Chapter 13

Living systems, ‘total design’ and the evolution of the automobile: the significance and application of holistic design methods in automotive design, manufacture and operation

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Abstract

During the latter decades of the 20th century as products became increasingly complex it became necessary to formalise engineering and product design methods, reputed exponents of which include Gerhard Pahl and Wolfgang Beitz, L. Bruce Archer, Nigel Cross and Stuart Pugh. Pugh’s ‘total design’ method is described as a linear activity in that product manufacture and use are considered but not what happens to the product at the end of life. This chapter discusses the need to update the ‘total design’ model by comparing the product life cycle and that of the automobile in particular with systems and cycles in the natural world.

1 Introduction

A tool is ‘a device or implement . . . used to carry out a particular function’ [1]. The term tool is usually associated with hand-held devices but, in the broadest sense, all labour-saving devices that have been produced to make the execution of tasks easier, more efficient and precise may be described as tools.

Tools are used by several species of animal including members of the Ape family although none are as complex or sophisticated as those used by human beings (*Homo sapiens*). The simplest tools are natural objects such as stones and cactus spines, the former being used by Egyptian vultures to crack ostrich eggs while the latter are used by the woodpecker Finch to extract grubs from trees [2].

Other found objects may be modified or processed in order to perform a particular task and require greater physical dexterity and mental ability for production. Wild chimpanzees, for example, trim blades of grass to facilitate the extraction of termites from mounds [3] while early humans similarly learned to shape stone to make spearheads for hunting. The use of tools contributed to the development of the human race, society and culture while man's advancing knowledge simultaneously encouraged the development of increasingly complex tools and manufacturing processes. In this context, tools may be seen as a demonstration of man's ability to solve problems.

Some tools function as extensions of the body so that the hammer for example is an extension of the fist, the washing machine – the hands, the bicycle and car – legs and feet and the computer – the brain. In other instances tools enable the completion of tasks that would not otherwise be possible such as cutting diamonds, viewing DNA material through an electron microscope, the prolonged storage of food in a fridge or freezer and flying in an aeroplane. The production of each object involved conscious thought to determine the structure (what the object is), the behaviour (what the object does) and function (what the object is for) [4] and can therefore be said to have been 'designed'.

In traditional craft-based societies, objects are conceived or 'designed' through making and it is unlikely that any drawings or models are produced prior to realisation. The Industrial Revolution encouraged a shift from making by hand to manufacture by machine which in turn necessitated planning (design) prior to production. Consequently in industrialised societies, design and manufacture became separate processes and encouraged the development of the modern design profession.

The design profession is comprised of many specialist areas including fashion, textiles, graphics, illustration, film, theatre, architecture and interiors, industrial, product, automotive and engineering although many projects now involve multi-disciplinary teams. The emphasis of this chapter is holistic automotive design and manufacture and so considers the industrial, engineering product and automotive design disciplines. Although difficult to determine an exact date when these disciplines were first practised, they evolved throughout the 20th century in response to and as a result of the development of automated manufacture and mass-production processes. As products became increasingly complex it became necessary to formalise engineering and product design methods, reputed exponents of which include Gerhard Pahl and Wolfgang Beitz, L. Bruce Archer, Nigel Cross and Stuart Pugh. There are parallels and similarities in each of their design methods and the above experts' respective publications have influenced engineering and design education and the design profession.

Each model advocates an integrated approach to the design activity although, following the publication of *Total Design, Integrated Methods for Successful Product Engineering* in 1990, Pugh is usually associated with the term 'total design' which he defines as

the systematic activity necessary, from the identification of the market/user need, to the selling of the successful product – an activity that encompasses product, process, people and organisation [5].

In this chapter we use the term 'total design' to describe a holistic approach to design rather than just the method associated with Pugh and we refer to and study other models.

Design methods were developed to help designers, engineers and design managers to create the most appropriate design solutions in response to particular parameters. The British Standards model for design management systems (Fig. 1) [6] describes this complete system. However, the most important element within the system is the product, because without it there would not be any other elements or businesses. Although the emphasis of the above authors' publications is the product development process (PDP) (which influences all other elements), because the system

Figure 1: Design management systems based on BS 7000 (Part 10 – 1995: Glossary of terms used in design management), London: BSI (1995).

is *integrated* all other elements should have *some* bearing on the development of the product. However, as will be made evident in our study of the design and manufacture of automobiles, this presumed bearing of all elements is not always borne out in practice.

Holistic and whole systems are not of course discrete to the man-made environment or products. Many systems have been identified and investigated in the natural world and recognition of their significance led to the formation of the International Society for the Systems Sciences (ISSS). Living systems range in size from the sub-atomic to the galactic and have the special characteristics of life, one of which is the ability to maintain a steady state in which the entropy (or disorder) within the system is significantly lower than its non-living surroundings. For our purposes, we may postulate that the essence of life is *process*, expressing the fact that living systems interact with their environment through information and material-energy exchanges and when these processes end, life also ends. Regardless of complexity, every system depends upon the same essential

processes in order to survive and thus continue the propagation of their species or types beyond a single generation. All living systems are self-organising and (most importantly in the context of this chapter) may be described as ‘open’ because they evolve and adapt in response to change in order to survive [7].

In our chapter entitled ‘The evolution of land-based locomotion: the relationship between form and aerodynamics for animals and vehicles with particular reference to solar powered cars’ (Volume 1 of *Design in Nature* series) we showed that the forms of the fastest animals on land, in the air and in water are both aerodynamic and energy-efficient and that they evolved in response to and as a result of their natural environment. We further showed that solar powered cars adhere more closely to the laws of nature than mass-market personal transportation vehicles in that they too are aerodynamic and energy-efficient and may be viewed therefore as optimised design solutions. The development of mass-market cars, however, was very different to that of solar cars and their design is inefficient in many respects. Levels of car ownership and car use are going to continue to rise until at least 2050 and, because their overall impact on the environment is detrimental, it is both pertinent and necessary to consider changes in existing automotive design and manufacturing paradigms and the processes that maintain them.

In this chapter then, in order to illustrate the importance and relevance of a holistic (total) approach to design we first discuss several examples of living systems and the value of biomimesis as an aid to innovation. The PDP, the need to update ‘total design’ methods and life cycle assessment (LCA) are then described in detail. The history and development of the motor car is then compared to those of two other products (namely the radio and personal stereo) in order to appreciate why the contemporary motor car is as it is. A discussion about the need for change and various current trends in the automotive industry follows. Although ‘total design’ cannot rectify all wrongs in existing products and in the motor car in particular, we propose that if adopted it would improve the car in its own right and so lead to improvements in the environmental system as a whole. We then investigate alternative automotive manufacturing paradigms including the Rocky Mountain Institute ‘Hypercar’ and GM ‘AUTOnomy’ and examples of automotive environmental assessment.

We conclude that a great deal can be gained from adopting the principles of living systems and argue that these principles must be incorporated within the ‘total design’ process in order to solve some of the problems deriving from current automotive design, manufacture and operation and perhaps even for the survival of the automotive industry.

2 Living systems, biomimesis and the ‘closed loop’ economy

A *system* is a set of connected things or parts of things forming a complex whole [1] and many have been identified in the natural world. These systems have formed the basis for study in various fields and have applications, for example, in medicine and economics. Natural systems vary in size and complexity and range from the sub-atomic to galactic. Regardless of size, the properties (or behaviour) of a system as a whole emerge as a result of the interaction of the components comprising the system. Living systems have the special characteristics of life, the unique properties of which derive from DNA, RNA, protein and some other complex organic molecules, none of which are naturally synthesised outside of cells. Living systems are also self-organising and interact with their environment through information and material-energy exchanges.

We will introduce discussion of Living Systems Theory via the model devised by James Grier Miller. It is a general theory that describes how all living systems ‘work’, how they maintain themselves and how they develop and change and proposes that there are eight metaphorical levels of living systems (Fig. 2):

Cells: the building block of life organs – essentially multi-cellular systems
Organisms: formed from life organs – Three types – fungi, plants, animals – each has distinctive cells, tissues and body plans that enable life processes to be carried out
Group: 2 or more organisms and their relationships
Organisations: 1 or more groups with their own control systems for doing work
Communities: include both individuals and groups, as well as groups which are formed and are responsible for governing or providing services to them
Societies: these are loose associations of communities, with systematic relationships between and among them
Supranational systems: organisations of societies with a supra-ordinate system of influence and control

Figure 2: Living Systems Theory: James Grier Miller [7].

Grier also states (as we have already postulated for the current study) that the essence of life is process and that when the processing of material-energy and information ends, life also ends. Likewise whether comparatively simple or complex, each system is dependent on the same essential subsystems (or processes) in order to survive and to thus continue the propagation of the species or types beyond a single generation. Processes function as input–throughput–output, some of which deal with material and energy for the metabolic processes of the system. Other subsystems process information for the co-ordination, guidance and control of the system while some subsystems and their processes are concerned with both. In general, with the possible exception of computers, living systems process more information than non-living systems and maintain their energetic state by taking in the required material-energy and information inputs from the environment and, as a result of various processes, discharge information and material-energy back into the environment [7]. Living systems respond to changes in their surroundings and adapt and evolve in order to survive, and in this sense may be described as 'open'. They are also elements within 'loops' or closed systems in that taking, for example, the end of life, residual material will form nutrients and therefore energy for elements within the same or other systems.

2.1 Human physiology and homeostasis

There are many examples of self-organisation and regulation in living systems in the human body. The human body is a highly complex organism, comprised of nine interrelated and interactive systems, namely the endocrine (hormonal), circulatory, digestive, muscular, nervous, reproductive, respiratory, skeletal and immune systems, the normal functions of which are described as physiological processes. These systems and the overall body function are regulated to ensure that a stable equilibrium between the independent elements (known as *homeostasis*) is maintained [8, 9]. Homeostatic mechanisms operate at various levels within organisms and these mechanisms regulate and are regulated by molecules and proteins, cells and tissues and the behaviour of the entire organism. Homeostatic mechanisms also compensate for changes in the environment [10]

so that, for example, a constant average body temperature of 37°C is maintained in humans. Perspiration is one manifestation of the homeostatic control of body temperature.

2.2 Life and reproductive cycles

All living organisms have a finite lifespan. A generalised overview of this begins with division of a nucleus or fertilisation followed by germination or birth, growth and maturation, reproduction and eventual death. All organisms have the potential to reproduce when mature and although some organisms are able to produce either sexually or asexually (examples are water fleas (*Daphnia*), aphids and some fungi) the majority have evolved to exploit one means or the other. Both means of reproduction perpetuate the species and while asexual reproduction allows for rapid population growth and promotes uniformity (except in rare mutations), fertilisation during sexual reproduction combines chromosomes and DNA and thus promotes variability. Both reproductive processes are closed loops, as shown in Figs 3 and 4. The overall life cycle forms another example of a living system closed loop.

In an ideal environment and unless early death is caused by a predator, disease or some other external factor, lifespan varies in length and complexity according to species. Different organisms age at different rates so that, taking three contrasting examples, the average lifespan of *Homo sapiens* is about 75 years, that of a Californian redwood tree (*Sequoia sempervirens*) is 2,500 years and for an 'annual' plant like the wild cornflower (*Centaurea cyanus*) lifecycle lasts for one to three seasons and is complete within one year [11].

During life, organisms undergo an ageing process. This may be genetically pre-determined as suggested by the senescence theory or it can be caused by free radicals. The free-radical theory purports that ageing occurs because certain chemicals (free radicals) are produced as a by-product of biological activity. These are particularly harmful to healthy cells and gradually destroy cells until they can no longer function; as a result whole organ systems break down and eventually the

Figure 3: Asexual/sexual reproduction [11].

Figure 4: Sexual reproduction in animals and plants [11].

organism dies [12]. Following death, organic plant and animal matter decompose and become nutrient material for other organisms, thus again closing the loop.

2.3 Gaia theory

Many scientists and philosophers have hypothesised that the earth is a living entity and during the 3rd century BC an early exponent, Plato of Athens, described the cosmos as a 'Creature' [13]. One of the more recent proponents of this concept is James Lovelock (a British atmospheric chemist), who developed the Gaia theory during the 1960s in conjunction with Lynn Margulis, an American microbiologist. The Gaia theory is named after the Greek goddess of the earth and here we quote from Lovelock's 1979 exposition *Gaia: A New Look at Life on Earth*:

... the physical and chemical condition of the surface of the Earth, of the atmosphere, and of the oceans has been and is actively made fit and comfortable by the presence of life itself. This is in contrast to the conventional wisdom, which held that life adapted to the planetary conditions as it and they evolved their separate ways [14].

Lovelock postulated that the planet is essentially self-regulating and that the earth's surface temperature, atmospheric composition and oceanic salinity are systemically controlled. The processes are highly complex but are described here in simple terms. Lovelock knew that, since life began on earth and despite the fact that the sun's heat rose by 25%, the temperature has remained more or less constant thus suggesting the influence of a regulatory mechanism. Collaboration with Margulis (who was then studying the processes by which living organisms produce and remove gases from the atmosphere) revealed this and other feedback loops, all of which could act as regulating manner.

Now the atmosphere consists of a highly unstable mixture of reactive gases, the composition of which is maintained by the continual removal and replacement of these gases by living organisms. The early atmosphere had a higher concentration of CO₂ than that of today and the consequent greenhouse effect warmed the earth beneficially. A subsequent increase in methane and oxygen was produced by living organisms and cycled through oceans and rocks. This cycling is maintained by evolving species while atmospheric CO₂ is minimised by the biological 'pumping down' of carbon. Without greenhouse gases the earth's surface temperature would be approximately

–19°C. Similarly cells cannot tolerate salinity above 5% and it is apparent that oceanic salinity is similarly regulated to around 3.4%. Regulation derives in part through evaporite beds and lagoons where limestone deposits created by marine organisms are buried. In addition Lovelock suggests that this process also contributes to tectonic movement so that salts are moved from the oceans to landmasses [14].

In essence, Lovelock's theory promotes the idea that the earth is a homeostatic entity (in that self-regulation brings equilibrium) and evolution is the result of co-operative rather than competitive processes. Margulis' later modified the hypothesis suggesting that the earth tends towards homeorhesis: in other words the earth survives because it is in a state of persistent creativity where new organisms evolve continually while others become extinct [15]. Consequently the earth is not a living organism that can live or die all at once, but rather a community of trust which can exist at many discrete levels of integration and where all inhabitants are members of a symbiotic union [16].

Other scientists (including Richard Dawkins) have attacked and criticised the Gaia theory arguing that under no circumstances would natural selection (and Darwinism) lead to altruism on a global scale because such a system would require genetically predetermined foresight and planning by organisms. The existence and evolution of regulatory feedback loops are similarly disputed, as is the concept that Gaia is alive, this latter of course because it (or she) is incapable of reproduction. Further arguments state that the theory is not scientific because it cannot be tested by controlled experiment. Although Lovelock responded by developing a computer model called 'Daisyworld' as mathematical evidence to refute most of these criticisms, the debate continues [17]. Other debate derives from Judeo-Christian theory in which the earth is described as a garden. In this context human beings are defined as custodians of the earth with particular responsibilities [18] rather than as elements within a system. Even if the Gaia theory is inaccurate or inconclusive, the existence of other closed loop and self-regulatory living systems is proven some of which have served as models for man-made systems. We now discuss the importance of what can be learned from nature and *biomimesis*.

2.4 Biomimesis

One of the key factors that distinguishes man from animals is that man knows that he knows something. For example, a horse may know where to place a foot safely to avoid falling but a man knows that he knows where to place his foot safely. For millennia artists, designers and engineers have been inspired by the natural world, some of the earliest remaining examples of which are cave paintings of animals and date from the Ice Age. These images are said to represent more than their depicted subjects because the artists who created them believed that the images had spiritual power.

In addition to the ability to copy and replicate (like a bird learning how to build a nest) *Homo sapiens* also have the ability to abstract and learn from their surroundings, all of which are both natural and progressive. The exploration of nature is necessary for survival but as man moves from substance to meaning and back again, he is also searching for immortality and a meaning in nature itself [19]. Thus painting, sculpture and poetry have become known as the *mimetic arts*, not because they make literal copies but because the surrounding world and ideas inspired their creators. Aristotle discussed this concept at length and in his context, although the Greek *mimesis* literally means to imitate, this definition is somewhat over-simple when applied to the creative arts. When Aristotle wrote that all human action was *mimesis* he meant that it is not merely the holding of a mirror up to nature but that it is 'producing something in the fashion' of nature. He also discussed *poiesis* (which includes all arts and crafts and skills of manufacture as well as

poetry as well as what we understand as poetry in the 21st century) and defined it as 'a general name for calling something into being out of what was not'. Similarly, *techné* was defined as a way of proceeding, and accumulating experience and expertise thereof. He stated that they too are ways of making imitations of nature but like *mimesis*, transcend the literal and copying [20]. It can be appreciated how comprehensively Aristotle studied the range of activities including *our* use of the word design.

Biomimesis (sometimes called bio-mimicry) derives from the Greek *bios* meaning 'the course of human life' (although in modern scientific terms this is extended to include all organic life) and from *mimesis*. But as in the mimetic arts, biomimesis is more than copying nature, rather that it is conscious reference to and inspiration from the natural world, the formalised study of which is becoming increasingly popular. Biomimesis is said to value what can be learned from nature rather than what can be extracted from it and the science of biomimesis regards the natural world as a database of proven solutions from which designs and processes can be imitated and abstracted to solve human problems [21]. Biomimesis may also be political, an example of which is bioregional democracy, wherein political borders conform to natural eco-regions rather than human cultures or the outcomes of prior conflicts. Biomimesis is also used as a guide for economic reforms as advocated by Amory Lovins and others in *Natural Capitalism* where efficient use of energy and materials is rewarded and waste is harshly punished [22]. Based on the premise that all natural life forms minimise energy and material needs as a matter of survival, such a hypothesis mimics the larger process of ecological selection where failures are removed by eco-regions and ecological niches.

Although almost all engineering could be said to be a form of biomimesis, the modern origins of this field are usually attributed to Robert Buckminster Fuller (1895–1983) and its later codification as a field of study to Lynn Margulis. An inventor, architect, engineer, mathematician, poet and cosmologist, Buckminster Fuller is perhaps best known for the development of the geodesic dome. Although his prediction that poverty would be conquered by 2000 remains unfulfilled, the success of the geodesic dome is unquestionable and is the apotheosis and physical embodiment of Buckminster Fuller's philosophy. This structure is cost effective and easy to construct and can cover more space without internal supports than any other enclosure while becoming proportionally lighter and stronger as size is increased. Buckminster Fuller successfully exploited technology to create 'more and more life support for everybody, with less and less resources' [23].

Other examples of biomimesis include the now ubiquitous Velcro, developed by George de Mestral. In 1948 de Mestral noticed that adhesive plant burrs were covered with microscopic stiff hooks. Working with a weaver from a textile mill in France, he perfected the hook-and-loop fastener, which was patented in 1955. Further the layer by layer development of antlers, teeth, bones and shells through bio-mineralisation led to the development of computer-aided rapid fabrication processes. Finally the Wright brothers were birdwatchers and their successful aeroplanes were undoubtedly inspired by their subject [24].

In addition to the development of architectural and engineering solutions and products the natural world also serves as a source of inspiration for the development of non-material and conceptual solutions, one example of which is systems. We have already learned that when life ends, residual material will form nutrients and thus energy for elements within the same or other systems. This principle can also be applied to products at the end of life, but it is important to remember that when dead leaves are dropped from a plant, for example, they cannot be absorbed by that plant or other plants until they are processed by various micro-organisms. Similarly secondary materials produced from product reuse and recycling may need to be processed or to be used for different applications. We now discuss the 'closed loop' economy with particular reference to the automotive industry.

2.5 Learning from living systems and the ‘closed-loop’ economy

In the theoretical closed-loop (or ‘dematerialised’) economy, no new raw materials are added, only the existing pool of secondary materials is used, reused and recycled and any energy used during reuse and recycling has to come from renewable non-fossil sources. Similarly any net increase in emissions is not permitted and only readily absorbed emissions can be tolerated, an example of the latter being CO₂-neutral energy generation where the fuel is harvested coppice wood. The CO₂ released in combustion is balanced by absorption of CO₂ by growing coppice. Given the quantity of secondary materials currently available to world economies, with judicious recycling and reuse, a car could indeed be made without extracting additional raw materials, in other words by recycling what has already been extracted in the past. Macquet and Sweet [25], however, challenge the view of ‘closed loop’ recycling and highlight a number of issues that make it unworkable if discrete to individual industrial sectors. They state that it is only practicable in less complex industries (such as the newsprint industry), although regulators still often adhere to this narrow view.

In the automotive context the degradation of many materials during repeated reprocessing is a major issue. Thus coated steel sheet used for bodies (which is one of the most recyclable of automotive materials) can rarely be economically recycled back to body sheet without adding some percentage of virgin material. Similarly, aluminium sheet is normally downgraded and used in castings after recycling as are many plastics. While thermoplastics are downgraded for less demanding applications, thermoset materials are notoriously difficult to recycle, although they can be used in other ways. In natural processes genuine ‘closed loops’ are also rare. As stated above, in practice several intermediate steps are needed before the same matter can be reused by its original source. Thus, viewing the ‘closed loop’ in relation to the wider ecosystem or economic system is more realistic. Jones would describe such systems as ‘open loop’ [26]. Despite this taking a wider macroeconomic view and applying it to an entire economy, one could still argue in favour of the term ‘closed loop’. We therefore use the term ‘closed loop’ in a wider sense, reflecting a situation whereby the whole of the economy would close the loop, rather than an individual sector.

2.6 Summary

It is evident that, in spite of the philosophical and scientific debate surrounding the Gaia theory, living systems do exist and that the natural world has served and will continue to serve as a source of inspiration and information for designers, engineers and other experts. It is recognised that all natural life forms minimise energy and material needs for survival, that living systems adapt and evolve in response to changes in the environment and that nature involves the principle of macro-economic ‘closed loop’ and self-regulating systems. We propound that there are great opportunities to learn from and employ these factors as a means of developing more efficient and sustainable products.

In the introduction we noted that man-made and mass-produced products in particular can be said to have been ‘designed’ and that formal design methods were developed to help designers, design engineers and managers to create the most appropriate solutions in response to given parameters. We now discuss the design process and several specific methods. We include the approach developed by Stuart Pugh known as total design and explain what can be learned from living systems in order to update these models, so re-expressing them as ‘closed loop’ systems.

3 Total design, process and methods

3.1 The design process

In the design management systems diagram (Fig. 1) we have already recognised that 'design' (PDP) is the most important element because without it, no other elements would exist. 'Design' is a complex and demanding process that can be assisted and enhanced through use of design methods. In reality it is often difficult to separate process and methods because design is an experiential activity and it is not possible to design without doing and therefore to use a method of some sort. Design methods are in the broadest sense procedures, techniques, aids or 'tools' that assist designers and design engineers; it is fair to say that if a product is successful, whatever the means or method used to develop the product can also be viewed as successful. It is important to note, however, that adherence to a design method does not automatically guarantee development of a successful product at the end of the process: the best designers and engineers have innate ability and although ability can be developed through education and practice, it must be present *ab initio*.

The simplest model of the design process consists of four principal stages (Fig. 5) but this is only a descriptive overview and the process is better seen in Archer's prescriptive model (Fig. 6) [27]. This is more systematic and therefore more representative of a design methodology. Design process models vary in complexity but all include the activities as summarised by Pahl and Beitz [28]:

- Clarification of the task: collect information about the requirements to be embodied in the solution and also about the constraints.
- Conceptual design: establish function structures, search for suitable solution principles; combine into concept variants.

Figure 5: Four-stage design process [5].

- Embodiment design: starting from the concept, the designer determines the layout and forms and develops a technical product or system in accordance with technical and economic considerations.
- Detail design: arrangement, form, dimensions and surface properties of all the individual parts finally laid down; materials specified; technical and economic feasibility rechecked; all drawings and other production documents produced.

Most models suggest that the creative process is a linear activity, which is rarely the case because design involves both divergent and convergent thinking as well as ‘flashes’ of inspiration and serendipity. In reality designers explore and develop solutions simultaneously as illustrated in Fig. 7 ([40], p. 58). This integrative model describes the essential nature of the design process in which understanding of the problem and the solution co-evolve and contains the seven stages of

Figure 6: Three-phase model of the design process [27].

Figure 7: The symmetrical relationships of problems/sub-problems/sub-solutions/solution in design [6].

the design process. This model also describes the design process as a loop and therefore correlates with systems found in the natural world.

3.2 Design methods

The increasing complexity of products and projects, the need to eradicate errors and minimise lead-time from concept to market all lead to a rationalisation of the design process and formalisation of design methods. Design methods combine long-standing or 'traditional' design techniques (e.g. drawing) and concepts from other disciplines such as operational research, decision theory and management sciences. In addition to drawing (and in some instances sketch-modelling), creative and rational methods are used.

Creative methods include brainstorming in groups and synectics, which is analogous thinking that identifies parallels and connections between apparently dissimilar topics and therefore includes biomimesis. Creative methods are particularly appropriate tools for dismantling pre-conceptions about products thus widening the search and potential for innovative ideas. There are numerous accounts of sudden creative insight among highly creative individuals and so the importance of serendipity and the 'flash of inspiration' must also be acknowledged although these instances are invariably the results of background work, prior knowledge of the subject and experience.

Rational methods actively encourage teamwork and group participation and also serve as a checklist to ensure that nothing is overlooked. Different types of rational design methods can be utilised at each of the seven stages of the design process in Fig. 7.

- Clarifying objectives: Objectives tree
Aim: to clarify design objectives and sub-objectives and the relationships between them
- Establishing functions: Function analysis
Aim: to establish functions required and the system boundary of a new design
- Setting requirements: Performance specification
Aim: to make an accurate specification of the performance required of the design solution
- Determining characteristics: Quality function deployment
Aim: to set targets to be achieved by the engineering characteristics of a product in order to satisfy customer requirements
- Generating alternatives: Morphological chart
Aim: to generate a complete range of alternative design solutions for the product and thus widen the search for potential new solutions
- Evaluating alternatives: Weighted objectives
Aim: to compare the utility values of alternative design proposals on the basis of alternatives against differently weighted objectives
- Improving details: Value engineering
Aim: the contemporary approach is concerned with increasing the product value for the same or lower cost to the producer ([40], pp. 57–58).

3.3 Total design

Pugh defines 'total design' as

the systematic activity necessary, from the identification of the market/user need, to the selling of the successful product to satisfy that need – an activity that encompasses product, process, people and organisation. ([5], p. 5).

The design core (comprised of market (user need), product design specification, conceptual design, detail design, manufacture and sales) is central to the activity ([40], pp. 57–58). This model (Fig. 8) again describes design as a linear activity, which, as we have already discussed, is not an accurate representation of the design process.

Moreover since the publication of *Total Design, Integrated Methods for Successful Product Engineering* in 1990, awareness of and concern about the environmental impact of the manufacture, use and sustainability of products has grown. It is therefore both pertinent and necessary to update the total design activity model and to consider the product life cycle and ‘end of life’ within

Figure 8: The total design activity model (5).

the process. 'Disposal – recycled elements and scrap' (or 'end of life') is included as the final element of design management systems (Fig. 1) but in many instances, this is currently viewed as additional rather than integral to the design process.

'Closing the loop' and the holistic approach to design are not new concepts and several products have been designed to facilitate dismantling, recycling of materials and reuse of components. Others embody a comprehensive LCA, which incorporates consideration of resource consumption and emissions at all stages of production and use. These are, however, a minute percentage of all products in production. In order to raise designers' awareness of 'end-of life', life cycle assessment issues, this element must now be included within the product design process and 'design core' and could, for example, be placed in the centre of Cross's model (Fig. 7). 'End -of life' and LCA will subsequently have a significant impact on materials selection, manufacturing and assembly processes.

We have already seen that closed loop and self-regulating systems are beneficial in nature where the waste from one process becomes the input/raw material for the next one. This will also be the case when the design loop is closed but will only happen when life cycle assessment becomes a key consideration within the design activity. It is important to note that recycled materials may not necessarily be used to re-make the same component or product but end-of-life product components and materials should be used and will thus be part of a larger system. Nevertheless, only when the loop is closed will the design activity genuinely warrant the term 'total' design.

4 Sustainability and Life Cycle Assessment

The term 'sustainable development' was first coined by the United Nations in 1972 and was later defined by Baroness Bruntland as

meeting the needs of the present without compromising the ability of future generations to meet their own needs [29–31].

and is therefore a process of 'trade-offs' involving interaction between biological, economic, and social systems [31] in which the ideal is achieved when all three values coincide (Fig. 9).

Life cycle assessment is used to identify what improvements can be made to reduce the environmental impact of existing products or processes and as a guide for the development of

Figure 9: Sustainability [31].

Figure 10: Life cycle analysis based on INCPEN (The Industry Council for Packaging and the Environment) [electronic version], retrieved August 2002 from <http://www.incpen.org/html/lca.htm>.

new products. The former involves the collection of data to produce an inventory while the latter includes evaluation of the inventory. These techniques determine the environmental aspects and potential impacts of existing and new products and processes at all stages of life from the acquisition of raw materials through manufacture, use and disposal (Fig. 10). Resource (materials and energy) use, human health, and ecological consequences are considered to determine the extent to which a product is sustainable.

In 1998 a series of international standards (ISO 14000) was published and an increasing number of companies officially comply with the directives. ISO 14000 (Environmental Management) specifies requirements for establishing an environmental policy, determining environmental aspects and impacts of products, activities and services, planning environmental objectives and measurable targets, implementation and operation of programmes to meet objectives and targets, checking and corrective action and management review. ISO 14000 was criticised because the measurement of environmental impact is not standardised but the family of standards are regularly updated and improved. Either way the fact that many manufacturers now recognise and adhere to the guidelines is a positive consequence.

Several computer programs and tools have also been developed to assess product life cycle, and perhaps not unexpectedly the results from these differ considerably. This difference is due to variation in product complexity, the number and type of components used and the inevitable complexity of environmental systems. As yet there is no overall agreed methodology for LCA but a consensus is nonetheless beginning to emerge. Until such a consensus is fully reached, providing that the reports from various studies state the methodology used and the assumptions made, LCAs provide a useful indication as to where improvement is needed [32–34].

5 Three product case histories

We have discussed life cycle assessment and established the importance of its inclusion within the ‘total design’ process. In order to appreciate how ‘total design’ can improve existing products (and the automobile in particular), it is necessary to first discover why certain products are ‘the way they are’ and so we now briefly review the history and development of the radio, the personal stereo and the automobile.

5.1 The radio

Initially dependent on face-to-face speech and the written and printed word, several inventions transformed the speed of verbal communication over distance during the latter part of the 19th century. In detail the electric telegraph and Morse code were first demonstrated in 1844,

Alexander Graham Bell patented the telephone in 1876 and Thomas Alva Edison patented his phonograph in 1877.

In 1895 the electrical engineer (and later Nobel prize winner) Guglielmo Marconi succeeded in sending wireless signals over a distance of one and a half miles to become the inventor of the first practical system of wireless telegraphy. In 1896 he took his apparatus to England, and after introduction to the engineer-in-chief of the post office, was granted the world's first patent for the wireless telegraphy system. Marconi's experiments continued and the distance between transmitter and receiver gradually increased leading to wireless communication across the English Channel in 1899. Marconi then proved that radio waves were not affected by the curvature of the earth and transmitted signals across the Atlantic Ocean from Cornwall to Newfoundland in 1901 [35].

Wireless telegraphy was initially used for military and maritime purposes but became an increasingly popular amateur pastime following World War I. By 1922, broadcasting was so popular that a licensing scheme was established to regulate broadcasting in the UK and the British Broadcasting Company (later the British Broadcasting Corporation) was founded. Public wireless radio broadcasting dramatically extended the dissemination of information eventually bringing live entertainment and information into the homes of millions of people [36, 37].

The radio may be considered a *dynamic* product in that, when first conceived, it had no precedent and was therefore a new invention although the radio as we now know it evolved over several decades. The first sets were built by enthusiasts and were essentially examples of technical equipment (Fig. 11). As popularity and the demand for radio receivers grew, manufacturers began to produce sets for domestic use and sought a new aesthetic. Furniture makers were employed to build cabinets for early domestic receivers and so they resembled familiar household items such as linen chests and tallboys. In 1928 Broadcasting House, the purpose-built home of the BBC, was opened in London. This monument to radio technology impressed one manufacturer in particular and E.K. Cole subsequently commissioned one of the architects of Broadcasting House to design a new type of radio. Wells Coates exploited Ekco's plastics manufacturing capability and developed the AD65 Bakelite model in 1932 (Fig. 12) [37]. This circular radio proved seminal and in addition to influencing the design of many other radios, gave the radio a specific product identity.

Innumerable radios were manufactured in various shapes, but until the invention of the transistor in 1948, size was determined by the use of valves. The transistor revolutionised established radio

Figure 11: 1919–20 panel set with separate speaker.

Figure 12: Ekco AD65, 1932.

Figure 13: First British transistor set Pye PAM 710, 1956 (at rear).

design by decreasing size and weight and increasing portability. The first pocket model appeared in the US in 1954, followed by Sony's first pocket set in 1955 and the first British transistor radio in 1956 (Fig. 13). Ease of portability and lower purchase costs changed the way in which radio was used so that it became as much an accessory as a product.

Invented in 1936, the television became increasingly popular in the UK during the 1950s and 1960s. Comparatively low purchase cost means that ownership rather than non-ownership of a television is now considered to be the norm and this in conjunction with the development of the transistor lead to its replacement of the radio as a domestic focal point or 'household god' [36].

Nevertheless, whether in the background or foreground, broadcast sound has become ubiquitous in the 'developed' world.

5.2 The personal stereo

Dr Fritz Pfeumer and AEG began to construct magnetic tape recorders in 1931 but the Sony Walkman personal cassette player was not launched until 1979. The first public demonstration of sound tape recorders took place in 1935 and the first live concert was recorded on tape in 1936. Reel-to-reel magnetic tape technology was further developed and led to the introduction of pre-recorded tapes in 1954. Stereo hi-fi technology was introduced to the public in 1958 followed by stereo headphones in 1959 and Philips demonstration of its first compact audiocassette in 1963. This technology was initially used in dictation machines and Philips failed to anticipate the demand for blank tape used for personal music recording. In 1966, American auto-manufacturers began to install eight-track cassette tape players in cars. This technology was swiftly superseded by Philips smaller cassette playback and recording technology, which, along with CDs replaced the LP record to become the dominant consumer music format by 1988 [38].

The Sony Walkman is analogous to the radio in that it is now ubiquitous and *dynamic* because prior to invention there was no comparable product. Sony presents itself as a paradigm of a 'designed' organisation, which both responds to and creates consumer 'needs' in a highly flexible manner. Many manufacturers invariably carry out market research before developing a product but, like the radio, the Walkman was the result of technological progress rather than market strategy. There are various accounts of the invention of the Walkman concept, one of which propounds that the founders of Sony wanted to be able to listen to music when playing golf and flying. Another account suggests that it was the result of intense internal competition as departments strove to miniaturise and personalise products. Either way the forerunner to the Walkman was The Pressman, a small mono-recorder used by journalists. The fundamental difference between these two products was that the Walkman did not have a recording facility but played in stereo. Sony's founders believed that the personal stereo would succeed and so urged engineers to develop smaller lightweight headphones to complete the product.

Although conceived as a consumer product, the original TPS-L2 model closely resembled office equipment and standard cassette players. While technological developments meant that The Walkman II (WM2) was both smaller and lighter than its antecedent, the Walkman aesthetic evolved so that the cassette was concealed inside a beautiful metallic box. The controls were also moved from the side to become details on the front of the product. These changes all ensured that the personal stereo developed a specific product identity and as a result of 2.5 million sales, like 'Biro' and 'Hoover', 'Walkman' became a generic term. Widespread use of the Walkman has also made an impact on expectations about behaviour. Even though the transistor radio enabled consumers to transport music into public places, listening to the radio and stereo system was regarded as a private activity until the introduction of the Walkman. This product offered the same choice of listening as the domestic stereo but took private listening into the public domain and so blurred the boundaries between the public and private spheres [39, 40].

5.3 A brief history of the motor car

The first petrol-powered, internal combustion-engined car was invented approximately 120 years ago but it was not a completely novel concept. Various antecedents were developed prior to the invention of the car as we now understand it. These include clockwork vehicles built during

the Renaissance, Dutch-built wind-powered land yachts based on Chinese precedents and several generations of steam-powered vehicle. The bicycle could also be regarded as an immediate ancestor of the car and so we will return to this point.

The invention of the car by Daimler and Maybach on the one hand and Carl Benz on the other was made possible by the coming together of a number of enabling technologies in the 1880s. First, the internal combustion engine had been developed by Lenoir, a Luxembourger living in France in the 1860s. This was improved and promoted in Germany primarily by N.A. Otto of Cologne who, using a principle first suggested by Frenchman Beau de Rochas, introduced the four-stroke cycle in 1876. Otto's firm became the engine manufacturer Deutz (today KHD), which also employed Wilhelm Maybach [41]. These new faster running engines provided more power at lower weight, making them suitable for automotive use for the first time.

While Daimler and Maybach first put their engine in a two-wheeler in 1885 – which thus became the first motorcycle. Benz used modern bicycle technology for the first three-wheeler Patent Motorwagen in 1886 (Fig. 14). The bicycle concept contributed bent tube technology, which made the construction of light but stiff chassis frames possible. It also contributed wire wheels, rubber tyres, chains, bearings, steering systems, freewheels and other basic building blocks (Fig. 15). This was historically followed by Daimler's first four-wheeled car built in 1887, which incorporated a wooden chassis and was based on traditional carriage building technology [42].

Reaching maturity just as the car started life, the bicycle was a key enabling technology for the car with Starley's Rover safety bicycle (the prototype of the modern diamond frame bike) first appearing in 1886. It was also a key social and cultural enabler, for it established the market for mechanised personal transport. The bicycle also established the notion of freedom of movement and the 'open road'; concepts still associated with the car today. However, the bicycle is in many respects superior to the car. It is probably the only means of land-based transport where man has improved on nature; cycling is the most energy efficient means of human propulsion, and (as discussed in 'The evolution of land-based locomotion, *Design and Nature*, Vol. 1') even surpasses walking [43].

Frederick Lanchester appears to be the first person to have designed a car from *first principles*. This was described by his brother George in the following terms:

... after absorbing all that was being done on the Continent, he came to the conclusion that they were all crude adaptations of cycles or coach engineering, and decided to start 'de nove', working from first principles [44].

George Lanchester also refers to a remark in *The Autocar* [44] stating that his brother Fred was responsible for 18 of the 36 primary features of the modern car at that time (Fig. 16). Among other advanced features, the Lanchester Company were pioneers of a key enabler of mass production, namely the interchangeability of components and subassemblies. This was also a significant departure from the ways of nature, where no item is directly interchangeable in that nature does not produce exact duplicates. Unlike a replacement car part, no replacement in nature is identical even if a part has the same function. Rather nature aims to achieve functional equivalence without identical replacement. Examples are plentiful and include a lizard's replacement tail (which, although usually shorter, is functionally equivalent to the original), a broken bone that heals (although the development of scar tissue may result in a slight difference in shape), and plant re-growth after pruning. Thus part replacement in the natural world can be seen to resemble the traditional 'craft' approach to manufacturing (where each replacement part is made by hand to fulfil an equivalent function to the part it replaces), rather than mass-production processes that replicate identical components. Although this delayed the introduction of the cars to the market, Lanchester saw the longer-term advantages [45]. He also introduced the use of counterbalancer shafts in order to reduce mechanical vibration, which he considered destructive. Lanchester outsourced very little

Figure 14: Benz 1886.

Figure 15: Pennington autocar 1896.

Figure 16: Lanchester 1895. Published with permission from Chris Dowlen.

and Bird [46] describes the first Lanchester as ‘the first car to be designed entirely by one man, owing nothing to another source’ and so this was probably the first example of ‘total design’ in a car.

Interchangeability of components became a major feature of industrialisation in the USA. The country lacked the craft skills needed for large-scale production, yet a growing territory and population created an insatiable demand for manufactured goods, which appears to be the essential catalyst for the development of mass-production processes in the USA. Cadillac first used interchangeable components in cars, a system more famously adopted by Henry Ford of Detroit, Michigan, who became the chief advocate of the mass-produced car. Introduced in 1908, the Ford Model ‘T’ was essentially a craft-built car. These traditional ‘craft’ techniques were then adapted to mass production as the production system was gradually designed and built around the car itself. For example, in 1913 Ford introduced the moving assembly line without materially changing the design of the car itself (Fig. 17).

Mechanising the production of composite ash-framed, metal, fabric or leather-clad bodies was difficult and so Ford initially failed to mass-produce and construct car bodies successfully. Moreover the main bottleneck in car production at that time was the painting of bodies, which effectively prevented the mass production of complete cars. Firing painted bodies in drying ovens frequently led to the burning of the ash frames. Natural drying was therefore preferred, but this could take weeks, and lighter colours in particular took longer because they contained less pigment. Ford’s famous preference for black derived from this because darker colours only took several days to dry. Thus outsourcing most bodies gave Ford greater control over his production process.

The mass production of bodies was therefore a major breakthrough in the establishment of the modern mass car production system. This innovation is due to Edward Budd and his partner Joe Ledwinka [47, 48] who developed the all-steel welded body patented in 1914. This technology became predominant in the industry because it facilitated the development of the unitary body, or monocoque, and the consequent abandonment of the chassis on which Ford had relied. Unitary body technology now dominates the way cars are made and a modern car assembly plant is essentially a machine for making car bodies. In our natural analogy this move represents a move from the internal or endoskeleton of vertebrate structures to invertebrates with an external carapace or exoskeleton. From that point the production system was no longer adapted to the car: the car had to adapt to the production system and cars had to be designed so that they could be made

Figure 17: Ford Model ‘T’, 1915. Published with permission from Chris Dowlen.

using Budd technology. Consequently design optimised for use was downgraded as a criterion and examples of 'total design' are therefore rarely seen in cars these days.

The very high fixed investment costs of Budd's all-steel body technology mean that costs need to be recovered by making large numbers of cars, an approach to which the technology is ideally suited. Budd technology works best when identical cars are built in very large numbers. Minimum economies of scale occur at volumes of over 100,000 a year, maintained over several years. Optimum economies of scale occur at around one to two million a year although this figure was never actually achieved [49]. Nevertheless, after 120 years of history we have achieved a situation where cars are designed to be produced, rather than to be used; a far from ideal situation from a design perspective. This is also far removed from the way in which nature operates in that our man-made world produces large numbers of absolutely identical individual units.

This design and manufacturing paradigm still dominates modern car design with the exception of those small-scale carmakers who never adopted 'Buddism'. These carmakers still tend to use a separate chassis, maintaining the vertebrate approach to car design. Bodies are made of plastic composites, or hand formed metal. Both techniques allow much greater flexibility of form. This is one of the reasons why TVR's sports cars, for example, have such adventurous forms. Plastic composite unitary, or monocoque, bodies have been made, but are still rare. The first example was the Lotus Elite of 1959; some UK kit cars still use this technique, notably the Welsh Davrian and Darrian club racing cars including the Quantum Coupé. The same holds true for all modern formula one racing cars, which use carbon fibre monocoque construction to make a central 'tub' which holds the driver and to which all mechanical ancillaries are attached.

However, after 120 years of mainstream car design and production we have reached a situation in which large centralised factories, with vast global supply networks, make large numbers of somewhat baroque personal transport devices of debatable fitness for purpose. These are distributed through a complex global logistics system and sold via an extensive world-wide network of largely independent localised dealers. This rather unwieldy organisational activity is accompanied by the fact that few parties in this system are very profitable [48]. Indeed, as is clear from Pelfrey's account of General Motors' history, profitability has been declining over time [50] indicating that the whole system is becoming increasingly economically, as well as environmentally, unsustainable.

5.4 Summary

The radio, Walkman and automobile are all ubiquitous products and the millions sold have encouraged social and cultural change. All three products are similar and were not the result of market forces, rather they were the result of engineering and design inspiration, although the 'inventors' all had prior knowledge and experience as described in Section 3.2. The most significant difference between the radio and Walkman and the automobile is the way in which they evolved: although all were dependent on technological development, neither the radio nor the Walkman had precedents and so can be viewed as new inventions. It must not be forgotten that the radio and the Walkman are considerably smaller and less complex than the car. The number of mass-produced products sold must exceed investment in tooling in order to make a profit, and because initial costs for a radio and a Walkman are lower than that of a car, the cost of redesign and change is far lower than that associated with change in the automotive industry. Moreover mass-production of radios did not really begin until the late 1920s and manufacturers probably therefore learned from more established mass-production processes (including car manufacture).

By the time that the Wells Coates was commissioned to design a radio for E.K. Cole, the influence of the Bauhaus (established in 1919) and Modern Movement in general was spreading. Principal Bauhaus ideologies were integrity of materials, economy of form and that 'form follows function' while modernism in general consciously strove to break with the past and to develop a machine aesthetic [51].

The main component of Wells Coates design for the Ecko AD65 was a press-moulded phenol-formaldehyde (bakelite) body, the form of which was determined in part by both the manufacturing process and behaviour of the material. Although some plastics manufacturers produced objects that aped a craft aesthetic, plastics manufacturing processes were not based on traditional craft processes. These factors and the influence of modernism encouraged Wells Coates to seek a new aesthetic that reflected this new radio technology ([37], pp. 204–206), thus establishing an aesthetic paradigm for audio equipment. When the Walkman was launched in 1979, the public were familiar with comparatively hi-tech products and expected an appropriately hi-tech aesthetic. Similarly mass-production processes had become highly sophisticated and the practice of integrated design and manufacturing thinking became the norm.

Man has used land-based, animal-assisted transport for more than 5,000 years as recorded in Mesopotamian pictographs with engraved images of carts dating from 3200–3100BC [52]. As the direct descendants of horse-drawn carriages and carts the earliest automobiles resembled and were sometimes described as horseless carriages. Bicycle technology influenced and was exploited in car design and manufacture as were coach-building materials and manufacturing processes. Mass-production processes were first developed in the USA in response to the desire and market for consumer goods and Henry Ford among many others recognised and supplied this market. We have already explained the fact that Ford's fundamental error was to design a mass production process around a vehicle initially designed to be made using 'craft' and hand-making techniques rather than adopting first principles and redesigning the vehicle and production process simultaneously. Despite again as we have seen, Budd and Ledwinka's contribution of the all-steel welded body, to this day we have suffered the consequences of energy-inefficient and uneconomical design solutions. Moreover these solutions are contrary to the premise that all natural life forms minimise energy and material needs as a matter of survival.

Just as the earliest radios lacked product identity and were no more than boxes of components with external controls the earliest automobiles were little more than carriages without horses. This is evident in Figs 18–20. Both open and closed models soon developed a more distinctive visual identity as cars in their own right (Fig. 21). Product identity continued to evolve but whether they were luxury vehicles (the Alfa Romeo B 'Lungo' (Fig. 23)) or mass-motoring vehicles (the Austin 7 (Fig. 22) and Hillman Minx (Fig. 24)) all were very definitely 'motor cars'.

The overall product has proved so popular that the number of cars on the road globally now exceeds 600 million [53, 54] and the World Bank has predicted a further rise to 1 billion by 2030 [55]. The level of car ownership is expected to stabilise in developed countries (such as the UK) by 2020 but will continue to rise in some parts of the 'developing' world until 2050 and beyond [56]. The popularity of the motor car and its extensive use have both positive and negative outcomes. We now discuss how and why the car became so ubiquitous, the benefits from and negative outcomes of car use and the urgency for and importance of change in automotive design, manufacture and operation.

Figure 18: Knight, 1895.

Figure 19: Bersey electric cab 1897.

Figure 20: Fiat 3 1/2 hp, 1899.

Figure 21: Bugatti type 15, 1910.

Figure 22: Austin 7 Pearl Cabriolet, 1938.

Figure 23: Alfa B Lungo, 1938.

Figure 24: Hillman Minx Magnificent, 1938.

6 The need for change in automotive design, manufacture and operation

Car ownership was facilitated by availability which proved to be synonymous with increased income [57] and following World War II the world economy grew rapidly; between 1951 and 1972 average weekly earnings increased by 83% in Britain. Ownership of registered vehicles in the UK increased concurrently from 2,034,400 at the start of the war, to 3,525,800 in 1955 and 14.7 million in 1975 [58] 11.8 million of which were private cars [59]. Since then the number of cars on the road in the UK has almost doubled and there are now approximately 25 million.

Car use has risen concurrently with car ownership so that in the UK, for example, between 1970 and 1999 the number of annual passenger vehicle miles travelled increased 133% to more than 387.5 billion miles (620 billion km) while the number of journeys by public transport and on foot have either remained static or decreased [60]. The motor car has initiated and contributed to cultural, societal, economic and environmental changes, both positive and negative and many of the latter are related to the way in which cars are designed, manufactured and fuelled.

6.1 The economics of automotive manufacture and use

Mobility has contributed to and is a consequence of economic growth in industrialised countries, while in less developed countries it is viewed as a necessary requirement for sustaining economic growth and a perceived benefit of such growth [57]. Car ownership is therefore indicative of both national and personal success and consequently something to which non-owners aspire. The extent to which individuals value mobility is reflected in their expenditure on it. Although not the highest in Europe, UK expenditure on motoring accounts for approximately 15% of total expenditure on consumables while non-motoring travel accounts for 2% and other household expenditure 83% [61].

Automotive manufacture and use have contributed to global economic development and many national economies are now dependent on both the manufacturing and associated industries while others are reliant on income from oil production. Automotive manufacture has become the largest industry in the world and, until the demise of the Ford plant in Dagenham, for example, the annual turnover of the UK motor industry represented more than 5% of GDP. In the EU automotive and allied industry represents 1.61% of GDP and 8.2% of the total employment of

manufacturing industry. Hence at least 55 million vehicles were manufactured globally in 1999 and almost 2.5 million cars were sold in Britain in 2001 [62]. In addition to revenue from vehicle sales, fuel sales also generate revenue and, the British government collected £2.6 billion from the oil and gas industry in 1999 [60]. Significant change in automotive manufacture and use would create economic instability and is therefore unlikely.

6.2 The role of the car

The car fulfils various roles, all of which contributed to its rise in popularity and growth in use and ownership. These roles can be grouped into two main categories, namely practical and psychological.

Practical roles and practicality include

- increased travel speeds which change perception of time and distance,
- transportation of passengers and goods ([58], p. 39),
- freedom to travel when and where desired [63, 64],
- providing a comfortable travel environment [65],
- rapid and convenient refuelling [66], and
- increased work and leisure opportunities [67].

Psychological roles include

- status symbol – an object of desire so that ownership is an aspiration [68],
- costume [69],
- thrill – changes in perception when travelling at speed provoke physiological responses [70],
- sense of power and control – ‘an aphrodisiac’ [69],
- a liberator – reduces people’s sense of isolation [71], and
- a place of safety, privacy and a ‘home from home’ [65, 72].

Such is the popularity of the car that the majority of car users claim that they are unwilling to change their habits [73] and perceive the car to be indispensable [74] and the majority of the young people want to own a car as soon as they can [63]. All evidence indicates that there will not be any decline in levels of car ownership and use.

6.3 The negative outcomes of car use

Extensive car ownership and use has created many environmental and other problems. These include

- changes in infrastructure that
 - damage and destroy ecosystems and the environment [75],
 - limit work and leisure opportunities for those without access to a car or private transport [76],
 - result in social exclusion and isolation [77];
- congestion which
 - prolongs journey times [78],
 - causes stress and contributes to ‘road rage’ [79], and
 - costs an estimated £20bn per annum in the UK alone [80];

- traffic accidents, injury and death [81, 82]
- detrimental emissions which
 - affect people's health [83, 84],
 - damage both the built environment and natural ecosystems [85], and
 - include CO₂ and other 'greenhouse' gases that contribute to global warming and climate change [86].

All of the latter factors account for enormous hidden costs, which will rise concurrently with car use. For example, the World Bank estimates that traffic accidents alone cost the global economy about 500 billion US\$ annually resulting in losses between 1 and 3% of a nation's gross domestic product [87]. Annual recorded road traffic accidents account for 1,171,000 deaths and 10 million injuries globally although the actual figures will be higher because in many parts of the world, road accident fatalities are unreported and so actual costs will also be higher [84]. Nevertheless, all evidence shows that the public currently tolerate these negative factors and will continue to do so in the foreseeable future.

In addition to the social and environmental costs of car use, automobile manufacture requires considerable resources (raw materials and energy) some of which also produce pollutants and emissions, as does vehicle disposal at the end of its life.

6.4 Resource consumption – propulsion fuels

Internal combustion engine vehicles obviously require fossil fuels during use and with average UK car consumption at 30 mpg [88], a total of approximately 2,500 gallons of fuel and 50 gallons of oil [89] will be used during a car's life. Total UK transport fuel consumption in 2000 was equivalent to 55 million tonnes of oil [88] which accounted for 46% of energy consumed in the UK, while the transport sector consumed 32% of all energy used [60].

Oil is a finite resource and, although estimates vary about when known reserves will near exhaustion, many experts believe that this could be by 2050 [90–92]. Current data shows that in the UK, the transport sector consumes by far the greatest proportion of petroleum [93] (Fig. 25) so research into alternative fuels and energy supplies is ongoing the results of which will have a significant impact on the design of future vehicles.

Figure 25: Petroleum products used for energy in UK, 2000 [60].

Current design and manufacturing processes mean that cars are highly inefficient. This is despite the fact that during the past 10 years in particular, manufacturers have sought to improve fuel economy through more efficient engines and transmission and by reducing weight. The latter is achieved by increasing the percentage of plastics, composites and aluminium used. Nevertheless, only about 2% of energy consumed for operation is used to transport the average number of passengers (1.5) while the remaining 98% is used to transport the vehicle itself [94]. Similarly no more than 20% of available energy is used to turn the wheels while the remaining 80% is lost as heat and exhaust ([22], p. 24). This is a reflection of the second law of thermodynamics consequence for equilibrium heat engines rejecting a substantial amount of the energy input in the form of heat.

6.5 Automotive manufacture – materials and energy consumption

In 1999, 16,734,250 trucks and 38,946,820 cars were sold globally, meaning that approximately these numbers were manufactured [95], thus accounting for a considerable quantity of raw materials. A typical vehicle is constructed from high-strength carbon, stainless and other steels, iron, plastics and composites, lubricants and fluids, rubber, aluminium, glass, copper and zinc. Cars vary in weight from the small 2-seat Smart car (MCC Smart City Coupe) at 720 kg (1,584 lbs) to the Rolls Royce Silver Seraph at 2,350 kg (5,170 lbs) as does the ratio of materials used. In order to reduce car body weight and improve fuel economy, during the past 10 years in particular, manufacturers have increased the percentage of plastics, composites and aluminium used. The percentage breakdown of materials by weight in a typical current European model is shown in Fig. 26.

Reports about the amount of energy used during car manufacture vary considerably according to source and definition of product life cycle [96, 97] with lower estimates being 6% [98] and higher estimates at exceeding 16% [99] of total energy consumption during vehicle life. Nevertheless, the average amount of energy consumed in 1999 was equivalent to 0.61% of the total annual global primary energy consumption of 380 quads [100] (1 quad = 1 quadrillion British thermal units or 25,199,577.242763 tonne of oil equivalent).

Figure 26: Average 1998 car – material breakdown by weight.

6.6 Vehicle disposal at end of product lifetime

Between 1.3 and 1.8 million end-of-life vehicles (ELVs) are scrapped in the UK every year [101] with total ELV scrap in the EU generating between 8 and 9 million tonnes of waste [102]. At the end of useful life cars were generally sold to a vehicle dismantler but changes in policy now mean that dismantlers are usually paid to dispose of vehicles. It has long been the case that engines, gearboxes and similar components have been removed and re-manufactured in what is known as the 'core' recycling business. Dismantlers also have to remove potentially environmentally polluting materials such as operating fluids and batteries, and parts that can be sold on to undergo a shredding operation where the hulk is broken into fist sized parts. In subsequent processing the ferrous and non-ferrous metals are extracted and recycled, and the residual non-metallic material is sent to landfill sites. In the UK between approximately 74% of a vehicle is currently recycled (64% of materials are recycled and 10% of parts are reused) while approximately 490,000 tonnes of the remaining total material from ELVS is buried in landfill sites annually [103].

6.7 Summary

It is evident that current cars are inefficient in that the majority of fuel consumed during operation is used to transport the vehicle rather than goods and passengers. Similarly mainstream automotive propulsion technologies require fossil fuels, which are a finite resource and produce detrimental emissions and pollutants. These latter impact on people's well-being and quality of life and damages the environment at local, national and global levels. Although automotive manufacture, oil and associated industries employ millions of workers and are considered essential for economic growth, a considerable percentage of income generated is consumed by the hidden costs deriving from extensive car ownership and use. Current automotive design and manufacturing processes also account for a notable percentage of global energy production while current policy means that approximately 490,000 tonnes of material from ELVs ends up as landfill in the UK every year. Nevertheless, all evidence shows that the car is integral to 'developed' societies and its ownership an aspiration in 'developing' societies and that it is therefore here to stay.

It is therefore essential to reduce the environmental impact of vehicles for personal transportation as much as possible. We have already discussed the development of current design and manufacturing paradigms and will now consider the impact of impending changes and what further beneficial changes should be introduced. It is increasingly evident that these changes must include the adoption of a truly 'total design' process.

7 Current trends in automotive design and manufacture

In Section 5.3 we discussed the development of the automobile. Some sources (including Pugh) state that the conceptual plateau for the contemporary car was initially established with the introduction of the Ford model 'T' (Fig. 27) and that the majority of cars still incorporate

- a body with windows and doors,
- four wheels, one at each corner,
- a front engine with rear wheel drive and brakes on each wheel,
- front and rear lights,
- pneumatic tyres, and
- front and rear bumpers (fenders) ([5], pp. 158–160).

Figure 27: Ford model 'T', 1924. Published with permission from Chris Dowlen.

This analysis is, however, somewhat naïve and many of the product characteristics listed are somewhat spurious. The 'conceptual plateau' above was not really established with the model T, and, as we argued earlier, the model T was in no way innovative as a product. It was based on an existing tradition of car design, the so-called 'système Panhard', established by the French firm of that name. This embodied the basic concept of: front engine and rear wheel drive, as listed by Pugh. Even at the time Pugh was writing (1990) the majority of carmakers had changed to the front wheel drive system that prevails to this day. BMW, Lexus and Jaguar (with the exception of the X-type) are the only mainstream carmakers who still use rear-wheel drive. However, many so-called sports utility vehicles (SUVs) and pick-up trucks (which together with multi-purpose vehicles (MPVs) now represent over half the US market) have retained the separate chassis found in the model T and its contemporaries, although even here the pre-Budd paradigm is now under threat. We have also established that Ford did not introduce the 'manufacturing paradigm' still prevalent today. Although he made a significant contribution, the key element of the modern car-manufacturing paradigm is due to Budd [48]. Nevertheless, the car has been designed around production methods and the manufacturing paradigm remains more or less unchanged since the introduction of 'Buddism' and the overall concept is thus described as *static* rather than *dynamic*.

Developments in the subsystems such as engine technologies and materials selection have occurred but they tend to be incremental, as are modifications in vehicle aesthetics and styling. Thus contemporary vehicles look very different to those produced at the beginning of the 20th century but again change was gradual (Figs 28–30). Alfred Sloan, a manager at General Motors, developed 'Sloanism', to maximise profit through the annual introduction of superficially modified, fashionable models [104]. This practice was first introduced during the 1920s but the annual model change characteristic of US carmakers in the 1950s and 1960s has largely disappeared because it led to high costs, lowering of residual values in the market and consumer resentment. Sloan also introduced the concept of the product range within each brand and beyond that a range of brands for each manufacturer. General Motors pioneered the concept from the 1920s onwards, with Chevrolet as the entry level, the next step up being variously Pontiac and Oakland, then Buick and Oldsmobile and La Salle with Cadillac at the top of the range. Makes such as Oakland and La Salle have come and gone over time and Oldsmobile (which appealed primarily

Figure 28: Cadillac, 1960s.

Figure 29: MGA, 1956.

Figure 30: VW Beetle, 2001.

to import buyers), were recently phased out. Nevertheless, this system is now mirrored by Ford, Fiat, Volkswagen and others, who offer a range of brands in different market segments [48].

The introduction of robots automated many of the processes once carried out by a human workforce and again, the majority of vehicles are produced on an assembly line similar to that first conceived by Ford in 1908 [105]. Concern about the eventual depletion of oil reserves, pollutants, emissions and CO₂ in particular has encouraged research into and development of

more fuel efficient fossil-fuelled vehicles and alternative fuel and power sources while problems deriving from disposal of vehicles at end of life have encouraged EU legislation relating to the recycling and reuse of automotive materials and components. Although these factors are significant, evidence to date confirms that changes arising from the above and the overall trend in vehicle design and manufacture remain incremental.

7.1 Internal combustion engine vehicles

Since the oil crisis in the early 1970s vehicle manufacturers have sought to improve fuel economy by developing engine technologies, reducing aerodynamic drag and vehicle weight. Market forces and, more recently, government schemes such as the Partnership for New Generation Vehicles (PNGV) in the USA [106, 107] and the Foresight Vehicle and 'Clean Fuels' programmes in the UK [108] encouraged these developments as has a voluntary agreement between the European Commission and European Automobile Manufacturers Association (ACEA) reached in 1998 [109]. This committed manufacturers to reduce the CO₂ emissions from new passenger cars by over 25% to an average of 140 g/km by 2008 and was eventually followed by similar agreements in Korea and Japan.

PNGV stipulated that vehicles should be three times as fuel efficient as current conventional, mid-sized sedans, while improving recyclability and maintaining comparable performance, utility, safety, and cost of ownership. Ford subsequently produced the Prodigy (and later P2000), DaimlerChrysler, the Dodge ESX3 and GM, the Precept. The P2000 is an internal combustion engine vehicle constructed from aluminium, titanium, composites and other low weight materials and is therefore 40% lighter than a conventional vehicle and capable of 70 mpg. The ESX3 and Precept both exploit 'mybrid' or mild internal combustion–electric hybrid diesel technologies and are thus capable of 72 mpg and 80 mpg respectively [106]. The PNGV was cancelled by the Bush administration and replaced in January 2002 by FreedomCAR (for Cooperative Automotive Research). Energy conservation is no longer the primary issue and has been replaced by a move to hydrogen power produced from domestic renewable sources in order to reduce the country's reliance on imported oil. FreedomCAR is a public–private partnership between the US Department of Energy and the 'Big3', namely GM, Ford and DaimlerChrysler and although the new project refers to PNGV achievements, there is little if any intention of altering the typical US product characteristics in the way PNGV did. The vehicles developed under PNGV therefore remain concepts although it is possible that what was learned will influence car design in the future [110].

In April 2001 the British government also introduced graduated vehicle excise duty (VED) so that new (and generally smaller) cars with lower CO₂ emission levels are now subject to lower duty [109]. During the 1990s the percentage of smaller cars on the road increased and the Mercedes Smart Car (Fig. 31), for example, achieved cult status immediately after launch. However, it is too early to assess whether graduated VED has further influenced the choice of vehicle.

Diesel cars have been popular in mainland Europe for many years and have become increasingly common in the UK because distance travelled per litre is higher than that of petrol. CO₂ emissions are lower than from petrol and petrochemical research has led to reduced sulphur emissions [109], both of which are environmentally beneficial. However, diesel still produces damaging particulates and one detrimental emission is therefore exchanged for another. Nevertheless, research into various aspects of diesel and related engine technology is ongoing and lower fuel consumption could also encourage an increase in ownership of diesel cars ([54], pp. 28–29) [111].

The significance and impact of vehicle aerodynamics were discussed at length in *Design and Nature*, Volume 1 (The evolution of land-based locomotion: the relationship between form and

Figure 31: MCC Smart City Coupe, 2000.

aerodynamics for animals and vehicles with particular reference to solar powered cars), which demonstrated how a low coefficient of drag (C_d) contributes to energy efficiency. Most manufacturers have sought to reduce drag [112], one example being the Volkswagen Group who achieved a 30% reduction in their most popular models between 1980 and 1990. This is equivalent to a 10% reduction in fuel consumption further reductions of which will be concurrent with further reductions in drag [113].

In May 2002 Volkswagen revealed their latest concept car: a two-seater car capable of travelling 100 km on 1 l of fuel. This car is constructed from composite materials including carbon fibre, aluminium and magnesium and at 290 kg, weighs 430 kg less than the Mercedes Smart Car. At 3.5 m it is only 1 m longer than the Smart Car despite the fact that the driver and passenger sit in tandem (one behind the other). The single cylinder mid-mounted engine is a high-efficiency, direct-injection naturally aspirated diesel engine. These features in conjunction with low road resistance (comprised of aerodynamic drag and road/tyre friction) contribute to the fuel economy. The streamlined overall body form and reduced frontal area (A) mean that this car has a far lower coefficient of drag ($C_d A$) than other cars on the road. The tandem seating means that the car is 1.25 m wide and 1 m high. This makes for a frontal area of 1.25 m^2 which is half that of an average family saloon car at approximately 2.5 m^2 . The composite material wheels are only 400 mm in diameter, which with low rolling resistance tyres also contribute to fuel economy [114].

In addition to the above developments changes in materials in mass-market vehicles have reduced body weight and thereby fuel consumption. Since 1980, for example, the use of non-ferrous metals such as aluminium has increased and the use of thermoplastics and thermoset plastics has risen to approximately 10% of overall vehicle weight. Fundamental vehicle structure and manufacturing processes remain unchanged in the majority of cars despite the utilisation of lighter-weight materials although there is evidence of more radical approaches in some alternatively powered vehicles.

7.2 'Alternative' and emerging fuels and technologies

7.2.1 Clean Fuels

The British government describes liquefied petroleum gas (LPG), compressed natural gas (CNG), methanol, and ethanol as 'clean fuels' because CO_2 emissions are marginally lower than those

produced through petrol combustion. LPG is a by-product from petrol refining and, like CNG, is plentiful and with minor modification, these fuels can be used in petrol engines. Like diesel, they have been widely used in mainland Europe for many years, but lack of a fuel supply infrastructure prohibited use in the UK until recently. The 'clean fuel' and PowerShift programmes were launched in 2000 to encourage use of LPG and CNG in particular and supply has risen to more than 1,000 outlets although the majority of the 40,000 users are fleet vehicles. Nevertheless, as more LPG vehicles are produced, thus eliminating conversion costs, lower tax may yet encourage greater use by private owners [108].

7.2.2 Biodiesel

Biodiesel can be used in standard diesel engines and is processed from oilseed rape or recycled from used vegetable oil. Although biodiesel produces CO₂ and other emissions when combusted, it is also described as a 'clean fuel' because it is argued that the crops grown for fuel production act as carbon sinks and absorb CO₂. Again this fuel is comparatively readily available in mainland Europe but will be available in the UK from August 2002 where use could increase as a result of a 20p per litre reduction in fuel tax [115, 116].

7.2.3 Electric vehicles

Invented at the same time as the internal combustion engine, electric vehicles were initially as popular as their internal combustion counterparts and particularly among women drivers because they did not require cranking to start. They were comparable in speed but developments in internal combustion engine technologies led to travel at higher speed and that in conjunction with the development of the electric starting motor in 1912 and the limited range of electric vehicles contributed to the dominance of the internal combustion engine vehicle [117]. Nevertheless, developments in battery technologies (namely nickel metal hydride (NMH), nickel cadmium (Ni-Cd), lithium ion (Li-ion) and lithium polymer batteries) and more efficient motors and motor controllers have all increased the electric vehicle range [118, 119]. Some electric vehicles, known as conversions, are standard steel-bodied internal combustion engine vehicles with replacement electric powertrains (e.g. the Peugeot 106E (Fig. 32)) but others (including the Ford Th!nk, GM EV1 (Fig. 33) and Nissan Hypermini (Fig. 34)) embody a more radical approach and are described as 'ground-up' vehicles. These incorporate plastic body panels so that lower body weight therefore increases vehicle range.

Although limited, use of electric cars in California and particular European towns is considerably higher than in the UK where purchase is restricted to commercial operators. Average daily mileage in the UK is less than 16 km and so with an average range of 80 km urban and use of electric vehicles as second cars is perfectly feasible and if manufacturers open the private market in the UK electric vehicle ownership could also increase.

7.2.4 Internal combustion–electric hybrid vehicles

Introduced to the UK in 2000, the Honda Insight (Fig. 35) and Toyota Prius (Fig. 36) are both Internal combustion–electric hybrid 'dual-fuel' vehicles where an electric motor and batteries are combined with an internal combustion engine in order to reduce fuel consumption without limiting range. The two standard hybrid systems, series and parallel, operate slightly differently in that a series hybrid system utilises the heat engine to power a generator whereas in a parallel hybrid, power from the heat engine and generator is delivered directly to the drive train. Unlike a series hybrid, the electric drive in a parallel hybrid vehicle can therefore function autonomously or in conjunction with the heat engine [120].

Figure 32: Peugeot 106E.

Figure 33: GM EV1.

Figure 34: Nissan Hypermini.

Figure 35: Honda Insight.

Figure 36: Toyota Prius.

The two-seat Honda Insight and the four-seat Toyota Prius both switch between series and parallel hybrid mode. With lightweight plastic body panels, an overall weight of 773 kg (1700 lbs) and low drag coefficient of 0.25, the Insight combined (urban and motorway) fuel consumption is 83.1 mpg (3.4 l/100 km) [121]. The metal-bodied first generation Prius is more traditionally styled and constructed with a body weight of 1200 kg (2640 lbs) and a drag coefficient of 0.29. Consequently average combined fuel consumption is 57.6 mpg (4.9 l/100 km) [122] but this is considerably better than average UK fuel consumption at 30 mpg.

Like many pure electric vehicles, the Prius exploits regenerative braking to further charge the batteries. Again like electric vehicles, when stationary, the internal combustion engine does not run in either vehicle, thus reducing emissions and saving fuel although in certain circumstances, the hybrid's electric motor may continue to run. The Insight and the Prius are thus defined as super ultra-low emission vehicles under California Air Resources Board rules, with CO₂ emissions at 80 gm/km and 114 gm/km respectively. These levels are well below the permitted maximum of 140 gm/km for all new cars that will be introduced as an EU mandate in 2008 [109].

Some experts claim that, because hybrid technology does not limit range, it is the optimum means of reducing emissions until or unless battery and other electric vehicle technologies can be seen to compete with that of internal combustion engine vehicles. However, the dual system makes these vehicles more expensive than internal combustion engine equivalents and design costs alone are estimated to be between \$100 and \$300 million [123].

Both Honda and Toyota see these particular models as retail prototypes and both were 'loss-leaders' in that they are sold for less than the cost of manufacture [124, 125] but investment in the Prius has paid off and Toyota have now 'broken even'. Ford recently dropped the planned introduction of a hybrid version of the Explorer SUV in 2005, because, at 27 mpg, fuel economy was not as good as expected [123]. They still plan to introduce a smaller hybrid SUV, the Escape, with an urban fuel consumption of 40 mpg in 2003 [123, 126]. At a time when automotive industry profits have decreased, making manufacturers even more cautious than when the market is buoyant, it is possible that the high design cost of hybrids could deter some manufacturers from investing in hybrid vehicles and that only those with existing plant will continue production thereof.

7.2.5 Hydrogen fuel cell vehicles

First invented in 1839, fuel cells were developed by NASA for the Gemini and Apollo space programmes in the 1960s. Using gaseous or liquid hydrogen, methanol, ethanol or natural gas, electricity is produced by combining hydrogen and oxygen to produce water and is thus the reverse of hydrolysis. Fuel cells are comparable to batteries in that they store electricity, but, as opposed to being discarded like primary batteries, they are slowly and continually recharged while in use like secondary batteries [119]. The majority of current fuel cell applications are stationary, but the proton exchange membrane fuel cell (manufactured mainly by the Canadian company Ballard) has already been demonstrated both in buses and in several concept cars including the DaimlerChrysler Necar 5 (new electric car), the Jeep Commander 2 and the Honda FCX-V3.

Storage of liquid or gaseous hydrogen can be problematic because it is somewhat unstable when compressed, whether subjected to heat or cold. Research relating to the storage of hydrogen as NMH is ongoing but use of methanol as a hydrogen carrier appears to be the most prevalent solution for vehicle propulsion at present and has been adopted by Honda and DaimlerChrysler in all the above models.

The large physical volume of early fuel cells prohibited their use in anything other than concept cars because they occupied a considerable amount of interior space. The size of fuel cells has now been reduced and is reputed to be comparable to a standard internal combustion drive system. Had this not happened, fuel cell dimensions would have influenced overall vehicle size and in addition to prohibiting their use in smaller urban-type cars, would have adversely influenced fuel consumption. Similarly the cost of fuel cells was, until recently, 10 times higher than that of high efficiency diesel engines [127]. Costs have decreased but it is more than likely that, like the Insight hybrid vehicle, the Necar and others will be 'loss-leaders' in market research programmes. A further and significant reduction in fuel cell cost will be imperative if they are to become feasible power sources for personal transportation. Nevertheless, although prototypes for pilot programmes, in 2003 Honda intends to introduce 300 FCX-V3 or similar cars to the US and Japanese markets and DaimlerChrysler will introduce city buses in 2002 followed by a version of the Necar in 2004 [121].

Fuel cell systems are approximately twice as efficient as internal combustion engines, but although fuel cell vehicles emit only water, production of hydrogen from methanol or natural gas produces emissions although these 'up stream' emissions are lower than those produced by use of fossil fuelled internal combustion engine vehicles. However, as with pure electric vehicles, these vehicles could be truly zero emission if electricity generated from renewable sources is used for hydrogen production [128]. Because problems relating to the use of gaseous and liquid hydrogen are as yet unresolved, the use of sustainably produced hydrogen is unlikely in the immediate future.

As yet there is no fuel supply infrastructure, although DaimlerChrysler claim that oil companies are backing the development of a methanol supply infrastructure [121] which could include the decentralisation and installation of an on-site hydrogen production plant [128]. It is reasonable to suppose that not only will oil companies want to supply fuels in addition to oil derivatives, but that they will also support the most economic means of fuel supply via the existing filling station network in order to minimise investment costs.

7.3 EU policy on ELVs

Until recently there was no definite policy pertaining to vehicle disposal but recent EU legislation under the Priority Waste Streams Programme demands that this waste must be managed correctly. Thus, by 1 January 2007 a minimum of 85% of the average weight of a vehicle must be reused or recovered, rising to a target of 95% by 2015 including the recovery of energy through waste incineration. In addition to the banning of hazardous substances in cars from 2003, from July 2002, the EU directive will force manufacturers to pay for the disposal of cars manufactured after April 2001 and the subsequent disposal of all cars from 2007 [102].

7.3.1 The implications of EU policy

As could be expected this well-intended initiative is already provoking comment from motor manufacturers because these responsibilities will add approximately £250 to the price of a new car. In a recent consultation paper the Department of Trade and Industry stated that the total cost to business could be between £161m and £346m a year between 2006 and 2015 rising to £209m to £438m thereafter. The Society of Motor Manufacturers and Traders (SMMT) states that the cost of recycling should not just be the responsibility of manufacturers but also that of owners, insurance companies and financiers lending money for car purchases. SMMT also believes that the Treasury should contribute some of the value added tax gathered from new car sales towards recycling but as yet these financial issues remain unresolved [129]. Recycling facilities are limited at present and require investment for plant construction but whether they will be constructed in time to meet the legislation in the UK is unknown and the record for recycling to date is poor.

Recycling in parts of mainland Europe is reputedly better than in the UK at present where 80% of 28 million tonnes of domestic waste is put into landfill sites although EU law will force a cut to 33% by 2016. Members of the public have, however, already expressed concern about the impact of waste recycling and incineration plants near their communities [130, 131] and more protests may follow. In 2001, European legislation on waste electrical and electronic equipment was implemented. This requires the substitution of various heavy metals and brominated flame retardants in new electrical and electronic equipment by 2008 and until then products must be disposed of appropriately [132]. It is now illegal to deposit fridges in landfill but there are not yet adequate recycling facilities in the UK and although 900,000 fridges have been collected, they have been stockpiled until they can either be sent to Germany and the Netherlands for recycling or a new plant is opened in the UK [133]. Various bodies consequently fear that similar delays will affect automotive recycling.

7.3.2 Current automotive recycling

It has been suggested that although automotive manufacturers will be responsible for ELVs, the EU directive is not absolute and so certain components could be stockpiled on site. A review of current recycling issues and facilities indicates that there is no complete recycling infrastructure as yet and that changes in materials selection are probable.

7.3.2.1 Metals Recycling and disposal of metals varies according to type with 95 to 98% being recycled; these metals comprise of ferrous and non-ferrous metals including aluminium, copper and magnesium. Platinum, rhodium and palladium will also be recycled in greater quantities as more catalytic converters reach end of life and more ceramic casings will be recovered and powdered for refining [134–136].

7.3.2.2 Plastics Use of automotive plastics has risen to between 10 and 15% of total car components during the past 20 years, the majority of which are polyethylene, polypropylene (which accounts for approximately 40% of thermoplastics used), while polyurethane and polyvinylchloride (PVC) account for 12% of thermoplastics used. Variations in filler content and other additives including colorants mean that most cars comprise of up to 25 different types of both thermoplastics and thermoset plastics such as composites. PVC recycling is particularly problematic partly because it emits dioxins when incinerated and includes phthalate plasticisers, which are thought to be endocrine disrupters, and so there are currently no large-scale recycling schemes in operation. However, in addition to a proposed EU directive relating to the sustainable disposal of PVC [107], car manufacturers are currently investigating alternatives to PVC [137].

At present recycling of automotive thermoplastics is limited due in part to the way in which various types have been combined and because separation into type is deemed not to be cost effective. In some newer models, however, plastics recycling is now a design consideration although unlike metals (which can be reused numerous times) reuse of plastics (like aluminium) is limited because they deteriorate and lose their inherent qualities when recycled. Nevertheless, they can be used in non-structural elements as illustrated in Fiat's Cascade Recycling process: first use as a structural component like a bumper (Fig. 37), second use as a non-structural component like ventilation ducting (Fig. 38) and third use as floor covering (Fig. 39) [138]. EU legislation means that other companies are adopting similar strategies and the quantity of thermoplastics recycling should therefore increase. Composite and thermoset materials are more difficult to recycle because like eggs, when heated their chemical state changes. There is little composites recycling at present although they can be ground and used as filler but research into composites recycling is on-going.

7.3.2.3 Fluids The majority of fluids for disposal are lubricating oils accounting for 480,000 tonnes annually. Much waste oil collected for recovery in the UK is processed (by removing excess water and filtering out particulates) and burnt as fuel in heavy industry and power stations. However, tighter emission limits and fuel quality controls resulting from environmental legislation could mean a reduction in the amount of waste oil thus used. The preferred option for lubricating oils is re-refining for reuse as a base lubricant, although this does not currently occur on a large scale in the UK.

7.3.2.4 Batteries The recovery of lead-acid batteries in the UK is well established, the majority being collected by garages and local authorities. In 1998/1999 over 90% of the 144,000 tonnes consigned in England and Wales were recycled. However, many batteries are neither recovered nor recycled and may even be shredded within ELVs.

7.3.2.5 Restraint systems In 1993 secondary restraint systems such as airbags became standard components in all new UK vehicles and so some vehicles are arriving at car breakers' yards with undetonated airbags. Because they do not contain high value materials, reclamation is not a cost-effective option. However, vehicle manufacturers are being encouraged to make the dismantling thereof safer and more efficient [103].

Figure 37: Bumper (fender).

Figure 38: Ventilation ducting.

Figure 39: Floor covering.

7.3.2.6 Tyres Approximately 100,000 worn tyres are removed from vehicles every day in the UK, accounting for a total of 39.5 million tyres (467,650 tonnes) in 1998, 70% of which were recovered and reused. A significant proportion of the remaining 30% was buried as landfill where they will remain for decades because they do not degrade. However, from 2003, under the EU Landfill Directive, tyres will be progressively banned from landfill sites and so the Used Tyre Working Group is aiming for 100% recovery. Recycling and reuse include the production of retread tyres, granulation for use in children's playgrounds, running track surfaces and as carpet underlay and landfill engineering projects such as motorway embankments and a variety of marine applications. In 1998 energy recovery accounted for 18% of reuse and used tyres were incinerated to produce electricity for use by industry and local communities while two cement kilns now use tyres for fuel and other kiln operators are investigating their potential use [139, 140].

7.4 Summary

It is evident that the automobile design concept is static and that change in mass-market, internal combustion engine cars has been and continues to be incremental. At present the most radical design developments are found in concept vehicles such as those produced through the PNGV. The most innovative commercially available vehicles (e.g. the Ford Th!nk and the Honda Insight) use alternative power technologies and lightweight body materials to increase efficiency. They are 'ground-up' designs and therefore more akin to 'total design' solutions.

As stated in Sections 7.1 and 7.3.2.2 the composition of materials used for vehicle manufacture is already changing in order to reduce fuel consumption and the way in which cars are designed and constructed has developed to facilitate ease of recycling. However, the EU directive acknowledges that the guidelines on energy recovery could inhibit any increase in use of both thermo and thermo-set plastics [102]. Similarly thermo-set plastics and other lightweight materials including composites cannot be as readily recycled as thermoplastics which will in turn influence the design of lighter-weight vehicles.

Recycling processes also use energy, the amount of which will vary according to initial vehicle construction methods and material type. These factors must all be considered as part of the product lifecycle and design process, as must the production and disposal of toxic substances during both manufacture and dismantling. In short the increasing demands of environmental considerations mean that these form a significant constraint on overall design, and we now discuss the potential for change in automotive design and manufacture.

8 Potential changes in the automotive industry

The above information all indicates that current methods of designing and manufacturing mass-produced cars are contrary to the premise that all natural life forms minimise energy and material needs as a matter of survival. It is apparent that ownership and use of the private car is going to increase but rather than asking *what if* the car survives in its present form, we should ask *can* the car survive in its present form to which the answer should be *no*. It is also apparent that the need for change is urgent and that if the automotive paradigm cannot be changed immediately, it must change very soon.

We have seen several concept vehicles, the majority of which are more fuel efficient than current mass-market models but unless there is a significant change in manufacturing processes and paradigm, they will remain only as concepts. However, these are not the only examples of

radical thinking and we now discuss other potential solutions from both inside and outside the automotive industry.

8.1 The 'customised' car

In her book *No Logo* Naomi Klein discusses the many cultural and counter-cultural issues related to globalisation and associated product branding. There have already been anti-globalisation protests at G7 summits and Klein predicts that, based on current 'underground' reaction to multinationalism, corporate products and homogeneity will be rejected if not for political reasons then because consumers seek greater individuality [141]. Ironically some companies have already begun to exploit the potential for what has become known as *mass customisation*. For example, some Levi jeans' shops offer a 'tailoring' service with computerised measuring booths while an Internet-based luggage company allow customers to 'design' their own products. For the latter materials, colours, number of pockets and other details are selected from a range of options to produce customised bags. Similarly mobile phones can be personalised in various ways with clip-on covers, screen logos and ring tones either downloaded from the Internet or 'composed' on the phone itself.

As stated in Section 5.3 'Buddism' encouraged and is best suited to the manufacture of (ideally) millions of identical vehicles but there is evidence of car customisation both inside and outside the industry. We have already noted that Ford preferred black paint because it dried more quickly than lighter colours. Other pigment-related problems such as running or dripping have been eliminated so choice of colour has increased significantly. Industry's response to the increasing similarity between mass-market models (Figs 40–42) is the launch of 'limited editions': these models are cosmetically enhanced with graphics and/or special paint colours again to meet market demand for individuality. Alternatively owners can purchase add-on accessories (ranging from steering wheel covers to spoilers and wheel arches) at high-street retailers but the most extreme examples represent a sub-culture in which mass-market cars (known as 'custom cars') are modified by enthusiasts to the extent that original models are no longer recognisable. Such modifications involve significant manual input and are thus very costly and, because 'Buddist' car production does not lead to cars that are easy or cheap to modify, often exceeds the value of the car.

Markets, and in particular those in the industrialised countries, demand increasing differentiation and increasingly visual differentiation. The incumbent Buddhist production system centred round steel unitary construction cars cannot easily accommodate this. Consequently as the demand for differentiation increases and the resulting market fragmentation leads to lower per-model volumes, breakeven points can no longer be achieved for a growing number of models and the Buddhist paradigm will eventually be stretched beyond breaking point. The much-hailed *mass customisation* will therefore be accommodated within the narrow confines of 'Buddism', unless there is a paradigm change in mass car production.

The *mass-customisation* of vehicles can be extended beyond the application of cosmetic detail and over time will prove beneficial to consumers, the automotive industry and the environment. Increased design flexibility and 'tailored' vehicles will not only satisfy market demand for greater individuality but will also reduce materials and possibly energy consumption as vehicles are modified to suit owners' changing needs and desire for new models. This is of course dependent on adoption of new manufacturing paradigms which, by lowering the 'break-even' point, means that manufacturers are not restricted to the production of such large numbers of identical vehicles, thus permitting greater freedom of choice. One of the more radical concepts developed inside the automotive industry by GM is an example of *modular platform engineering* called AUTOnomy.

Figure 40: Nissan Micra.

Figure 41: Hyundai Amica.

Figure 42: Toyota Yaris.

Figure 43: GM AUTOnomy. Published with permission from General Motors.

8.2 AUTOnomy – reinventing the chassis

If we consider the existing car making paradigm, which we have called ‘Buddism’, AUTOnomy can be regarded as an extreme example of a ‘platform’ approach. In a platform strategy, the key elements of the monocoque and a limited set of powertrain and chassis components are shared among a number of models to reduce costs. This technique tries to combine a reduction in mechanical diversity with an increase in perceived diversity.

AUTOnomy (Fig. 43) is a concept vehicle and was exhibited by General Motors at the 2002 Detroit International Auto Show. Few commentators outside GM appear to appreciate the full significance of this concept; rather they focus on the fuel cell powertrain, which is of course novel. This vehicle consists of a flat base unit about 15 cm thick, which contains the entire fuel-cell powertrain and holds the wheels and suspension and, known by the GM engineers as the ‘skateboard’, is essentially an autonomous mobile structure. Unlike conventional internal combustion systems, fuel cell technology and the electric powertrain allow for very flexible packaging while use of various lightweight alternative materials in its body and its chassis mean that it differs significantly from the Buddhist solution. This ‘skateboard’ has one central ‘docking point’, which serves as a communications interface between the body and the powertrain module.

AUTOnomy is far removed from the steel monocoque and is based around a modular system. In some respects it reintroduces the separate chassis and body structures used by Henry Ford on the model T but fully exploits the separate body and chassis. Providing that the docking points are standardised, AUTOnomy allows for a wide range of bodies to interface with the standardised ‘skateboard’ powertrain unit. The current concept model is fitted with a two-seater sports car body although the standardised mass-produced ‘skateboards’ will accommodate saloon, estate, MPV, coupé, roadster and more radical body styles either made by independent small specialists or by mainstream manufacturers.

On the one hand this spells a potential return to the luxury cars of the past, which were supplied as a chassis onto which a body from a coachbuilder of choice was fitted. Within the modern idiom

it can on the other hand be compared with exchangeable covers for mobile phones. Storage space would probably prevent most customers from owning large numbers of bodies; nevertheless, many people might consider owning one or two spare bodies in addition to their daily driver. For daily commuting (if that still exists when such vehicles become mainstream) a sports car body could be used while an estate or MPV option could be fitted at the weekend. Alternatively, dealers or independent body rental firms could provide this service creating a new sub-sector. Bodies and 'skateboards' could be updated independently as technology needs, fashions and options change. More efficient powertrain items could be fitted to the 'skateboard' without affecting the bodies, provided the interface could accommodate such an upgrade. Much of such upgrading, including tuning to the needs of individual customer, could be carried out through software reconfiguration.

GM's AUTOmomy is the first purpose designed fuel cell vehicle. It also introduces drive by wire (or 'driver control unit') where all controls actuated by the driver in the body module communicate with the power module via the electric/electronic docking points in a dedicated control unit. The driver control unit works through a new generation 42 V electrical system supplied by Swedish firm SKF, and means that conventional pedals, steering wheel and steering column are no longer required. GM also argues that low tooling costs and the flexibility of dedicated body types for differing market segments could help to bring automobility to developing countries and hence to the 88% of the world's population who currently do not enjoy its benefits.

AUTOmomy is a significant attempt to start from first principles. Rick Wagoner (Chief Executive Officer at GM) claims that GM started by asking the question:

What if we were inventing the automobile today rather than a century ago? What might we do differently?

He was indeed correct when he went on to say that

AUTOmomy is more than just a new concept car; it's potentially the start of a revolution in how automobiles are designed, built and used.

All fixed points in the design are located within the 'skateboard' and, assuming that there are connections to the chassis, the body can be configured in any way. The traditional limitations of engine bay, bulkhead, steering column, pedals, suspension no longer exist thus permitting the body designer almost unlimited freedom. Being centred around people and their needs rather than the needs of the production system that makes the car (as is the case under the existing Buddist-Fordist system), AUTOmomy represents a return to true automotive design while the basic 'skateboard' structure would last . . . *'much longer than a conventional vehicle'* [142].

8.3 The hypercar and 'whole systems thinking'

Developed at the Rocky Mountain Institute (RMI) in Colorado, the 'Hypercar' (Fig. 44) is one of the most radical concepts to evolve outside the automotive industry. Amory and L. Hunter Lovins established the RMI in 1982 as

an entrepreneurial, non-profit organisation that fosters the efficient and restorative use of resources to create a more secure, prosperous, and life-sustaining world [143].

In addition to education programmes, the research and consulting team works with corporations, governments, communities and citizens to help them to solve problems, gain competitive advantage, increase profits, and create wealth through a more productive use of resources. Areas of expertise include the impact of businesses, communities, energy, buildings and land,

Figure 44: RMI Hypercar. Published with permission from Hypercar Inc.

climate, water and transportation and several RMI efficiency innovations have subsequently won awards.

The RMI credo is founded in systems thinking and the identification of interactions, while interdisciplinary knowledge of advanced technologies and techniques and end-use/least-cost analysis is used to develop integrative design solutions, one of which is the Hypercar.

Initially described as a 'supercar' Amory Lovins began to explore the synergistic benefits of combining ultra-light, ultra-aerodynamic construction and hybrid-electric drive in 1991. The team refined the concept, which was launched publicly in 1993 at the International Symposium on Automotive Technology and Automation and for which RMI received the Nissan Prize. Established in 1994, the Hypercar Center is dedicated to support the rapid commercialisation of ultra-light hybrid vehicles. Between 1994 and 1996 the Center concentrated on computer modelling and the publication of technical papers to prove that the Hypercar could meet all market requirements and that the innumerable technical challenges could be overcome. During the same period, the Center advised carmakers about the Hypercar concept and by mid-1997 it was engaged in various forms of discussion and collaboration with approximately 30 current or intending auto-manufacturers. Increasing interest from manufacturers then prompted the Center to launch Hypercar Inc. in 1999 in order to further develop the Hypercar concept through the application of innovative design and development practices, new automotive business concepts and the establishment of collaborative business and technology partnerships.

In the past many technical innovations which had been developed outside the automotive industry were purchased and purposefully shelved by individual motor manufacturers. The Hypercar Center adopted a radical strategy to avoid this situation and placed the majority of its intellectual property (published as *Hypercars: Materials, Manufacturing, and Policy Implications*) in the public domain. While raising capital for the Center this strategy also encouraged competition among carmakers and their utilisation of elements of Hypercar technology.

The Hypercar remains an ultra-light, aerodynamically efficient, hybrid-electric vehicle and further, hydrogen fuel cell technology ensures that the only emission is water. Use of a frameless monocoque body reduces the number of components required (currently about 15,000 in a standard internal combustion engine vehicle) while use of lightweight materials including carbon fibre and aluminium means that the vehicle is two to three times lighter than an equivalent steel-bodied model. Hydrogen fuel cells are also potentially easier to fabricate than internal combustion engines (which have about 1,000 parts). The vehicle uses 92% less iron and steel, 33% less aluminium, 60% less rubber and 80% less platinum than a traditional vehicle and production tooling costs are reduced by 90%. Similarly painting (which currently accounts for about 25% of production

costs and is one of the main pollutants produced during manufacture) will be eliminated as colour is embedded during moulding. The four principal manufacturing parameters (namely time from concept to street, investment in production, time and space needed for production, and the number of parts in the autobody) are subsequently reduced by a factor of 10. Other upstream pollutants and emissions are also minimised because the Hypercar requires no more than 10% of the amount of consumable fluids (antifreeze, brake and transmission fluids and oil) used by a standard vehicle.

As stated above the RMI applies systems thinking and interactions to develop design solutions. The Hypercar concept is, as an example of 'whole systems thinking', greater than the sum of its parts. We have discussed the history and evolution of the contemporary motor car and learned that change has been and is incremental. Lovins and his colleagues, however, returned to first principles and so the Hypercar is more than just a fuel-efficient transport solution. Like James Grier Miller's Living Systems Theory diagram (Fig. 2) that describes a hierarchy of systems beginning with *cells* and culminating with *supranational systems*, the Hypercar has been developed as a component within larger systems.

The RMI argues that the current automotive manufacturing paradigm is 'disintegrated' because the causes of and connections between problems are not defined. The increasing complexity of cars has produced increasingly specialist designers and engineers whose job is to improve and optimise a given component or subsystem. Consequently the modern mass-market car has evolved incrementally through small improvements in individual components and little change in the overall concept. The optimisation of isolated components frequently undermines the whole system because of a lack of integration and synergy, which, in the case of the car, has resulted in over-complex, oversize and inefficient designs.

Conversely the 'whole system' approach analyses the entire system (rather than individual components) and every element is considered simultaneously to reveal mutually beneficial interactions. Individually none of the defining features of the Hypercar offer enormous economic or technical benefits but when integrated, the resultant vehicle is at least three times more efficient, is less polluting, cheaper to run, and may even be cheaper to manufacture than traditional models.

The Hypercar has also been designed as a component within a larger system: prompted by the high cost of fuel cells (which is one of the factors that currently prohibits their use in cars), Lovins *et al.* propose means of both minimising costs and limiting pollution. They argue that cost will be reduced as production increases and advocate use of fuel cells in buildings to increase market share. The energy from the hydrogen will be maximised with 60% used for electricity generation; the remainder is then used to heat water to 77°C and to run heating, cooling and dehumidification systems. Excess electricity will be sold to the grid and the profit will pay for the methanol reformer, which is used to extract hydrogen for water. In-vehicle fuel cells could be purchased but leasing would be preferable and spread the cost. In order to cover leasing or purchase costs, when parked (which, for a typical car, is approximately 23 hours a day) a fuel cell vehicle would also be used as a generator. The car would be plugged into the electricity grid and the sustainably generated electricity would then be sold and both help to cover vehicle costs while reducing the need for supply from coal-fired and other polluting generators.

The final example of paradigm shift relates to scale of manufacturing plant, which is important because the US economy is, like so many others, dependent on the automotive and allied industries. Rather than decreasing the workforce, the RMI claim that Hypercar manufacture will employ as many if not more people although they will be employed in smaller, local and decentralised plants. As previously stated fuel cell costs are high as are the cost of composite body materials. In 1995 the cost of carbon fibre was 20 times higher per kilo than steel but this dropped to 12 times by 2000 with the prospect of further reductions. Some of these initial costs will be countered by cheaper tooling but vehicle purchase cost could also be limited by selling directly to the public. In the

Figure 45: 'Revolution' concept car designed by Hypercar Inc. using 'Hypercar' principles. Published with permission from Hypercar Inc.

USA vehicle production cost currently accounts for 50% of purchase price and so the Hypercar will be sold via the Internet in order to minimise overheads and thus purchase cost.

Hypercar Inc. claims that when produced, this will be a highly desirable vehicle. Congestion will thus inevitably exacerbate and the many social problems deriving from extensive car use, but the number of accidents should decrease. Crash testing has shown that innovative ultra-light vehicles are at least as safe as the standard cars due in part to structural design and dissipation of crash energy because composite materials absorb about five times the energy of steel. Lighter vehicles also means that injury to pedestrians and cyclists should be lower although the inclusion of rear view cameras and other safety features is also expected to reduce the overall number of accidents. Nevertheless, Lovins *et al.* advocate that car use should be discouraged by considering land use before mobility, developing genuinely competitive alternatives to private transport and making drivers pay the true cost of parking and driving ([22], pp. 22–47; [144–148]). However, in a country and culture in which the car is central, this seems more difficult to achieve than the straightforward introduction of an alternative to the steel-bodied, internal combustion-engined behemoth.

To date the Hypercar remains a concept on paper although Hypercar Inc. designed another vehicle based on the whole systems approach. Although not yet manufactured, a full-size model of the Revolution has been developed as shown in Fig. 45.

8.4 Summary

We have reviewed two radical alternative design and manufacturing paradigms, each of which will be technically and economically viable within the foreseeable future when a fuel supply infrastructure has been established. At present the greatest barrier to change appears to be manufacturers' lack of will. The introduction of mass-customisation and design flexibility through platform-based concepts such as GM AUTOnomy are both economically and environmentally beneficial. While these approaches meet current consumer demand for more individual and personalised products, given the prevailing attitudes of today's teenagers (and therefore tomorrow's car buyers), the introduction of design flexibility is essential to meet their future demands. Although adequate water and food supplies are of a higher priority GM claims that AUTOnomy would

contribute to automobility in the 'developing' world. As an exemplar of 'whole systems thinking' the Hypercar concept adheres more closely to living systems than other automotive paradigms. While significantly different to existing design and manufacturing paradigms, the Hypercar Center acknowledges that their model bypasses social lifecycle costs [149–152] and that there is a need for further development of composite and other recycling technologies. Therefore although full life cycle assessment is considered, it is not yet integral to their design process. Given that levels of car ownership will increase until 2050 and beyond it is now appropriate to discover if, how and when 'total design' is likely to be adopted as the preferred automotive design method and to learn about current practice.

9 LCA and automotive manufacture

During the past decade in particular there has been an increase awareness about and research related to aspects of vehicle lifecycle, much of which deals with propulsion systems and fuels and is known as the *well-to-wheel* or *mobility chain*. Analysis of the mobility chain includes primary energy consumption, greenhouse gas emissions, exhaust (tailpipe) emissions and pollutants through fuel extraction/energy generation and delivery of supply (upstream impacts), fuel use and disposal of hardware if appropriate. Both indirect and direct costs resulting from these activities are also considered. Other research relates to specific components and the *product chain* but as yet there is little life cycle assessment work relating to the integration and interrelationships between these chains in the form described in Fig. 46. We now investigate some examples of current practice beginning with a discussion about what should be included in a complete vehicle life cycle assessment.

9.1 Early eco-rating models

Although there is general agreement that cars are harmful to our environment, making a precise assessment of the environmental impact of a particular car is not easy. An ideal model developed

Figure 46: Vehicle LCA. Andrews, D. and Simpson, A.G. (adapted from Ogden, J., a diagram presented at the Workshop on Well-to-Wheels Comparisons for Alternative Fuelled Vehicles Nice France, May 14, 2001).

Figure 47: Car life cycle environmental impact. (Nieuwenhuis, P., Centre for Automotive Industry Research, Cardiff University).

by Nieuwenhuis and Wells in 1997 (Fig. 47) considers all materials, energy used and production of pollutants ([48], p. 140). The complexity and diversity of cars means that use of this model and conventional eco-ratings (such as those used for white goods) present insurmountable difficulties.

Nevertheless, a number of environmental ratings systems for cars have been used, notably in Germany [153, 154], Sweden's rototest (as used by *What Car?* magazine) [155], but also in the UK [156, 157]. These are all primarily aimed at private consumers. However, they omit a number of key indicators, such as product durability. In addition, the European Commission is introducing its own eco-rating for cars. This is currently based on CO₂ emissions, although a more comprehensive system will be introduced in due course [158].

9.2 The Centre for Automotive Industry Research (CAIR) Environmental Segmentation System (ESS)

Nieuwenhuis and Wells [159] presented a simple rating system aimed at corporate fleet buyers, who are facing the increasing pressure relating to their company's environmental performance and image. In the UK market, fleet or corporate sales represent between 50% and 70% of all new car sales, depending on the definition used. In 1997, for example, 1,018,419 cars were registered to businesses. This system used a number of proxies to represent a simplified lifecycle approach by using readily available data. It has since been used by a number of companies to 'green' their fleets. A number of approaches were tried, but for the sake of simplicity and availability of data it was decided to use a simple proxy formula representing the impact made by a vehicle on the environment. This formula is proving surprisingly robust and has been welcomed by

Table 1: The CAIR Environmental Segmentation System: examples. (Nieuwenhuis, P., Centre for Automotive Industry Research, Cardiff University).

Model	$L(m) \times w(m) \times wt(tonnes)$	ESS
MCC Smart City Coupe	$2.50 \times 1.51 \times 0.72$	2.72
Old Mini	$3.05 \times 1.41 \times 0.685$	2.94
Lotus Elise	$3.73 \times 1.70 \times 0.67$	4.25
Mercedes A140	$3.575 \times 1.71 \times 1.061$	6.48
BMW 3-series	$4.435 \times 1.70 \times 1.235$	9.31
Audi A4	$4.48 \times 1.735 \times 1.225$	9.52
GM EV1 by Saturn	$4.31 \times 1.765 \times 1.301$	9.89
Volvo V70	$4.71 \times 1.76 \times 1.42$	11.75
BMW 5-series	$4.775 \times 1.80 \times 1.41$	12.12
Audi A8	$5.03 \times 1.88 \times 1.46$	13.8
Lamborghini Diablo	$4.46 \times 2.04 \times 1.57$	14.27
Lexus LS 400	$4.995 \times 1.83 \times 1.68$	15.35
Land Rover Discovery	$4.52 \times 1.81 \times 1.92$	15.70
Mercedes S-class	$5.11 \times 1.88 \times 1.89$	18.15
Lincoln Town Car	$5.56 \times 1.945 \times 1.83$	19.79
Rolls-Royce Silver Spirit	$5.295 \times 1.915 \times 2.43$	24.64

industry experts. It relates to a vehicle's size and weight as follows:

$$\text{Vehicle length (metres)} \times \text{width (metres)} \times \text{weight (tonnes)} = \text{ESS}, \quad (1)$$

where ESS represents Environmental Segmentation System. As a proxy for the environmental impact of a vehicle it is a fair measure as it relates the vehicle's weight to its 'footprint' and thus relates literally to its impact on the earth, and on other environmental factors such as use of resources. Table 1 gives some examples of the performance of a range of cars in terms of this first measure [159].

This ESS figure is then used as an input measure for a formula that incorporates the vehicle's performance against the regulatory and agreed requirements for various emissions as well as enabling any other measure to be incorporated. The system illustrates the benefits of weight reduction in larger cars (e.g. the Audi A8 competes with the Mercedes S-Class) but also tackles the price anomaly that would put the Lotus Elise and Land Rover Discovery in the same segment. In each case we use the lightest variant listed; i.e. with the lowest level of specification. It must be remembered that optional extras can significantly increase the weight of a car.

Although the issues are complex it is increasingly important to make available some sort of eco-rating for cars. Both private car users and fleet buyers are beginning to expect such information while EU and individual country legislation and taxation is increasingly reliant on environmental criteria; an example is the UK company car taxation system introduced in April 2002 and based on CO₂ emissions. It is, however, important to move away from the narrow toxic emissions-only view of the environmental impact of cars, as previously argued in *The Green Car Guide* and *Motor Vehicles in the Environment* [54, 160]. The urgent necessity is to consider how to make motorised mobility sustainable, and we will now discuss this.

9.3 Towards sustainable automobility

Sustainability is the most fundamental of environmental concepts and ultimately defines any practice in which we cannot indulge indefinitely without lasting environmental damage or impact as 'unsustainable'. We will investigate what this means for the automotive sector below. However, practices may also be sustainable for shorter periods. Thus in one sense, oil use is sustainable for the next 10 years, less so for the next 150 years and is unsustainable in a pure sense, in that we cannot continue to use oil indefinitely.

But what does sustainability mean in practice? An environmentally sustainable motor industry would not use finite resources and would not cause pollution that could not be easily absorbed by nature. At first this appears to be an impossible task, but it is actually technically possible to operate in this way. The first requirement would be a 'closed loop' economy as discussed in Section 2.4. Given the secondary materials currently available to world economies, with judicious recycling a car could be made without extracting additional raw materials. Also any energy used in this process would need to come from sustainable and renewable sources and not cause pollution that could not be readily absorbed. This would of course also apply to the transport of these secondary materials.

Use of renewable energy sources would be part of the answer but although this technology exists, it is not yet widespread enough to make an impact. It may never in fact meet our current requirements, so in addition to a reduction in the overall level of consumption, a 'closed loop' sustainable system would also imply a dramatic cut in energy use. This would involve a correspondingly dramatic reduction in the numbers of new cars produced. Again this is all technically possible; although the means by which this can be achieved together with examples of best practice as analysed by von Weizsäcker and Lovins [161] are not yet practised on the requisite scale. Despite the apparent fanciful nature of these concepts, they are becoming mainstream among environmentalists as well as some regulators and in the longer term will be unavoidable. Thus these future concepts must be considered when devising any longer term strategy at the present time.

For several years, the new more comprehensive environmental sustainability concept was largely confined to the environmental and academic communities but an award-winning paper in the *Harvard Business Review* by Stuart Hart [162] brought it to the attention of the wider business community. Hart asserts that sustainability should not be confused with mere pollution prevention or waste reduction, but requires a fundamentally different mind set. He writes that: '*... in meeting our needs, we are destroying the ability of future generations to meet theirs*'.

Hart foresees the development of completely new technologies together with completely new types of businesses in order to meet emerging sustainability needs. He predicts that in the developed economies the demand for virgin materials will decline as reuse and recycling become more common and that over the next decade or so sustainable development will become one of the biggest opportunities in the history of commerce. He postulates that businesses will have to decide whether they are part of the problem or part of the solution. Hart does not ignore the car sector and states that '*Although the auto industry has made progress, it falls far short of sustainability*'. He also extends the concept of producers' responsibility of producers further than ever before when he asserts that

Companies can and must change the way customers think by creating preferences for products and services consistent with sustainability.

He concludes by saying that although changes in policy and consumer behaviour are essential, business can no longer hide behind these 'fig leaves' and must actively work to change consumer behaviour through education.

Figure 48: The four system conditions. (Nieuwenhuis, P., Centre for Automotive Industry Research, Cardiff University).

Figure 49: A model for sustainable automobility. (Nieuwenhuis, P., Centre for Automotive Industry Research, Cardiff University).

Inspired by The Natural Step (developers of which include Natrass and Altomare) a model for sustainable car making and sustainable automobility was developed at the Centre for Automotive Industry Research. The Natural Step is a practical model for business sustainability originally developed in Sweden and used by a number of companies. It recognises a number of basic principles, or 'system conditions' as given in Fig. 48 [163].

In Nieuwenhuis [164] these general conditions were adapted for automotive use and are shown in Fig. 49:

Clearly these simple statements describe an approach that is very far removed from current practice. Nevertheless, having established this set of desirable outcomes and a vision of a sustainable automotive future, we must ask how this could be achieved. One key element is the so-called closed loop economy which we discussed briefly in Section 2.5.

9.4 Achieving a closed-loop economy

We have already stated that in a 'closed-loop economy', firstly, no new raw materials are added and only the existing pool of secondary materials is used, reused and recycled, and, secondly, any

energy used in reusing and recycling has to come from renewable non-fossil sources. In addition, no net increase in emissions is allowed. This means that emissions must be readily absorbed, for example, by growing crops.

In practice many developing countries are much closer to a closed-loop economy than most of the developed world which, it must be admitted, is far removed from it. Nonetheless, there are some areas where economic reasons have encouraged a move in this direction. As we know, paper and glass already use some recycled material. Similarly, steel bicycle frames, for example, tend to be made from recycled steel sourced from minimills, rather than the predominantly ore-derived steel used for car bodies [165]. The incidence of such examples is increasing and in many cases the appropriate technology is available. The main problem lies with economics considerations, which do not yet encourage reuse and recycling. The taxation of raw materials would be one way of moving in the right direction and this and other policy measures are being discussed by environmentalists and environmental economists around the world. The vehicle-recycling sector in particular will also have to play a key role in any serious moves towards a closed-loop economy. Although apparently utopian at present, in the longer term such a move seems inevitable because most current calculations show that many key raw materials will run out during the present century.

There are other serious considerations: although there are already enough secondary materials in the world economy to sustain a (limited) automotive industry on this basis, the ability even to experiment with new alternative materials will be restricted unless diverted from other uses. As previously stated use of renewable energy has been growing rapidly in recent years, particularly in countries like Denmark, but availability is still very limited. Although there is scope for a dramatic increase in this area, a concurrent dramatic cut in energy use through increased efficiency would greatly reduce overall requirements and thus make a closed-loop economy more achievable.

9.5 'Total design' and the automobile

This agenda has major implications for all types of design and that of the automobile in particular. In order to bring these technologies closer to natural sustainable processes, designers will need to change their mindset. Working in harmony with natural processes will become a basic requirement and will obviously affect both the *mobility chain* (choice of fuel and powertrain technologies) and the *product chain*. The latter comprises materials selection, finishes and vehicle form, (which will influence production processes and energy requirements for manufacture) and vehicle performance characteristics and efficiency. Simultaneous consideration of both chains is of paramount importance because of the influence each has on the other, while customer appeal and utility are vital for business success. It will only be possible for the automotive industry to progress and to begin to resolve the many problems deriving from current design and manufacturing paradigms when LCA becomes a key element within the design process and design methods.

10 Conclusion

This chapter began with a discussion about the key characteristics of natural systems, one of which is that they are self-regulating. While they may be described as 'open' (in that they respond to change in their surroundings and adapt and evolve in order to survive), they are also 'closed loops' so that when life ends, for example, residual material forms nutrients and therefore energy for elements within the same or other systems. We then learned that records of man's inspiration from the natural world date from the Ice Age and that the concept of *mimesis* and 'producing something in the fashion of nature' dates back to Classical Greece. Subsequent academic study of the science

of biomimetics and formal recognition of its value to the design and engineering professions is, however, comparatively recent and really developed during the 20th century. An examination of biomimesis and living systems and their relevance to the automotive industry followed. This revealed that, like living systems, in order to create a 'closed loop' economy, the use and reuse of automotive materials must involve intermediate processes and the entire economy rather than the individual sector.

We then explained the design process and reviewed several current examples of design methods (including that developed by Stuart Pugh known as 'total design') and found them to be incomplete and described as linear activities. Having explained life cycle assessment, we proposed that there is an urgent need to update these models and to integrate life cycle assessment within design methods to make design a holistic activity; only then will Pugh's model genuinely warrant the name 'total design'.

It was then appropriate to discover why the motor car evolved in the way that it did and to compare it with the development of the radio and the personal stereo (or Walkman). We discovered that both the radio and Walkman were 'new inventions' and are thus described as *dynamic* products. The designers and engineers who developed these products were unconstrained by historical precedents and were therefore able to develop products around user needs. In contrast the immediate antecedents of the motor car were horse-drawn vehicles and, in addition to exploiting bicycle technologies, the earliest models were designed and constructed using traditional coach-building processes and materials. These cars were thus known as 'horseless carriages'. The motor car gradually developed a specific product identity but was still constructed using 'craft' processes. Henry Ford is usually credited with democratising the car and certainly increased availability by adopting Cadillac's idea of using interchangeable parts and by introducing the assembly line production process. However, Ford's fundamental error was to design this process around craft techniques and to then design subsequent models around the production process. Many of the ensuing problems related to body construction and were resolved by Edward Budd and Joe Ledwinka when they developed a welded steel body process (that is here called 'Buddism') and replaced the separate chassis and body with a monocoque body. Since then change in the automotive industry has been incremental. Although contemporary cars are now more fuel efficient, produce lower emissions and look very different to those produced during the 1920s and 1930s, the automotive industry still adheres to a Fordist-Buddist paradigm and the motor car is therefore described as a *static* product. Moreover cars are still designed around an out-dated manufacturing process rather than around the users; consequently as drivers and passengers, we have no option other than to use vehicles that at best only partly meet our changing needs.

Nevertheless, the car has become one of the most popular and ubiquitous products in the entire world and there are currently more than 600 million on the road globally; by 2030 there will be 1 billion and the global market is not expected to stabilise until at least 2050. Car ownership and use have both contributed to and been encouraged by societal, cultural and economic change and the car fulfils a variety of psychological and practical roles. All evidence shows that, despite the numerous negative outcomes from extensive car use, the automobile or a similar form of personal transport is here to stay. However, this expected permanence is not without problems. Pollution and emissions are produced during car use and manufacture, both of which also consume finite resources; materials and energy while current disposal methods create waste, landfill and other pollutants. There is therefore an unquestionable and urgent need for change in both automotive design and manufacturing paradigms.

Research into 'alternative' fuels is ongoing as is continuing improvement in fossil-fuelled internal combustion engine technologies. However, the majority of commercially available 'alternatively powered' vehicles are adaptations of the industry standard while the most radically

designed vehicles remain as concepts. On first reading, the EU directive on ELVs may appear to be a positive change and will undoubtedly encourage the redesign of vehicles to facilitate recycling and reuse. However, unless we learn from living systems and ensure that the 'closed loop' includes the entire economy rather than just the individual sector, opportunities to develop new design and manufacturing paradigms could well be limited and even though components, materials and technologies are recycled, many current issues will still remain unresolved.

Both GMAUTOmy and the RMI 'Hypercar' concepts represent an encouraging and dramatic paradigm shift and a return to first principles. In the Hypercar concept the vehicle is designed around the user rather than the production process. RMI adopted a synergistic approach to the problem describing the Hypercar as an example of whole-system thinking. As an example of platform engineering on the other hand, the GM AUTOmy offers a level of flexibility unseen in the mainstream automotive industry until now. Although both concepts embody economic manufacture and zero-emission energy efficient propulsion systems, neither project includes LCA and so it is not yet possible to assess the overall level of sustainability of either vehicle. Nevertheless, they are currently the most advanced automotive concepts and could be indicative of the future of personal transportation solutions.

In the final section of this chapter we stated the need to fully integrate the *mobility* and *product chains* because of the impact each has on the other. We acknowledge that while it is difficult to develop and apply a comprehensive vehicle LCA system there is a need for a more comprehensive eco-rating system because many current examples omit a number of key indicators, such as product durability. The CAIR Environmental Segmentation System is acknowledged as one of the more extensive models although this was developed in response to industry's existing needs rather than future requirements and resultant changes will therefore be incremental. Based on The Natural Step model for business sustainability, the CAIR Sustainable Car Making and Car Use models are, however, far more visionary than others and embrace all aspects of vehicle design and operation. Although they appear to be somewhat fanciful at present, it is inevitable that they or similar models will be utilised in the long term because many natural resources will be depleted during this century.

We conclude therefore that like living systems, the automotive industry must be prepared to adapt and evolve in order to survive. Change will include a return to first principles and the development of new design and manufacturing paradigms, which will be determined in part by the integration of life cycle assessment within the automotive design process and methods. The eventual integration of LCA is inevitable but until this happens there will always be unanswered questions about the optimum vehicle design solution. However, rather than waiting until this practice becomes mandatory, it would be economically, socially and environmentally beneficial for a holistic design process (involving genuinely 'total design' methods) to be adopted by the automotive industry immediately.

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