pheasant (1986).

An appraisal of drivers entering and leaving the cab showed that drivers would experience difficulties by being required to twist and bend due to the narrow door width and low ceiling height. It was also found that a high entrance step and severely limited standing space just inside the cab door served to compound the difficulty drivers would experience. Drivers were forced to adopt uncomfortable, unstable and somewhat contorted postures when entering the cab, especially when carrying their log books and personal equipment bag (see Figure 20.33). As a consequence potential modifications to the ceiling height, floor panels, side door gear boxes and the rear wall cupboard were discussed between the designers and customer with a view to substantially improving cab access.

A range of man-models was used to determine a best possible driver package based upon a wraparound console design. The end result was a packaging
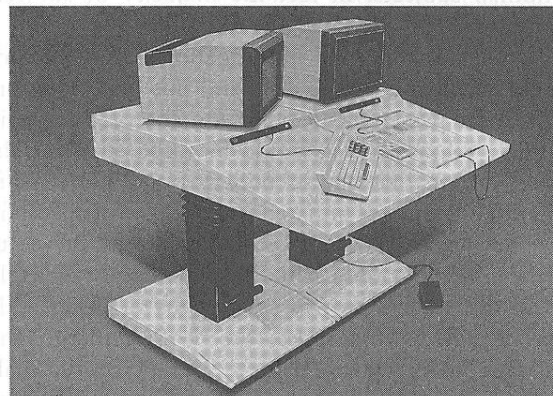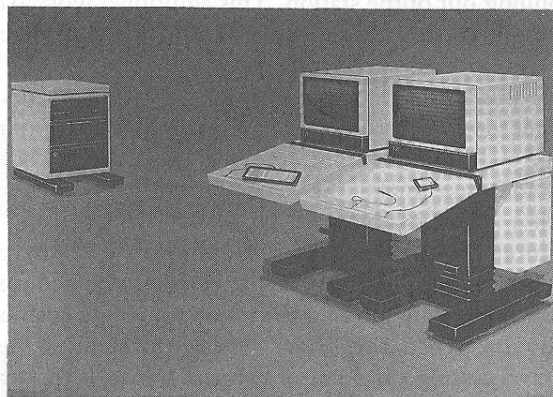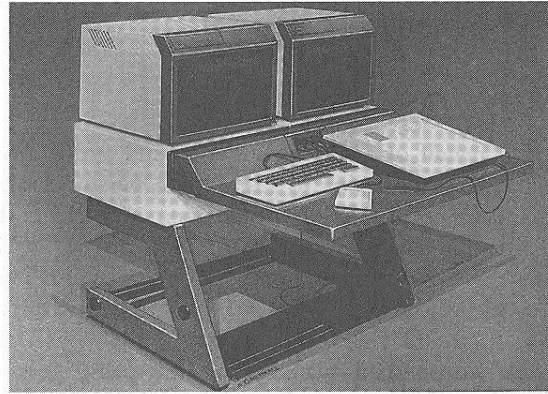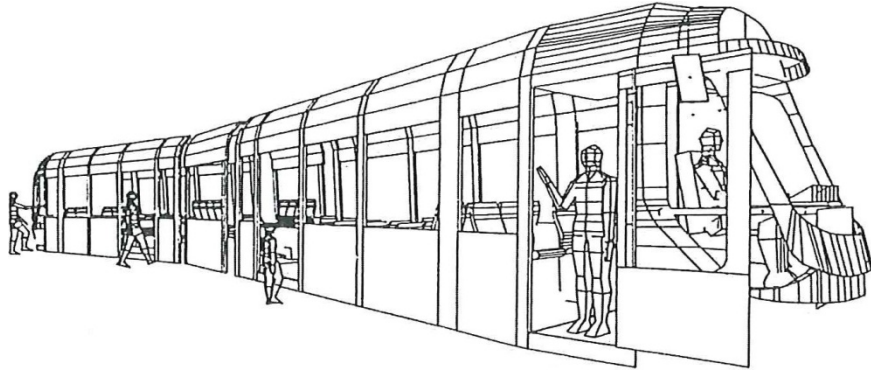
Figure 20.32. Three alternative design of computer workstations: (a), (b) and (c) were the low cost, expensive and medium cost alternatives respectively. The plots were enhanced by an industrial designer

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Figur20.33. The model of the STIB Tramway 2000 vehicle. A variety of passenger sizes, including a child, are shown

specification that identified a range of seat position and angle adjustments, the console height, positions for the main driving controls and displays and the external visual field for a range of drivers from small females through to large males. A number of packaging problems were identified. Firstly it was shown that there was a need for an adjustable foot rest, since seat height adjustment alone was insufficient to allow all drivers to operate the main driving controls, with ease and in comfort, at a fixed height console while resting their feet on the floor. Secondly the specified seat was shown to have too long a seat cushion for many smaller drivers. Thirdly the combination of a high seat position (for optimal external vision) and the console height (limited by the need to ensure it does not limit downward external vision in town traffic) and structural elements of the cab walls and console supports meant that knee and leg space under the console was severely limited causing problems when adjusting the original seat swivel mechanism. Lastly there was shown to be a conflict between the two main driver tasks, i.e., driving the tram and selling tickets to the passengers. A package designed to allow the best possible ease of operation, vision and comfort when driving was found to be severely compromised by the requirement to have the driver swivel around and sell tickets through the cab back wall (a reasonably frequent task). Changes to the seat position were needed to allow the driver to swivel the chair fully and to be able to remain seated while operating the ticketing equipment (there was insufficient space to consider standing operation). In conjunction with the rest of design team a variety of new seat swivel mechanisms and rotation points were investigated (see Figure 20.34). A mechanism was identified that allowed the seat to move and swivel such that both main driver tasks could be easily accomplished, without the need to make major structural changes to the cab or console, and which was both mechanically feasible and cost effective.

SAMMIE's mirror surface facility was used to identify acceptable external

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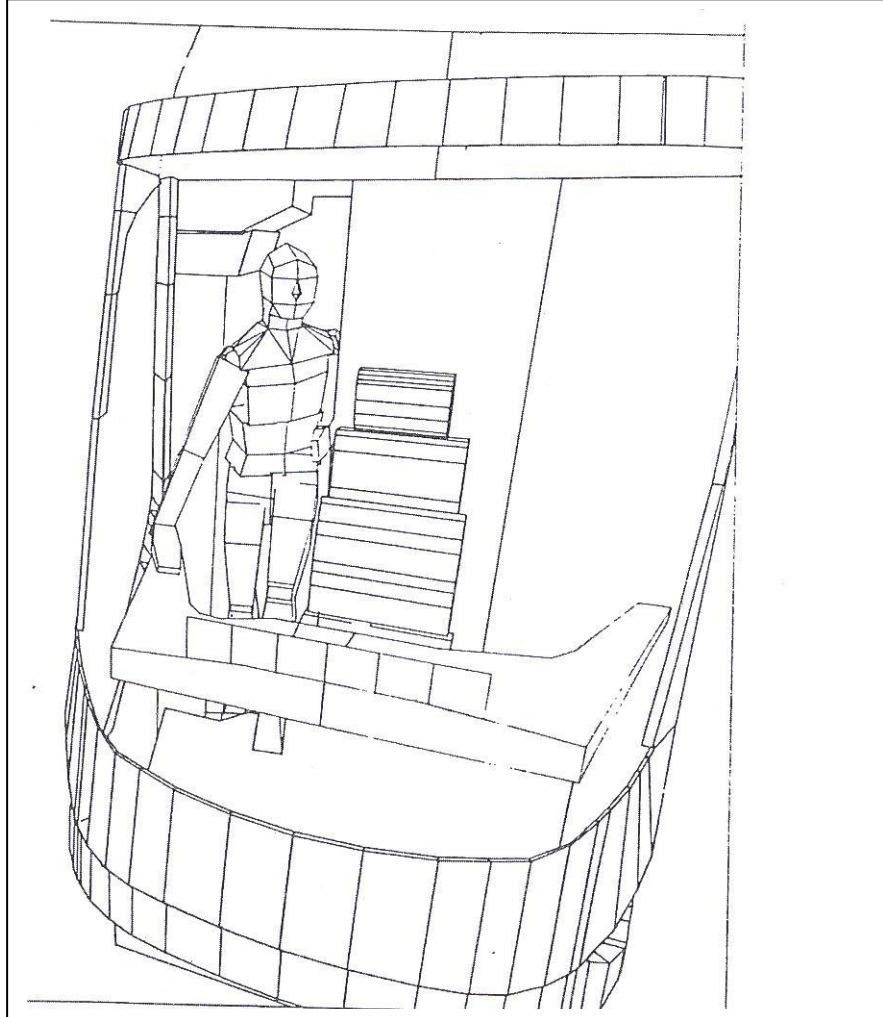
Figure: 20.34. A view through the front of the cab showing a large operator twisting and bending *as* he enters the cab through the door as originally designed

mirror locations and to demonstrate that the full range of drivers could obtain adequate views of passengers entering and leaving the tram and of vehicular traffic (see Figure 20.35). This involved testing across a number of compromise solutions, involving engineering, cost, production feasibility and passenger safety considerations, as well as optimum viewing.

Man-modelling in CAD enabled both the identification and quantification of ergonomics problems with the design and, being graphical, enabled these problems to be communicated easily to other members of the design team and to the customer. Importantly, good communication, leading to a clear understanding

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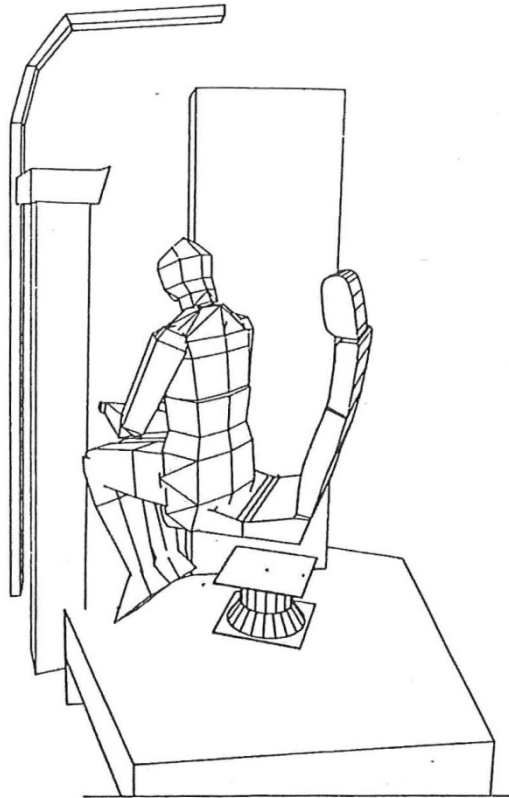Figure 20.35. A view, from the front of the cab showing the driver swiveled around on one of the seat options to sell tickets to passengers. Note that much of the cab structure has been 'turned off to show the situation more clearly

of the problems, allowed the design team to rapidly generate a range of alternative solutions and furthermore enabled the customer to weigh up the strengths and weaknesses of various compromises. The iterative nature of the evaluation process allowed the quantification of various design alternatives and the eventual development of a best possible ergonomic tram design. The tram will eventually be put into service in Brussels. Projects such as this highlight the value of computer based man-modelling techniques in the evaluation and design of complex working environments. Other SAMMIE projects have been described in Bonney *et al.* (1979a,b), Case and Porter (1980), Levis *et al.* (1980), Porter (1987) and Porter and Case (1980), and see Figures 20.28, 20.36, 20.37 and 20.38.

## *The advantages of using CAD*

There are several important advantages to using 30 man-modelling CAD systems in design and these are now discussed briefly.
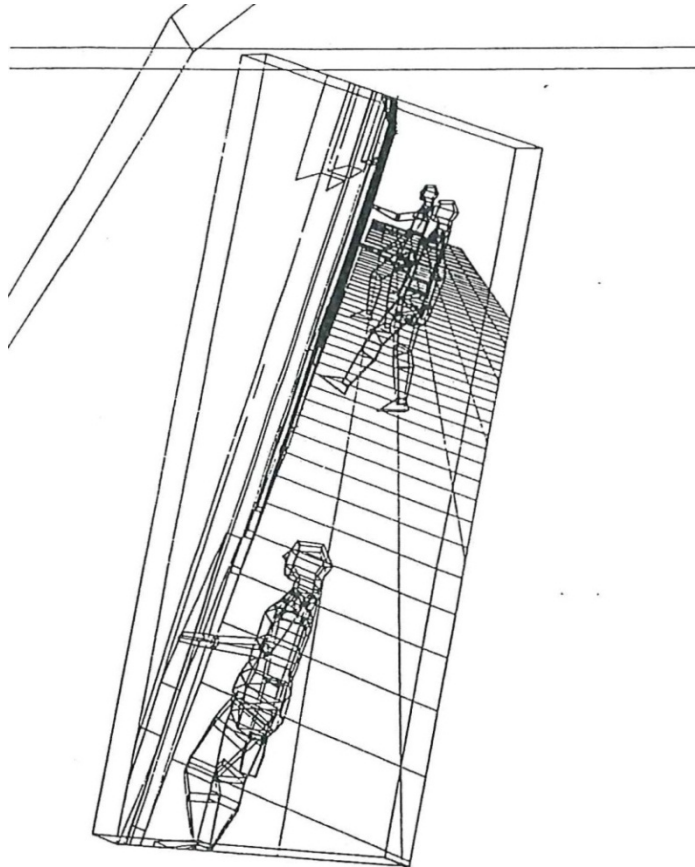
Figure 20.36. A driver's eye view of an external mirror showing passengers boarding the tram from ground level. The figure in the foreground is a 50th percentile 10 year old. The mirror positions, angles and focal length were varied to obtain the optimum field of view

## Reduced timescale

This clearly can be a major factor and it may often decide whether or not the project receives any ergonomics input at all. Time can be saved in several areas, for example, the construction of a computer-based mock-up might take between 1 (simple) to 5 (complex and large) days compared to as many months using wood, glass fibre or other materials. Subject selection can be a time-consuming process when conducting user trials, whereas the anthropometric data base of the computer system can be used to select the required man-models in seconds. For example, when designing driving packages it is important to consider people with long legs and short arms because they will have a personal conflict between positioning the seat rearwards for good leg posture, whilst having the steering wheel at full stretch, or having the seat further forwards for good arm posture at the sacrifice of

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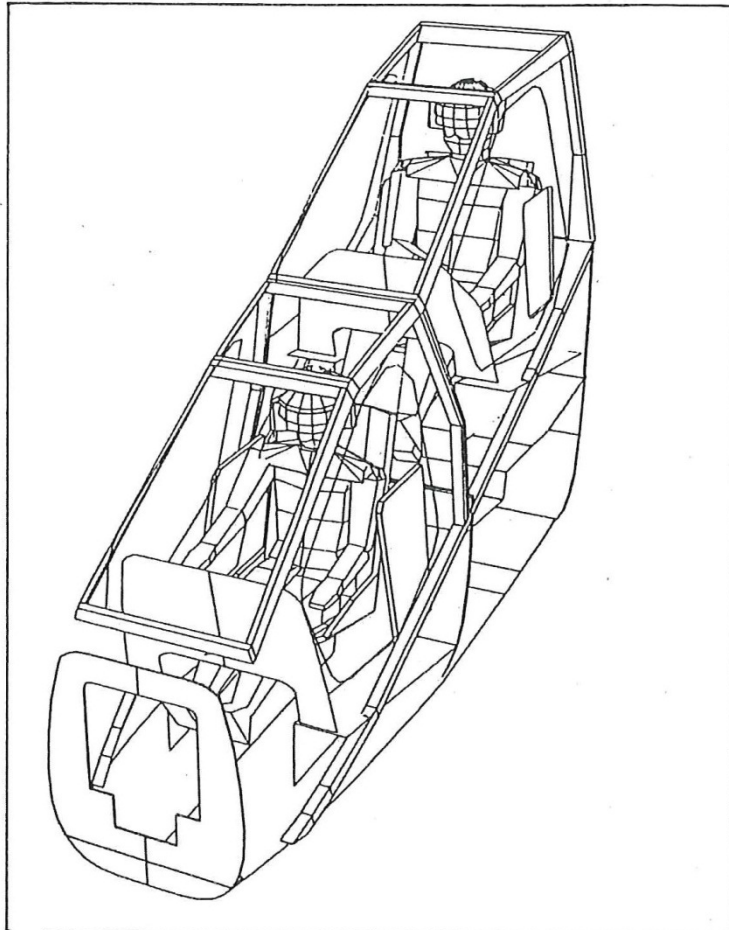
Figure 20.37. A tandem cockpit helicopter model

leg posture. The best solution is to provide steering wheel adjustment but this requirement may not be apparent if user trials are rushed using only a small handful of subjects who may have similar percentile reach with their hands and feet. Another saving is made at the evaluation stage as only a few man-models are examined compared to 20-30 subjects, with the ensuing lengthy data analysis.

**Early input of ergonomics expertise**

Because of the rapid modelling facilities it is possible to start the ergonomics input right at the beginning of the project. This is particularly necessary as engineers are using CAD systems themselves and the design might be virtually

Figure 20.38. An valuation of a cockpit design for an advanced maritime control centre

finished from their point of view by the time the first full size mock-ups are ready for traditional user trials.

### Iterative design

Early commencement coupled with reduced timescale make it very easy to establish an iterative design programme and to promote the exploration of a wide range of design solutions. Compromises are an essential feature of design and the above features are important ingredients in developing the optimum trade off between, for example, cost and the ergonomics specification.

### 3D analysis

Apart from user trials, other traditional techniques involve using anthropometric data or 20 manikins. Both of these methods are unsatisfactory for complex tasks, for example, driving a tractor and ploughing a field (see Figure 20.39). The driver will have both feet operating foot controls, one hand will be on the steering wheel and the other will be on a hydraulic control lever to adjust the height of the plough. The driver will be looking both in front and, twisting the spine, over the right shoulder to the furrows behind. This posture cannot be assessed without using 3D analysis.
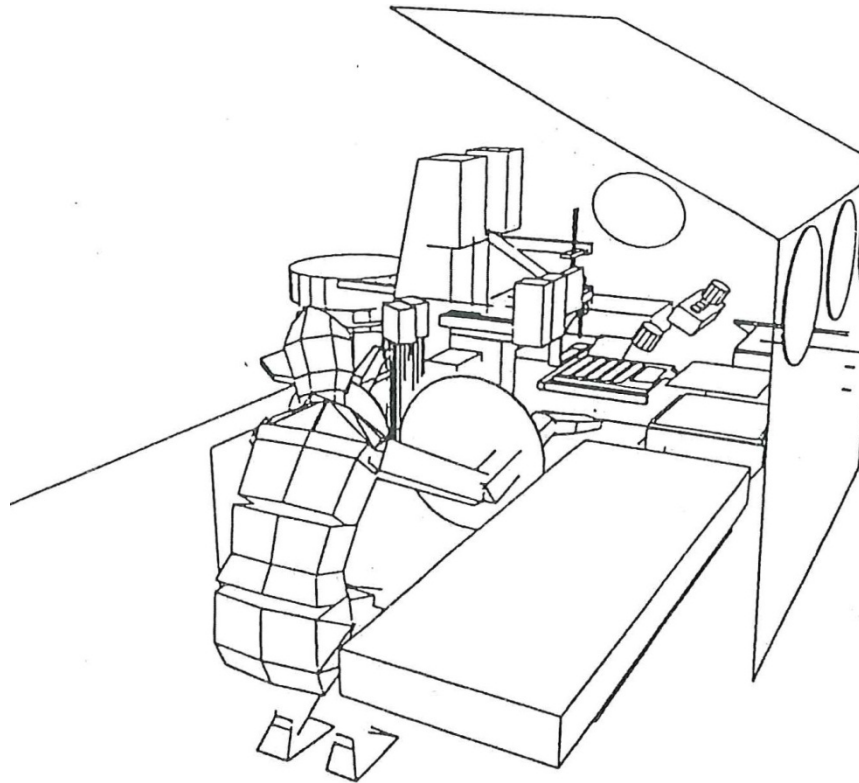
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Figure 20.39. An operator performing maintenance on a machine through glove ports. The nature of the machine's process requires that it remains sterile. Note that much of the glass shielding between the operator and the machine has been 'turned off' for clarity

**Improved communication**

Computer graphics provide an excellent means of presenting ergonomics input to design committees. The visual impact of the ergonomics specifications is far stronger and easier to grasp than numerous recommendations in a report. Additional realism can easily be supplied using the services of an industrial designer or stylist (see Figure 20.40) and this collaboration improves communication within the design team.

**Cost effective ergonomics**

The use of CAD is cost effective because of the advantages described above. If the ergonomics input lags behind the engineering, then the end result is often last minute modifications which take time and money to implement or a product that does not meet the full ergonomics specification. Both of these are undesirable; the first because it increases the development and production costs, whilst the second
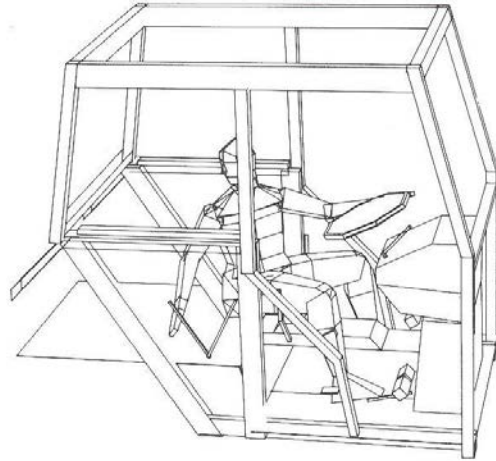
Figure 20.40. Being three-dimensional, the man models can assume complex postures. For example, the tractor driver shown above must be able to reach the hydraulic control and watch the plough as well as operating the normal driving controls
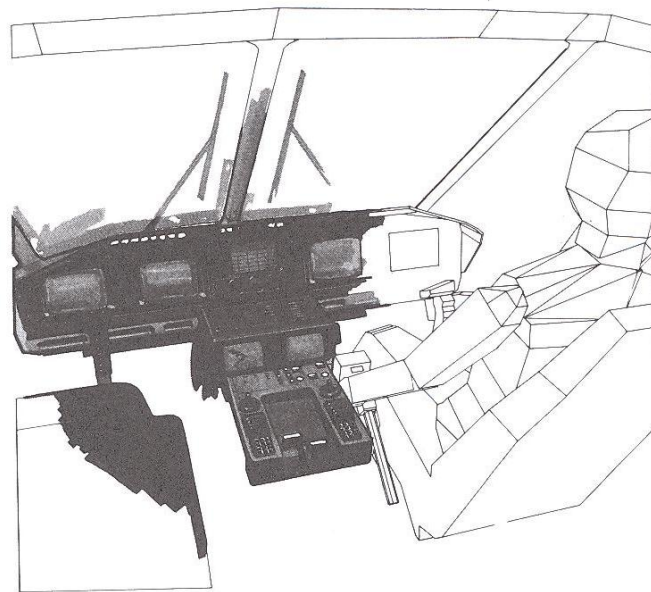


Figur20.41. A concept model of a helicopter cockpit interior. The combined strengths of the ergonomist and stylist are clearly shown in the above photograph. The ergonomics contribution to the design can be communicated powerfully using 3D graphics

is likely to reduce the success of the product or service.

There are few disadvantages, and these are more to do with restricting the potential advantages. One problem is that CAD is a powerful tool and, like any tool, it can be dangerous in the wrong hands. The selection of relevant and accurate data bases and decisions concerning workstation design and posture require the skills of an experienced ergonomist or a designer/engineer with suitable training. The systems are designed to supplement an ergonomist's skills, not replace them. It would be short-sighted to think that such systems can replace totally user trials; they should only be used to explore alternative designs, to eliminate the poor ones and select and, if possible, improve upon, the promising ones. The results of the CAD evaluation should lead straight to an in-depth user trial with working prototypes, especially if the tasks are complex and performed under adverse conditions.

## *Future developments*

The future of man-modelling CAD systems looks very promising as manufacturing organizations are always looking for ways to reduce development times and costs, whilst producing high quality design for the increasingly 'design aware' public. Useful developments might variously include: increasingly sophisticated and realistic dynamic strength modelling, improved methods of man-model control (data gloves, whole body co-ordinate measuring suits, etc.), expert systems that support design and evaluation, human behavioural modelling (e.g., functional control operations, fatigue, movement strategies, etc.), animated human movement and collision avoidance and perhaps human response to environmental variables such as temperature and vibration. Increasingly man-modelling would seem likely to move into the field of virtual reality, especially for looking at dynamic human movement in systems and animated visualization. With regard to SAMMIE, the following enhancements are under development.

### Control of the man-model's posture

The current methods for setting the posture are limited by the fact that it is often difficult to predict the actual posture that people would adopt in some circumstances. For example, could you specify exactly how you would get out of a car without taking mental notes as you do it? Even if you do this, it would be quite tedious to set up such complex postures for the man- model. One interesting solution to this problem, currently being investigated, is the use of a catsuit worn by the user with strain gauges at the major body joints. This device enables the user's posture to be recorded in the form of voltages which could be linked directly to the control of the man-model's posture. Another use of the catsuit would be to collect postural data from a sample of people performing a variety of

tasks and use the findings as a data base.

**Anthropometric data base**

Very few anthropometric surveys take sufficient measurements to define an accurate 3D model of people. In addition both external dimensions and the location of joint centres, including ranges of movement, are required. It has been suggested (Bonney *et al.,* 1980) that surveys should take into account these requirements and take more comprehensive measurements to maximize the potential applications of their data. The major problem with this request is the time and cost required. However, new developments in recording methods allow the automated collection of thousands of measurements that define points across almost the entire body surface in a matter of seconds. Such data would allow the direct definition of man-model body shapes and forms in a much more complex and realistic manner than is the case in current systems. A man-model described by this sort of data is currently under development, the major effort being the development of manageable ways of controlling the complex curved surfaces used to represent the man-model such that users can still make use of more conventional data sources, covering a wider number of subjects and nationalities, and the identification of joint centres within the flesh envelope. A major enhancement that this kind of body surface model would provide is the ability to have actively deforming flesh shapes (e.g., the buttocks change shape when the man-model is moved from a standing to a sitting posture). Apart from a more realistic and visually attractive model this facility will allow the modelling of other non-solid surfaces such as seat cushions, and importantly it will allow man-models to be placed on seats in a highly realistic manner, where both the man-model and seat will deform. This is not possible in any man-modelling system at present. Currently users of these systems rely on H-points, best estimates or, if the proposed seat is available, seat compression tests.

Other development areas under investigation include an expert system design shell, more complex constraint modelling (e.g., the ability to define multiple constraints stich as fixing a foot to a pedal and the hips to a seat and causing knee and ankle angles to remain within comfort tolerance as either the anthropometry of the leg is changed or the seat is moved) and a dynamic strength modeller which takes account of the complex interactions between muscle groups in different postures (e.g., the forearm can exert a greater lifting force with the hand facing upward than with the hand facing downward).

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