FOUNDATIONAL ISSUES OF ENGINEERING DESIGN

Peter Kroes

1 INTRODUCTION

The *homo faber* notion stresses the tool-making aspect of human agency.[1] Such tools are technical artefacts, they are the material outcomes of human productive activity (or work). Due to their increasing complexity, the production of technical artefacts has evolved; there has been a shift from experience-based crafts to professions where use is made of highly specialised scientific and technological knowledge. With professionalisation has come division of labour bringing to the fore the different kinds of activities that often remain implicit and inextricably intertwined in the crafts. One of the main divisions of labour follows the dividing line between the mental and physical activities involved in making technical artefacts, between conceiving a technical artefact and actually making or producing one [Dym, 1994, p. 15; Pahl and Beitz, 1996].[2] The conceiving side is termed designing and it is done by specialised professionals, namely designers. The result of any designer's work is a design of a technical artefact. A design, roughly, is a plan or a description (which may include drawings) of a technical artefact. As such, a design is not a technical artefact in itself but merely a representation thereof. A design may include a plan or a description of how to make the artefact in question and may go on to function as a blueprint for its physical realization, that is, for the actual manipulation of matter so that it results in a particular kind of material object.[3] It is in this making phase that the production or manufacturing engineers and the production facilities come into play. The designing aspect of making technical artefacts appears to be of particular importance in cases where making involves more than simply *re*producing an existing kind of technical artefact. Copying the design of a technical artefact is not really designing.

[1]For an interesting discussion on the notion of *homo faber*, see [Arendt, 1958].

[2]For instance, Pahl and Beitz [1996, p. 1] remark that "The mental creation of a new product is the task of the design or development engineers, whereas its physical realization is the responsibility of manufacturing engineers."

[3]The notion of making a technical artefact is ambiguous; it can refer to the intentional creation (designing) of an artefact with a particular function or to its actual physical/causal production (for instance involving workers in a production facility who may not know what they are producing); for an interesting discussion on these two interpretations, see [Thomasson, 2007]; here we concentrate on making technical artefacts in the first sense.

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Making designs or plans for new technical artefacts points to a feature of human agency that extends far beyond the domain of material production. We make all kinds of plans in the sense of considered series of actions, which may or may not involve the use or making of technical artefacts. The *homo faber* idea presupposes that human beings are *planning* agents, agents with the ability to form and execute plans [Bratman, 1987]. According to Bratman we are planning agents because we are, at least to some extent, rational agents in that we reflect on the outcomes of possible courses of actions, in other words, on the execution of possible plans. On top of that we need to plan our actions in order to coordinate our own actions in relation to the different goals we pursue simultaneously while coordinating our actions with those of others. The making of technical artefacts presupposes such planning capacity not only with regard to the production of an actual artefact on the basis of a plan or design but also with regard to the planning how to use the technical artefact in question. In Section 7 we will argue in more detail that engineering design may be interpreted as an activity of making 'use plans'.

In order to avoid misunderstanding it is necessary to qualify the above-mentioned sharp distinction between the designing and the producing of technical artefacts in terms of mental and physical activities. Especially when it comes to mass produced products, the designing of a technical artefact may also involve actually making a prototype. The function of such a prototype is to test and evaluate the proposed design before it goes into mass production. In much engineering design practice demonstrating that a proposed design 'works' by building a prototype is seen as an integral part of the actual designing phase. In such cases, the actual mass production of the technical artefact remains external to the design task but the designing part itself is no longer a purely mental activity since it involves building and running experimental tests on prototypes. Still, the outcome of the design phase, insofar as it is a plan for a technical artefact, is a mental product. In some design practice prototype creation may be virtually impossible (for instance, when designing a new harbour). Even then drawing a sharp distinction between design and production may be problematic because during implementation it may well be necessary to redesign part of the original design so that the design activity actually extends into the production phase. So, while conceptually we may distinguish between the mental and physical creation of technical artefacts it may, in practice, be difficult to separate them.

In the following discussion we will restrict ourselves to the design aspect of creating or making technical artefacts. This is generally considered to be the most interesting aspect because it is assumed to require a degree of intelligence and creativity, whereas the actual production side simply involves executing a plan (the design) whilst tapping the appropriate physical and organisational skills and making use of production facilities. This attitude towards the design and production aspects of technical artefacts may reflect the rather pervasive difference in the way science and technology have been appraised as part of Western thinking since Greek antiquity. We will not question this attitude here but will merely reiterate our observation to the effect that in actually making technical artefacts both aspects may be intertwined in inextricable ways.

We will focus on the engineering aspects of designing and not so much on the aesthetic aspects. Clearly, in some engineering design practice, such as in industrial and architectural design, aesthetic considerations often play a prominent part. There the notions of designing and design are often primarily associated with the aesthetic qualities of designed objects and aesthetic criteria may figure prominently in the criteria used to evaluate proposed designs. Such engineering design practice comes very close to art. In many branches of engineering design, though, aesthetic considerations only play a minor role, if at all. There it is the design and development of technical artefacts that can fulfil practical functions that takes centre stage. In those branches, proposed design solutions are primarily evaluated on the basis of criteria such as effectiveness, efficiency, costs and durability rather than on aesthetic criteria. It is this kind of engineering design, in which the solution to technical problems has a major role, that we are primarily interested in here.

Two questions relating to engineering design will concern us: (1) What kind of activity is engineering design? and (2) What is a technical design? The first question in which the notion of design is verbal is about the process of designing; while the second is about design in the nominal sense and so concerns the outcome of a design process.

Before we can turn to these questions there is yet another preliminary issue that has to be addressed. Just a brief look at the range of engineering design disciplines and at the divergence in the kinds of things designed by engineers is sufficient to make one question whether it is indeed sensible to endeavour to generally characterise engineering design either as a process or as a product. There are dozens of different engineering disciplines (mechanical, electrical, civil, chemical, agricultural, bio(medical), material, mining, computer etc.) that design myriad products ranging from mass produced computers to purpose-built oil platforms, from telephones to high rise buildings, from components to complex systems, from micro-organisms to software, from multi-purpose materials to highly specialized single-purpose devices etc. Accordingly there is also great variety in engineering design practice, not only as far as the required competences and skills of design engineers goes but also in the composition of the design teams. Some design projects may be carried out by a single designer while others require large, multidisciplinary teams of design engineers. There is also much variety in the kinds of design problems that need to be solved. Vincenti [1990], for instance, distinguishes between normal and radical design problems and between design tasks that are high and low in the design hierarchy.

Does such variety reflect any unity? Is it possible to generally characterise engineering design processes and to pinpoint domain-independent principles and procedures for engineering design? This has been a topic of controversy (see, for instance, [Reymen, 2001]). Naturally much depends on the level of abstraction chosen. It is easy to cite very general problem solving strategies (e.g. analyse, synthesise and evaluate) to characterise engineering design but in that way much if not all of what makes engineering design a specific kind of problem solving is lost. Conversely, if we zoom in too much it becomes difficult to recognise the common elements in different design practices. One factor driving the search in engineering practice for systematic, domain-independent design principles is the ever-growing complexity of the objects of design. In recent decades this has led to the emergence of new fields such as system design and design methodology which study the principles and procedures of engineering design in order to rationalise and improve design practice [Sage, 1992; Cross, 1994 (1989); Hubka and Eder, 1996; Pahl and Beitz, 1996; Dym and Little, 2000]. Within these fields, the analyses of and proposals for engineering design methods are often domain-independent. In the following section we will take as our starting point some general, domain-independent features of engineering design as proposed by engineers themselves.

2 ENGINEERING DESIGN AND SCIENCE

Modern engineering design is a science-based activity but that does not make it a branch of applied science. Indeed, the solving of design problems is taken to be something very different from the solving of scientific problems. Designing is even considered by some to be the salient feature of technology that distinguishes it from science [Mitcham, 1994, p. 220]. We will discuss two features of engineering design that make it an intrinsically different activity from scientific research. The first concerns the decisional nature of engineering design, the second the wide variety of constraints laid down for designs.

As our starting point we take the following general characterisation of engineering design by the Accreditation Board for Engineering and Technology (ABET); it states that engineering design:[4]

> is the process of devising a system, component, or process to meet desired needs. It is a decision-making process (often iterative), in which the basic science and mathematics and engineering sciences are applied to convert resources optimally to meet a stated objective. Among the fundamental elements of the design process are the establishment of objectives and criteria, synthesis, analysis, construction, testing and evaluation.

Although not explicitly stated, the systems, components and processes devised are assumed to be of a material nature; the design of (part of) an organisation or institution is not considered to be the domain of engineering design proper.[5]

[4] http://www.me.unlv.edu/Undergraduate/coursenotes/meg497/ABETdefinition.htm; accessed November 14, 2006. Note the prevalence of the technology-is-applied-science idea in this conception of engineering design: the application of scientific knowledge to engineering design is explicitly mentioned.

[5] According to Simon [1969/1996, p. 111], however, the intellectual activity of designing material artefacts is not fundamentally different from the designing of organisational structures or procedures.

The stated objective is laid down in what is usually termed a list of specifications. The list is derived from the function or functional requirements that the thing to be designed (i.e. the system, component or process) is expected to satisfy. These functional requirements are related, in turn, to certain human ends (or needs). If the designed artefact meets all the specifications, it is deemed suitable to realize the desired function. Whether that indeed turns out to be the case depends very much on whether the list of specifications adequately meets the functional requirements. If it does and if the reasoning from end to function has also been performed adequately, then the designed artefact may be expected to be a reliable means to the specified end.

A striking feature of the ABET definition given above is that it characterises engineering design as a *decision*-making process and not simply, as is so commonly done, as a problem solving process. Characterising engineering design as mere problem-solving may indeed be misleading because of the dominant view that problem-solving involves finding or discovering the 'right' solution, the solution which, in principle, is uniquely determined by the problem structure. This discovery-picture has been traditionally associated with the kind of problem-solving that takes place in science or mathematics but it does not correspond to the kind of problem-solving peculiar to engineering design. Design problems are often ill-structured [Simon, 1984] or wicked problems [Rittel and Webber, 1984], which for instance means that there may be no definite formulation of the design problem itself, insufficient criteria to evaluate proposed solutions and no clear idea of the solution space. As indicated by the ABET definition, engineering design is partly all about clearly establishing objectives and criteria by which to judge the proposed alternatives. Decisions thus have to be made that are to a large extent underdetermined by the problem formulation. Such decisions may have a significant effect on the aim and the outcome of the design project. But even if there is a clear and unambiguous formulation of the objective in the form of functional requirements together with a list of specifications, decisions have to be made concerning the promising options to work on. It may turn out that some of the specifications conflict in which case decisions about trade-offs have to be made. Alternatively, given the state of the art technology or the available resources it may not be possible to come up with a solution that satisfies all specifications. One then has to decide how the list is to be adjusted. When there is a set of alternative solutions satisfying all the specifications, there is no guarantee that one particular solution can be embraced as the best or optimal solution for rather fundamental reasons linked to multiple criteria evaluations [Franssen, 2005]. In such cases the lack of rational procedures leading to the determining of the best option means that decisions again have to be taken about which option to choose.

These various kinds of decisions are all part and parcel of engineering design practice. The actual decisions taken may have far-reaching consequences for the outcome as they will shape the artefact that is being designed. This 'decisional' nature of engineering design reflects the idea that engineering design is much more a process of invention than a process of discovery. It is about the creation of new objects, not the discovery of what already exists. So the decisional nature of engineering design is not so much to be interpreted as the making of choices between pre-given, existing options but as the creating of various design options leading to the final technical artefact by making decisions that fix their properties.

Note that not all the problems that have to be solved in engineering design necessarily involve the kind of decisions discussed above; for instance, part of a design process may involve 'finding out' the maximum load a proposed construction can bear. Such problems are the domain of technological (engineering) research; they are not the kind of 'creative' decisions that have to be made when solving design problems.[6]

The second important feature of engineering design to be discussed here is the variety which exists in the kinds of constraints that design engineers have to deal with when designing. According to the ABET engineering students have to learn to solve engineering design problems under a (*ibidem*) "variety of realistic constraints, such as economic factors, safety, reliability, aesthetics, ethics and social impact." This variety of constraints is reflected in the list of specifications, which means that a variety of factors (economic, safety, reliability, ethical etc.) determines the design problem and the ultimate shape of the object of design. With scientific problems such constraints are virtually absent; because of this scientific and engineering design problems are essentially different.[7] Both domains are governed by different kinds of values, norms and success criteria. According to the 'ivory tower' model, science as a cognitive activity is ideally guided by epistemic values only, such as truth, empirical adequacy, simplicity and explanatory power. In practice this view of science may be inadequate but it nevertheless highlights an important feature of scientific research, namely that from a cognitive point of view the results ought to be basically independent of the wider social context. More or less the same may be said of engineering research or 'applied science': once the technologically interesting topics have been chosen, the research will proceed according to the same values as those abided by in science. Research, whether scientific or technological, is mainly guided by the values and norms of theoretical rationality that deal with the issue of what to believe.

In contrast to science, the wider social context is of paramount importance to engineering design, since it is embedded within a broader framework of product creation processes. As part of these processes, problem solving in engineering design is subject to other kinds of values, norms and success criteria. Proposed so-

[6]This is not to say that science is not a creative enterprise. In science the creative aspect is traditionally considered to reside primarily in the activity of representing some pre-existing world, not in creating that world. This traditional view of science has come under attack from social constructivist quarters (see, for instance, [Barnes *et al.*, 1996]). Hacking [1983] has also challenged this view by claiming that in experiments physical phenomena are created. For a criticism of this view, see [Kroes, 2003].

[7]Of course, just as in engineering design, scientific research as a human enterprise is subject to all kinds of constraints, for instance, constraints deriving from the limited resources, the risks associated with performing experiments, the possible social consequences etc. In this respect, there is not much difference between engineering design and scientific research.

lutions are evaluated in terms of pragmatic criteria such as effectiveness, efficiency, feasibility, costs and safety. Indeed, engineering design is guided by the demands of practical rationality, with issues relating to the course of action to take in order to achieve given ends. These kinds of actions and ends are always embedded in broader, value-laden social contexts that impose their own constraints on viable solutions. These constraints may change in the course of time; for instance, in recent decades sustainability has emerged as a new important constraint on engineering design.

The following domain-independent definition of engineering design by Dym [1994, p. 17] suggests that engineering design is subject to two different kinds of success criteria:

> Engineering design is the systematic, intelligent generation and evaluation of specifications for artifacts whose form and function achieve stated objectives and satisfy specified constraints.

One set of criteria for evaluating proposed design solutions is the list of specifications that has to be 'achieved' and is derived from the stated objective and related function. The other set consists of constraints that have to be 'satisfied'. Dym remarks that one may question whether a clear distinction between the set of constraints and the list of specifications can be made. For instance, the condition that a car engine has to satisfy a legal standard in conjunction with pollution may be taken as an element of the list of specifications but it may also be seen as a constraint. Whether the distinction is meaningful or not, it is the variety in kinds of constraints/specifications imposed on design solutions that is important. Because of this variety conflicts between constraints/specifications may easily arise (for instance, between safety (more mass) and sustainability (less mass) requirements for cars). This is the reason why finding 'clever' trade-offs between conflicting specifications/constraints plays such a prominent role in engineering design practice.

These two features of problem solving in engineering design, its decisional nature and the wide variety of constraints, are what make it an activity that is very much distinct from the kind of problem solving that goes on in science. Although modern technology is science based, problem solving in engineering design is not a type of 'applied science'. Any characterisation of engineering design as an activity deriving from science neglects or downplays the importance of the features sketched above. Below, in Section 5, we will discuss yet another feature that distinguishes design from scientific research. It concerns the kinds of reasoning employed by scientists and design engineers in their problem solving. Virtually all analyses of scientific reasoning amount to variations of inductive, (hypothetical-)deductive or abductive forms of reasoning. In designing, a different kind of reasoning takes centre stage, namely means-end reasoning. For a further explanation of the nature of engineering design we first turn, however, to the work of Simon who in his classic *The sciences of the artificial* [1996 (1969)] presented an analysis of technical artefacts and of designing that nicely indicates what engineering design is all about.

3 THE NATURE OF ENGINEERING DESIGN

According to Simon engineering design deals with the synthesis of artificial things and engineers, in particular designers, are [1969/1996, p. 4-5] "concerned with how things *ought* to be — how they ought to be in order to *attain goals*, and to *function.*" Instead of taking the world for what it is (as in science) engineering design seeks to change the world to meet given needs, desires or goals. More specifically, engineering design contributes to the development of the material means that people may use to achieve their goals. These material means, technical artefacts, have a function; when functioning and used properly they are supposed to bring about effects that are conducive to achieving the ends associated with their function. The normative character of what engineers have to deal with is reflected in normative statements about technical artefacts.[8] A malfunctioning television set or a bad screwdriver are not the things they ought to be in the sense that they do not show the kind of behaviour (when used properly) they ought to show.

Simon analyses the function or purpose of a technical artefact in the following way [1969/1996, p. 5]:

> Let us look a little more closely at the functional or purposeful aspect of artificial things. Fulfilment of purpose or adaptation to a goal involves a relation among three terms: the purpose or goal, the character of the artifact, and the environment in which the artifact performs.

For instance, the purpose of a clock is to tell time and the clock's character has to do with its physical makeup (gears, springs etc. in the case of a mechanical clock). Finally, the environment is important because not every kind of clock is useful in every environment; sundials can only perform their function in sunny climates. Simon's analysis of artefacts is represented in a schematic way in Figure 1.[9]

According to Simon the environment of an artefact is very important because it is what moulds the artefact. He considers the artefact to be a kind of [1969/1996, p. 6] 'interface' between "an 'inner' environment, the substance and organization of the artefact itself, and an 'outer' environment, the surroundings in which it operates." The inner environment of the artefact, its character, is shaped in such a way that it realises the goals set in the outer environment. Therefore, the science of the artificial must focus on this interface, since the [1969/1996, p. 113] "artificial world is centred precisely on this interface between the inner and outer environments; it is concerned with attaining goals by adapting the former to the latter."[10] The task of engineering design is to come up with descriptions of

[8]For an analysis of the normativity of technical artefacts, see Franssen's contribution to this Volume.

[9]The arrows stand for conceptual implication: the notion of an artefact conceptually implies the notion of a character, a goal or purpose and an environment.

[10]This remark suggests that there is just a one-way influence from the outer to the inner environment. The design of technical artefacts, however, may also be a matter of adapting the outer to the inner environment (for instance, by adapting the behaviour of prospective users through training).

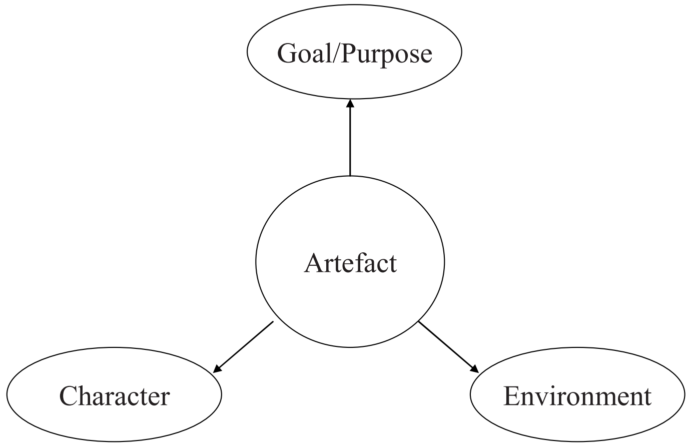

Figure 1. Simon's interpretation of a technical artefact

technical artefacts for which the inner environment is appropriate or adapted to the outer environment.[11]

What makes Simon's analysis of technical artefacts and engineering design so interesting is that it draws attention to the tensions between the inner and outer environments of technical artefacts, the tension between what artefacts do or are capable of doing, and what they are expected to do within some context of human action (i.e. the 'rich' outer environment that imposes so many constraints). It is this tension which, according to Staudenmaier [1985, p. 103], is the defining nature of technology. Indeed, engineering design is about filling in the "substance and organisation" of the inner environment so that it meets all the requirements or constraints imposed from the outer environment. In so doing, engineers have to take into account what is physically and technologically possible. It is the tension between the set of physical and technological constraints that apply to the contents of the inner environment and the set of constraints that derive from the outer environment (contextual constraints: functional specifications and other requirements) that defines the core of engineering design (see Figure 2) (for more details, see [Kroes, 1996]). This tension is one of the main driving forces behind the development of technical artefacts (see, for instance, Petroski's [1992] principle of 'form follows failure'). Obviously apart from these 'market pull' factors, advances in technology may also drive the development of technical artefacts (the 'technology push').

This interface character of technical artefacts explains the difficulties engineers have when disambiguating and fixing the meaning of the notion of function, especially in relation to notions of behaviour and purpose. Rosenman and Gero

[11]It is the distinction between inner and outer environment that also lies at the basis of Hubka and Eder's [1996, p. 108-114] theory of the properties of technical systems (technical artefacts).

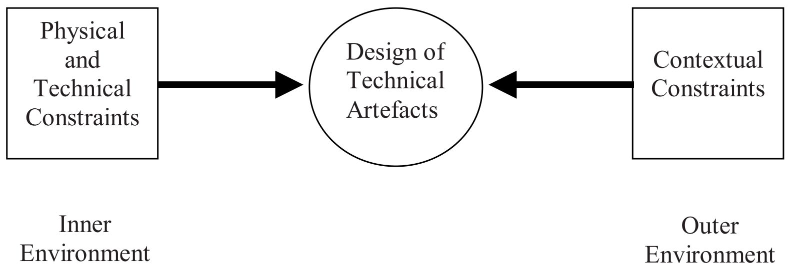

Figure 2. Design and the tension between inner and outer environment

[1994, p. 199], for instance, remark that engineering design involves concepts from "both the human sociocultural environment and the physical environment"; this means, in Simon's terminology, concepts from the outer and inner environment. Within engineering practice, functions are usually represented in terms of input-output relations. However, there is no consensus on whether functions correspond to properties of the physical system making up the inner environment of the technical artefact or to properties of the outer environment in which the artefact is embedded. The former interpretation links it to physical properties (capacities) of the technical artefact, the latter to the ends pursued in the outer environment. Pahl and Beitz [1996, p. 31] apply "the term *function* to the general input/output relationship of a system whose purpose is to perform a task" whereas Hubka and Eder [1996] interpret the notion of function in terms of the internal processes taking place within a technical system. According to Roozenburg and Eekels [1995, p. 96] "the function of a system is the intended transformation of inputs into outputs." Sometimes a distinction is made between two different kinds of function, one referring to actual behaviour, the other to intended behaviour (see Chandrasekaran [2005] for various definitions of functions within an engineering context; Chandrasekaran and Josephson [2000] distinguish between environment-centric and device-centric views on function, which roughly correspond to functions as seen from the outer and inner environments). This ambiguity surrounding the notion of function appears to be closely connected to the fact that technical artefacts act as an interface between a social/intentional outer environment and a physical inner environment.

Simon's distinction between inner and outer environment points to two different ways of contemplating technical artefacts. Looked at from the outer environment, which is typically the user's perspective, the technical artefact presents itself primarily, whatever its inner environment, as a means for achieving a goal or end. From this means perspective the artefact is characterised primarily in a functional way; the inner environment remains a black box. If we look at it from the inner environment and forget that the object is the result of a process of adaptation to the outer environment then the artefact presents itself merely as a physical system; from this perspective, the goal that it fulfils in the environment remains a black box. This is typically the way a physicist would analyse a technical artefact. As Simon [1969/1996, p. 7] remarks: "*Given* an airplane, or *given* a bird, we can analyse them by the methods of natural science without any particular attention to purpose or adaptation, without reference to the interface between what I have called the inner and outer environments."

Different kinds of descriptions of technical artefacts are associated with the inner and outer environments or with the physical and functional descriptions. If we take engineering design to be a process of devising an artefact that is adapted to some specific environment, then it starts from the outer and proceeds to the inner environment. So, engineering design may be interpreted as a process in which a transition is made from a function to a physical structure.

4 ENGINEERING DESIGN: FROM FUNCTION TO STRUCTURE

From the point of view of the object of design, an engineering design process does indeed start with a description of the anticipated behaviour of that object, (i.e. its function), and end with the description of a physical structure that realises that expected behaviour.[12] In engineering design, therefore, a functional description of an object has to be translated into a structural description. The latter description specifies, for every relevant detail, the geometrical and all the other physical and chemical properties of the technical artefact. What is relevant in the description is primarily determined by the function of the technical artefact. Anything that has a direct bearing on the performance of the function is relevant. Let us first have a closer look at these two different ways of describing.

In a functional description the object of design is represented as a 'black box', which is the means that transforms a certain input into a desired output. Quite how this input is transformed into the output is left in the dark. It is precisely the aim of the design process to come up with a viable proposal for how this may actually be achieved. Depending on the case in hand, the input and output may be described either in a more qualitative or or a quantitative way. For instance, in the ASM Handbook *Materials Selection and Design* [1997, p. 22 ff] the function of a fingernail clipper is described as serving to "remove excess length on fingernails" and the inputs and outputs of this function are specified in terms of energy, material and signal flows (see Table 1; also [Otto and Wood, 2001, Ch. 5]).

In certain cases, the relation between input and output may be partly represented by a mathematical function, for instance the relation between the input and output signal of an electronic circuit. Note, however, that in these cases the mathematical function is not to be confused with the technical function of the electronic circuit. The mathematical function can only *partly* represent the technical function because it does not include the normative aspect of the technical function (that is, that the device ought to, or is intended to realise the specific mathematical relation between input and output signal).

[12]See also [Dym and Little, 2000, p. 113].

Table 1. Input and output of fingernail clippers

	Input	*Output*
Energy	Finger force Kinetic (hand motion)	Sound Sound Kinetic energy in nail
Material	Fingernail Hands, Debris	Cut nail, Hands Debris
Signal	Long nail, hang nail, rough nail	Good appearing nail

A purely functional description is opaque with regard to the structure of the object that realizes the function. This is a direct consequence of the fact that a functional description is the result of viewing the object from a means-end perspective. What is of primary importance from this perspective is that an object, irrespective of its specific constitution, can be used as an effective and efficient means to a certain end. In other words, this is — as already mentioned — typically the perspective of the user of a technical artefact.

When we turn our attention to structural descriptions of technical artefacts, the situation is the reverse: just as a functional description is opaque with regard to the structure that realizes the function described, so a structural description of an object is opaque as regards the function performed by that object. Just to illustrate this, imagine that the fingernail clipper of Figure 3 drops out of an aeroplane and lands at the feet of the chief engineer of an as yet undiscovered tribe in the Amazon forest. She carefully studies the structural properties of this object that is totally unknown to her and its behaviour under various circumstances before coming up with all kinds of input-output schemes, that is, with all kinds of possible functions. If she is lucky, the input-output scheme of Table 1 will be among these functions. But even then, how is she to determine which one of the many input-output schemes is the intended one corresponding to the function of this object? In principle this appears impossible on the basis of a structural description of the object; even the most detailed description of all structural properties of the object and of its physical/chemical behaviour will not enable the engineer to deduce that it is a fingernail clipper.[13] Thus, from a functional point of view, a structural description is also a black box description. The situation is in fact symmetric from the point of view that each mode of description black boxes the other.

Purely structural descriptions of technical artefacts are typically of interest in the context of the production of technical artefacts. Such descriptions provide all

[13]Such situations may occur in archaeology but also in ‘reverse engineering’, in which technical products are taken apart in order to analyse their working and the functions of their parts. Sometimes it may not be possible to reconstruct the function of a part on the basis of its physical properties and its place in the whole artefact.

Figure 3. A 'physical object' with input-output relations

the information that is necessary for the making of a technical artefact; in principle it is not necessary to know the function of the object being made. Examples of purely structural descriptions of technical artefacts underscoring their importance for engineering practice may be found in ISO norms for standardised technical objects. In order to ensure that such standardised technical objects can in practice be replaced by any other item of the same kind, these norms minutely register every relevant structural detail.

Structural and functional descriptions of technical artefacts correspond to descriptions from the physical and design stance as defined by Dennett [1987, p. 15 ff]. Nevertheless, the role of such stances in engineering practice differs from that attributed to them by Dennett. His distinction between the physical and design stance is of a methodological nature; it concerns the best strategy for predicting the behaviour of systems. Depending on the complexity of the system under consideration, the behaviour of a system may best be predicted from a physical or a design stance (here we do not consider the intentional stance). Descriptions from the physical and design point of view always provide different ways of dealing with the same problem of predicting behaviour. Within engineering design practice, the structural (physical stance) and functional (design stance) descriptions have different methodological roles to play. In this respect it is not the prediction of the behaviour of an already existing system that is at stake, but rather the design of a system that is expected to exhibit certain behaviour. The description of an object *qua technical artefact*, that is, as a physical object with a function, requires a structural *and* a functional description, irrespective of the complexity of the relevant system. The difference regarding the methodological role of these two types of description clearly comes to the fore with simple technical artefacts. It is often possible to apply either the physical or the design stance to predict their behaviour. In such cases, the structural and functional descriptions become alternative descriptions for predicting behaviour. From an engineering point of view, however, they are not alternative descriptions but they do complement each other and each is indispensable when it comes to describing the object involved as a technical artefact.

The above view of engineering design as a translation of a functional description into a structural description of the object of design, raises interesting questions on how engineers do such translating and the kind of relations that exist between the functional and the structural descriptions of an object. As regards the last point, it should be noted here that function does not uniquely determine structure, since different objects may perform the same function and that the reverse is also true because one and the same object may perform different functions. If it is assumed that the functional description of an object implies normative claims (about what it ought to do), then from a logical point of view the deduction of a functional description from a structural description is problematic. Such a deduction would be vulnerable to some form of naturalistic fallacy objection from adherents to the is-ought dichotomy. Furthermore, just as it is generally considered problematic to derive 'ought' from 'is', so it is considered problematic to do the reverse, that is, to deduce the actual physical properties of an object ('what it is') solely from a knowledge of its function ('what it ought to do').

There therefore appears to be a logical gap between the functional and structural descriptions of an object. Nevertheless, the function and structure of technical artefacts are taken to be intimately related, not only in the sense that the physical structure realizes (or is supposed to realize) the function, but also in the sense that apparently designers are able to reason successfully from functional to structural descriptions or vice versa (for instance when they justify a proposed design by explaining why it realises the required function).[14]

5 MEANS-END REASONING

What kind of reasoning and knowledge is involved in translating a function into a structure? In practice designers make use of methods like constructing morphological charts or function-means trees to go from function to structure; these charts or trees give a graphical representation of functions (and sub-functions) and the various known ways of realising them [Cross, 1989/1994, p. 106 ff; Dym and Little, 2000, p. 116, 146 ff]. They present in a condensed way the available alternatives for filling in the black boxes corresponding to the (sub)functions. As mnemonic devices they do not give any clues about what kind of reasoning may lead from a function to a structure. In solving this translation problem, 'means-end' reasoning appears to be of paramount importance, since the design process is all about finding or constructing the appropriate means for achieving certain ends. In spite of its importance to engineering practice and daily life in general, the formal (logical) analysis of means-end relations and reasoning has received relatively little atten-

[14] For a discussion on the 'coherence' of structure and function of technical artefacts, see [Kroes, 2006].

tion [von Wright, 1963; 1972; Segerberg, 1992]. Recently, research into artificial intelligence has triggered more interest in this kind of reasoning [Pollock, 2002]. Within engineering design practice there is also a great interest in the formal analysis of functional reasoning, a phenomenon which appears to be closely related to means-end reasoning, because of attempts to develop formal tools to represent the objects of design and supporting functional reasoning about these objects [Dym, 1994; Chittaro and Kumar, 1998].[15]

Means-end reasoning may be seen as a form of practical inference about what needs to be done to achieve an end. In that respect actions are taken to be means to certain ends (states of affairs in the world) [Hughes *et al.*, 2007]. From a technological point of view, however, objects may also be viewed as means to action ends (for instance, a knife is a means to cutting bread, a pencil a means to writing). A formal analysis of means-end relations and reasoning in which objects and not actions are means has still to be made.

In his seminal paper on practical inferences von Wright [1963, p. 161] analyses the following kind of reasoning:

> One wants to attain x.
>
> Unless y is done, x will not be attained.
>
> Therefore y must be done.

Von Wright calls x the end and y, which is an action, a means to that end. This type of argument concerns necessary means to ends and the conclusion, which states an action, expresses a practical necessity. This practical necessity is derived from the statement of an end and from a conditional statement based on the causal structure of the world. The question one has to ask is whether such arguments are logically conclusive. *Prima facie* this seems not to be the case since the premises consist of descriptive statements and the conclusion remains prescriptive. But for von Wright this is not a convincing argument against logical conclusiveness.

Two features of these types of arguments are of particular interest from the point of view of engineering design. The first has to do with the fact that with these kinds of practical inferences a transition is made from descriptive to prescriptive statements. This strongly supports our claim that this kind of reasoning may play an important role in engineering design. We have already noted that reasoning from function to structure and vice versa is problematic because of the alleged logical gap between functional and structural descriptions of technical artefacts, a logical gap stemming from the is-ought dichotomy. But here we come across a form of reasoning that appears to defy this dichotomy and may therefore open up possibilities for reasoning from function to structure and vice versa. There are still, however, many problems to be solved. The practical kind of inference studied by von Wright concerns practical necessity in relation to human actions. But function statements about technical artefacts are connected to statement about what objects, when considered as means, ought to do and not about what human

[15] For a discussion on means-ends reasoning, see Hughes's contribution to this Volume.

agents ought to do. It is not clear how such statements about objects are related to 'ought to do' statements about human beings and whether it is possible to construct practical inferences for objects analogous to the one above about human actions. Furthermore, engineering design is primarily about reasoning from function to structure, that is, reasoning from the normative to the descriptive, whereas in the example given above concerning practical inference, the reasoning proceeds in the opposite direction. Again, whether practical inferences from the normative to the descriptive may be constructed remains open to discussion. Finally, given the multiple realisability of technical functions, practical necessity seems too much to ask of the conclusions of means-end reasoning that goes on in engineering design.

The second feature concerns the second premiss, the content of which is a conditional relation between the means and the end, and which, as von Wright remarks, is based on a causal relationship. Not surprisingly this closely links means-end reasoning to the causal structure of the world. If we know that event A causes event B,[16] then we may realise the occurrence of event B by bringing about event A, if this is technologically possible and if there are no interfering circumstances. So the action of bringing about event A may be considered to be a *means* for the occurrence of event B, the *end*. The causal relationship in itself does not imply practical necessity, that is to say, event A is not a necessary means for event B. For that to happen a much stronger conditional statement is required, namely that the bringing about of the occurrence of A is the only practically feasible course of action for bringing about event B.

The intimate relation which exists between means-end reasoning and causal relations explains why scientific knowledge plays such a dominant role in modern design practice. This leads to the question of the kind of knowledge used to solve design problems. As has been argued, it would be misleading to assert that engineering design is simply the application of scientific knowledge (or knowledge produced by the engineering sciences). A knowledge of natural phenomena is certainly not all that is needed to solve design problems. Hubka and Eder [1996] have attempted to develop a design science, which they take to be a system of logically related knowledge about designing and for designing. In their enumeration of the various kinds of knowledge needed for engineering design, knowledge from the engineering sciences is just one item in a long list [1996, p. 72]. In a similar vein, Dym and Little [2000, p. 22-3] remark that the majority of the many questions that have to be posed when designing a relatively simple object such as a safe ladder cannot be answered by applying the mathematical models of physics. According to Vincenti [1990, Ch. 7] the anatomy of engineering design knowledge includes at least six different categories of knowledge, some of which do not derive from scientific knowledge at all, such as the 'know how' acquired on the shop-floor. All these various kinds of knowledge are important for turning a functional description of the object to be designed into a structural description. Ryle's [1984] distinction between 'knowing that' and 'knowing how' may be of particular relevance when

[16] More precisely, tokens of event type A cause tokens of event type B etc.

analysing the kinds of knowledge used to solve design problems, because of the intimate relationship between designing and knowing how to make or do things.

To conclude, when compared to science the kind of problem solving prevalent in engineering design not only appears to employ distinctive forms of reasoning but also distinctive forms of knowledge. Up until now, the nature of design knowledge, or more generally technological knowledge, has not received much attention in epistemology.[17] This is even more true of the formal analysis of means-end reasoning in logic.

6 PHASE MODELS IN ENGINEERING DESIGN

We now briefly move to a topic that has received much more attention, especially from design methodologists, namely the matter of the modelling of design processes in terms of rationally prescribed steps or phases and the development of design tools.[18] These phase-models and design tools are supposed to contribute to the improvement of actual design processes. Most of the models are more or less detailed variations on the basic analysis-synthesis-evaluation cycle. As long as designing remains an activity performed by one single individual, these phases will be mainly relevant from a conceptual point of view. As soon as designing becomes a matter of teamwork, which tends to be the situation in modern industry where complex and large systems are dealt with, the phasing of the design process becomes an important management tool for organising, controlling and steering the process of product development.

One matter that hampers discussions on the usefulness of implementing such phase diagrams in engineering practice is the criteria for evaluating and measuring the success of the outcome of an engineering design process. From a strict engineering point of view, the simplest success criterion is to meet the list of specifications while satisfying the given constraints. This assumes that the list of specifications is immutably fixed at the beginning of the design process, which is not often the case. Because of problems encountered on the way, they may have to be adjusted during the design process. Moreover, as was remarked before, decisions about the performance criteria to use and the development of methods for measuring such performance criteria are often an integral part of the design process. On top of this, various participants in the design process may evaluate the outcome in different ways. In spite of these difficulties, design methodologists claim that the implementation of systematic approaches to design improves the design process (see, for instance, [Pahl and Beitz, 1996, p. 499-501]).

[17]For a discussion on the nature of technological knowledge, see Houkes's contribution to this Volume.

[18]A more detailed account and discussion of these phase models may be found in the chapter on *Rationality in design* of this volume. See, for instance, also [Cross, 1989/1994, Ch. 2].

7 DESIGNING PLANS RATHER THAN MATERIAL OBJECTS

So far we have analysed the nature of engineering design mainly from the point of view of the object of design. Our overall perspective has been the making of a (new) technical artefact and we have particularly analysed how a technical artefact, as an object of design, is described at the beginning and at the end of the design process. This object-oriented view on engineering design is rather dominant among engineers. It is true that the usual characterisation of the outcome of a design process stresses that it is a production plan and not a real material object but that is simply a consequence of the prevailing division of labour. The design phase is followed by the production phase which results in the real, material technical artefact to which the designing was geared. If one changes perspective, though, from the technical artefact making to the using side one sees that this cannot be the whole story behind engineering design. From the perspective of the user it is not the making of a technical artefact that matters but rather how to implement it in order to realise his or her goals. To that end it is not a fabrication plan that the user needs but an instruction manual which describes how the artefact can be implemented. An instruction manual or use plan is needed to make the function 'accessible' to the user. A technical artefact without a manual or a use plan is in principle of no practical use.[19] Thus, from the point of view of the user it is not the production plan for the material technical artefact that matters, but rather its manual or use plan.

It may well be the case that when designers characterise the outcome of design processes as production plans for technical artefacts, they implicitly take the manual to be part of the technical artefact. It is, however, important to make its role explicit because it enables attention to shift from material objects to actions and plans in which objects have a role. From an action-oriented view, engineering design is about making use plans concerning how goals may be realised with the help of technical artefacts. Technical artefacts may be said to be embedded within such use plans. Following this line of reasoning, Houkes and Vermaas *et al.* [2002; 2004] have developed an action-theoretical account of the designing and using of technical artefacts. In it they reconstruct the design and use of technical artefacts in terms of plans, intentions and practical reasoning. They take plans to be goal-directed series of considered actions and they see a use plan for an object as a series of actions involving the manipulation of the object in order to achieve the goal of the plan. They divide the design process into two different activities, namely use plan design and artefact design. Each of these activities is reconstructed in terms of plans and the plan for artefact design is embedded in the plan for use plan design. In their account, the interaction between designers and users does not simply involve the transfer of a technical artefact but also, and primarily, the communication of a use plan [Vermaas and Houkes, 2006, p. 7].

[19]The most common form of a use plan is a written manual; simple technical artefacts often come without a manual as the use plan is presumed to be known to the user and so remains implicit.

An attractive feature of this action-theoretical interpretation of engineering design is the central role it attributes to practical rationality/reasoning. If plans are the outcome of engineering design then these plans, irrespective of whether they involve the manipulation of objects, have to satisfy the demands of practical rationality. This applies to the use plan but also to the plan for artefact design which is embedded in the use plan. Bratman [1987, p. 31] discusses two of the demands placed on plans. The first concerns consistency constraints; plans should be internally consistent (they should not include incompatible goals) and consistent with the beliefs of the agent who executes them. Plans should furthermore be means-end coherent which requires that they be broken down into preliminary steps, sub plans and means so that in the eyes of the agent they may be successfully executed. According to Houkes *et al.* [2002, p. 320] these demands of practical rationality may lead to norms for good and bad design and use. They question, however, whether such demands on plans exhaust the norms operative in engineering design and artefact use. They note that their approach to engineering design and artefact use has an intellectual bias: in line with what was posited in the introduction, the actual executing of plans is not considered to be an interesting topic in its own right. This leads to an interpretation of the demands placed on practical rationality that relates primarily to rational deliberation, a situation which also appears to be the case regarding the demands that Bratman imposes on plans. Actually making things or executing plans may impose additional demands. For instance, it is not clear whether or to what extent the notion of means-end coherence can independently account for the important role of the norm of efficiency in engineering design.

This action-theoretical approach to engineering design analyses the nature of designing and its output from the point of view of what Simon calls the outer environment. It takes as its precept practices of intentional human action in which technical artefacts are used to realise ends. Without recourse to this context of human action it is impossible to adequately characterise engineering design and technical artefacts. Unfortunately this approach engenders the same problem of how to translate a function into a structure as that encountered in the object-oriented approach to engineering design. From an action-theoretical point of view, technical artefacts provide ways of achieving certain goals; but how can we move from an 'outer environment' description of artefact x in terms of what it is for (x is for y-ing) to an 'inner environment' description that specifies the physical make-up of x? How do engineers manage to jump back, so to speak, over the 'for-operator' to the object itself? Whether we examine engineering design from an object-oriented angle or from an action-oriented angle the problem remains.

8 A TECHNICAL DESIGN

So far the notion of design, when used nominally, has referred mainly to the outcome of a given design process. From the point of view of the product creation process, this outcome is usually taken to be a production plan for objects that are still virtual. This is not the noun-type notion of design we are interested in here. When referring to a car design, for instance, what is meant is not usually its production plan but something that has more to do with the properties of the car itself, irrespective of whether that car actually exists or how (if it indeed exists) it was actually produced. It is not easy to grasp what this 'something' is. Whatever it is, the design of the car remains an important facet since it more or less determines the accompanying structural and functional properties. It even becomes a defining feature of the car in the sense that its design makes the technical artefact an artefact of a particular kind, namely the kind 'car'.

In order to come to terms with what, in this sense, a design actually is consider the design of the Newcomen steam engine, which is represented graphically in Figure 4. The main function of this kind of steam engine was to power pumps to drain mines, and this was achieved by producing a reciprocating motion in the great beam, which was activated by the motion of the piston etc. The drawing not only provides information about structural features of the design but it also presents part of the form and the layout or organisation of the various parts of the Newcomen engine. Even if we were to add all the relevant structural information to this drawing we would still not end up with a complete representation of the design of the engine. As a designed object, the Newcomen engine has a purpose but that purpose is not contained in the structural representation of the design. For a representation of this aspect of the design of the Newcomen engine it is necessary to add information about its overall function, the functions of its parts, means-end relations and how the machine operates. In order to highlight the purposeful character of a design, a representation of a design thus has to include information about its structural and functional features.

Note that, by contrast, a design as a production plan for a still virtual technical artefact does not necessarily include information about the functional properties of the artefact and all its parts. According to Dym and Little [2000, p. 10] a production plan has to be such that "the fabrication specifications must, on their own, make it possible for someone totally unconnected to the designer or the design process to make or fabricate what the designer intended in such a way that it performs just as the designer intended." It is sufficient for the production plans to contain a purely structural description of the technical artefact. In principle it is not necessary to include a functional description of the artefact since a functional description does not specify in a "clear, unambiguous, complete, and transparent" (*ibid.*) way the physical properties of the object to be produced. So the notion of a design seen as a production plan is clearly different from the notion of a design that is central to determining the category to which a technical artefact belongs.

Anything that is called a design in the sense intended here may vary greatly in engineering practice in terms of level of detail and can be anything from a rough sketch, as displayed in Leonardo Da Vinci's drawings of machines, to a complete description of every minute detail of a prospective or existing artefact. We will assume that a representation of a design of a technical artefact has to be a combined description of all of its relevant physical and functional properties (relevant in the

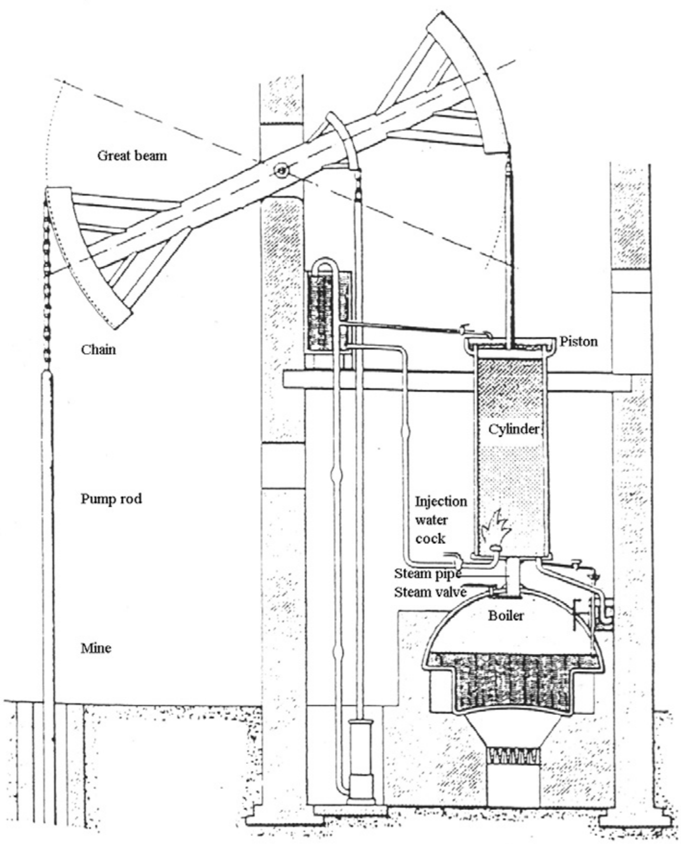

Figure 4. The design of a Newcomen engine

light of the performance of its overall function). A functional description represents only half of the design of a technical artefact since different physical structures may realise the same function and different physical realisations imply different designs of the artefact. The same is true of structural descriptions of a technical artefact: one and the same physical object may perform different functions on the basis of different designs (reflected in different structural and functional decompositions of the same object). Neither the functional nor the structural descriptions on their own completely capture the design of a technical artefact; the functional design omits the structural side while the structural design lacks the functional design properties. This just goes to show that when describing technical artefacts both the structural and the functional properties are indispensable in engineering practice [Kroes, 2006, p. 139].

A main difficulty when further clarifying the notion of a technical design lies in its association with the notions of purpose and function. Artefacts based on a technical design are said to have a purpose and this purpose is conferred on them by their design. Indeed, the notion of a design has strong teleological connotations in that a designed object (i.e. an object based on a design) has a specific property of '*for*-ness': it is *for* doing something or *for* being something.[20] This teleological character of designs may be captured by characterising them as some type of plan since plans are associated with purposes and goals. In this context, however, a plan is not a considered series of actions. As technical artefacts do not execute plans that would not make any sense. A plan may rather be taken to be something like a 'purposeful or teleological arrangement or organisation' of physical objects showing the adjustment of means to an end. But how is this to be interpreted?

One way to interpret the purposeful nature of a design (or of an object based on a design) is by tracing a design, like a kind of plan, back to its origin. A plan is a mental construct that has its origin in the mind of the designer. It may be taken to inherit its purposeful nature from its designer. This line of reasoning is used in arguments from design. In its most famous form, it is an argument for the existence of God. The purposefulness (together with other features) of certain natural systems, in particular of biological organisms and their parts, is taken to be proof that they are designed objects, a fact which is then used as an argument for the existence of a supernatural intelligent designer [Ratzsch, 2005; Russell, 2005]. According to Ratzsch [2005, p. 2] arguments from design are rather unproblematic in the case of technical artefacts or, more generally, in the case of things that "nature *could* not or *would* not produce." He claims for instance that for a DVD-player the conclusion that it was designed by human beings is "nearly inescapable".[21] A similar claim was made more than two hundred years ago by Paley with regard to a watch; he stated that when we examine a watch, what we see are [Paley *et al.*, 2006, p. 14]:

[20]For an analysis of the notion of teleology in relation to technical artefacts see, for instance, [McLaughlin, 2001; Perlman, 2004].

[21]Fehér [1993] presents an interesting thought experiment that puts this claim to the test.

> contrivance, design; an end, a purpose; means for the end, adaptation to the purpose. And the question, which irresistibly presses upon our thoughts, is, whence this contrivance and design. The thing required is the intending mind, the adapting hand, the intelligence by which that hand was directed.

In this way, the purposefulness of a technical design (and of a technical artefact based on that same design) may be directly related to, and considered to be derived from, the intentionality of a human designer.

Still, this does not lead to a clearer picture of what a design, as a defining feature of a prospective or real artefact, is. Things become even more complicated when a technical artefact, as a designed object, is taken to be the 'embodiment' or 'material realisation' of a design. What does it mean for a physical object to embody a design, a mental plan, and to what extent does it inherit the purposefulness of a design? This notion of technical artefacts appears to turn them into objects made up of a mental (i.e. intentional) and a physical side; they become, so to speak, creations of mind and matter. The physical features of technical artefacts are necessary when accounting for their causal efficacy and their intentional features account for their purposefulness (i.e. their functions). Insofar as they are products of the mind they inherit the teleological nature of the intentional action of the designer. In line with this thread of argument, technical artefacts are objects with a dual nature; they have physical features as well as intentional features.[22]

To conclude, from a conceptual point of view no clear analysis of the notion of a design of a technical artefact has yet been provided. In engineering practice these conceptual problems do not appear to be very important. In fact, one can search almost in vain in engineering handbooks for an elaborate analysis of what a design, in the sense intended here, incorporates.[23] From a pragmatic point of view, what is much more important is how designs of technical artefacts are unambiguously represented. The growing complexity of modern technical artefacts and the use of computers in supporting solutions to engineering design problems have increased the need for more formal, unambiguous representations of designs. Such representations are vital to the development of engineering data management systems for computer aided design (CAD). It is especially the formal representation of functions that proves to be problematic [Dym, 1994]. Much work is currently being done on developing taxonomies of functional primitives (a field sometimes referred to as 'functional modelling'), on functional representation and functional reasoning in AI-quarters, the aim being to support engineers in their solving of design problems and in the accurate representation of designs.

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[22]For a discussion on the dual nature of technical artefacts, see the special issue "The dual nature of technical artefacts" in *Studies in History and Philosophy of Science*, vol. 37, no. 1.

[23]When used as a noun, the notion of design usually refers to a fabrication plan. Hubka and Eder [1996, p. ix] mention the interpretation of a design as the outward appearance and pattern of artefacts; this interpretation is not particularly of relevance to the present discussion.

9 COMPLEXITY AND THE TRADITIONAL DESIGN PARADIGM

In this final section I will draw attention to a new field of engineering that has emerged in recent decades, namely systems engineering. It focuses on the design, development, maintenance and control of complex, large scale technological systems (see, for instance, [Sage, 1992]). It is interesting to take a closer look at this field because it is where engineers meet the limits of the applicability of what I will call their traditional design paradigm.

Let us first take a closer look at this design paradigm. It is made up of three assumptions about the kind of technical artefacts that are designed. This category is exemplified by stand alone consumer products. Most of the examples used so far fall into this category. These technical artefacts may be used by individuals or by groups, more or less in isolation of their wider technological and social context. What is required for the proper performance of their function is a technical artefact that does not malfunction and is properly implemented. To phrase it in Simon's terminology, the inner and outer environments of the technical artefact have to behave as they ought to. This brings us to the first important feature of the traditional design paradigm, namely the assumption that it is possible to clearly separate the object of design from its environment. In his analysis of engineering design Simon, for instance, simply assumes that this does not give rise to any problems. The second feature concerns an assumption about the nature of the object or system to be designed or, more to the point, the content of the inner environment. Traditional engineering concerns itself with the designing of the hardware (the manual is more or less taken for granted). What is designed is a material technical object. The final feature of the traditional design paradigm is that it is assumed that the behaviour of the systems designed can be fully controlled by controlling the behaviour of its parts, at least when the designed system is used under conditions specified within the design specifications. Given that the artefact is made up of physical parts, this control amounts to the control of the behaviour of these physical parts through a set of control parameters. These three assumptions about the objects of design, which are not independent of each other, together characterise the traditional design paradigm.

Certain features of the kind of systems designed within the field of systems engineering appear to undermine the applicability of the traditional design paradigm in this field. Systems engineering arose in response to the ever more complex systems designed and developed by engineers. This development not only challenged engineers in relation to the designing of such complex systems but it also presented questions concerning the designing and organising of the engineering design process allied to such complex systems [Ottens *et al.*, 2006]. Here we concentrate on two features of the kinds of systems designed that pose questions in conjunction with the applicability of the traditional design paradigm. The first feature concerns the socio-technical nature of the systems designed, the second the possibility of emergent behaviour in complex systems.

One of the types of systems studied and designed within systems engineering is large-scale infrastructural systems, such as electric power supply systems or public transport systems. The behaviour of these systems is significantly affected by their technical elements but the functioning of the systems as a whole depends as much on the functioning of these technical components as on the functioning of social infrastructures (legal systems, billing systems, insurance systems etc.) and it depends on the behaviour of human actors. From an engineering point of view this draws attention to the issue of whether the social infrastructure is to be regarded as part of the outer environment and modelled as a series of constraints for the design of technical systems or simply taken as part of the system to be designed. An important argument in favour of including these social elements within the system is that the technological and social infrastructures have to be attuned to each other if such systems are to operate successfully. If social elements are included within the system, as is often advocated, then the implication is that systems engineering has to deal with socio-technical systems. These are hybrid systems consisting of elements of various kinds, such as natural objects, technical artefacts, human actors and social entities like organisations and the rules and laws governing the behaviour of human actors and social entities.[24]

The traditional design paradigm no longer seems to be a suitable basic framework for the design and control of socio-technical systems. To begin with, there is the problem of where to draw the line between the system under consideration and its environment. This is a conceptual problem that systems engineering inherits from systems theory [Kroes *et al.*, 2006]. If the function of a system is taken to be that which gives the system cohesion, then it is rather obvious that all elements relevant to the functioning of the system should be included. So human agents and social institutions would have to become integral parts of the infrastructure systems alluded to above. But how is the function of, for instance, an electric power supply system to be defined? Different actors may have different views on this and may therefore have different opinions on what constitutes part of the system and what belongs to its environment. The socio-technical nature of the systems designed also means that the nature of the system to be designed changes. The inner environment will no longer consist of only material objects. The design of these systems not only involves the design of technical but also of social infrastructures from the point of view that they are tailor-made to match each other. Finally, the idea that these systems can be completely designed and controlled has to be abandoned. The behaviour of human agents and social institutions cannot be controlled in the way that the behaviour of technological systems can be controlled. In the traditional design paradigm it is assumed that there is a vantage point outside the designed system from which design and control is overseen. That is not the case with socio-technical systems in which various actors, with their own interpretations of the function of the system and their role in realising it, set out

[24]Within the field of STS these systems are often referred to as heterogeneous systems; see, for instance, [Bijker *et al.*, 1987].

to change or re-design parts of the system from within. For this reason even the notion of designing socio-technical systems becomes problematic.

The second feature of complex systems that threatens the applicability of the traditional design paradigm lies in the possible occurrence of emergent phenomena. In recent times, emergent phenomena in complex technological systems have become quite a topic of debate in engineering circles [Buchli and Santini, 2005; Deguet *et al.*, 2005; Johnson, date unknown]. The science and engineering of complex systems are turning into fields in their own right in which emergent phenomena are widely coming to be seen as a defining feature of complexity.[25] Complex systems may exhibit non-linear, chaotic behaviour that results in processes of self-organisation and in emergent systemic properties like adaptivity, robustness and self-repair [Bertuglia and Vaio, 2005]. From an engineering point of view such properties may be desirable but the drawback is that their occurrence may be unexpected and unpredictable. That makes it difficult to control such features. The desire to control emergent phenomena in complex systems is driven on the one hand by the fact that they may be dangerous (blackouts in electric power supply systems are often claimed to be such emergent features) and on the other hand by the fact that they may contribute to some desired property of complex technological systems (e.g. complex adaptive systems may be more robust in relation to changing conditions in the environment).[26]

Whether blackouts in electric power supply systems are genuine examples of emergent phenomena or whether other real examples can be given, remains to be decided. Assuming, however, that emergent phenomena may occur in complex technical systems, they do pose a real challenge to the traditional design paradigm. This challenge is not related to the first and second features of this paradigm. Emergent behaviour may occur in systems where it is not problematic to establish where the boundary with the environment lies and where there is not necessarily evidence of 'hybrid' systems (although the socio-technical systems discussed above may prove to be a promising class of systems exhibiting emergent behaviour). It is the third feature, the assumption about the control of the behaviour of the system that has to be renounced with regard to emergent behaviour. The emergent behaviour of a system cannot, more or less by definition, be reduced to the behaviour of the constituent parts of the system. This means that techniques like functional decomposition cannot be applied to functional properties of systems that are based on emergent phenomena. It also implies that the behaviour of the system as a whole cannot be completely controlled by controlling the behaviour of its parts. So, emergence and control do not go hand in hand. According to Buchli and Santini [2005, p. 3] "there is a trade-off between self-organization [and

[25]See, for instance, the pre-proceedings of the Paris conference (14-18 November 2005) of the European Complex Systems Society, ECCS'05 (http://complexite.free.fr/ECCS/); this conference hosted satellite workshops on topics such as *Engineering with Complexity and Emergence* and *Embracing Complexity in Design*.

[26]Kasser and Palmer [2005] distinguish between three types of emergent properties namely undesired, serendipitous and desired; serendipitous features are described as "beneficial and desired once discovered but not part of the original specifications".

emergence; P.K.] on one hand and specification or controllability on the other: if you increase the control over your system you will suppress self-organization capabilities." Such a new trade-off principle would indeed constitute a significant break with the traditional design paradigm.[27]

Given the growing complexity of the systems that engineers have to deal with, it is to be expected that systems engineering will become an ever more important branch of engineering. This growing complexity will pose new challenges to engineering design practice. Whatever the precise nature of this complexity it will, without any doubt, stretch the applicability of traditional methods for designing and controlling technical systems to their limits or even beyond their limits. This means that for these systems the traditional design paradigm with its idea of 'total design control' may have to be left behind and alternative design paradigms may have to be developed instead.

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[27] For a more detailed analysis of the notion of emergence and its relation to the control issue in engineering, see [Kroes, 2009].

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