

# PRINCIPLES OF ENGINEERING DESIGN

## SYNOPSIS

Engineering requires that much time and skill is spent ensuring the delivery of products, projects or services to a required performance and quality specification, on time and within budget. A great deal of the education and training of the engineer is devoted to ensuring his or her ability to effect such a delivery.

Because of this practical focus the importance of the early decision making processes is frequently not appreciated, and major decisions are left in the hands of the non-engineering professions, the politicians, lawyers, accountants or marketing experts. The creative and analytical skills of the engineer may be used only to develop, or make practical, the decisions of others.

The Corporate Plan, 1999-2002, of the Royal Academy of Engineering has as one of its four key objectives:

***‘To promote the importance of engineering nationally and internationally; to improve the quality of advice to Parliament and ministries; to promote greater understanding and interest in engineering; ...’***

It is clear that the abilities of the engineer can make a valuable contribution to primary decision making. Primary decision making is the first step in design. All human beings make decisions. The design process begins with major decisions as to the need to be met. As engineers it is important to recognise that this stage benefits from, and indeed requires, a professional engineering contribution. Paradoxically, because of our great success in the delivery process, we have reduced our contribution to primary decision making by associating the design activity with the development of decisions made by others.

The role of the Royal Academy of Engineering Visiting Professors in Principles of Engineering Design is to demonstrate and transmit to students and staff at Higher Education Institutions the fundamental characteristics of Engineering design, based upon their own experience and success in this area. They are appointed because they, as individuals, are actively engaged in primary decision making activities, and understand the nature of this stage in the meeting of human needs. They have developed the ability to envision solutions to defined needs and then to ensure the delivery of these solutions. Design is the essential creative process of engineering, which distinguishes it from science, and which calls for imagination, creativity, the knowledge and application of technical and scientific skills, and skilful use of materials.

This paper attempts to demonstrate that there are principles of design, used by all experienced designers, but not always consciously articulated. Given a statement of such principles and examples of their use it is valuable to students to be shown how to tackle design projects in a systematic manner, integrating detailed technical competencies as required by these fundamental principles.

# **PRINCIPLES OF ENGINEERING DESIGN**

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# **The Royal Academy of Engineering**

## **Principles of Engineering Design**

### **1.0 Introduction**

The effect of engineering decisions upon the quality of life in the global community is undoubted. It is important therefore that engineers be equipped to play a full and significant role in ordering the affairs of societies, not as technicians carrying out the instructions of others, but as major strategic decision-makers

The Corporate Plan, 1999-2002, of the Royal Academy of Engineering (The Academy) has as one of its four key objectives

***‘To promote the importance of engineering nationally and internationally; to improve the quality of advice to Parliament and ministries; to promote greater understanding and interest in engineering; .....’***

Engineering requires that much time and skill is spent ensuring the delivery of products, projects or services to a required performance and quality specification, on time and within budget. A great deal of the education and training of the engineer is devoted to ensuring his or her ability to effect such a delivery.

Because of this practical focus the importance of the early decision making processes is frequently not appreciated, and major decisions are left in the hands of the non-engineering professions, the politicians, lawyers, accountants or marketing experts. The creative and analytical skills of the engineer may be used only to develop, or make practical, the decisions of others. To meet the objective of The Academy, engineers need to become more aware of the major contribution that their abilities can make to the primary decision making sectors, which affect the nature of the tasks to be achieved.

Design is a particular aspect of the generalised human activity of decision making. Engineering design is a precise, ordered type of decision making. Every time we make a decision we are using the design process. It is of great importance to all engineers to realise this – on the one hand it frees us from the feeling that we are ‘special’, cutting us off from the rest of humanity as ‘specialists’, and on the other it frees us to use our skills at the earlier stages of decision making, instead of leaving such decisions to be made by other professionals – lawyers, politicians, accountants, architects etc.

The Academy’s first objective is to:

***‘maintain a crusading, leadership role... recognising the engineer’s responsibility for leading debate and action on a wide range of issues of national interest and importance which have an engineering dimension, such as sustainability, biomedical engineering and emerging disciplines.....’***

The role of The Royal Academy of Engineering Visiting Professors in Principles of Engineering Design (of whom there now about 140 working in some 44 Universities) is to demonstrate and transmit to students and staff the essential characteristics of Engineering design, based upon their own experience and success in this area. It is particularly important that the general and interdisciplinary aspects of design be demonstrated at every stage in the

design process. Design is the essential creative process of engineering, which distinguishes it from science, and which calls for imagination, creativity, the knowledge and application of technical and scientific skills, and skilful use of materials. The teaching of design has an integral place in the formation of all engineers.

The need to attract first class students, both men and women, into engineering and to develop a well trained national cadre of professionals is constantly reiterated by the Academy, the Engineering Council and the Professional Institutions. The challenge and delight of meeting engineering needs must be well presented by those who have themselves enjoyed their professional engineering careers. The Visiting Professors are well equipped to play a significant role in this work.

This paper attempts to demonstrate that there are general stages in the design process, used by all experienced designers, but not always consciously articulated, which if well understood, would certainly express the challenge and delight in engineering. Given a statement of such principles and examples of their use, it will be of value to students to be shown how to tackle design projects in a systematic manner, integrating detailed technical competencies as particular disciplinary postulates, as distinct from fundamental axioms or principles. There can be said to be a hierarchy of principles – from the general to the particular.

The Royal Charter of the Institution of Civil Engineers describes the role of the engineer as:

***“...harnessing the great forces in nature for the use and convenience of Man.”***

At the inaugural meeting of the Institution of Civil Engineers, on the 2 January 1818, Henry Palmer said:

***“The engineer is a mediator between the philosopher and the working mechanic and like an interpreter between two foreigners, must understand the language of both, hence the absolute necessity of possessing both practical and theoretical knowledge.”***

## **2.0 The nature of Design Principles**

Discussion and formulation of design principles has traditionally focussed on the technical and scientific rules and laws underpinning the delivery process. In this paper there has been an attempt to move the consideration of principle to the primary stages in decision making, in design.

The Oxford University Dictionary defines a principle as:

- Origin, source; source of action
- That from which something takes its rise, originates, or is derived
- A fundamental truth or proposition, on which many others depend; a fundamental assumption forming a basis of a chain of reasoning.

An understanding and knowledge of principle is essential if design decisions are to produce desirable results. In engineering terms a desirable result is likely to be a useful physical entity or system - valuable in meeting some need and improving the quality of life of individuals or of communities.

In engineering it is possible to identify basic principles which can be referred to by all designers of any discipline when initiating their work, or testing the quality of design

decisions - whether their own or another's. Such general principles are not to be confused with postulates, definitions, hypotheses, standards or rules. These latter terms are applied to particular instances, and are well known and formulated in engineering practice, and included in undergraduate courses.

The "principles" presented below are not those of the purely scientific, axiomatic kind, such as the laws of statics, dynamics, thermodynamics or electro-magnetism, which are already an essential part of the engineering curriculum. These principles are intended to provide a total context for good design. They are not necessarily rooted in physics or mathematics, and derive more from experience, practice or pragmatism than from formal theory. They are the substance of professional engineering judgement. An understanding of these basic principles enables an engineer to engage in the highest level of decision making – to which he can then bring his professional skill and training.

There are many excellent texts available setting out rules and guidelines to assist in the design of particular engineering projects. This paper attempts to show how such subject or discipline based procedures are related to the initial formation stages of design, enabling engineers to contribute to the early decision making processes more fully using their particular talents and training.

There is perhaps an analogy with the composer, conductor and performer of a musical composition. The composer understands the detailed laws of harmony and counterpoint, but his inspiration comes from his professional talent. He is served well by the conductor and performer, indeed his work cannot be properly appreciated without them, but the contribution of the great composer requires a grounding in principles, as well as creative talent.

Engineering design involves many parameters upon which the success of the project depends, each of these specific areas of concern has its own sub-set of laws, standards, practices, codes and regulations. The volume and detail of these particular constraints and directions can make it difficult to appreciate the fundamental principles, which may be well known to experienced designers, but may not have been formulated in a way which can be communicated to students. The Visiting Professors task is to enable students to appreciate the differences between the specific and the general principles by demonstrating each step in practical design exercises and/or in case studies.

### **3.0 Statements of Principle**

In formulating Principles for Engineering Design an attempt has been made to consider simply these essential initiating activities of all design projects.

It is possible to consider engineering design as encompassing three stages. The definition of the need to be met, the conception of a response to that need, and the organisation and management, which can affect the design process, of the delivery of that response. These three areas of activity can be summarised as:

- (i) The **definition of Need** requires the recognition and understanding of the nature of society, of economics, of humanity's needs. The human qualities of reason, compassion, service and curiosity all contribute to the definition of need.

*All design begins with a clearly defined need*

- (ii) **Creative Vision** requires the ability to think laterally, to anticipate the unexpected, to delight in problem solving, to enjoy the beauties of mind as well as of the

physical world. The ethos within which the problem is being addressed must be understood.

*All designs arise from a creative response to a need*

- (iii) **To Deliver** a solution to the recognised need requires the assembly and management of resources and of team members with the necessary skills and knowledge of natural laws and of the materials and energies needed to effect an efficient and appropriate creative design.

*All designs result in a system, product or project which meets the need*

#### **4.0 Engineering Design Practice**

To demonstrate something of the relationship between these three basic design concepts and the discipline specific laws, rules and standards we have selected a few high-profile projects from a variety of disciplines. We have asked those concerned with the overall design to prepare short notes showing how the projects were conceived, how the design solutions were arrived at and how the delivery procedures contributed to the realisation of the project. We have attempted to present these principles in each case in a similar format in Part B of this paper.

The examples chosen represent a wide range of engineering designs, and a great variety in size and discipline. They are:

Blatchford & Sons: An Intelligent Prosthesis (Saeed Zahedi)  
Mott MacDonald: The Tsing Ma Bridge (J S Young)  
Norton Healthcare: An Asthma Inhaler (Dr Ray Bacon)  
Psion Computers plc: Personal Digital Assistant (Kevin Brewer)  
Rolls Royce plc: the Trent Aero-Engine (J T Hawkins)

Very full and helpful responses were received from the designers of these projects and products. These will be published as an appendix to this paper.

#### **5.0 Conclusion**

The four objectives of The Academy's Corporate plan for the years 1999-2002 can be abbreviated as:

*'To maintain a crusading, leadership role..... recognising the engineer's responsibility for leading debate and action on a wide range of issues of national interest and importance which have an engineering dimension, such as sustainability, biomedical engineering and emerging disciplines.....'*

*'To support engineering education and training at all levels.....'*

*'To work towards greater cross fertilisation between industry and academe.....'*

*'To promote the importance of engineering nationally and internationally; to improve the quality of advice to Parliament and ministries; to promote greater understanding and interest in engineering; .....'*

The Academy's visiting professorship scheme in principles of engineering design can

contribute to the attainment of all these objectives. Design is a pervasive activity, a specialised branch of decision making. An early appreciation of the difference between creative design and logical analysis encourages young engineers to participate in the earlier decision making processes of defining need and envisioning possible ways of meeting that need, in addition to contributing to the essential processes of delivering that vision in reality.

Some ways in which the Visiting Professors can, and do, contribute to the realisation of the Academy's objectives are:

- By promoting and assisting in research and development activities in design methodologies and in design teaching.
- By regularly and clearly formulating their personal contributions to design teaching, making best practice available for wider dissemination.
- By stimulating the enthusiasm of undergraduate and young engineers. This is well complemented by the RSA/RAEng initiative in undergraduate awards for imaginative final year design projects. Participation in this exercise could be increased considerably. *(Details of the scheme will be available at the Churchill College workshop in September)*
- By furthering closer collaboration between academe and industry, not only by their own example, but also through other activities, such as staff secondments between the two sectors.
- By demonstrating the roles engineers can play in the early stages of design – identifying need and conceptual design – based on their own experience.

The five case studies appended set out the methods and factors involved in each of the three key principle stages of product realisation – **need**, **vision** and **delivery**. They have been chosen deliberately to present a wide range of disciplines and scale of project. All of the Academy's Visiting Professors bring to their particular University their own experience. It is of value to set out the nature of each of these stages for every design exercise, and to show how these stages employ the skills and technical principles of particular disciplines. The engineer is well equipped to play a full role in the strategic direction of society, as encapsulated in the objectives of The Academy.

## **PART B – Case Studies**

### **B/1 Introduction.**

In this section of the report the principles proposed in Part I are used to demonstrate the activities associated with each stage for the five projects researched. The full submissions from the project teams have been summarised and tabulated for ease of cross-reference and to show the similarities of design effort at each stage for the apparently very diverse examples chosen.

### **B/2 Case Studies**

#### **Summary notes of the characteristics of key stages for all projects**

#### **NEED**

##### **All Design begins with a clearly defined need**

Defining the need is a multidisciplinary task – either by a selected team of experts, or by an experienced and multi-skilled individual. Skills required are not exclusively engineering, but include economic and political skills, marketing and understanding of industrial organisations. It is important that a clear definition of the need is formulated, with the reasons for the decisions given.

There must be commitment at the highest level, and maximum feedback from prior developments.

#### **VISION**

##### **All designs arise from a creative response to a need.**

The controlling team or individual must have access to all necessary specialist advice. On larger scale projects the management of the variety of inputs must be strong and effective, without inhibiting lateral, creative, thinking. On smaller projects good self-discipline is necessary to ensure that the development does not deviate from the perceived need. External advice must be well co-ordinated, and its role in the design development understood. Specialist consultants must appreciate the total context and aims of the project. Project aims should not be confused by individual disciplinary objectives.

Design development is an iterative process; a good relationship with the team defining the need is essential. Modifications of need may take place during this stage – particularly for smaller projects. Concept evaluation requires a full understanding of the formulated need, and of the delivery constraints likely to affect the design formulation. There must also be knowledge of the market constraints and the production processes

#### **DELIVERY**

##### **All designs result in a system, product or project, which meets the need.**

As the scale and complexity of projects increases so does the need for a clearly defined management structure, and of the several design and construct components and their relationships to the whole project. Smaller projects may permit more flexibility, but care is needed to avoid making too many alterations on a manufacturing expediency basis. The original and formulated aims and proposals should provide the platform needed for the production activities.

There is a need for regular team reviews to ensure continuity of concept, and for testing and management to ensure a high and consistent quality in the end product.



## Case Studies – Summary Notes

Case Reports	Need	Vision	Delivery
B/3.1 BLATCHFORD & SONS – INTELLIGENT PROSTHESIS	<p>The aim of the project is to improve limb function. Two definitions of need are identified – by user and by supplier. Interpretation of need by manufacturer is based on market considerations. In this case an experienced manufacturer provided the skill and resources needed, but in collaboration with both the end user and the service provider.</p> <p>The immediate need was to provide a prosthesis that could change characteristics with walking speed. Interest in working towards this end was stimulated by developments in technology – particularly by using microprocessors to control the mechanical components in the artificial joint. This also required a change in manufacturing culture – away from hand skills to systems engineering.</p>	<p>The small multidisciplinary team of scientist and engineer from the research department of the manufacturer provided the expertise and the willingness needed to carry the project forward. It was recognised that this was a further step in the development of even more effective prostheses. Feed back has enabled continuing development and improvement of the prosthesis. The support of senior management was secured to ensure that the work would be implemented.</p>	<p>The most important step in delivery was to assemble a team with the agreed single aim of producing the improved prosthesis, thus ensuring that the project remained 'alive'. Members of the team represented all the disciplines – electronic engineering, mechanical engineering, management, prosthetic fitting, marketing, customer support etc, as well as the various manufacturing skills.</p> <p>Co-ordination with test consultants and government agencies was also arranged.</p> <p>The supply organisation was developed during the production stage to move from specialist sub-contractors and suppliers, to increasing the in-house skills and facilities of the principle manufacturer.</p>
B/3.2 MOTT MACDONALD – TSING MA BRIDGE	<p>Identified by Client team – the Hong Kong Authority. Using a variety of consultant inputs to formulate the detailed needs for extended transport facilities and residential accommodation. Studies confirmed need for a replacement airport, on Lantau Island, hence need for fixed link bridge/tunnel. Team led by client, but dependent upon specialist consultant input – economic, planning, transportation, engineering (marine, tunnels, bridge, highways, railways), risk assessment.</p> <p>This team also considered the context and location of the major facilities.</p>	<p>The project focussed on the fixed link as part of the overall plan. The team was led by Mott Macdonald and brought together needs and context, including engineering restraints (sub-soil, marine context climate, typhoons, etc.). Formulation of possible solutions included considerations of cost, constructability, programme, hazards, etc.</p>	<p>The agreed outline design was passed as an implementation contract to Mott Macdonald to establish and co-ordinate a team of designers and contractors as part of the ten Airport Core Projects (ACP). Independent checks and quality assurance procedures were established and maintained. Contract documents were prepared by this team, who also were appointed to supervise the project. This entailed close co-operation with the contractors and with many specialist sub-contractors and suppliers.</p>
B/3.3 NORTON HEALTHCARE, DR.BACON BREATH ACTUATED ASTHMA INHALER	<p>Existing pressurised metered dose inhalers (pmdi) are extensively used, but the majority of patients receive sub-optimal treatment. Poor inhaler techniques result in poor asthma control. A need was identified for a breath-actuated inhaler, which would automatically synchronise the intake of breath with the release of a dose of the prescribed drug.</p> <p>The need was identified by an experienced senior pharmacist with multidisciplinary skills, who was able to assess the market for such devices, as well as the patient need. His seniority gave him the essential authority to carry the project through to completion.</p>	<p>A holistic view of the project is essential, together with access to all the skills needed for a full definition of the final product. Flexibility of creative thinking is important. The development team consisted of the 'specifier', who defined the need, and the 'inventor', who interpreted the need into a concept. The design is flexible for different drug formats and different propellant combinations, as well as modifying presentation to suit local preferences around the world. Development work was sub-contracted to experienced external consultants to supplement the resources of the drug manufacturer. The recognition of the need to 'out source' the expertise is an important factor in producing a very professional end product.</p>	<p>The product delivery was co-ordinated by a small core team – pharmacist, clinical scientist, and production engineer - under the management of the original specifier. The need to secure the advice of a variety of differing agents was recognised - regulatory, marketing, sales, clinical trials personnel etc. and integrated with the overall understanding of the core team. Flexibility was permitted in the manufacturing process, whilst maintaining the concept development during the 'vision' stage in design. This is a key element in enabling continued development to take place, producing further generations of similar devices.</p>

<p>B/3.4 PSION COMPUTERS plc – PERSONAL DIGITAL ASSISTANT</p>	<p>The aim was to produce a new generation of PDA (Personal Digital Assistant) that would meet the needs of the modern mobile professional. It was also to act as a platform for a new software operating system.</p> <p>Individual and customer feedback on existing products was used to define needs that converged with enabling technology (EPOC 32 operating system) and an appropriate ASIC (Application Specific Integrated Circuit).</p> <p>The final product had to be an ‘object of desire’ that people would aspire to own.</p>	<p>Competitive products were analysed to identify weaknesses and strengths, with every effort made to eliminate perceived weaknesses from the emerging design idea, which had to be clearly differentiated in the market place.</p> <p>All necessary disciplines were available in the company, supported by consultant designers, and were involved in the concept design of the product with a Project Manager employed to make it happen.</p>	<p>Multidisciplinary teams (comprising 4-7 members) were used to achieve delivery of the product. The team was highly motivated and led by a Project Manager, using a detailed Product Design Specification to control the delivery process.</p> <p>Regular progress reviews ensured that the identified needs were being met. Throughout the project the teams were guided by the desire to ‘do the right thing in the right way’.</p>
<p>B/3.5 ROLLS-ROYCE – TRENT AERO ENGINE</p>	<p>The Trent is a three-spool high bypass ratio turbofan. Although this arrangement emerged from design studies undertaken in 1964 it has a capacity, in the industry, for adaptation to meet changing requirements. The Trent 700/800 derivation emerged from the use of multiple sources to identify and confirm need. These sources were drawn from the entire customer and supplier chain.</p> <p>The internal needs of the company were also included, as was the essential need for adherence to regulatory requirements.</p> <p>Regular reviews of needs and the ability of the design to satisfy these needs were made. The review group included representatives from customer and supply chain organisations.</p> <p>The review process recognised that the needs of customers are ever changing. A small ‘core’ multidisciplinary team was formed to define the product proposal that emphasised the integration of identified needs with business opportunities</p>	<p>Teamwork is essential to develop the design of a product such as the Trent 700/800. The team also has to grow in number in line with the needs of the project and remain in a co-ordinating role throughout.</p> <p>It is also important to assess continuously the proposed ideas against the needs via the regular design reviews at various levels within the company and to use a Product Design Specification to guide reviews and decision making. In short, generate a plan to meet the business opportunity identified.</p>	<p>An effective Project Director was essential to manage the increasing scale of the project and to co-ordinate the growing multi-disciplinary team involved in the delivery process.</p> <p>Continuous liaison with the customer and supplier chain organisations as well as the regulatory bodies is an essential part of the delivery process, as is the need for physical verification that the design will meet the identified need by prototyping. At Rolls Royce well-defined established engineering procedures are used to guide and monitor the delivery process.</p>