# Engineering Concepts in Industrial Product Design With A Case Study of Bicycle Design


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## ABSTRACT

Industrial product design, as a field of design discipline, borrows concepts and methods from other disciplines, one of which is engineering, in order to develop its own knowledge in research and industry contexts. In the means of strengthening its place among other disciplines, a concentration on 'designerly' ways of knowing, thinking and acting should be provided. Therefore, in this study, the intersection between industrial product design field and engineering discipline is searched for revealing the engineering concepts and non-intuitive design methods within intuitive design methods used in industrial product design. Engineering design field is stated, since its being close to industrial product design, and a comparison is made between industrial product design and some engineering fields through their approach to design problems and the tools they use. Engineering design methods are stated and their advantages in design activity are revealed. This study is a part of design systems area, with formal approaches to models of design processes and knowledge. Finally, a case study of bicycles is carried out in order to prove the design approaches and the priorities of engineering and industrial product design on a product.

***Keywords:*** industrial product design, design criteria, engineering design, design methods, bicycle

## ÖZ

Endüstri ürünleri tasarımı, kendi disipliner bilgisini, araştırma ve endüstriyel bağlamda geliştirebilmek amacı ile, mühendisliğin de dahil olduğu pek çok disiplinin öngörü ve metotlarından faydalanır. Bu doğrultuda, diğer disiplinler arasında kendi çalışma alanı içerisindeki yerini güçlendirebilmek amacı ile, "tasarımcı yaklaşımlı", bilme, düşünme ve hareket etme eylemlerine konsantre olmalıdır. Bu çalışmada, mühendislik disiplininin içerisindeki mühendislik öngörülerinin ve sezgisel olmayan tasarım metotlarının, endüstri ürünleri tasarımı alanında kullanılan sezgisel tasarım metotları içerisindeki yerini ortaya koyabilmek amacı ile; endüstri ürünleri tasarımı alanı ve mühendislik disiplini, kesişme noktaları bağlamında araştırılmıştır. Endüstri ürünleri tasarımına olan yakınlığı sebebiyle mühendislik disiplini tercih edilmiş; bu doğrultuda, endüstri ürünleri tasarımı alanının bazı mühendislik alanları ile birlikte, tasarım problemlerine ve araçlarına yaklaşımlarının karşılaştırılması gösterilmiştir. Ayrıca, mühendislikte kullanılan tasarım metotları ve bunların tasarım aktivitesi sürecindeki avantajları da konunun daha net bir şekilde açıklanabilmesi amacı ile belirlenmiştir. Bu çalışma, tasarım sistemleri alanının bir parçasıdır ve sonuçta, tasarım sürecine ve bilgisine yönelik akılcı yaklaşımların belirlenmesini amaçlanmaktadır. Sonuç olarak; mühendislik disiplininin ve endüstri ürünleri tasarımı alanının tasarım yaklaşımları ve öncelikleri, endüstriyel bir ürün olan bisiklet örneği üzerinde irdelenmiştir.

***Anahtar kelimeler:*** endüstri ürünleri tasarımı, tasarım kriterleri, tasarım mühendisliği, tasarım metotları, bisiklet

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# Chapter 1

# INTRODUCTION

Design occurs in nature with humans while they abstract the nature and concretize the ideas and visions in their minds. The relationship between humans and nature differs from the relationship between animals and nature, since humans define and use nature (materials and resources) for their prosperity instead of the simple and direct help derived from nature in animals' life. In Paleolithic ages, physical needs of human beings caused them to sharpen the edges of stones in order to kill the animals and feed themselves, and psychological needs of human beings have caused them to carve figures on stones, paint the caves, etc. This two dimensional structure of needs appears to be the key concept of designing, since it is the reason of design to come into existence.

From dictionaries it can be learnt that the word "design" has various meanings, ranging from conceiving a plan in the mind –whatever this plan may be- to making a drawing or pattern of something to be made or built. This study focuses on design in the more limited sense of "designing material products". For that purpose design is defined as "to conceive the idea for some artefact or system and/or to express the idea in an embodiable form (Roozenburg and Eekels 1995: 53 quoted Archer 1971: 1-2)" in this study.

The term design began to be used in the language in the fifteenth century, with the aim of revealing the departure of design from "doing". After the Industrial Revolution in the eighteenth century, division of labor, mechanization, standardization, rationalization became the features of the new world. These developments encouraging new demands and changing demands encouraging new developments, helped the new world evolve faster. Humans develop technology to meet the needs they have perceived for themselves, not for the universal needs over which the nature rules. Gaston Bachelard, the French philosopher, states that " 'obtaining the more than the enough' has stronger warning on souls as humans are not the creatures of needs, but they are the creatures of desire (Basalla 1996: 18)". This desire has brought about today's artificial world, which includes three times more variety than the organic world does. This incredible amount of objects can only be produced by the human mind that longs, dreams, and desires.

A lot of specializations have been developed that verify the desires of humans today, one of which is the profession of industrial designer that emerged in the twentieth century, also as a feature of the division of labor and specialization characteristic of large-scale modern industry. Industrial design is concerned with determining the qualities (materials, construction, mechanism, shape, color, surface finishes and decoration) of objects, which are reproduced in quantity by industrial processes, and their relationship to people and the environment. The industrial designer is responsible for these aspects of products and their impact on society and nature.

Industrial design is the most widely used term for the professional design of objects intended for mass production. However, it is not always used correctly since many industrial designers may work on products for craft manufacture and in related fields such as exhibition or interior design. In order to make a clear distinction in this study, as it is the subject of this study, "the industrial product design" is going to be used. This field includes the design of 2 and 3-dimensional forms with transportation, furniture, home-office (accessories like clock, pencil, etc.), high-tech (Dvd player, monitor, etc.), lightening, fashion (accessories like umbrella, wristwatch, etc.), toys and games, food, packaging, gift/promotion, sports, medical and other functions and related production techniques (metal lightening, wooden furniture, etc.) in sectors.

### 1.1. Definition of the Problem

Designing an industrial product is a multidisciplinary activity as functional, psychological, technological and economical criteria are all involved. Industrial product designer, acting through these criteria and fulfilling the design function, also acts as a team synthesist that builds a communication bridge between other professions like engineering, sociology, marketing etc. This formation is because of the demands of the modern world. Within many specializations that have been developed, needs of the modern world like airplanes, fast trains, spaceships have caused to bring these specializations together and act in a team towards the common purpose. At this point industrial product design has become one of the most important strategic elements of competitive advantage in industrial context.

Following this advantage, new constitutions in educational context have been developed like IDBM (International Design Business Management), which is a collaborative program between three leading Finnish universities. The aim of this programme is to produce professions (designers, marketers) with a multifaceted view on product development, and with a holistic understanding of the design dimension. This constitution reveals the interdisciplinary approach to both design and business educations.

Creating an interdisciplinary discipline, fails to connect between sub-disciplines, fails to reach common understanding, and fails to develop new knowledge and perceptions of design as Nigel Cross states in the proceedings of the Politecnico di Milano Conference (2000: 46). Because of dealing with a lot of criteria, the industrial product design field can be stretched to other fields easily, and other fields can be welcomed in industrial product design field easily, which causes conflicts in developing industrial product design knowledge. Cross states that the design should be taken as a discipline. In this study, industrial product design is going to be taken as a field of design discipline that accumulates and develops its own design knowledge. Referring to this formation, industrial product design might create and strengthen its place among other overlapping fields and disciplines.

Industrial product design, as a field of design discipline, borrows concepts and methods from sciences, arts, engineering, and humanities in order to develop its own knowledge in research and industry contexts. Thinking and acting in this way might strengthen the place of industrial product design while still keeping it as an advantage of the modern world. In order to do this, as the problem with which this study is concerned, the intersection between the fields of industrial product design and the discipline of engineering is researched in order to reveal the engineering concepts and methods used in industrial product design.

Engineering, where scientific knowledge is applied to artifacts, is the most important features of industrial product design in the means of bringing design to an end product that is sold in the market. Its priority might change according to the product that is going to be designed. More or less it is still involved in the designing activity. In order to reveal the importance of engineering and its balanced combinations with design, the bicycle, as a transportation function of designing, is taken as a case in this study. The reason for choosing the bicycle as an example is that this object bespeaks one of the best harmonies that the engineering and the design concepts dissolved in.

### 1.2. Aims of the Study

**1.** Searching for non-intuitive and intuitive concepts and methods used in the industrial product design field is the primary aim of this study in order to try to put a milestone in developing industrial product design knowledge in design discipline. With this aim, this study belongs to the area of design systems those researches for formal approaches to models of design processes and knowledge.

**2.** Revealing the advantages of using non-intuitive methods in designing activity, is the following aim in the study. Although design naturally is soft, intuitive and hard to formalize, it is one of the complementary ways of looking at the same thing with science. Intuitive and non-intuitive methods acting together can give the best solutions to design problems.

**3.** Giving an understanding of unions and intersections between industrial product design and engineering criteria will be an advantage in activities of these professions both in industrial and educational contexts, whether working in a design team or working alone on the product. Although the advantages in industrial product design are brought to the fore, this will be an advantage for the engineering discipline and professions as well.

**4.** Arriving at an understanding of how scientists, engineers and industrial designers approach the design problem will be another advantage of observing the artifacts in using this knowledge for designing.

**5.** Design priorities change according to different products. Although only bicycles are mentioned in this study, there is the aim of giving at least an idea about determining the design and engineering priorities according to the product, depending on the big variety of the bicycle area.

### 1.3. Methods of the Study

This study is structured in three parts throughout the considered problem and the aims mentioned above.

Chapter 2 consists of two parts comprising design and industrial product design. This chapter is for constituting a general understanding of design and industrial product design. It starts with the importance of giving an explicit definition of design in an academic language and continues with the nature of design. After making two statements about the nature of design, which concern its integrative and intuitive natures, the relationships between the disciplines of design and science are discussed according to these characteristic natures of design and an example is given in order to reveal the scientific and the artistic features of design. Then, referring to Cross, the importance of taking design as a discipline is emphasized throughout the multidisciplinary and interdisciplinary activities of design. A general classification of design is made in the following title and some design specializations of the design discipline are given for a step to reach industrial product design.

In industrial product design part, industrial product design’s brief history, definition, and evolution from being taught in Fine Arts and Architecture Faculties to Engineering Faculties are given. By revealing this evolution, the importance of engineering concepts and methods used in the products of modern world is emphasized. Industrial designer’s abilities, tools and techniques, and some product design areas are mentioned in the following titles in order to reveal a general panorama of industrial product design. Then the design criteria in industrial product design and the intersecting engineering criteria are indicated, as these are the criteria (priorities) in certain products that usher the field of industrial product design into the fields of engineering.

Chapter 3 constitutes the mainstay of the study with the title of “engineering concepts in industrial product design”. It is divided into three parts, that the first part gives general knowledge about engineering discipline (definition, functions, and raw materials) and engineering design field –as being close to industrial product design-, and additionally, a comparison of industrial product design with some other engineering fields is made through seven measures of type of objects, type of problem, form-function relation, decomposition potential, language complexity, graphic complexity, and design methods. Three of these measures, which are form-function relation, decomposition potential and language complexity, are mentioned briefly here, while measures of type of problem and design methods have constituted the other two parts of this chapter. In the second part, design problems (characteristics, structures, types); as an example of mature design, bicycles; design abilities of scientists and designers (industrial and engineering designers) and their approach to design problems; and being a successful designer are mentioned. Third part constitutes of design methods and process. Emergence of scientific and design methods, the comparison between them, and four unifying principle of methods are described as an introduction to this part of the chapter. Then some examples of design process and design methods are handled deeply, in the following of this part. In constitution of Chapter 3, the researches of Ullman, Cross and Jones are taken into consideration generally.

Chapter 4, focusing on products, has an aim of revealing the engineering and the design criteria on bicycle examples. Change in design priorities are indicated on different types of products, using the advantage of variety in bicycles.

In this study, documentary reading and critical research methods are used, and for providing a better explanation of the subjects, related bicycle examples are given. Since this study involves a case of bicycles in Chapter 4, most of the examples are tried to be chosen from bicycles in order to provide a complementary meaning in the language of the study as a whole.

# Chapter 2

# DESIGN AND INDUSTRIAL PRODUCT DESIGN

## 2.1. What is Design?

Design has a fuzzy meaning in terms of its functions that literature cannot put a clear definition. Looking at a dictionary or researching the meaning of design in books, articles, etc. cause even bigger problems in understanding it simply. It is a noun and a verb. Briefly, the verb design can be defined as "to conceive and plan out in the mind, to have as a purpose: intend, to devise for a specific function or end (Merriam-Webster Authority & Innovation 2000: Version 2,5)" and the noun design as "way something is made, picture of something's form and structure, decorative pattern, process of designing, scheme, something planned (Encarta World Dictionary 2001: developed for Microsoft by Bloomsbury Publishing Plc.)".

The verb "design" comes from the Latin *designare,* which means to *specify,* as in pointing out what to do. The modern sense of design is held to have originated in the Renaissance, when architect and builder functions came to be two separated functions. The architect would no longer always be present on site during building and therefore had to specify what to build, which previously hadn't been necessary (Gedenryd quoted Herbert 1998: 42). Similarly, the noun "design" comes from *signum*, which is not so much in the modern sense of root "sign" (as in symbol, mark; semantics, semiotics, etc.) as is sometimes claimed. It rather has the meaning of something that you follow, in the sense of the specifications passed on from architect to builder. "Around the sixteenth century, there has emerged in most of the European languages the term "design" or its equivalent. The emergence of the word has coincided with the need to describe the occupation of designing. Above all, the term indicates that designing is to be separated from doing (Gedenryd quoted Cooley 1998: 42)."

### 2.1.1. Defining Design

Defining design is not easy and it is much more than describing the occupation of designing. It is difficult, because it is broadly and subjectively used in colloquial language. On the other hand, it is needed to be defined in a common ground as it is an academically research subject like design theory, design methodology and etc. Below states Papanek, how design is in life with people, and indicates the complexity of defining design.

> All men are designers. All that we do, almost all the time, is design, for design is basic to all human activities. The planning and the patterning of any act toward a desired, foreseeable end constitute the design process. Any attempt to separate design, to make it a thing-by-itself, works counter to the fact, design is the primary underlying matrix of life. Design is composing an epic poem, executing a mural, painting a masterpiece, writing a concerto. But design is also cleaning and reorganizing a desk drawer, pulling an impacted tooth, baking an apple pie, choosing sides for a back lot baseball game, and educating a child (Papanek 1984: 3).

Papanek discusses separating design from life and making it a thing-by-itself is injustice to people and life. Design is natural in life to people and therefore it is as relative as life for the people. People define design differently, and then they change their minds and define it again and again for each case and scenario in their life. It becomes a translation problem not only as a language, but also as a socio-cultural fact.

On the contrary, it needs to be defined in a common ground for academic activities. Researchers seek for explicit definitions and try to reach a consensus in design definition. Chuck Burnett, design researcher, states the importance of a clear general understanding in academic research while paying respect to the nature of design within its complexities:

> Both higher-level theories and professional conduct need a common framework of reference, interaction, and assessment. Design thinking is a universal discipline, the instantiation of which depends on its particular intent, context, and background. The "common ground" sought for design theory, research, and practice will never be encompassing enough if it is focused primarily on professional competence in the field in which

> we practice. Nor will it have practical value if it cannot support situated thought and behavior in any field or on any subject. As designers, design educators and researchers we need to reframe our goals to seek a comprehensive integrated theoretical framework that is operationally (computationally and behaviorally) defined as well as emotionally meaningful and personally useful. Computational and behavioral because the interactive complexity warrants it, personally useful and meaningful because we are individually (and collectively) human (Friedman quoted Burnett, PHD-DESIGN Archives – July 2003).

A clear general understanding at the comprehensive domain level across the full domain and its fields, and subfields enables researchers and practitioners to understand and work with issues in all areas within the domain. Burnett's statement summarizes the value of clear conceptual structures in this effort.

Explicit definitions of design are important for a common ground in academic language and also for understanding the usage of the term in daily life. The editors and lexicographers at Merriam-Webster's Dictionary, Encarta World Dictionary, Oxford English Dictionary etc. have clearly intended the published definitions in an explicit way. Their goal is to record and capture the primary usages of a term, to reflect those usages in an accurate definition, and to provide accurate definitions as a guide to understanding.

Merriam-Webster Authority & Innovation (2000: Version 2,5) defines the verb design as:

**1 a:** to conceive and plan out in the mind <a savage on seeing a watch would at once conclude that it was designed— Samuel Butler, 1902>

**b:** to plan or have in mind as a purpose: intend, purpose, contemplate <he was sociable by disposition, and I believe he designed particularly to shine in the world of talk and manners— Osbert Sitwell> <when some other foreign power designed division or seizure— Roger Burlingame>

**c:** to devise or propose for a specific function <a book designed primarily as a college textbook> <a program obviously designed as a first approach to this problem>

**2 archaic:** to indicate with a distinctive mark, sign or name

**3 a:** to make a drawing, pattern or sketch of (an object or scene)

**b:** to draw the plans for

**c:** to create, fashion, execute or construct according to plan <he was also a clever artist and designed scenes with a flair for color— Winifred Bambrick> <buildings of the institution are so designed that each patient's room opens upon a porch— American Guide Series: Michigan>

Merriam-Webster Authority & Innovation (2000: Version 2,5) defines the noun design as:

**1:** a mental project or scheme in which means to an end are laid down: plan

**2 a:** a particular purpose held in view by an individual or group: a planned intention <my design in writing this preface is to forestall certain critics>

**b:** deliberate purposive planning <what superficially may appear to be a masterpiece of design was likely to have been just an empirical policy of muddling through— Times Literary Supplement>

**c:** direction toward an ultimate end <the teleological, which shows the marks of design in nature, and from them argues to a great designer— Encyc. Americana>

**3:** a preliminary sketch or outline (as a drawing on paper or a modeling in clay) showing the main features of something to be executed: delineation

**4 a:** a painter or sculptor's preliminary drawing or model

**b:** a scheme for the construction, finish, and ornamentation of a building as embodied in the plans, elevations, and other architectural drawings pertaining to it

**c:** a conceptual outline or sketch according to which the elements of a literary or dramatic composition or series are disposed

**d :** a settled coherent program followed or imposed; usually: an underlying scheme that governs functioning, developing or unfolding: pattern, motif

**5 a:** the arrangement of elements that make up a work of art, a machine, or other man-made object <systematic art instruction begins with the study of design, which includes little except the perception and creation of formal relations— Hunter Mead>

**b:** the process of selecting the means and contriving the elements, steps, and procedures for producing what will adequately satisfy some need <industrial design> <included in design are the arrangement of the basic text page, choice of typeface, title page, and special pages— Joseph Blumenthal>; specifically: the drawing up of specifications as to structure, forms, positions, materials, texture, accessories, decorations in the form of a layout for setting up, building, or fabrication <the design of the ship's bridge>

**6 a:** a visual arrangement or disposition of lines, parts, figures, details usually unified by an implicit key or clue of signification or an artistic motif (as in engravings, medals, textiles, metalwork) <linoleum in a great number of designs>

**b:** a pattern or figuration applied to a surface (as of a vase): decoration <porcelain with carved or engraved floral designs>

These definitions are broad. They cover all instances of design and design process, and any instantiation of design and design process will fit within them.

For example, Leonardo da Vinci’s (artist, inventor, engineer, architect, scientist, geologist, physicist, and musician lived between 1452-1519) bicycle drawing (Fig. 2.1) is “a preliminary sketch or outline (as a drawing on paper or a modeling in clay) showing the main features of something to be executed; a painter or sculptor's preliminary drawing or model; the arrangement of elements that make up a work of art, a machine, or other man-made object; a visual arrangement or disposition of lines, parts, figures, details usually unified by an implicit key or clue of signification”. And this drawing has been “had in mind as a purpose, intended; devised for a specific function; and sketched”.

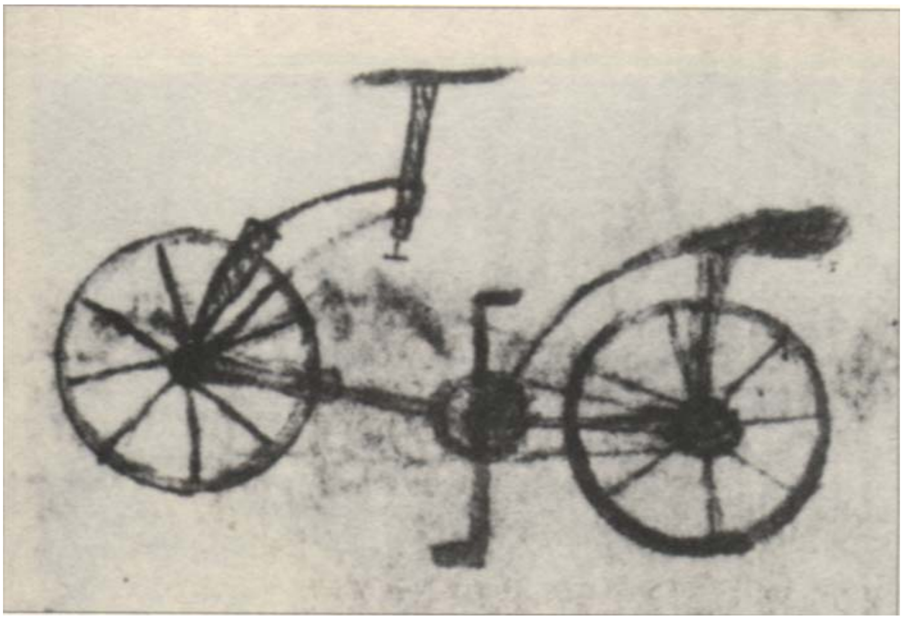


Figure 2.1 (Perry 1995: 7)

Leonardo da Vinci’s Codex Atlanticus Bicycle, from Biblioteca Ambrosiana, 1493

This drawing of a bicycle design can be defined and described explicitly by the definitions given above (Merriam-Webster Authority & Innovation 2000: Version 2,5), and therefore it is called a design. It is also a very interesting example as it is accepted as the evidence of the earliest true bicycle idea. It has been found in Leonardo da Vinci's notebook Codex Atlanticus (also it might be drawn by his assistant, it is unknown), but the drawing is not available for date testing, and therefore a few historians regard it as a fake. If it is not a fake, this drawing also reveals the design as invention and it can be accepted as the invention of the bicycle.

### 2.1.2. Nature of Design

Basic characteristics in the nature of design are as follows:

- "Design is naturally integrative, not separative (Owen 1988:5)".
- "Design is intellectually soft, intuitive, informal, and cook-booky (Simon 1996: 112)".

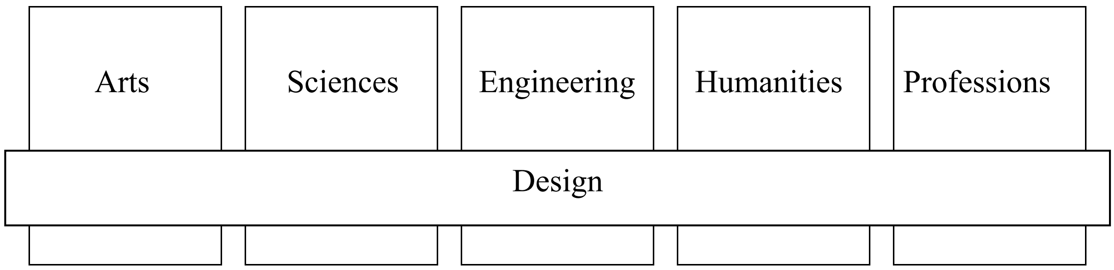



Figure 2.2 (Owen 1988: 5) Design is integrative

Design is in life with people while they reorganize a desk drawer, educate a child, decorate a house, and etc. As Figure 2.2 indicates, design integrates (Owen 1988: 5) all human activities in research and industry contexts as well.

Professionally managers, engineers, architects, scientists etc. all act designerly in the context of industry while they conceive and plan out in the mind, and devise for a specific function or end. Design is also at the heart of professional training as schools get their pupils ready to meet the needs of life.

Academically, design is in humanities (literature, history, philosophy, mathematics etc.), in sciences (natural, mathematical, behavioral, physical, economical sciences, etc.), in engineering (electrical, civil, chemical, textile, human engineering, etc.), and in arts in the means of research context.

Design is the epitome goal of engineering discipline since it facilitates the creation of new products, processes, software, systems, and organizations through which engineering contributes to society by satisfying its needs and aspirations.

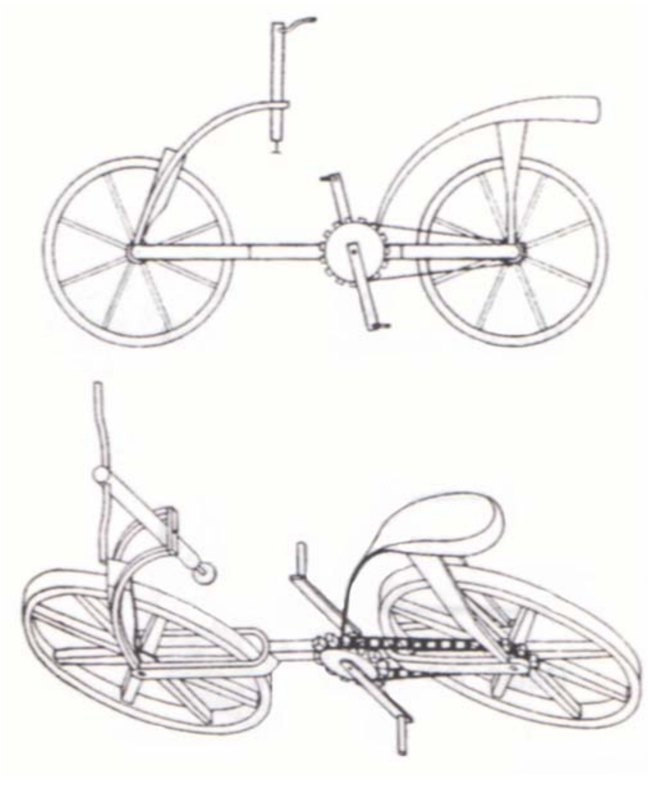
Design has been the task of arts for many years. Arts discipline has developed its knowledge benefiting from design. Unifying principles of design in arts are stated as repetition, variety, rhythm, balance, emphasis, and economy (Zelanski, Fisher 1996: 33). Design is defined with these principles in the discipline of arts.

The base of academic studies has been accepted as the scientific principles through years. Academicians have sought for the explicit knowledge and a common ground for discussions that is found in science, as the academic respectability has called for subject matter that is intellectually tough, analytic, formalizable, and teachable. However, design is intellectually soft, intuitive, informal, and cook-booky (Simon 1996: 112). Design is naturally hard to be formalized as it is stated above. This strict structure of science and this nature of design have delayed benefiting from design knowledge in science discipline and from scientific knowledge in design discipline until twentieth century. In this century with the modern movement of design three different interpretations of the relationship between science and design have become significant: Design Science, Science of Design, and Scientific Design.

“Design Science, firstly used by Buckminster Fuller, refers to an explicitly organized, rational and wholly systematic approach to design; not just the utilization of scientific knowledge of artifacts, but design in some sense a scientific activity itself (Cross 2000: 45)”. “The Science of Design refers to that body of work which attempts to improve our understanding of design through ‘scientific’ (i.e., systematic, reliable) methods of investigation (Cross 2000: 45)”. “Scientific Design refers to modern, industrialized design –as distinct from pre-industrial, craft-oriented design- based on scientific knowledge but utilizing a mix of both intuitive and non-intuitive design methods (Cross 2000: 44)".

These developments are important in the task of design practice, especially the scientific design since design as a discipline provides non-intuitive design methods as well as intuitive methods in building its own design knowledge.

On the other hand, these developments have brought up many discussions, whether design is science or art. However, as Margolin states, "Design is as much expression of feeling as an articulation of reason; it is an art as well as science, a process and a product, an articulation of disorder, and a display of order (Doloughan 2002: 57 quoted Margolin 1989: 6)", design integrates art and science naturally although it is again naturally hard to be formalized in scientific context.



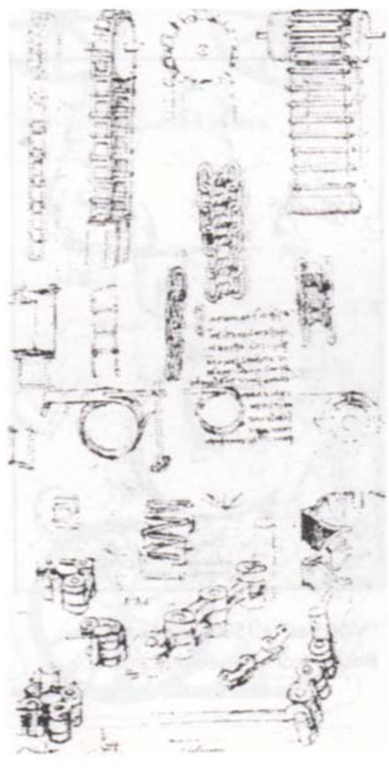


Figure 2.3 (Perry1995: 7 quoted Calegari)  Figure 2.4 (Perry 1995: 6)

Figure 2.3 Axonometric projections of the Codex Atlanticus Bicycle

Figure 2.4 Chains and cogs, from Da Vinci's Codex Madrid

As an example, Leonardo da Vinci's bicycle drawing, whose axonometric projections are shown in Fig. 2.3, and chains and cogs in Fig. 2.4; includes mathematics, physics and artistic knowledge. It is integrated naturally by the scientific and the artistic knowledge.

### 2.1.3. Design as a Discipline

As being integrative (not separative), design is considered as multidisciplinary or interdisciplinary activity in literature. Interdisciplinary and multidisciplinary are defined as follows (Merriam-Webster Authority & Innovation 2000: Version 2,5):

Interdisciplinary: characterized by participation or cooperation of two or more disciplines or fields of study <an interdisciplinary conference>
: drawing on or contributing to two or more disciplines <interdisciplinary approach to anthropology>

Multidisciplinary: combining several specialized disciplines (as those in the field of applied social science) for a common purpose <use of a multidisciplinary approach by a child guidance clinic>

For example, bringing out a bicycle into the market, in the means of modern world, brings together the disciplines like design, engineering, humanities, sciences and the related professions for a common purpose. This is a multidisciplinary activity in research and in industrial contexts. Heskett (2000: 363) states these multidisciplinary collaborations in Fig. 2.5 and Fig. 2.6 where he positions the disciplines according to their related subjects (material or human centered) and methods (synthesis or analysis) in acting towards the common purpose of bringing out a bicycle into markets. In this multidisciplinary activity design is taken as a discipline on its own among the other disciplines.

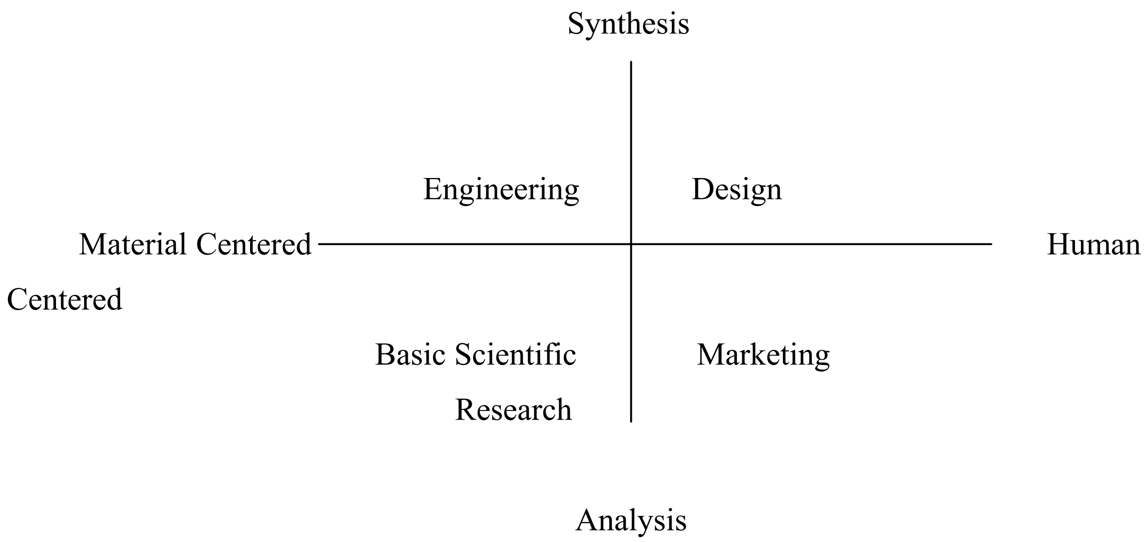



Figure 2.5 Heskett's positioning of design in an industrial context (2000: 363)

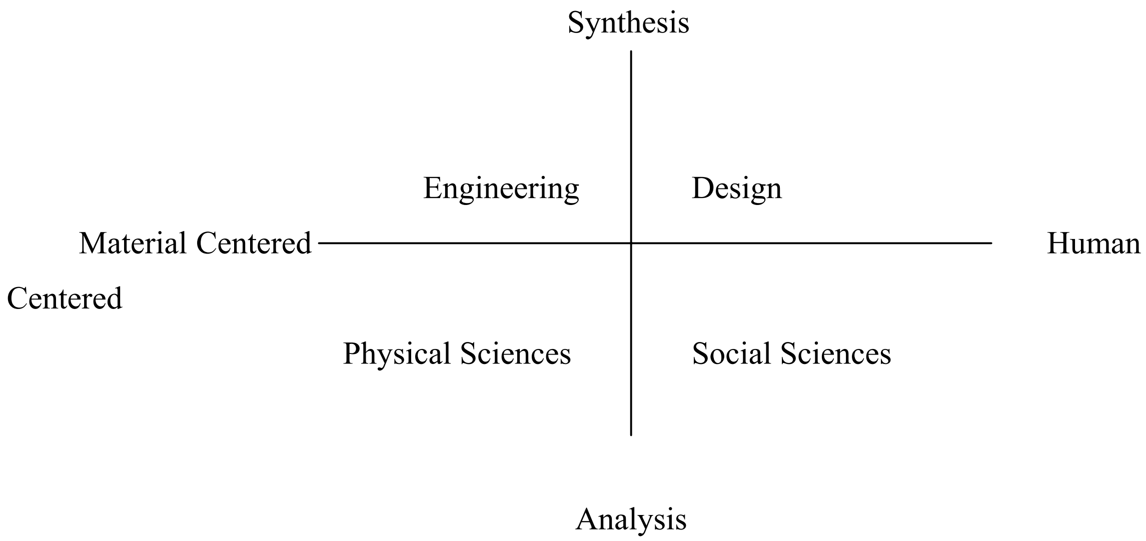



Figure 2.6 Heskett's model applied research (2000: 363)

On the other hand, design is also considered as an interdisciplinary activity because of its integrative nature where two or more disciplines participate. However, this formation causes some conflicts, as Cross states (2000: 46), in the means of developing design knowledge on its own. Therefore design should be taken as a discipline where it seeks for a common ground in itself among other disciplines while benefiting from other fields and disciplines:

> We do not want conversations that fail to connect between sub-disciplines, that fail to reach common understanding, and that fail to create new knowledge and perceptions of design. It is the paradoxical task of creating an interdisciplinary discipline. Design *should be taken* as a discipline. This discipline seeks to develop domain-independent approaches to theory and research in design. The underlying axiom of this discipline is that there are forms of knowledge peculiar to the awareness and ability of a designer, independent of the different professional domains of design practice. Just as the other intellectual cultures in the sciences and the arts concentrate on the underlying forms of knowledge peculiar to the scientist or the artist, so we must concentrate on the 'designerly' ways of knowing, thinking and acting (Cross, "Proceedings of the Politecnico di Milano Conference" 2000: 46).

In doing so, Cross ("Proceedings of the Politecnico di Milano Conference" 2000: 46) states that, "We must avoid swamping our design research with different cultures imported either form sciences or the arts. This does not mean that we completely ignore these other cultures. On the contrary, they have much stronger histories of enquiry, scholarship and research than we have in design. We need to draw upon those histories and traditions where appropriate, whilst building our own intellectual culture, acceptable and defensible in the world on its own terms. We have to be able to demonstrate that standards of rigour in our intellectual culture at least match those of the others".

### 2.1.4. Specializations in Design Discipline

Design can be classified into four broad categories according to its form, function, production and education. Form category includes 2D, 3D, 4D, and other artifacts, function category includes the areas for which the artifacts were produced like transportation, medicine, home-office, the production category includes the production techniques of any sector like metal lightning, glass objects, wooden furniture etc., education includes the fields of design professions.

Emphasizing the design professions that are studied in the education category of the design classification given above, the first thing that can be said for all professions (the schools of engineering, business, architecture, medicine, etc.) within the design professions is that design is the core of all professional training

(Simon 1996: 111). On the other hand, design as a discipline includes design professions like architecture, industrial design, graphic design, stage design etc. These professions have been generally studied in the Faculty of Fine Arts or in the Faculty of Architecture of the universities. But the demands of the modern world (like more complex designs with the developing technology) have created new structures like the Faculty of Industrial Design Engineering (a faculty of Delft University in the Netherlands, that brought industrial design close to engineering), Faculty of Design, etc. addition to this, new design professions like engineering design, product design, process design, etc. have come into existence, which are studied in the Faculty of Engineering of the universities. These professions use engineering and design knowledge and they constitute design discipline together with other design professions.

As a result of the nature of design, which is broad and integrative, the complex structuring of design in professions can be understood more easily. There are various specializations in the design disciplines one of which is given by Dhillon (1985: 225) in Fig. 2.7 that is appropriate to the subject of this study.

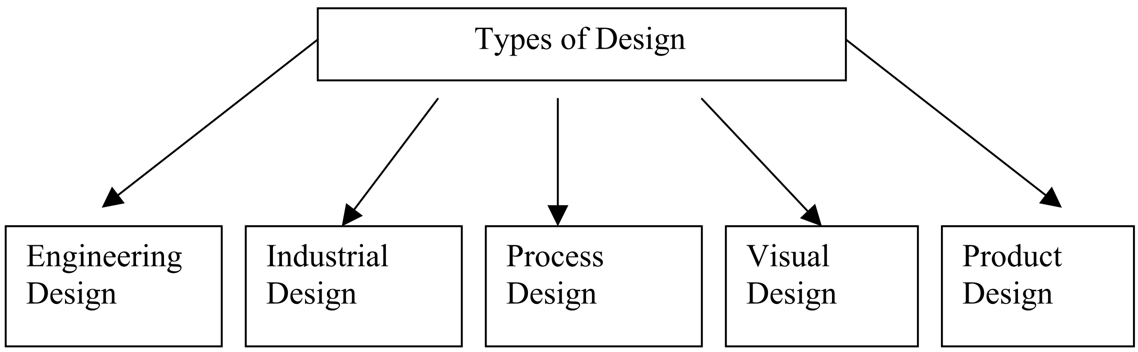



Figure 2.7 Types of Design (Dhillon 1985: 226)

**Engineering Design:** It is concerned with applying various techniques and scientific principles to the development and analysis of basic functional features of systems, devices, etc.

**Industrial Design:** It designates an independent design effort by the individual (consultant) with combined abilities in areas such as product design, styling, and engineering.

**Process Design:** It is usually concerned with the type of design that restricted to the design of components, tools, equipment, etc. (items for mass production systems)
**Visual Design (Styling Design):** It is concerned with the appearance features of an item.
**Product Design:** It is associated with specifically those items that are ultimately to be sold to consumers.

In this classification, the industrial designer is accepted as a consultant, not a part of a specific product manufacturing organization. However, industrial designer can be a part of these organizations such as Sony, Ford, Arçelik, etc. and work in a team that ultimately includes engineers, marketers, sociologists, etc.

The modern world has generated too many specializations in disciplines, which can be seen clearly in design area as well. The specializations above reveal only a small part of this result. It is difficult to distinguish design fields definitely through the developments in the design area, as they can easily overlap with other design fields and subfields while building their own knowledge to the design discipline.

Product design is more specifically the design of discrete, physical products. In some respects the concept "product design" is narrower than "engineering design", which also includes for instance the design of chemical and physical processes. But, on the other hand, it is a wider concept than "industrial design", which generally focuses on the usage and external appearance of products. So there is more engineering content in this treatise than in most works on industrial design, yet this is not a traditional work on engineering design. Engineering designers work with product and process designers while industrial designers work more with styling and product designers. Engineering designers take part in testing and design while the industrial designers take more part in design and styling. But they readily overlap with other fields and subfields, and an industrial designer should at least have an idea of how the product is going to be made, understand the engineering problems, and be able to read the engineering test results.

## 2.2. Industrial Product Design

Through many movements in art and culture in the twentieth century, design has come to be regarded as the professional occupation of bringing humanity to dehumanized and impersonal mass-produced items. Industrial design is concerned with all the human aspects of machine-made products and their relationship to people and the environment. The designer is responsible for these products and their impact on society and nature.

The term "designer" is too general since it includes architects, engineers, stage, and fashion designers, and the like. Industrial Design is the most widely used term for the professional design of objects intended for mass production. The term is not always used correctly since many industrial designers may work on products for craft manufacture and in related fields such as exhibition or interior design. In order to make a clear distinction, since such distinctions are the very subject of this study, the term “industrial product design” is going to be used.

### 2.2.1 History and Definition of Industrial Product Design

During the Middle Ages in Europe, crafts culture had been dominant. Craftsman (or men in small teams) was supposed to learn design, use skills and produce with the spirit of their culture. They worked in their studios or workshops and transferred what they had learnt from their masters to the crafts and as well teaching the skill to the new pupils. As craft came from copying, the principle of “little creativity, more tradition” was at work. Craftsmen did not carry the responsibility the industrial designer carries today. Dormer states “The greatest difference between the designer and the single craftsperson is that the craftsperson does not have the problem of communicating his or her intensions to others for translation into objects. The designer, however, must make his or her intensions explicit-communication is at the heart of industrial design (Dormer 1993: 9)”.

> The profession of industrial designer emerged in the twentieth century and can be seen as a feature of the division of labour and specialization characteristic of large-scale modern industry. Before this specialism developed the function of design in industry was less

> well defined and was performed by a variety of people, from major artists to anonymous workers who presented particular problems and challenges (Heskett 1987:110).

After the Industrial Revolution, accepted as the invention of the steam engine by James Watts in 1764-65, the power-driven machinery, assembly lines and growing automation (mass production) gave rise to concepts like mechanization, standardization, and rationalization. Industrialization within these concepts has caused two significances, which are division of labour and specialization. In the late 1920s in the USA, a body of specialists emerged who established industrial design as a discrete profession, bringing to activity a new status and recognition. Governments too began in this period to show a greater awareness of the economic role and propaganda possibilities of industrial design, often forming bodies to encourage its development, with, for example in Britain, the Council of Art and Industry being established in 1932, followed by the Council for Industrial Design in 1944.

The definition of industrial design announced by the International Council of Societies of Industrial Design (ICSID) as a general and a standard definition is as follows:

> Industrial Design is a creative activity whose aim is to determine the formal qualities of objects produced by industry. These formal qualities include external features but are principally those structural and functional relationships, which convert a system to a coherent unity both from the point of view of the producer and the user. Industrial design extends to embrace all aspects of human environment, which are conditioned by industrial production (Christiaans 1992: 1 quoted ICSID 1964).

Industrial design is concerned with the vast array of goods manufactured by serial or mass production methods. A high-wheeled bicycle factory in the United States of America, and a safety bicycle factory in England are shown in Figure 2.8 and Figure 2.9 respectively, as an example of mass production in bicycle industry.

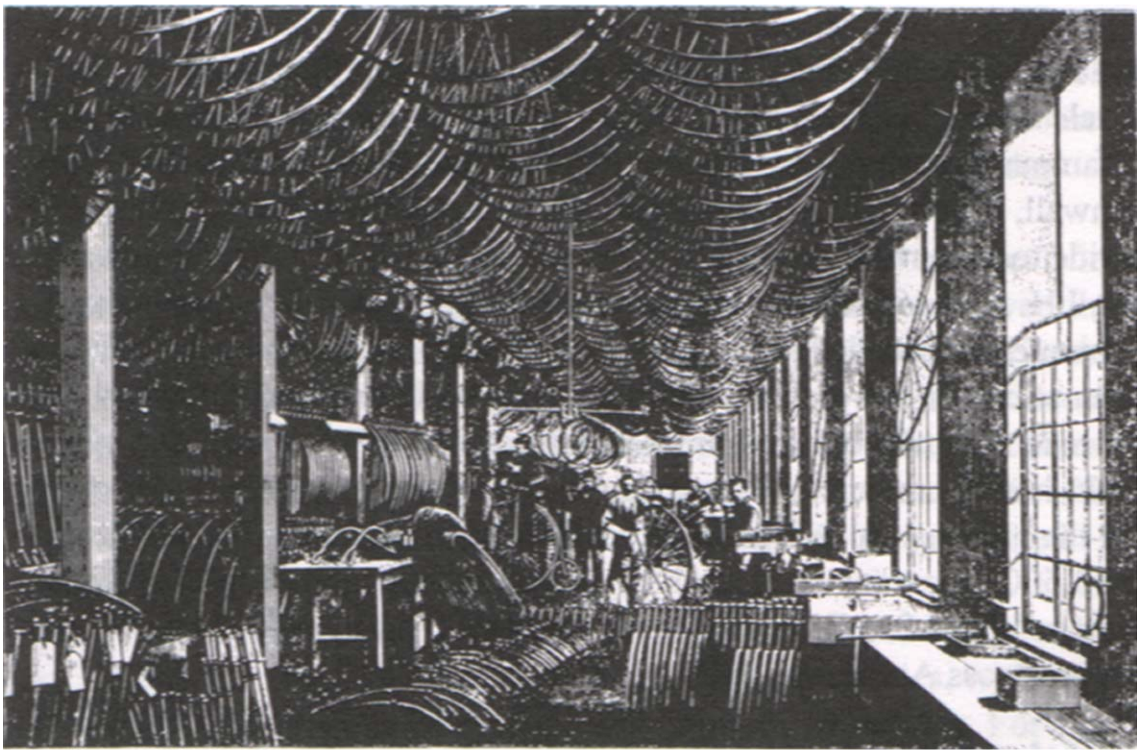


Figure 2.8 Assembly room, Columbia factory, Hartford, Connecticut, 1884
(Perry 1995: 29)

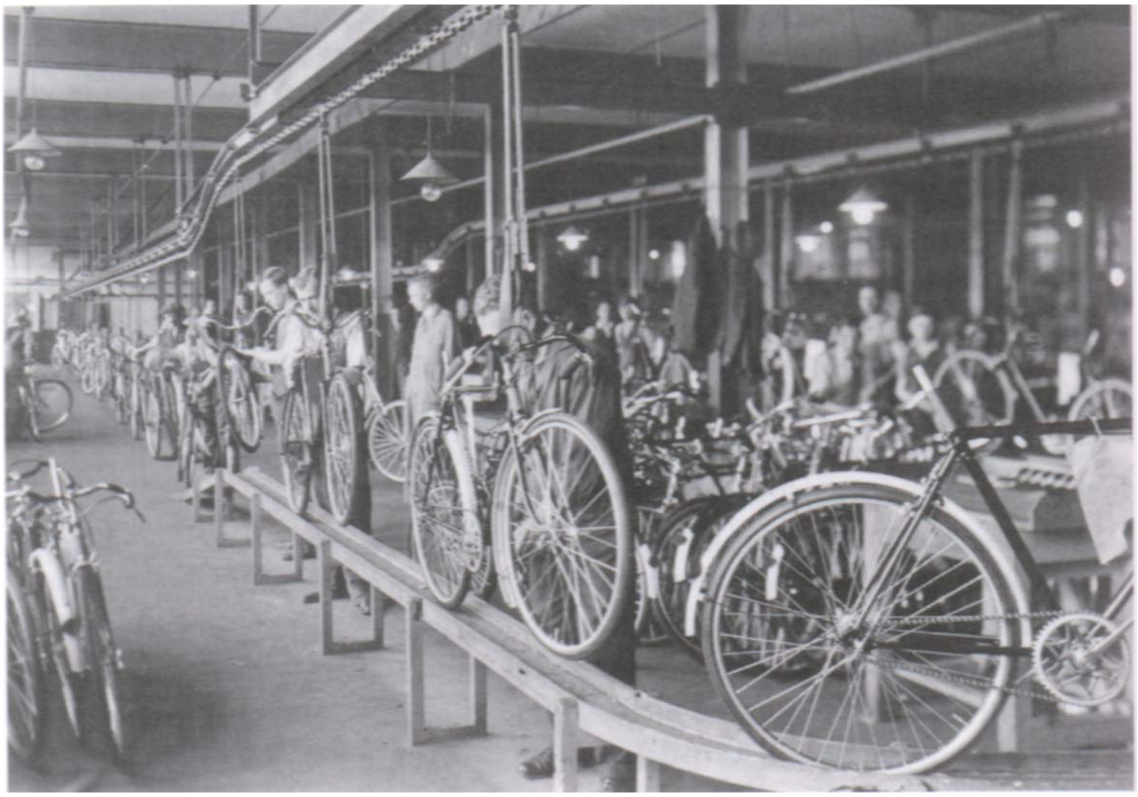


Figure 2.9 A conveyor on the final inspection line at Raleigh, England, 1935
(Rosen 2002: 66)

Design in industrial design is industrially produced. This is the significance of industrial design among other design professions. It has been indicated in ICSID's definition, that industrial design is an activity of determining the design through many criteria; this conception carries two important characteristics, namely creativity and multidisciplinarity. These characteristics come from the nature of design, as it is "intellectually soft, intuitive, informal, and cook-booky (Simon 1996: 112)" and, "integrative, not separative (Owen 1988: 5)".

### 2.2.2. Industrial Designer

#### 2.2.2.1. Multidisciplinarity and Creativity in the Industrial Designer's Ability

> An industrial designer is one who is qualified by training, technical knowledge, experience and visual sensibility to determine the materials, construction, mechanism, shape, color, surface finishes and decoration of objects which are reproduced in quantity by industrial processes. The industrial designer may, at different times, be concerned with all or only some of these aspects of an industrially produced object. The depth of designer's responsibility may range from the original conception of the product's mode of use to its visual and tactile finishes, and involves the correlation of its functional, cultural, social, and economic contributions to the betterment of the human environment (Asatekin 1997: 37 quoted ICSID 1964).

As designing is a multidisciplinary activity, when an industrial designer designs an object, he has to deal with a lot of criteria, which are stated in ICSID's definition of he/she has to overlap with other disciplines such as engineering, marketing, psychology, anthropology, etc. in order to determine the formal qualities of objects produced by industry. When he/she is working in a team, he/she becomes the only one who can perceive the work as a whole. Other team members, specialized in work, have difficulties in understanding each other. At this point, many times the industrial designer becomes the only one who is able to speak the various jargons from other disciplines and behave like the team synthesist. Besides fulfilling its normal design functions, industrial design also acts as a communication bridge among disciplines.

When an industrial designs an object, “he/she goes through analysis, synthesis and evaluation stages, which is one of the simplest and most common observations about designing (Jones 1992: 63)”. Simply, he/she breaks the problem into pieces (analysis), then puts them together in a new way (synthesis), and then tests to discover the consequences of putting the new arrangement into practice (evaluation). He acts creatively in each stage with the abilities of (Christiaans 1992:2 quoted Cross 1990: 132):

- Resolving ill-defined problems
- Adopting solution-focusing strategies
- Employing abductive/productive/appositional thinking
- Using non-verbal, graphical/spatial modeling media

Industrial designer fulfills the design function besides acting like a communication bridge between other disciplines.

#### 2.2.2.2. Industrial Designer’s Tools and Techniques

Industrial designer uses some techniques and tools while designing. These can be classified (http://sjsu-id.org/id/how-tools.htm) as: Ideation, Model Making, and Computer Programs.

Ideation is a process of making ideas visual by means of drawing with a utensil of some kind “quick impulsive drawing technique used to gather numerous ideas quickly (Brainstorming)”, “a finished sketch using rendering techniques to convey a solid idea of the final product concept (Color Rendering)”, “a refined sketch, sometimes using color, to convey a more understandable concept or idea (Concept Sketch)”.

Model Making is a stage of design process where one transfers a design project from a two- dimensional layout to three-dimensional using different techniques like “using one's hand or tool to shape a material into the desire shape (Shaping)”, “a mold of the project is made to allow us to mass reproduce the project (Molding)”, “using thermoplastic sheets and a mold to form the desirable shape

(Thermoforming)", and "applying paint onto a surface of a model to increase aesthetic (Painting)".

Computer Programs are also a stage of design process where one transfers a design project from a two- dimensional layout to three-dimensional using different techniques. Some of the important computer programs for industrial design are: Auto-Cad (used to draw technical drawings), Rhino (mostly used for 3-d modeling and rendering, and also does dimensioning but not as precise as auto-Cad or pro-E), Pro-E (able to do both technical drawing and 3-D computer modeling), Illustrator (for quick 2-d design layouts), Alias (complex 3-d modeling and rendering).

Industrial designer presents his/her final design with "a 2D representation of an object with its parts separated, but depicted in relation to each other (Exploded View)", "6 orthographic views (Control Layout)", "parts list and locations (Component Layout)". In final detailing logo, control markings etc. are added as graphics. Also a prototype is made by rapid prototyping and rapid tooling by using advanced computer and polymer technology. "The main benefits of rapid prototyping (RP) and rapid tooling (RT) are a dramatic cut in part/product development time and a shorter time to market (http://sjsu-id.org/id/how-model.htm)".

#### 2.2.2.3. Working as a Consultant or in an Organization

"Modern practice for industrial designers generally falls into two broad categories when he/she is either a direct employee of an organization designing exclusively for it, or an independent consultant commissioned to design for a variety of clients (Haskett 1987: 110)".

For the first type designers working for Sony, Ford, Teba, Vestel, Arcelik, and etc. can be given as examples. Such teams are responsible for translating the possibilities of scientific and technological invention into products that are appropriate and appealing to the buying public. Their success or failure can profoundly influence the performance of the company. Consultants perform a similar function but for a variety of clients and product types.

### 2.2.3. Product Range in Industrial Product Design

Heskett's phrase draws a panorama of the product types and the objects around us as: "Unlike design for ceramics, glass or textiles, industrial design is not confined to one material, nor, as in furniture or interior design, to a particular category of artifact or environment. The range of objects concerned may extend from 'a lipstick to a steamship' or from 'match to a city' (Haskett 1987: 110)". Such breadth can be problematic. The sheer extent and diversity of the innumerable products of industry is itself confusing. For example kitchen area, transportation area, etc. Any area reveals a diversity that contains a variety of objects to facilitate particular activities. All will have been conceived to serve a certain purpose and embody a particular set of values. … Our environment is composed of industrial products. They are so numerous and ubiquitous as to be frequently taken for granted. They form the material framework of our existence, enabling it to function, not only in practical or utilitarian terms, but also in ways that give pleasure, meaning and significance to our lives. They are elements of our material culture, tangible expressions of individual and social values.

Products can be categorized functionally in classification of design that reveals the design areas of products. Industrial designer deals with transportation, furniture, home-office (accessories like the clock, pencil, etc.), high-tech (Dvd player, monitor, etc.) lightening, fashion (accessories like umbrella, wristwatch, etc.), toys and games, food, packaging, gift/promotion, sports, medical and etc. functions, some of which are described and given examples below.

- Medical Products: Health care supplies and equipment are involved in this field, which provides better design and solution for medical society.
- Transportation: Design and manufacture in automobile, public transit, aviation and naval transit, and etc. are involved in this field.

- Furniture: This field involves the creation of pleasurable surrounding by designing innovative furniture that is both ergonomically comfortable and aesthetically beautiful.
- Sports: Design and innovation in all kinds of sports activity, gear and equipment are involved in this field, which provides better design and solution for people practicing variety of sports.
- High-Tech: This field involves the most advance technological equipments, which requires the highest knowledge and expertise.

Figure 2.10
Examples of Industrial Product Design
(http://sjsu-id.org/id/who-corp.htm)

Whatever the mode of employment, or type of product under consideration, the task of modern industrial designers is to produce a plan and specification of a form or mechanism for large-scale production.

**2.2.4. Core Characteristics of Industrial Product Design**

There are four core characteristics in industrial product design that are: quality, quantity, identity, and method. Quality gives the value, quantity means the mass production, identity gives the name, and the method produces the design. These characteristics are set up in order according to priorities of the product, but they should be all included and dissolved in the industrial product itself. For example, in race bike design, quality is more important as it is a design for a special purpose. On the other hand, for a road bike, identity might be put forwardly in a competing market strategy.

As mentioned before, industrial designers deal with a lot of criteria. While dealing with these criteria, they design the product with an eye to quality, quantity, identity, and the method.

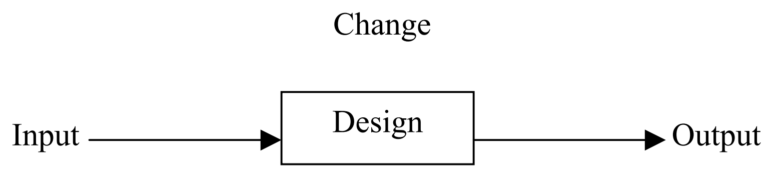



Figure 2.11 Basic Model of Change (Bayazıt 1994: 55)

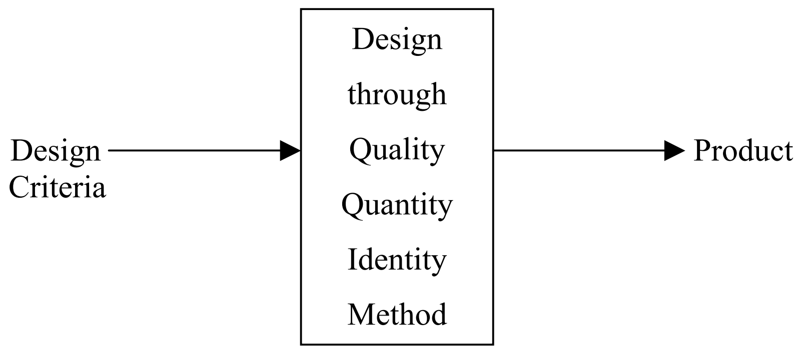



Figure 2.12 Design through Quality, Quantity, Identity, Method

### 2.2.5. Design Criteria in Industrial Product Design

Industrial product design carries a bunch of criteria such as being responsible to society, culture, environment, economy etc. Mehmet Asatekin (1997: 39-43) systematically classifies these criteria with a holistic approach to industrial product.

- Functional Criteria
    - Physiological Criteria
    - Environmental Criteria
    - Communicational Criteria
- Psychological Criteria
    - Perceptional Criteria
    - Socio-Cultural Criteria
    - Sensitive Quality (Criteria)
    - Explanatorily Criteria
- Technological Criteria
    - Material Criteria
    - Production Criteria
- Economic Criteria
    - At the Consumers' Level
    - At the Producers' Level
    - At Macro-Level

#### 2.2.5.1. Functional Criteria

Objects come in existence because of physical needs and their main duty is to suffice these needs. Functional criteria are directed to optimize the sufficiency of physical needs in the object.

**a. Physiological Criteria:** Physiological criteria are directed to optimize the fitting of object to human physically (visually, auditorily etc. as well) by formulating ergonomic data.

**b. Environmental Criteria**: Objects should relate to each other in the environment, and to environmental elements as well as to the users. Environmental criteria are directed to optimize the fitting in these relationships. The hanging components, standing components, combining details etc. are designed as a result of these criteria.

**c. Communicational Criteria:** The object itself should communicate to the user. Communicational criteria are directed to optimize the communication between the object and the user. The communicated knowledge can be the object itself or the usage directions of the object. According to this, communicational criteria may be classified as functional and conceptual criteria. Functional criteria are the usage directions of the object. It can be graphical like the play button of a cd player, or the image that occurred in user's mind through evolution like the hammer. Conceptual criteria destroy this functional image or graphics. The object itself becomes the communication knowledge conceptually. Philippe Starck's Juicy Salif Lemon Squeezer (Fig. 2.5) could be an example of this.

Figure 2.13 Juicy Salif Lemon Squeezer

Juicy Salif lemon squeezer's aim in communication is different than being an only lemon squeezer, Starck states:

> Sometimes you must choose why you design - in this case not to squeeze lemons, even though as a lemon squeezer it works. Sometimes you need more humble service: on a certain night, the young couple, just married, invites the parents of the groom to dinner, and the groom and his father go to watch football on the TV. And for the first time the mother of the

> groom and the young bride are in the kitchen and there is a sort of malaise - this squeezer is made to start the conversation (Lloyd and Snelders 2003: 243 quoted Starck 1998).

Whether this is the reason of Starck or not, but for sure, he uses conceptual communication in his Juicy Salif lemon squeezer design and meets the psychological needs of humans.

#### 2.2.5.2. Psychological Criteria

Human beings estimate everything in their life, environment and the objects that form the environment. The perception period before estimating, and the estimation period together cause the needs that form the Psychological Criteria.

**a. Perceptional Criteria:** Object's physical qualities and its form affect not only how it is going to be perceived, but also the estimation period followed. Perceptional criteria are directed to optimize the designing of the object according to its being perceived as the object itself and reliability in the estimation period.

**b. Socio – Cultural Criteria:** Every community brings up its rules and value systems within. Person growing and living in his/her community perceives the object not only with its functionality or formal qualities, but also with these social norms. Therefore, socio-cultural criteria are directed to optimize the fitting of the product design to social norms of the communities. Socio-cultural criteria differ according to time and place, and it has dynamic qualities. Aesthetics criteria rest on these qualities as well, and they should be handled as a part of this class.

**c. Sensitive Quality (Criteria):** People set up empathy while they approach to objects. Roughly they like the object, or not, and to do this they try to find something in the object that means something to themselves. They look for something that is identical to them. This likeness occurs in person's life. Therefore it is impossible to generalize, and it is not concrete either. These difficulties shouldn't make the designer behave like the sensitive qualities do not exist. These criteria are important to reveal the sensitive qualities that an object carries.

**d. Explanatorily Criteria:** A designer acts with the aims that he has determined while forming the object. He carries scientific aims and criteria as well as some idea that he wants to communicate with the user through the object. This kind of communication is the core of artistic explanatory. In architecture and industrial design functional aims compete with these artistic explanatory. Designer should be capable to harmonize these aims and reflect to the object. He should translate his interpretations of the object to the object language in giving a physical appearance to the object. With this language designer suggests his social, physical and psychological aspects to the user. This explanatory act is two dimensional that, not only the designer's ideas, but also the user's ideas should be considered.

#### 2.2.5.3. Technological Criteria

Technological criteria are directed to optimize the fitting of the object that is going to be to be produced to design process and manufacturing.

**a. Material Criteria:** The chosen material should fit the function and usage conditions of the object. The chosen material should fit the form of the object, and the form of the object should fit the chosen material (two directed determination, active-passive). If more than one material is going to be used in the object, the fitting of these materials should be also considered as material criteria.

**b. Production Criteria:** These criteria are also active and passive, and two directed in a way that the production methods of the object should fit the chosen form-material combination and the chosen form-material combination should fit the production methods of the object. Material criteria are connected to production criteria and cannot be thought separately.

#### 2.2.5.4. Economic Criteria

The production period and also the following usage period happen together in an economical environment. "The object that sufficing the need" aims economical profits in all units. Economical criteria take part in these economical environments.

**a. At the Consumers' Level:** The object should worth its price in satisfying the consumer's need. Giving a price to the produced object is a complex fact that, here, the designer should carry the responsibility of the least price is transformed to the object.

**b. At the Producers' Level:** Producers have some possibilities like production methods, marketing types, productive power, time and etc. with the aims like maximizing the profit. Designer should act in this environment for the production of his/her designs.

**c. At Macro-Level:** Designs are produced in mass that a lot of source like human power, raw material, energy and etc. is consumed. Designer is responsible not only in satisfying the consumers' needs, but also in using enough sources for the production of the object.

### 2.2.6. Engineering Criteria in Industrial Product Design

Industrial product design is a multidisciplinary activity. The industrial designer deals with numerous criteria, which are also among subjects of other disciplines. As he/she approaches design with a holistic view, he/she fulfills the design function besides acting like a communication bridge between other disciplines.

Engineering is one of these disciplines that industrial product design is tightly related. Industrial product design benefits from engineering knowledge in constituting the design knowledge as being a field of the design discipline.

Engineers apply the theories and principles of science and mathematics to research and develop economical solutions to practical technical problems. Their work is the link between scientific discoveries and commercial applications.

The intersecting criteria of engineering and industrial design in a product are:

- Functional Criteria
  - Physiological Criteria
  - Environmental Criteria
- Technological Criteria
  - Material Criteria
  - Production Criteria
- Economical Criteria
  - At the Producers' Level
  - At Macro-Level

Engineering fields such as human-factors engineering, materials engineering, mechanical engineering, industrial engineering, process engineering, manufacturing engineering, design engineering, product design engineering deal with the criteria given above, and participate in design of the industrial product.

Engineering Designers are responsible for applying various techniques and scientific principles to the development and analysis of basic functional features of systems, devices, etc.

Process Engineers are responsible for the type of design that restricted to the design of components, tools, equipment, etc. (Dhillon 1985: 226). (Items for mass production systems.)

Human-Factors Engineers are responsible for ergonomics of the product to the user and the environment.

Mechanical Engineers are responsible for developing machinery or mechanisms vital to the design of a product. Computer-Aided engineering and analysis are also done to determine failure and stress levels of specific products (http://sjsu-id.org/id/what-issues-eng.htm).

Manufacturing Engineers are responsible for determining if designs can be produced. Their expertise also involves rapid prototyping and assembly documentation of products.

Product Design Engineers are responsible for the design of discrete, physical products (Roozenburg and Eekels 1995: 53). They are associated with specifically those items that are ultimately to be sold to consumers.

Industrial Engineers are involved with the work environment and how the better can be improved for better productivity. They design, install, and improve systems that integrate people, technology, materials, and information (http://sjsu-id.org/id/what-issues-eng.htm).

Materials Engineers study the structure, properties and processing of materials used in products. The materials study done by these engineers is important to the performance of the product (http://sjsu-id.org/id/what-issues-eng.htm).

In the lack of these criteria, with which engineers too are engaged, the designs cannot come into existence as a product sold in the markets of the modern world. Since this is the purpose of the industrial product design and the significance of it among the other design fields, engineering can be considered as one of the closest disciplines to the industrial product design field.

# Chapter 3

# ENGINEERING CONCEPTS IN INDUSTRIAL PRODUCT DESIGN

## 3.1. Engineering and Industrial Product Design

### 3.1.1. What is Engineering?

Before the middle of the eighteenth century, large-scale construction work was usually placed in the hands of military engineers involving the preparation of topographical maps, the location, design, and construction of roads, bridges and the like. In the eighteenth century, however, the term civil engineering came into use to describe engineering work that was performed by civilians for nonmilitary purposes. With the increasing use of machinery in the ninteenth century, mechanical engineering was recognized as a separate branch of engineering, and later mining engineering was similarly recognized. The technical advances of the ninteenth century greatly broadened the field of engineering and introduced a large number of engineering specialties, and the rapidly changing demands of the socioeconomic environment in the twentieth century have widened the scope even further like automotive engineering, acoustic engineering, human factors engineering and so on (Encyclopedia Britannica Article).

#### 3.1.1.1. Definition of Engineering

The term engineering applied to the profession in which a knowledge of the mathematical and natural sciences, gained by study, experience, and practice, is applied to the efficient use of the materials and forces of nature (Encyclopedia Britannica Article).

Materials and forces of nature are converted to products, processes, systems etc. in order to suffice the needs of human beings. While doing this, engineers use engineering knowledge that is derived from studying, experiencing and practicing the knowledge of the sciences and mathematics. The application of engineering knowledge provides analysis and synthesis. Synthesis of experience and analysis of materials and forces of the nature is included that the engineer acts like an artist (designer) as well as a scientist in the expansion of the engineering knowledge.

Because of these characteristics, engineering is the most important feature of industrial product design in the means of bringing design to an end product that is sold in the market. The priority of using engineering knowledge might change according to the product that is going to be designed. However, more or less it is still involved in designing activity.

#### 3.1.1.2. Significance of Science and Design in Engineering

The British Institution of Structural Engineering defines structural engineering in every issue of *The Structural Engineering,* the official journal, as: "Structural engineering is the science and art of designing and making, with economy and elegance, buildings, bridges, frameworks, and other similar structures so that they can safely resist the forces to which the may be subjected (Petroski 1992: 40 quoted)". Petroski critisizes this declaration as follows:

> Since some engineers deny that engineering is either science or art, it is encouraging to see this somewhat official declaration that it is both. And indeed it is, for the conception of a design for a new structure can involve as much a leap of the imagination and as much a synthesis of experience and knowledge as any artist is required to bring his canvas or paper. And once that design is articulated by the engineer as artist, it must be analyzed by the engineer as scientist in as rigorous an application of the scientific method as any scientist must make (Petroski 1992: 40).

Florman agreeing with Petroski defines the engineering in a holism of synthesis and analysis in the names of science and art (design). But he also emphasizes that scientific principles have recognized engineering as a profession and brought up today's engineering concepts:

Engineering is the art or science of making practical application of the knowledge of pure sciences. In other words, although engineers are not scientists, they study the sciences and use them to solve problems of practical interest, most typically by the process that we call creative design. Engineers are not mechanics, nor are they technicians. They are members of a profession. Although this profession has its roots in the earliest development of the human species, it only achieved recognition as a 'learned profession' in the mid-nineteenth century, when scientific principles were first applied systematically to engineering problems, and when engineering schools and societies began to be established (Florman 1976: Preface to the first edition).

Science is very important in engineering education, and as well in engineering practice, where it validates the process results. Suh states the importance of scientific knowledge is engineering as follows:

> In the absence of a scientific basis, human intellectual endeavors ranging from fine arts to engineering are performed subjectively in the realm of the "creative" activity. Since the output of such activities cannot be understood rationally in the absence of commonly accepted criteria, they are treated as such. What this really means is that we can appreciate the outcome of the intellectual endeavor but do not understand the *process that produces the outcome*, and cannot quantify the results (Suh 1990: 6).

On the other hand, design is the epitome of the goal of engineering. It facilitates the creation of new products, processes, software, systems, and organizations through which engineering contributes to society by satisfying its needs and aspirations. Every field of engineering involves and depends on the design or synthesis process, which allows people to fulfill needs through the creation of physical and/or informational structures, including machines, software and organizations. Suh states the importance of design and the inability of using it in engineering as follows:

Design is important because it determines the ultimate outcome of engineering activities, including the manufacturing of the goods, improvement in the quality of life, and the provision of defense needs. Design decisions made at the initial or upstream stage of engineering affect all subsequent outcomes. … we often relegate the design decisions to the least experienced or the least educated of engineering professionals. The reason why this practice has lasted for so long lies in our inability to reduce design to absolute or scientific principles, rendering the educated and uneducated alike handicapped in this field (Suh 1990: 6).

As engineering includes science and art (design), it carries the paradox of complementing these two disciplines. Engineer, benefiting from scientific and design knowledge, designs products, systems, processes, that can be validated. However, this shouldn't be seen as a paradox as Pirsig states:

> …science and art are two different complementary ways of looking at the same thing. In the largest sense it is really unnecessary to create a meeting of the arts and sciences because in actual practice, at the most immediate level they have never really been separated. They have always been different aspects of the same human purpose (Pirsig, "Subjects, Objects, Data and Values").

### 3.1.1.3. Functions of Engineering

Through application of engineering knowledge to the products, engineering deals with time (delivery time, manufacturing time etc.), cost and quality (value added, consumer preference etc.) of the product (or process, software, system, organization), in other words, deals with factors of the "real world". The aims of engineering in this "real world" can be stated generally as follows:

- to find solutions to problems experienced in a complex industrial-social system
- to provide public services with highest reliability, quality, and safety at a lower cost
- to increase the pleasures of life (Dhillon 1985: 27)

Any engineering field must take into consideration the economic factors that the "real world" is associated with. As the environments in which the engineering product has to exist become increasingly competitive and demanding, more and more attention is being given to economic aspects as a fact of the "real world".

Industrial product design carries the same functions with engineering in some ways. It seeks for finding solutions to problems experienced in a complex industrial-social system, increases the pleasures of life, and provides public services. However, its priorities are different in verifying these. It acts through concepts of quality, quantity, identity and method that, it determines the qualities (materials, construction, mechanism, shape, color, surface finishes and decoration) of objects, which are reproduced in quantity by industrial methods, and their relationship to people and the environment. In this activity, industrial product design weighs in human-centered aspect of designs and generally focuses on the usage and external appearence of the products, where engineering more weighs in material-centered aspect of designs (aspects of “real world”) with the priorities of reliability, quality, and safety at a lower cost.

#### 3.1.1.4. Raw Materials of Engineering

Raw materials that forms the engineering knowledge classified by Dhillon (1985: 230) is as follows:

**a. Engineering Technology:** It includes areas such as manufacturing methods, experience, manipulations, etc.
**b. Mathematics:** Mathematical calculations simplify and help in engineering acting, however, they must be employed with caution and judgment as the mathematical models are always less complex that actual structures, processes, or machines.
**c. Natural Sciences:** They include life and space sciences, earth sciences, physics, chemistry, etc.
**d. Engineering Sciences:** They include areas such as electrical theory, fluid and solid mechanics, material sciences, and thermodynamics, etc.

The historian Edwin Layton has contributed to the topic of engineering knowledge the important insight that what engineers call “the engineering sciences” – mechanics, thermodynamics, materials science, and several others- have taken their pattern from science. They are mathematical and exact within prescribed limits, and their similarities to the “hard sciences” are so striking that Layton calls science and the engineering sciences “mirror-image twins”. The purpose of engineering sciences, however, is not to record “laws of nature” but to state relations among measurable properties –length, weight, temperature, velocity, and the like- to permit a technological system to be analyzed mathematically. The engineering sciences also differ from pure sciences in that they have an array of abstract concepts, independent of science, that serve as a framework within which technical problems can be analyzed (Ferguson 1994: 10).

**e. Miscellaneous:** It includes areas such as economics, information theory, psychology, literature, communications and etc.

These raw materials of engineering affect the design of the products directly in the means of finding the best solution to ergonomics, manufacturing, marketing problems, etc. that bring out the product into markets. In Figure 3.1, the use of engineering knowledge with the raw materials of mathematics, engineering sciences and natural sciences is shown on a bicycle frame.

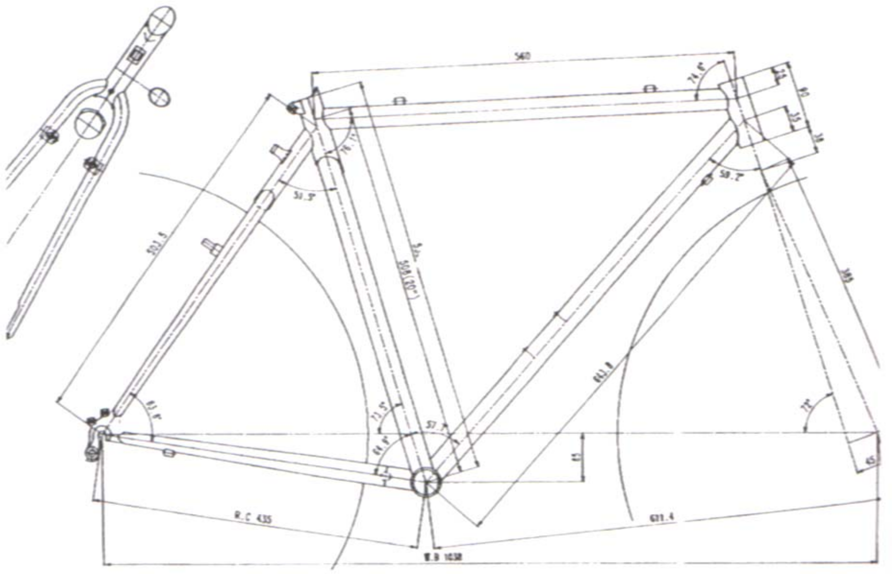


Figure 3.1 A diagram showing specifications for a bicycle frame
(Rosen 2002: 128)

### 3.1.2. Engineering Design Field

An architect and engineering designer, Jack Howe says that; "I believe in intuition. I think that's the difference between a designer and an engineer … I make a distinction… An engineering designer is just as creative as any sort of designer". And an industrial designer, Richard Stevens says that; "A lot of engineering design is intuitive, based on subjective thinking. But an engineer is unhappy doing this. An engineer wants to test; test and measure. He's been brought up this way and he's unhappy if he can't prove something. Whereas an industrial designer … is entirely happy making judgments which are intuitive" (Cross 2000: 19, 20).

Engineering designers seem closer to industrial designers relatively more than the engineers. Especially the engineers, as the engineering education focuses on mostly the scientific principles, get used to analysis more than synthesis. On the other hand, engineering designers apply the scientific principles to the products, processes, systems and etc. Therefore the engineering designer deals with more synthesis and uses more engineering knowledge, derived from experiencing, rather than scientific knowledge. He/she still tests and analyzes, but also knows to act intuitively during the design process. Although the priorities of the engineering designer and the industrial designer are closer to each other's more than the engineer's, their criteria in designing have some different focus. Where the industrial designer weighs in styling problems more, the engineering designer weighs more in functional problems. Their product focusing differs in some ways as well as their design problems.

#### 3.1.2.1. Modern Engineering Trends and the Complexity in Design

Modern engineering is characterized by the broad application of what is known as systems engineering principles. "The systems approach is a methodology of decision-making in design, operation, or construction that adopts (i) the formal process included in what is known as the scientific method; (ii) an interdisciplinary, or team approach, using specialists from not only the various engineering disciplines, but from legal, social, aesthetic, and behavioral fields as well; (iii) a formal sequence of procedure employing the principles of operation research (Encyclopedia Britannica Article)". Transportation engineering, time-study engineering, human factors engineering can be given as examples of modern engineering professions.

Because of the complexity of most problems, as shown in Figure 3.2, design work is generally done by teams or groups. The complexity of mechanical devices has grown rapidly over the last 200 years that cannot be afforded to by a single designer. "Devices such as the Boeing 747 aircraft, with over 5 million components, required over 10,000 person-years of design time. Thousands of designers worked over a three-year period on the project (Ullman 1992: 50)". Obviously, a single designer could not approach this effort; yet within design groups it is still the individual who has to solve design sub-problems. The individual designer still has to understand the sub-problem in the context of the larger product, has to generate ideas, has to evaluate the ideas, and has to make decisions about the solution.

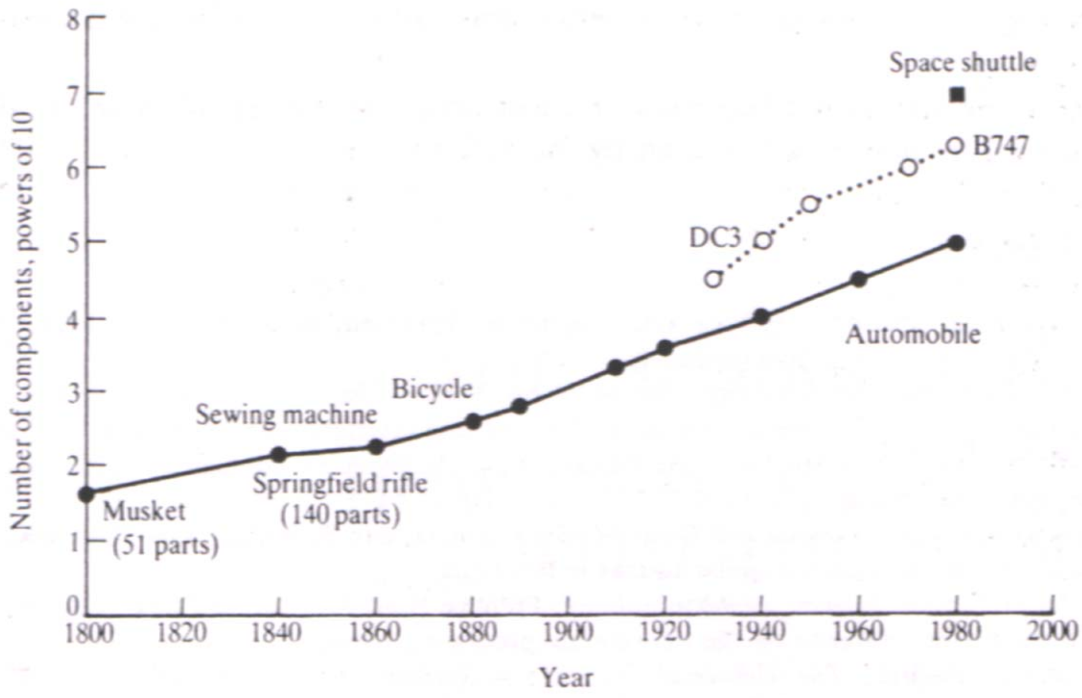



Figure 3.2 Increasing complexities in mechanical design
(Ullman 1992: 51)

There are two types of groups found industry. The first one is made up of designers who are all working on a single component or separate components in an assembly. On these teams, all participants have similar role to play in the design process. They are all designers with similar domain knowledge who work as a team because the problem is too large for one individual to complete in reasonable time.

Contrasted to this, in the other design team (concurrent), each member of the teams fills a different role. Teams of this type are typically composed of representatives from engineering, marketing, and production. Additionally, other team members may represent material engineering, purchasing, quality assurance, and training, as warranted by the device being designed and the size of the company. On these teams each member brings different domain knowledge to the problem, which both enriches and complicates problem understanding, idea generation, and idea evaluation. In small companies the design engineer may fill many of the roles of a concurrent design team.

#### 3.1.2.2. What is Engineering Design?

Engineering design is a relatively new discipline. It has a distinct academic identity and credibility in the last 50 years, where both the art of designing and the science of design are involving. "Due to the fact that it influences almost all aspects of creating artifacts for the society, engineering design has become the strategic element of competitive advantage (Horvath, Vergeest 2000)".

Engineering design is a distinguished discipline since it (i) synthesizes new information for product realization, (ii) establishes quality through defining functionality, materialization and appearance of artifacts, and (iii) influences the technological, economic and marketing aspects of production. By generating knowledge about design and for design, discipline-oriented (scientific) research is instrumental to the development of engineering design (Horvath 2001).

***Some Definitions of Engineering Design***

- Dhillon (1985: 4): Engineering design is the activity in which various methods and scientific principles are used to decide the selection of materials and the placement of these materials to develop an item that fulfills specific requirements.

- Hubka and Eder quoted Taylor (1959): Engineering design is the process of applying various techniques and scientific principles for the purpose of defining a device, a process, or a system in sufficient detail to permit its physical realization.

- Hubka and Eder quoted Asimow (1962): Engineering design is a purposeful activity directed towards the goal of fulfilling human needs, particularly those which can be met by the technology factors of our culture. And: (ibid.) Decision making, in the face of uncertainty, with high penalty for error.

- Hubka and Eder quoted Feilden (1963): Mechanical engineering design is the use of scientific principles, technical information and imagination in the definition of a mechanical structure, machine or system to perform pre-specified functions with the maximum economy and efficiency. The designer's responsibility covers the whole process from conception to the issue of detailed instructions for production and his interest continues throughout the designed life of the product in service.

In engineering design, all product and artifacts have some intended reason behind their existence: the product or artifact function. Some of them are as follows:

- Designing the product:
    - Producing a useful item
    - Producing a physically realizable product
    - Producing an item with economic worth
- Designing the artifact function
    - Reducing the cost
    - Developing a new way
    - Lowering hazard
    - Reducing inconvenience
    - Meeting competition
    - Developing the market
    - Meeting social changes

#### 3.1.2.3. Functions associated with Engineering Design

There are various functions involved in engineering design those can be classified into five broad categories (Dhillon 1985:225):

- **Manufacturing Functions:** It includes all those functions related to manufacturing such as assembly, finding out the tooling requirement, manufacturing planning, the design of tools, detail manufacture, keeping pace with the latest manufacturing methods, purchasing materials, cost control.

- **Commercial Functions:** It involves relationships with various clients. Some of the functions are conducting market surveys and tendering, managing contracts effectively, arranging delivery, advertising the company and its products, and arranging payment.
- **Engineering Functions:** These are subcomponents of the design activity such as developing new design concepts, designing for production, supporting functions (estimating cost, analyzing field problems, the provision of maintenance instructions, etc.)
- **Quality Assurance Functions:** It is concerned with the quality of the end product. These functions are relevant to areas such as design methods and procedures, design auditing setup, quality and design data.
- **Research Functions:** It is associated with research such as conducting basic applied research, preparing specifications for quality testing procedures, preparing process specifications for welding, preparing process specifications for the testing of highly stressed parts.

Related to these functions, in producing a new machine, structure, or other technological artifact, two separate but closely related processes are generally required. In the first, engineering designers convert the visions in their minds to drawings and specifications. In so doing, they solve an ill-defined problem that no single "right" answer but has many better or worse solutions. Engineers learn a great deal during the process of design as they strive to clarify the visions in their minds and seek ways to bring indistinct elements into focus. When the designers think they understand the problem, they make tentative layouts and drawings, analyze their tentative designs for adequacy of performance, strength, and safety, and then complete a set of drawings and specifications. The second process revolves around the first drawings and specifications. Those who will make or build the machine, structure, or system can now learn exactly what they are expected to produce. Until their task is complete and the project has been turned over to its user, those drawings and specifications will be their formal instructions that guide their work (Ferguson 1994: 2).

#### 3.1.2.4. Economics of Engineering Design

The economic, technical, and aesthetic merits of the engineering design are vital for its commercial success.

During the design phase of the product certain economic considerations are very important because they may be vital to the success or failure of the organization. The economic considerations concerning the market for the product are regarded as the most necessary economic factors.

The production and distribution of the designed product are dictated by the market requirement. Thus the designer must take into consideration the following factors when designing a new product (Dhillon 1985: 36 quoted Beakley and Chilton 1973):

- The competitive products' prices
- The percentage of the total market for the demand of the product
- The size and the type of the total market
- The price/sales relationship
  and so on.

During the product development, design selection mainly determines the cost of production. Therefore, engineering manufacturers emphasize that the production costs must be controlled during the design phase of the product.

The following are the principal elements of an item production cost (Dhillon 1985: 37):

- Material cost
- Labor cost
- Production overhead costs: The components of production overhead costs are the machinery depreciation cost, cost of indirect labor, services cost (fuel, electricity, etc.); cost of indirect materials such as small tools, lubricants, etc., cost of tool replacement and so on.

### 3.1.2.5. Engineering Design Knowledge

Knowledge can be classified generally as follows (Ullman 1992: 39):

- **General Knowledge:** Information that most people know and apply without regard to a specific domain. For example, red is a color, the number 4 is bigger than the number 3, and applied force causes a mass to accelerate- all exemplify general knowledge. This knowledge is gained through everyday experiences and basic schooling.

- **Domain-specific Knowledge:** Information on the form or function of individual objects or a class of objects. For example, all bolts have a head, a threaded body, and a tip; bolts are used to carry shear or axial stresses; the proof stress of a grade 5 bolt is 85 kpsi- all exemplify domain specific knowledge. This knowledge comes from study and experience in the specific domain. It is estimated that it takes about 10 years to gain enough specific knowledge to be considered an expert in a domain. Formal education sets the foundation for gaining this knowledge.

- **Procedural Knowledge:** the knowledge of what to do next. For example, if there isn't an answer to problem X, then decomposing X into two independent subproblems, X1 and X2, would illustrate procedural knowledge. This knowledge comes from experience, but some procedural knowledge is also based on general knowledge and some domain-specific knowledge. Especially mechanical designers use this knowledge in solving design problems.

- **Process Knowledge:** This knowledge is distinct from domain knowledge. Because of this independence, a successful product can result from the design process, regardless of the knowledge of the designer or the type of design problem. However, to produce any reasonably realistic design, substantial domain knowledge, which comes from the raw materials of engineering (like material science, engineering science, mathematics, etc.) is required.

In engineering design the designer uses three types of knowledge that are (Ullman 1992: preface xii):

- Knowledge to generate ideas: comes from experience and natural ability
- Knowledge to evaluate ideas: comes from experience and formal training
- Knowledge to structure the design process: comes from a dual setting of academic environment and, at the same time, in an environment that simulates industrial realities.

Generative and evaluative knowledge are forms of domain-specific knowledge, where the knowledge about the structure of the design process is largely independent of domain specific knowledge.

***An Example of Engineering Design Knowledge***

The formal knowledge that engineering designers use is not science, although a substantial part of it is derived from science. It includes as well knowledge based on experimental evidence and on empirical observations of material and systems. Walter Vincenti, an aeronautical engineer who has traced the evolution of engineering knowledge, argues cogently the it has been developed and formalized primarily to meet the needs of engineering designers. For example, the optimum or "correct" degree of the inherent stability of an airplane was by no means obvious until more than 30 years after the Wrights first powered flight in 1903. European designers of airplanes assumed at first that pilots would merely steer their craft in the manner of automobile drivers or mariners. Therefore, the need of inherent stability seemed obvious. On the other hand, as the Wrights saw, too much inherent stability would reduce a pilot's control over his airplane. A bicycle is inherently unstable, yet with practice it is readily controlled. But, as Vincenti reminds us, training wheels on a bicycle, intended to help hold the bike upright for the beginning rider, are soon discarded as the rider's reflexive responses make them obstructive rather than helpful.

The Wright brothers had recognized that airplanes, unlike automobiles and boats, must be controlled in three dimensions rather than merely steered. Their decision to build airplanes that would require skilled piloting was, in Vincenti's words, "largely deliberate, conceptually linked to the sideway instability of the bicycle, with which the Wrights were familiar." They devised an ingeniously simple and elegant system of wing warping to keep their first airplanes on an even keel and to allow banked turns.

By the 1930s, designers, pilots, aerodynamicists, and instrumentation specialists had reached a consensus that an aircraft should have enough instability to avoid disaster through a momentary aberration but enough instability to give the pilot optimum control. Vincenti points out that although aerodynamicists (scientists) were involved in the debates, the subjective response of pilots –a sense of what is flyable- and the experiences of designers (engineers) were the determining factors in the consensus. It was a collective "practical judgment (based largely on subjective opinion) of a sort that cannot be avoided in engineering" – "an instance *par excellence* of engineering, as opposed to scientific knowledge. Eventually the consensus was codified in reasonably unambiguous terms made a routine part of design specifications (Ferguson 1994: 9, 10).

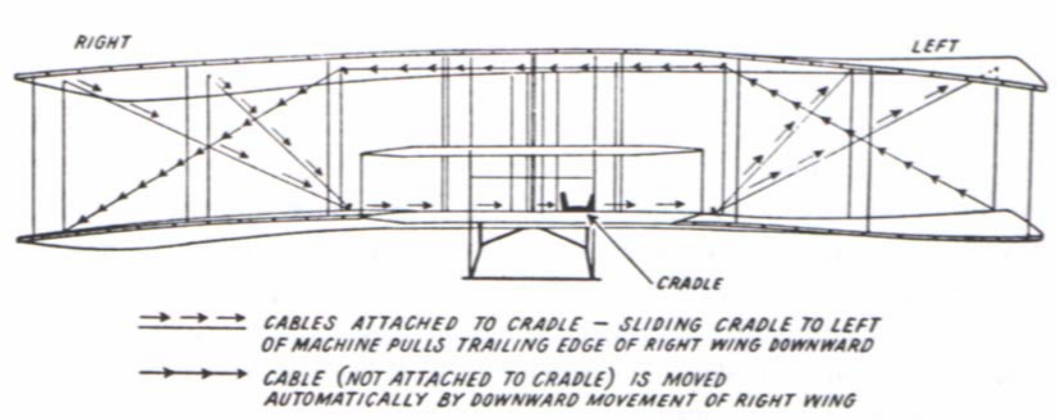



Figure 3.3 (Ferguson 1994: 11) Wing warping in the first Wright airplane, 1903.

To maintain stability, cables twisted the trailing corners of both wings simultaneously. In this front view, the right rear corners are twisted downward and the left rear corners upward. Wing warping (later, hinged ailerons) also made steering practicable, permitting a roll about the fore-and-aft axis as the rudder was turned.

### 3.1.3. Comparison of Industrial Product Design with Engineering Professions

Engineering is one of these disciplines that industrial product design is tightly related. Industrial product design benefits from engineering knowledge in constituting the design knowledge as being a field of the design discipline.

The intersecting criteria of engineering and industrial design in a product are:

- Functional Criteria
  - Physiological Criteria
  - Environmental Criteria

- Technological Criteria
  - Material Criteria
  - Production Criteria

- Economical Criteria
  - At the Producers' Level
  - At Macro-Level

Engineering fields such as human-factors engineering, materials engineering, mechanical engineering, industrial engineering, process engineering, manufacturing engineering, design engineering, product design engineering deal with the criteria given above (as it was mentioned in the previous chapter), and participate in design of the industrial product.

The comparison of industrial product design with some of the engineering professions, through seven measures, is shown in Figure 3.4, and the comparison with mechanical design engineering is briefly described as follows (Ullman 1992: 32):

| | Mechanical | Electrical | Software | Industrial |
|---|---|---|---|---|
| Type of objects | Many types across many disciplines | Standard components | Structures of text strings | Shape, texture, ar color |
| Type of problem | All types | Primarily selection and configuration | Selection and configuration | All types |
| Form-function relation | Overlapping | Most forms have specific function | Form specifies function | Form dominates function |
| Decomposition potential | Often strongly coupled | Along circuit and component boundaries | Into subroutines or procedures | Usually not a problem |
| Language complexity | All types mixed | All types mixed | Primarily textual | Usually graphic o: physical |
| Graphic complexity | 2-D, 3-D, and shaded images | 2-D | If any, 2-D flow-charts and trees | 2-D, 3-D, and shaded images |
| Design methods | Partially developed (as in this book) | Some available (VLSI design) | Methods exist (structured programming) | Some available |

Figure 3.4 Comparison of industrial product design with engineering professions (Ullman 1992: 32)

- **Type of Objects:**

  Mechanical Design: Many types of components and assemblies vary widely in shape, composition, functional complexity and technologies - fluid dynamics, thermodynamics, and kinematics.

  Industrial Design: Primary objects are those that affect the aesthetics or human factors of the product.

- **Type of Problem:**

  Mechanical Design: All types discussed before

  Industrial Design: All types discussed before

- **Form–Function Relation:**

  Mechanical Design: A component or assembly plays a role in many functions.

  Industrial Design: Little or no functionality, form dominates function.

- **Decomposition Potential:**

  Mechanical Design: Form-function relationship determines the potential to decompose a problem into sub problems. It is limited though, as form and function is overlapped in devices.

  Industrial Design: Decomposition is in form, not in function.

- **Language Complexity:**
  Mechanical Design: Semantic, analytical, graphical, physical.
  Industrial Design: Usually graphical.
- **Graphic Complexity:**
  Mechanical Design and Industrial Design: 3D, 2D, shaded images greatly complicate the process.
- **Design Methods:**
  Mechanical Design: Partially developed.
  Industrial Design: Many different philosophies.

#### 3.1.3.1. Decomposition

A system is generally considered a conglomeration of objects that perform a specific function. The car is a transportation system; its function is to move goods and people. The engine is the power subsystem; its purpose is to convert potential energy started in the fuel into kinetic energy. In the engine, the ignition is one of many subsystems. Thus, this is the decomposition of car into three system levels, while still referring to the function of objects.

Another view, the engine is an assembly of components in terms of the physical components or form of the engine. Engine assembly can be decomposed into subassemblies such as the carburetor and it can be further decomposed into smaller assemblies and, finally, into individual components. "System" and "assembly" used where the object of interest falls in the decomposition as it goes on sub…of sub… and "sub" is used to show one level of decomposition in a specific discussion.

In Figure 3.5, the decomposition of design fields (software, mechanical and electrical) is shown, where the function of system and its decomposition are considered first, and then the subs… and the components.

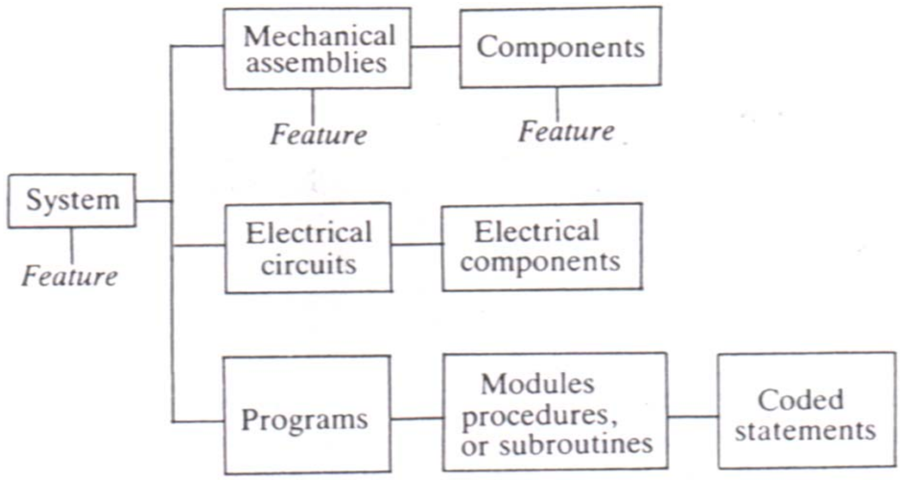



Figure 3.5 Decomposition of design fields (Ullman 1992: 19)

"For example, the ignition system and the controller on carburetor are electrical. These systems provide energy transfer and control functions in the engine. Some of the control functions are filled by microprocessors. Physically, these are electric circuits, but the actual control function is provided by a software program in the processor (Ullman 1992: 19)". It is often unclear whether the actual function should be met by mechanical assemblies, electrical circuits, software programs or a mix of these elements.

### 3.1.3.2. Form-Function Relation

Function= Operation= Purpose: to describe what the device does
Form: any aspect of physical shape, geometry construction, material or size.

Performance: measure of function - how well the device does what it is designed to do.

Earlier, mechanical systems are decomposed into assemblies and components physically. Functional decomposition is often much more difficult than physical decomposition, as each function may use part of many components and each component may serve many function. "For example, the handlebars of a bicycle. They are a single component that serves many functions. They allow for steering (a verb that tells what the device does), and they support upper-body weight (again, a function telling what the handlebars do). Further, they not only support the brake levers but also transform (another function) the gripping force to a pull on the brake cable. The shape of the

handlebars and their relation with other components determine how they provide all these different functions. The handlebars, however, are not the only component needed the steer the bike. Additional components necessary to perform this function are the front fork, the bearings between the fork and frame, the front wheel, and miscellaneous fasteners. Actually, it can be argued that all the components on a bike contribute to steering, since a bike without a seat or rear wheel would be hard to steer. In any case, the handlebars perform many different functions, but in fulfilling these functions, the handlebars are only a part of various assemblie (Ullman 1992: 20)". This coupling between form and function makes mechanical devices hard to design. Performance, as measure of function, clarifies how well the steering is fulfilled with handlebars.
Figure 3.6 shows and example of physical decomposition in a safety bicycle.

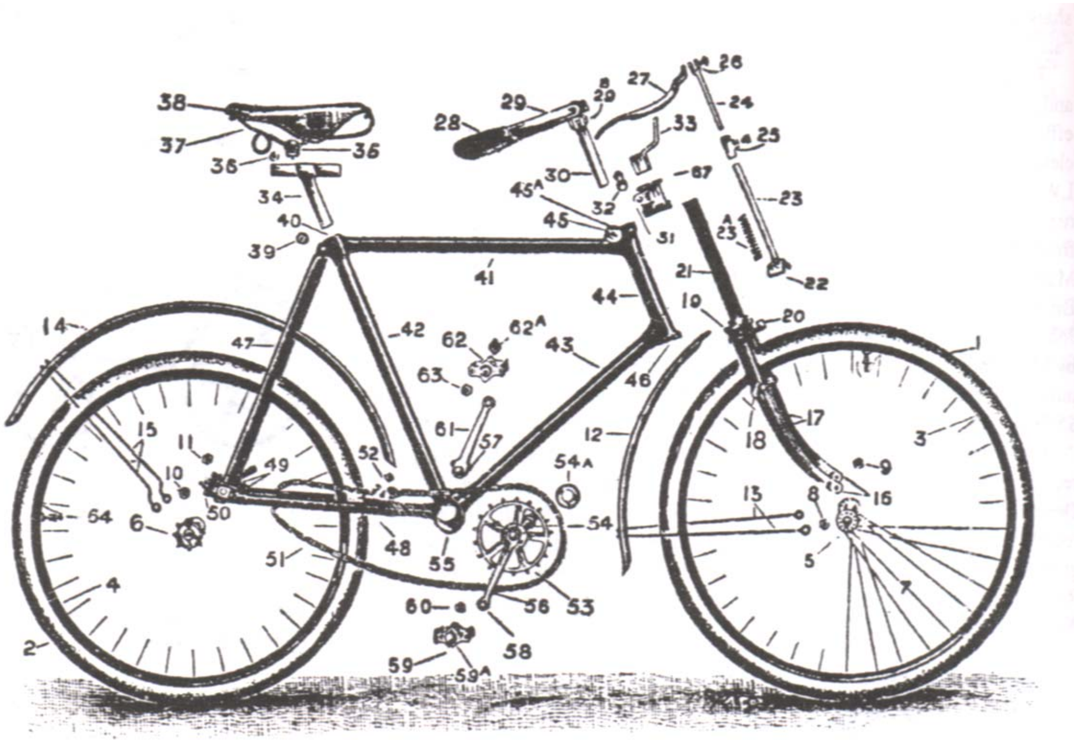


Figure 3.6 Exploded safety bicycle, 1900 (Perry 1995: 44)

### 3.1.3.3. Languages of Design

There are four types of design languages, which are as follows (Ullman 1992: 28):

- **Semantic:** The verbal or textural representation of the object – for example, the word "bolt," or the sentence "The shear stress is equal to the shear force on the bolt divided by the stress area."

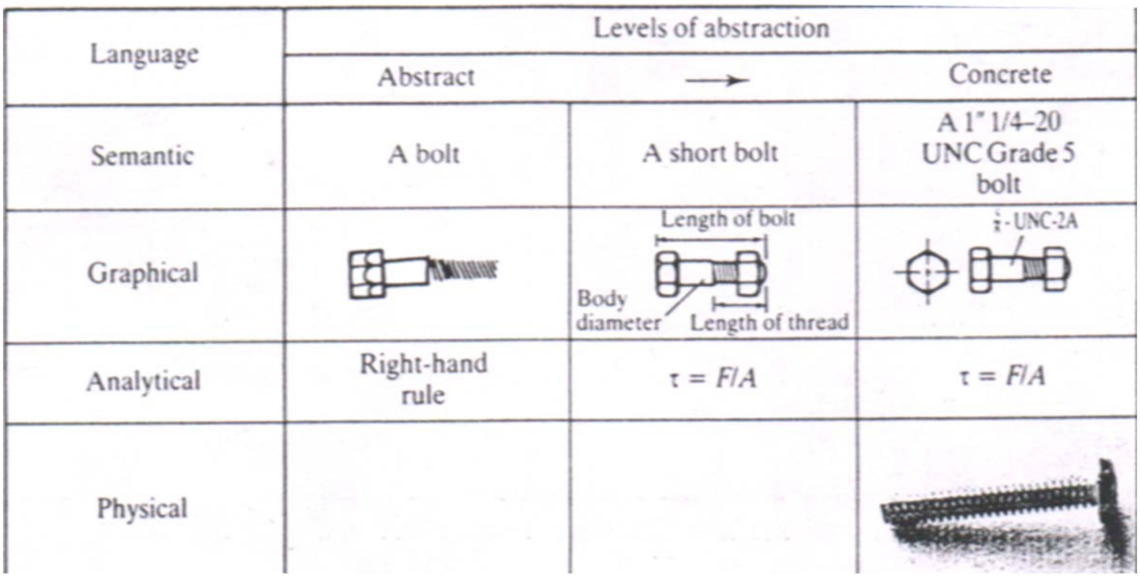
- **Graphical:** The drawing of the object- for example, scale representations such as orthogonal drawings, sketches, or artistic renderings.
- **Analytical:** The equations, rules, or procedures representing the form or function of the object –for example, $\tau=F/A$
- **Physical:** The hardware or a physical model of the object.

The initial need is expressed in a semantic language as a written specification or a verbal request by a customer or supervisor. The final result of the design process is a physical product. Although the designer produces a graphical representation of the product, not the hardware itself, all the languages are used as the product is refined from its initial, abstract semantic representation to its final physical form.

The process of making an object less abstract (or more concrete) is called "refinement". Especially, mechanical design is a continuous process of refining the given needs to the final hardware. Figures 3.7 and 3.8 reveal the refinement of the abstract representations as follows:

| | Levels of abstraction | | |
|---|---|---|---|
| **Language** | **Abstract** | → | **Concrete** |
| Semantic | Qualitative words (e.g., long, fast, lightest . . .) | Reference to specific parameters or components | Reference to the values of the specific parameters or components |
| Graphical | Rough sketches | Scale drawings | Detail drawings with tolerances |
| Analytical | Qualitative relations (e.g., left of) | Back-of-the-envelope calculations | Detailed analysis |
| Physical | None | Models of the product | Final hardware |

Figure 3.7 Levels of abstraction in different languages (Ullman 1992: 31)



| Language | Levels of abstraction | | |
|---|---|---|---|
| | Abstract | ⟶ | Concrete |
| Semantic | A bolt | A short bolt | A 1" 1/4–20 UNC Grade 5 bolt |
| Graphical | | Length of bolt; Body diameter; Length of thread | ¼-UNC-2A |
| Analytical | Right-hand rule | $\tau = F/A$ | $\tau = F/A$ |
| Physical | | | |

Figure 3.8 Levels of abstraction in describing a bolt (Ullman 1992: 31)

## 3.2. How Industrial Designers and Engineers Approach to Design Problems?

### 3.2.1. Design Problems

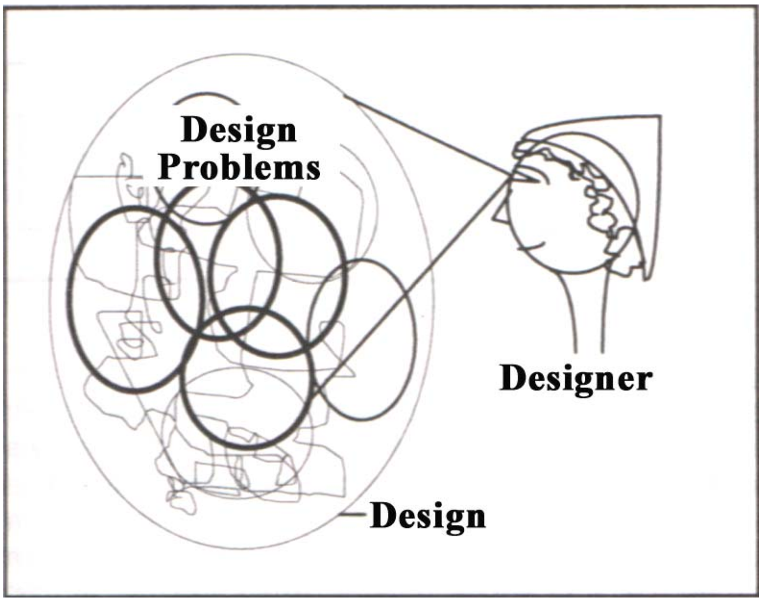



Figure 3.9 Designer and the design problems (Bayazit 1994: 109)

Design problems normally originate as some form of problem statement provided to the designer by someone else, the client or the company management. These problem statements, normally called a design brief, can vary widely in their form and content. “At one extreme, they might be something like the statement made by President

Kennedy in 1961, setting a goal for the USA, ‘before the end of the decade, to land a man on the moon and bring him back safely’. In this case the goal was fixed, but the means of achieving it were very uncertain. The only constraint in the brief was one of time –before the end of the decade. The designers were given a completely novel problem, a fixed goal, only one constraint, and huge resources of money, materials and people (Cross 2000: 11)”. This is quite an unusual situation for designers to find themselves in.

A typical example of design brief, unlike the extreme one given above, might be like the following brief provided to the design department by the planning department of a company manufacturing plumbing fittings. It is for a domestic hot and cold water mixing tap that can be operated with one hand (Cross 2000: 11 quoted Pahl and Beitz 1984).

*Design of one-handed water mixing tap:*

Required: one-handed household water mixing tap with the following characteristics:

| | |
|---|---|
| Throughput | 10 l/min |
| Maximum pressure | 6 bar |
| Normal pressure | 2 bar |
| Hot water temparature | 60 C |
| Connector size | 10 mm |

Attention to be paid to appearence. The firm’s trade mark to be prominently displayed. Finished product to be marketed in two years’s time. Manufacturine costs not to exceed DM 30 each at a production rate of 3000 taps per month.

What these examples of design problems have in common is that thye set a goal, some costraints within which the goal must be achieved, and some criteria by which a successful solution might be recognized. “If a goal does not require ‘searching for the solution’ period –constraints- the there cannot be a problem (Bayazit 1994: 110)”.

Design problems do not specify what the soltion will be, and there is no certain way of proceeding from the statement of the problem to a statement of the solution, except by designing. Unlike some other kinds of problem (mathamatical, economical problems, etc.), the person setting the problem does not know what the answer is, but he/she will recognize it when he/she sees it. However, this recognition of the solution of the design problem is not easy, and it might not be liked by the client or the company management. Especially the first step, which is determinig the design, is accepted as the hardest and the most important stage of design activity. Determining an object that does not exist, includes a huge uncertainty for the designers as well as for anybody. It is this uncertainty that makes desiging such a challenging activity. Because of this, the design problems are defined as ill-defined problems by many authors.

#### 3.2.1.1. Characteristics of Design Problems

The kinds of problem that designers tackle are regarded as ill-defined or ill-structured, in contrast to well-defined or well-structured problems such as chess-playing, crossword puzzle or standard calculations. Well-defined problems have a clear goal, often one correct answer, and rules or known ways of proceedings that will generate an answer.

The characteristics of ill-defined problems can be summarised as follows (Cross 2000: 14):

- <u>There is no definitive formulation of the problem:</u> When the problem is initially set, the goals are usually vague, and many constraints and criteria are unknown. The problem context is often complex and messy, and poorly understood. In the course of problem-solving, temporary formulations of the problem may be fixed, but these are unstable and can change as more information becomes available.
- <u>Any problem formulation may embody inconsistencies:</u> The problem is unlikely to be internally consistent; many conflicts and inconsistencies have to be resolved in the solution. Often inconsistencies emerge only in the process of problem-solving.
- <u>Formulations of the problem are solution-dependent:</u> Ways of formulating the problem are dependent upon ways of solving it; it is difficult to formulate a problem statement without implicity or explicitly referring to a solution concept. The way the solution is conceived influences the way the problem is conceived.
- <u>Proposing solutions is a means of understanding the problem:</u> Many assumptions about the problem, and specific areas of uncertainty can be exposed

onlt by proposing solution concepts. Many constraints and criteria emerge as a result of evaluating solution proposals.

- There is no definitive solution to the problem: Different solutions can be equally valid responses to the initial problem. There is no objective true-or-false evaluation of a solution; but solutions are assessed as good or bad, appropriate or inappropriate.

In order to take some steps towards improving the initial definition of the problem, the clients are questioned, data are collected, some research is carried out, and etc. There are also some rational procedures and techniques, which can be applied in helping to solve ill-defined problems. Whatever does the designer; he/she tries to move fairly quickly to a potential solution, or a set of potential solutions, and to use that as a means of further defining and understanding the problem.

#### 3.2.1.2. Problem Structures

Even the designer has progressed well into the definition of a solution; some difficulties may come to light because of the problem structure. A design problem can be divided into sub-problems, or decision areas, in order to reach to an overall design solution, which forms the problem structure as shown in Figure 3.10. In particular, sub-solutions can be found to be inter-connected with each other in ways that form a pernicious, circular structure to the problem, e.g. a sub-solution that resolves a particular sub-problem may create irreconcilable conflicts with other sub-problems.

An example of this pernicious problem structure was found in a study of housing design by Luckman (Cross 2000: 15 quoted Luckman 1984). The architects identified five decision areas, or sub-problems, concerned with the directions of span of the roof and first floor joists, and the provision of load-bearing or non-load-bearing (external) walls and partitions at ground and first-floor levels. Making a decision in one area had implicants for the other area, which had the implicants for the other area and so on until it becomes a full-circle back to the first decision area. This problem structure is shown diagrammitically in Figure 3.11, illustrating the circular structure that is often found in design problems.

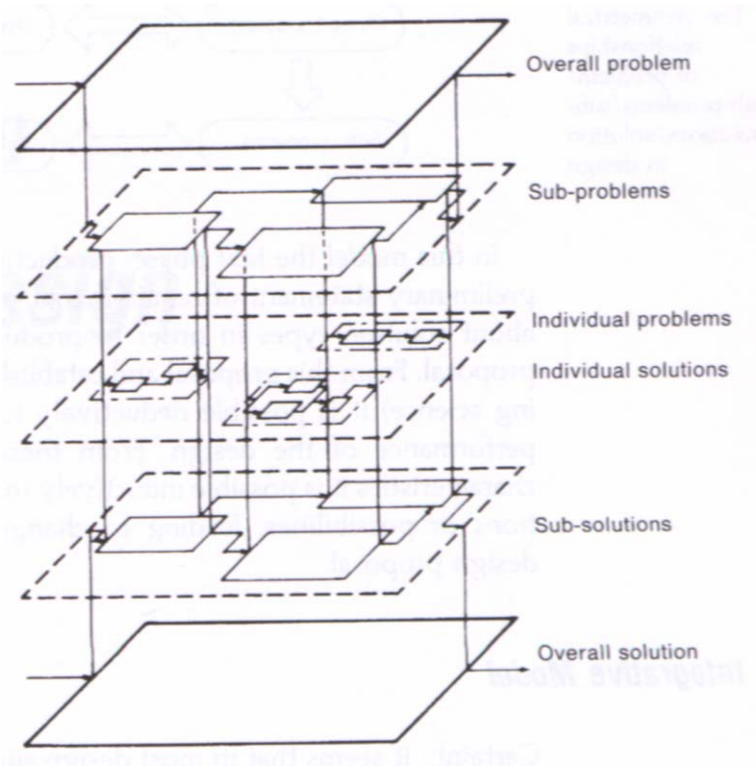



Figure 3.10 Division of design problem in order to reach overall solution

(Cross 2000: 41)

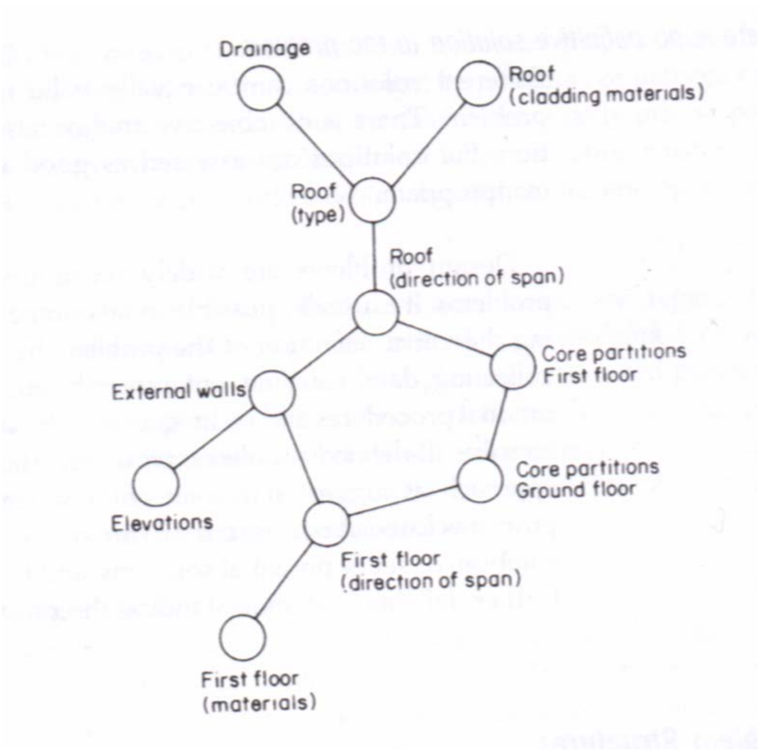



Figure 3.11 Problem structure found in a housing design problem

(Cross 2000: 16)

As part of the research study, the individual sub-solution options in each decision area were separated out and the incompatible pairs of options identified. With this approach, it was possible to enumerate all the feasible solutions (i.e. sets of five options containing no incompatible pairs). There were found to be eight feasible solutions, and relative costings of each could indicate which would be the cheapest solution. This approach was later generalised into a new design method: AIDA, the Analysis of Interconnected Decision Areas.

This technique helps to solve the design problem –the problem itself and the difficulty in the pernicious structure-, and brings it to a more well-defined position. Some designers argue that design problems are not always ill-defined or ill-structured as they might appear to be. On the other hand, "research into the behaviour of designers has shown that they will often treat a given problem *as though* it is ill-structured, even when it is presented as a well-structured problem, so that they can create something innovative" (Cross 2000: 16-17).

Therefore, designers often attemp to avoid cycling around the pernicious decision loops of design problems by high-level strategic decisions about solution options. Having identified a number of options, the designer selects what appears to be the best one for investigation at a more detailed level; again, several options are usually evident, and again a choice is made. This results in hat is known as a decision tree, with more and more branches opening from each decision point. An example is shown in Figure 3.12, based on a study by Dwarakanath and Blessing (Cross 2000: 18 quoted Dwarakanath and Blessing 1996) of an engineer designing a carrying/fastening device for attaching a back-pack to a mountain bicycle. This decision tree was derieved from an experimental study in which the designer's progress was recorded over a two-hour period. The decision tree shows how higher-level strategic decisions (such as positioning the device either the front or rear wheel of the bicycle) gradually unfolded into lower-level implications and decisions, right down to details of screws, pins, etc.

The decision tree analysis of the design process perhaps implies that the result is the best possible design, if the best options are chosen at each level. However, a decision at any particular level may well turn out to be sub-optimal in the light of subsequent options available at the other levels. For this reason, there is frequent back-tracking up and down the levels of hierarchy in the design tree. In Figure 3.12 this is confirmed by some of the 'time stamps' inserted at points within the tree, recording the time at which the designer considered the various alternatives and made decisions.

Resolving design problems by a top-down approach is quite common, although sometimes a bottom-up approach is used, starting with the lowest-level details and building up to a complete overall solution concept.

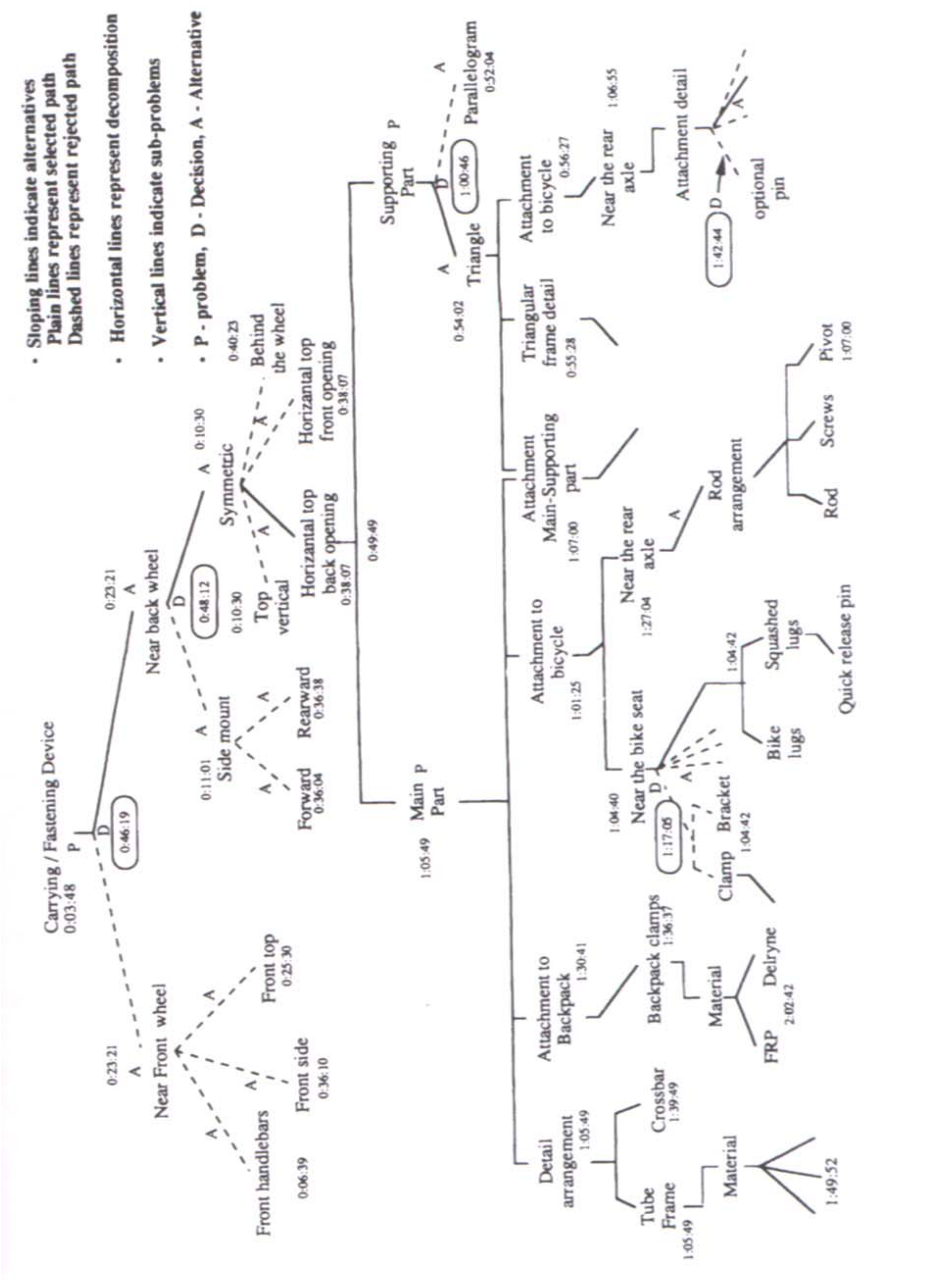



Figure 3.12 Decision tree derieved from the design of a device for carrying a backpack on a bicycle (Cross 2000: 17)

### 3.2.1.3. Types of Design Problems

Design situations have a mixture of design problems, and these design problems should be considered independent of disciplines, as design is a multidisciplinary activity. Types of design problems (www.med.umich.edu/rehabeng/curriculum.htm and Ullman 1992: 21) are as follows:

- **Selection Design:** It is a well-defined problem that can be solved by existing product e.g. picking the correct bearing or software from a catalog. Selection design is an activity of picking one (maybe more) item from a list that the chosen item meets certain requirements. To solve a selection design problem, it should be started with a clear need. The catalog or the list of choices effectively generates potential solutions for the problem. These potential solutions must be evaluated versus specific requirements to make the right choice.

- **Configuration Design:** It is a well-defined problem that requires assembly or combination of standard components, e.g. computer workstation configuration. All components have been designed and the problem is how to assemble them into the completed product.

- **Parametric Design:** It involves finding values for the variables, or design parameters, that characterize the object being studued, in order to optimize the design, e.g. designig a cylindrical tank to hold X gallons and having minimum surface area. These problems lend themselves to analysis, and often have standard solutions that are tabulated in handbooks.

- **Routine Design:** It is characterized by cook-book design solution steps for a well-defined problem, usually varations on a well-characterized centrel or basic design theme.

- **Original Design:** Any time the design problem requires the development of a process, component, or assembly not previously in existence, it calls for original design. These problems cannot be defined with algorithm and the solution starts with the design problem itself and a blank sheet of paper.

- **Redesign:** It starts with a well-defined problem and an existing product that is going to be studied on. It is the modification of this existing product to meet new requirements, to improve its function and etc. Because new processes, new materials, new enabling technologies, change in needs or demand, improvement in domain knowledge come into existence through years. Redesign must include substantial improvement over the original (existing product). Redesign problems have some advantages such as development costs are vastly reduced, proof of concept is already done, market is usually developed and the user input is available.

***Mature Design and the Bicycle***

Redesign often occurs on a ***mature design***, which is the design that remained virtually unchanged over many years such as scissors, pencil sharpeners, and etc. For these products, knowledge about the design problem is complete and there is nothing more to learn, as it is shown in Figure 3.13.

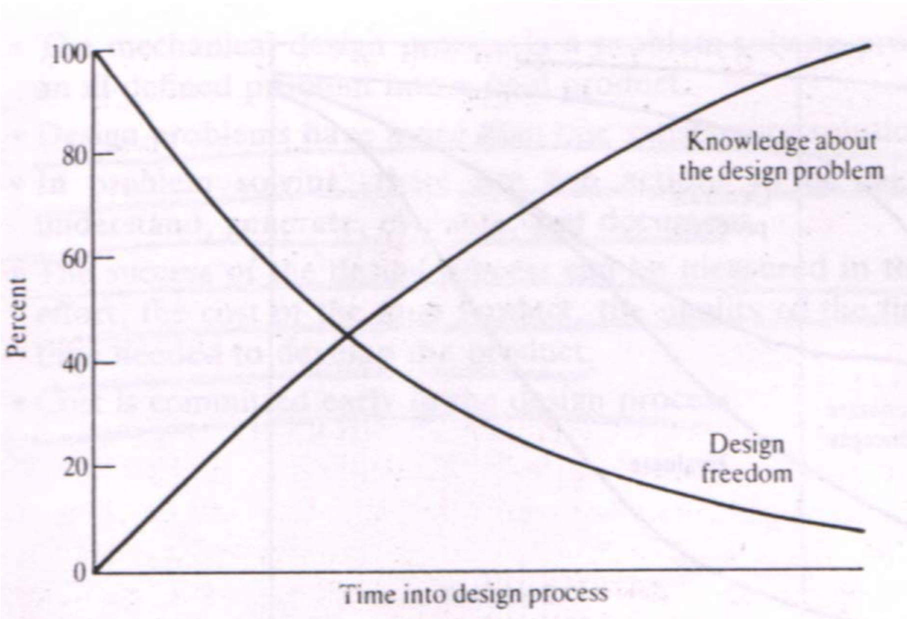



Figure 3.13 Design process paradox (Ullman 1992: 13)

The cleanly cutting material problem is thought to be solved in the Bronze Age as scissors. Whatever detailed variations have subsequently have appeared, and they are innumerable, the fundamental configuration remains unaltered. This kind of design concepts and forms often called as type-forms (mature designs), which have become firmly established due to their appropriateness and widely adopted to industrial mass-production. In principal, there is little difference of form in relation to function of modern scissors to those evolved long ago, despite the very different production technques used (Haskett 1987: 116)".

However, considering the bicycle as a mature design reveals the need of redesign problems and solutions. The basic configuration of the bicycle –the two tensioned, spoked wheels of equal diameter, the diamond shaped frame, and the chain drive- was fairly refined late in the last century. While the 1890 Humber shown in Figure 3.14 looks much like a modern bicycle, not all bicycle of this era were refined. The Otto dicycle, shown in Figure 3.15, had two spoked wheels and a chain; stopping and steering this machine must have been a challenge. In fact, "the technology of bicycle design was so well developed by the end of the ninteenth century that a major book on the subject, *Bicycles and Tricycles: An Elementary Treatise on Their Design and Construction* was published in 1896. (Ullman 1992: 26)".

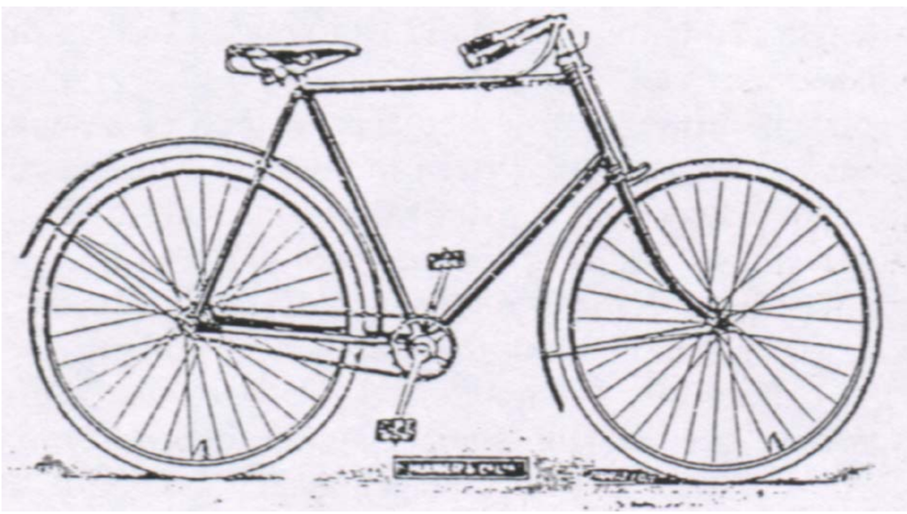


Figure 3.14 Humber bicycle 1890 (Ullman 1992: 26)

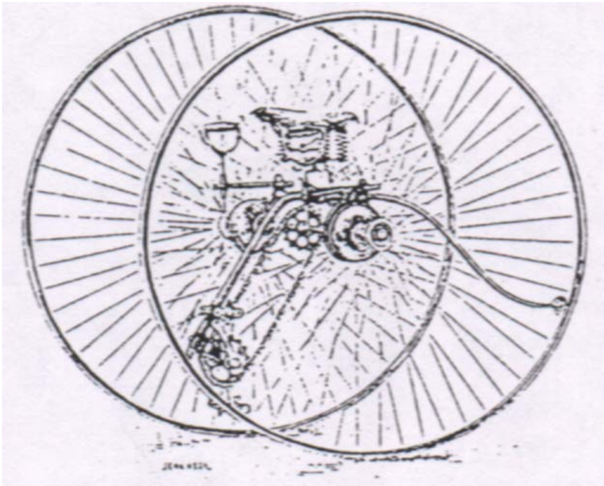


Figure 3.15 Otto dicycle (Ullman 1992: 27)

However, in the 1980s the traditional bicycle design began to change again, as it can be seen in Aero Bike of Burrows, shown in Figure 3.16.

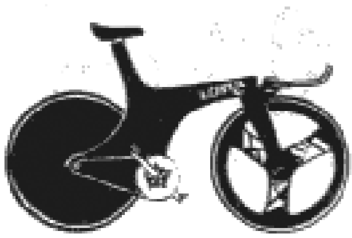



Figure 3.16 Aero bike of Burrows (Perry 1995: 11)

Why did a mature design begin evolving again? As it is metioned above in redesign section, new processes, new materials, new enabling technologies, change in needs or demand, improvement in domain knowledge have caused new designs to come into existence. The followings factors have affected the changes in bicycle design (Ullman 1992: 28):

1. New materials such as carbon-fiber were developed. At first these new materials were substituted for the old, as in most redesign problems; however, creative designers soon

began to develop original designs that made use of the unique properties of the new materials.

2. Domain knowledge is improved and new enabling technologies were developed. An increased understanding of aerodynamic drag and its effects on the speed of the bicycle prompted the design of streamlined wheels, frames, and other components.

3. The demand has changed. Improved understanding of the capabilities and the needs of the rider –that is, better knowledge of human factors- further encouraged original design, e.g. mountain bikes.

### 3.2.2. Design Ability

Some statements made by industrial and engineering designers (Cross 2000: 19) indicate their abilities that can be summarized as follows:

- Creativity and intuition
- Recognition that problems and solutions in design are closely interwoven
- The need to use sketches, drawings, or models of various kinds as a way to explore the problem and solution together

This summary reflects the view that designers have a particular 'designerly' way of thinking and working.

#### *Experiment of Designers and Scientists Solving a Design Problem*

In an experimental research study, Lawson (1984) compared the ways in which designers (in this case architects) and scientists solved the same problem. The scientists tended to use a strategy of systematically trying to understand the problem, in order to look for underlying rules, which would enable them to generate an optimum solution. In contrast, the designers tended to make initial explorations and then suggest a variety of possible solutions until they found one that was good, or at least satisfactory. The evidence from the experments suggested that scientists problem-solve by analysis, whereas designers problem-solve by synthesis; scientists use 'problem-focused strategies' and designers use 'solution-focused strategies' (Cross 2000: 21).

#### 3.2.2.1. How Designers Think?

Some other studies have also suggested that designers tend to use conjectures about solution concepts as the means of developing their understanding of the problem. “Darke (1984) found that designers impose a primary generator onto the problem, in order to narrow the search space and generate early solution concepts. This primary generator is usually based on a tightly-restricted set of constraints or solution possibilities derived from the design problem. Since ‘the problem’ cannot be fully understood in isolation from consideration of ‘the solution’, it is natural that solution conjectures should be used as a means of helping to explore and understand the problem formulation (Cross 2000: 21)”. Making sketches of solution concepts is one way that helps the designer to identify their consequences, and to keep the problem exploring going; in what “Schön (1983) called the ‘reflective conversation with the situation’ that is characteristic of design thinking (Cross 2000: 21)”.

Drawing and sketching have been used in design for a long time, certainly since long before the Renaissance, but the period since that time has seen a massive growth in the use of drawings, as designed objects have become more complex and more novel. Looking at the sketches of Leonardo and today’s designers, similar kinds of representations can be seen. Plans, elevation and section are all being considered together with the considerations of structure, and calculations of dimensions and areas. What can be learnt looking at these sketches? One thing that seems to appear is that sketches enable designers to handle different levels of abstraction simultaneously. Clearly this is something important in the design process. Designers think about the overall concept and at the same time think about the detailed aspects of the implementation of that concept. Obviously not all of the detailed aspects are considered early on, because if they could do that, designers could go straight to the final set of detailed drawings. So they use the concept sketch to identify and then to reflect upon critical details, particular details that they realise might hinder or somehow significantly influence the final implementation of the complete design. This implies that, although there is a hierarchical structure of decisions, from overall concept to details, designing is not a strictly hierarchical process; in the early stages of design, the designer moves freely between different levels of detail Cross 2000: 23).

“The identification of critical details is part of a more general facility that sketches provide, which is that they enable identification and recall of relevant knowledge. As the architect Richard McCormac had said about designing, ‘What you need to know about the problem only becomes apparent as you are trying to solve it’ (Cross 2000 24)”. There is a massive amount of information that may be relevant. These large amounts of information and knowledge need to be brought into play in a selective way, being selected only when they become relevant, as the designer considers the implications of the solution concept as it develops.

Because the design problem is itself ill-defined and ill-structured, a key feature of design sketches is that they assist problem structuring through the making of solution attempts. Sketches incorporate not only drawings of tentative solution concepts but also numbers, symbols and text, as the designer relates what he knows of the design problem to what is emerging as a solution. Sketching enables exploration of the problem space and the solution space to proceed together, assisting the designer to converge on a matching problem-solution pair. Problem and solution co-evolve in the design process. In sketching the designer takes the initiative in finding a problem starting point and suggests tentative solution areas. Problem and solution are then developed in parallel, sometimes leading to a creative redefinition of the problem, or to a solution that lies outside the boundaries of what was previously assumed to be possible (Cross 2000: 25).

Solution-focused strategies are therefore perhaps the best way of tackling design problems, which are by nature ill-defined. In order to cope with the uncertainty of ill-defined problems, the designer has to have the self-confidence to define, redefine and change the problem as given, in the light of solutions that emerge in the very process of designing.

#### 3.2.2.2. Drawings of the Artist and the Engineer

The drawings have two principal purposes. First they show designers how their ideas look on paper. Second, if complete, they show workers all the information needed to produce the object. The information that the drawings convey is overwhelmingly visual: not verbal, except for notes that specify materials or other details; not numerical, except for dimensions of parts and assemblies (Ferguson 1994: 5).

The differences between the direct design of the artisan and the design drawing of the engineer are differences of form rather than differences of conception. In both cases, "the design starts with an idea –sometimes distinct, sometimes tentative-which can be thrown on the mind's screen and observed and manipulated by the mind's eye (Ferguson 1994: 5)". Usually, the "big", significant, governing decisions regarding an artisan's or an engineer's design have been made before the artisan picks up his tools or the engineer turns to his drawing board. Those big decisions have to be made first so that there will be something to criticize and analyze. Thus, far from starting with the elements and putting them together systematically to produce a finished design, both the artisan and the engineer start with the visions of the complete machine, structure, or device.

#### 3.2.2.3. How a Successful Designer Acts?

From studies of a number of engineering designers, of varying degrees of experience and with varying exposures to education in systematic design processes, Fricke (1996) found that designers following a 'flexible-methodical procedure' tended to produce good solutions. These designers worked reasonably efficiently and followed fairly logical procedure, whether or not they had been educated in a systematic approach. In comparison, designers either with a too-rigid adherence to a systematic procedure (behaving 'un-reasonably' methodically), or with very unsystematic approaches, produced mediocre or poor design solutions. Successful designers (ones producing better quality solutions) tended to be those who (Cross 2000: 27):

- clarified requirements, by asking sets of related questions which focused on the problem structure
- actively searched for information, and critically checked given requirements
- summarised information on the problem formulation into requirements and partially prioritized them
- did not suppress first solution ideas; they held on to them, but returned to clarifying the problem rather than pursuing initial solution concepts in depth
- detached themselves during conceptual design stages from fixation on early solution concepts

- produced variants but limited the production and kept an overview by periodically assessing and evaluating in order to reduce the number of possible variants.

The key to successful design therefore seems to be the effective management of the dual exploration of both the ‘problem space’ and the ‘solution space’.

Designing is a form of skilled behaviour. Learning any skill usually relies on controlled practice and the development of techniques. However, performing is different that learning, where underneath lies mastery of technique and procedure. The performance of a skilled practitioner appears to flow seamlessly, adapting the performance to the circumstances without faltering.

### 3.3. Design Process and Design Methods

Around the year 1400, Filippo Brunellesci (1377-1446), the Italian architect and engineer, built the cupola (dome) of the new cathedral for the city of Florence. Until that time buildings were not really engineered at all. The craft was then known as *artisanship*, and basically involved using well-understood principles and trial and error methods of building. In the environment of artisanship, the artisan simply starts building or manufacturing the product. When problems are encountered, the entire project is started over again. This contributed to making engineers extremely conservative; innovation was rarely encouraged and often discouraged because of its implied risks.

Brunelleschi began by keeping a journal in which he sketched and described individual ideas for features and components of the cathedral from both architectural and civil engineering perspectives. Once he had developed what he believed were a wide enough assortment of different ideas and concepts for the cathedral, he started looking at the ideas with a more critical eye to see how the different concepts would work together. Not all of them made sense if used together. He pieced together an overall concept for the cathedral, which he described in a single master plan.

Brunelleschi did something new. He knew he would have to "subcontract" the construction of the building materials to other people, but he did not want to show them the master plan - for fear of having his idea copied before he could finish the project. So he created a large collection of individual drawings. Each drawing specified only a few components of the cathedral's structure - few enough that anyone getting one or two of the drawings would be unable to intuit the nature of the building as a whole. He then distributed the drawings to the various manufacturers. Brunelleschi did not tell them what the parts were for. He only wanted them made and delivered to a certain off-site location. Once he'd received enough of the parts, he began to build the cathedral.

Brunelleschi completed the cathedral, which was recognized as one of the most impressive buildings of its kind. Indeed, it still remains a masterpiece of engineering and architecture (http://deed.ryerson.ca/~fil/T/gen/history0.html).

***Design Aspect of Brunelleschi's Work***

Brunelleschi had unwittingly invented a design process. First he did some *conceptual design*, which included the sketches and ideas in his journal. He then examined and evaluated the concepts, blending some together and discarding others altogether, leading to a single overall concept of the cathedral; this is *concept evaluation*. Brunelleschi then detailed the idea to the level of a master plan - this is *detailed design*. Then, Brunelleschi developed all the different parts drawings. In order to do this properly, he needed to keep in mind some sort of assembly process, and make sure that the parts were designed in a way that he could fit them all together on the building's site. This is *process planning*. The parts were then "outsourced" for *manufacture*, and *assembled* on-site.

Because of the success of the project, this basic process - conceptual design, concept evaluation, detailed design, process planning, manufacture, and assembly - became the standard way that buildings were engineered. Indeed, any engineering design textbook up to the 1970s, finds the basic design process described just as Brunelleschi developed it (http://deed.ryerson.ca/-fil/T/gen/history0.html).

### 3.3.1. Introduction to Design Methods

When the scientific study of design emerged after World War II, it began as an effort toward developing new procedures for designing. In the face of the increasingly complex tasks that designers were encountering, the pioneers of the field saw a need for improved ways of designing, as they thought the existing procedures were inadequate (Alexander 1964, 1971, Cross 1984, Jones 1970, Rittel 1972). Therefore, the early work almost exclusively sought to develop such new procedures, or design methods; and so, the field was appropriately called design methodology—the study of such methods. It was also known as "the design methods movement" (Gedenryd 1998: 19 quoted Cross 1984).

#### 3.3.1.1. Design Methodology

Design methodology is the science of methods that are or can be applied in designing. In English the word 'methodology' has two meanings. The firs meaning is: a science or study of method, i.e. the description, explanation and valuation of methods. The second meaning of 'methodology' is: a body of methods, procedures, working concepts and rules employed by a particular science, art or discipline. In academic circles the term 'methodology' normally has the first meaning, i.e. field of study and research (Roozenburg and Eekels 1995: 29).

In design methodology (having the second meaning) there are two principle questions: (a) what is the essential structure of designing? And (b) how should the design process be approached to make it effective and efficient?

It is the task of descriptive design methodology to answer the first question, and the second should be answered by prescriptive design methodology. Descriptive design methodology tries to reveal the methods applied in design through logical structural analyses, and empirical research, as well as to identify the needs for methodical support. Prescriptive or normative design methodology forms an opinion based on descriptive analyses, and recommends for certain problems the application of certain methods, or even demands it. Prescriptive design methodology is, of course, not limited to the assortment of methods found in a descriptive manner, but must also construct new methods it for a certain part of the design process no satisfactory methods are available (Roozenburg and Eekels 1995: 29).

“Design methodology aims at providing conceptual tools for designers to organize the design process effectively and efficiently (Roozenburg and Eekels 1995: 29)”.

There are many similarities between the design process in such diverse fields as architecture, mechanical engineering, industrial design, software engineering, and the development of the ‘objects’ of management, such as policies, strategies, and organizations. The form of the design process appears to be hardly dependent on the content of the problem, nor on the type of the object being designed. On the whole, the same procedure is followed in all design processes, and consequently comparable methodological problems occur. Many product design methods are therefore also applied outside product development, and the opposite also occurs. That is not surprising, as quite a few design methods have their origin in the same, more general methodologies, such as the systems approach, operations research and decision theory.

**3.3.1.2. Comparison of Scientific Method with Design Method**

Over the years different disciplines have developed specific individual techniques within the general methodology. For example, scientists working in natural sciences have evolved what is called as the “scientific method” (Ackoff –1961). Over a period of time the philosophy common to all research methods and techniques is usually given the name scientific method. The scientist has to go on uncharted journeys of discovery through systematic investigation and experimentation in order to uncover the “truth”. The same can be said of the designer who has to explore and experiment in order to uncover and bring out the truth in its most innovative and beautiful form. Unlike in design there are no penalties for failing to uncover the truth in science. In the scientific method even if no truth get unveiled, the researchers contribution is valuated for charting and uncharted route. Therefore while determining the worth of a research project in science, the process itself has an equal value as that of the end result. In design methods, the emphasis has always been on the end result (a physical product, graphics etc). In the scientific method aspects such as validity, bias, reliability, repeatability and universality of the processes are supreme parameters of judging the truth-value of the outcome. In design the judgment has always been based on the end result.

The ensemble of methods employed in designing products, their systematic arrangements is called the methodology of product design. (Maldonado an Bonsiepe – 1989). In the case of design there exist a context to start with (Fig. 3.17) which has been termed as "state of the art". Within this state there exists an unfilled need or a problem of the user, which is to be solved. The design method like the scientific method has well defined processes at each stage, involving iterations. These iterations systematically reduce the factor of chance or arbitrariness of the result. In the words of Maldonado and Bonsiepe (1989) "methods operate in the range of possibilities laying between random success and rational determination" (Yammiyavar 2000: 252).

| SCIENTIFIC METHOD | DESIGN METHOD |
|---|---|
| Existing Knowledge | State of The Art (Market Requirement / Unfilled Need) |
| Scientific curiosity / Problem | Problem (Identification / Definition) |
| Hypotheses | Conceptualization (Analysis +Synthesis) |
| Analysis / Experimentation | Realization / Simulation |
| Proof | Production |

Figure 3.17 Comparison of Scientific Method with Design Method
(Yammiyavar 2000: 256)

### 3.3.1.3. Four Unifying Principles of Design Methods

The number of design methods (and accompanying diagrams) that have been published is immense. Probably no two authors have ever agreed on a method, so at least as many methods have been presented as there have been authors. But as people change their minds, the number is probably higher. Therefore, if someone reviews the field and the various methods, quickly becomes bewildered by the plethora of variants, the different labels on the various boxes, and the directions of the arrows.

Examining a large enough number of variants, patterns begin to form: certain features are due to the specific content of a domain; architecture is different from information design, and so the methods differ. In many cases, different labels disguise the same ideas; and different authors emphasize different aspect of design, so the methods focus on different aspects of the design process. Other variation comes from whether a method is an entirely theoretical construction, or if it has actually been confronted with real design projects, and so forth.

To make this essence explicit, Gedenryd (1998: 21) characterizes it in terms of four fundamental principles, which are of particular interest from a cognitive point of view:

1. Separation: The separation of the design process into distinct phases, with each individual activity being performed in isolation from the others.
2. Logical order: The specification of an explicit order in which to perform these different activities.
3. Planning: The pre-specification of an order in which to perform the activities within a phase.
4. Product–process symmetry: The plan being organized so as to make the structure of the design process reflects the structure of the sub-components of the resulting design product.

These principles make up the heart of design methods thinking, and give the various methods their family resemblance.

<u>1. Separation</u>

Out of the four principles, each consecutive one is an elaboration of those before it, drawing out their consequences and filling in their details. From this it follows that they are ordered, from the first being the most general and most fundamental one, to successively becoming more explicit and detailed. Although it may seem abstract and inconspicuous, separation is the most important principle, from which the remaining three follow as consequences. The most important separation is to divide the design process into three major phases: analyzing the problem, synthesizing a solution, and evaluating the outcome.

> One of the simplest and most common observations about designing, and one upon which many writers agree, is that it includes the three essential stages of analysis, synthesis and evaluation. These can be described in simple words as "breaking the problem into pieces", "putting the pieces together in a new way" and "testing to discover the consequences of putting the new arrangement into practice" (Jones 1970: 63).

This is the foundation of all design methods, and may well be the most consequential idea of design methodology as a whole.

Design methods normally make additional separations. In particular, the three major stages are often divided further into several smaller sub-activities. The principle of separation says that different functions of the design process are performed as separate activities. With respect to analysis and synthesis, one can say that design activity must serve two functions: understanding the problem and producing a solution. Separation then means that each of these two functions is worked on in a separate phase of problem solving. It is for instance easy to imagine a situation where both of these aspects are worked on together (Gedenryd 1998: 21).

2. Logical order

The second principle concerns the imposition of an order among the activities of a design method. Perhaps the distinction between the different activities that a design method is made up of may seem obvious, and the prescribed ordering among the activities may seem more significant. However, even though it might appear so, the working order is a necessity that follows directly from separation, whereas it is not obvious that they should be kept separated: If you do separate analysis from synthesis, then you must perform the analysis before the synthesis, as you have to have to understand the problem before you produce the solution. The same goes for evaluation, it requires that you have something to evaluate, and so must follow synthesis.

And conversely, if you do not separate the process into distinct phases then there is nothing to order, so an ordering doesn't make sense. This applies to all other separations that are made: the ordering among the activities is a logical consequence of the purpose that each serves. It is therefore the logical order (Gedenryd 1998: 22).

Taken together, the first two principles, separation and logical order, generate a basic three-stage model of design; shown in Figure 3.18.

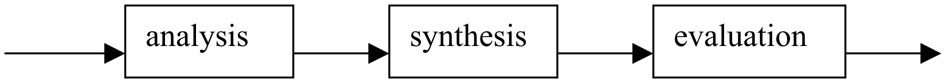



Figure 3.18 The basic three-stage design method schema
(Gedenryd 1998: 23)

3. Planning

Whereas the logical order concerns the relation between different phases, the third principle aims to lay down the organization of the design activities in even greater detail, to include the activity within a phase. Because of the size and complexity of design problems, each of the three major phases is quite complex. Without an internal order, each phase would be a large, unstructured activity, left by the methodologist for the eventual designer to decide. Planning consists in setting up a strategy, a plan, for how a particular activity should be performed. The prototypical case is when a plan is set up as the final part of the analysis, and the course of action in the synthesis is thereby laid down before this activity begins (Gedenryd 1998: 23).

4. Product–process symmetry

The fourth principle concerns the decomposition scheme used in the plan; the particular strategy that organizes activity inside the synthesis phase. There is not automatically any logical ordering within the phases. Therefore, a decomposition strategy needs to be chosen.

There is however one strategy that is particularly obvious. This is the idea of using the division of the product into subcomponents for the decomposition of the activity as well: As also the design solution is bound to be complex, it too ought to be broken down into manageable parts. Hence, part of the analysis typically consists in finding such suitable solution decomposition, usually a hierarchical one. And when you have this decomposition, it is not far-fetched to use it to structure the synthesis activity as well. In effect, the synthesis phase gets a hierarchical organization that mirrors the hierarchical structure of the final product. Hence the process and product are structured in the same way; the decomposition principle consists in a product–process symmetry. This lies particularly close at hand since the symmetry results in a natural one-to-one mapping between different parts of the synthesis and of the design product.

All four principles taken together yield a resulting schema that is more complex than the basic three-stage version. As the last two principles are elaborations of the first and second, the complex schema can be regarded as an "elaborated" version of the basic one.

Examples of the elaborated version are the classical "waterfall" model (Boehm 1975, Fig. 3.19) from software engineering, which centers on a technique for determining a suitable problem decomposition. The models like these are known as "structured design methods": analysis creates the decomposition structure of the artifact, and which the synthesis is to follow as a "structured decomposition". Together, the basic and elaborated versions capture the central features of most design methods (Gedenryd 1998: 24).

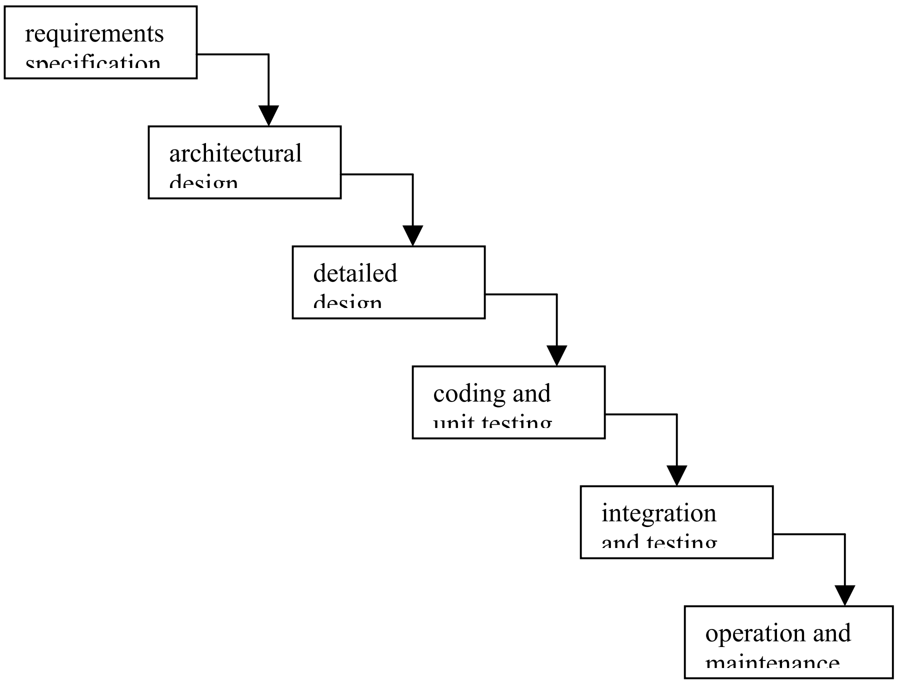



Figure 3.19 The waterfall model of software engineering
(Gedenryd 1998: 24 quoted Boehm 1975)

### 3.3.2. Design Process

Design process is a map for how to get from the need for a specific object to the final product. The knowledge required -through the map- for the design process is shown in Figure 3.20.

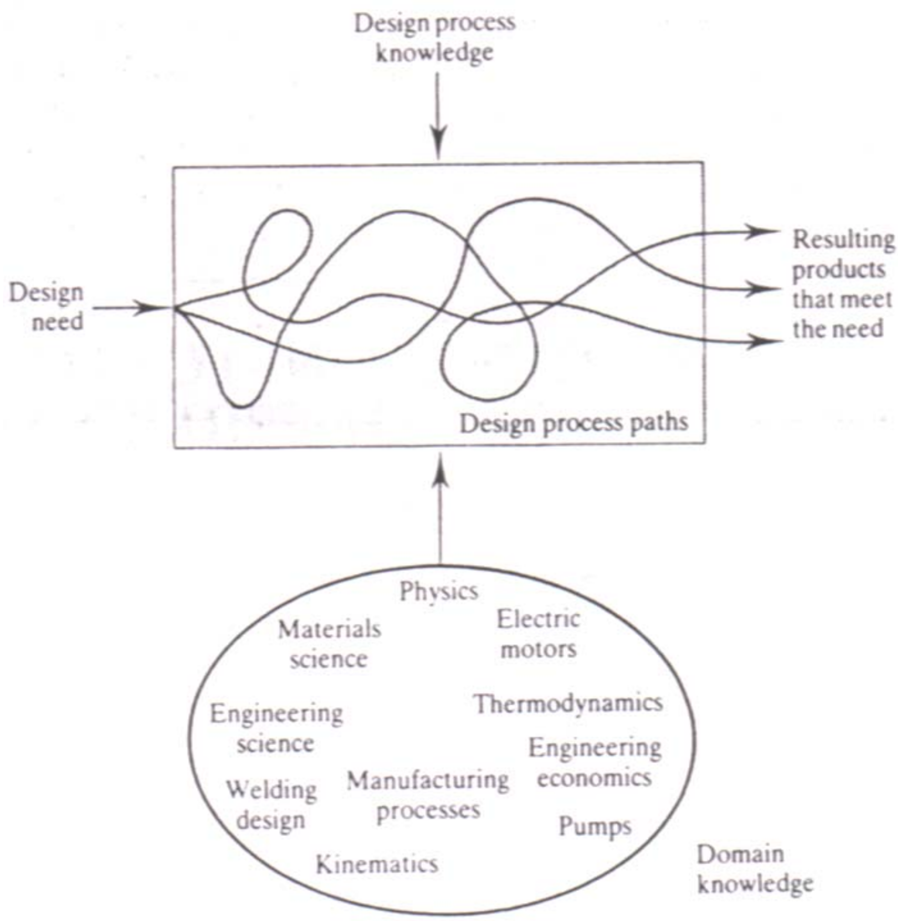



Figure 3.20 Knowledge used in the design process (Ullman 1992: 4)

"The three measures of the design process are cost, quality and time (Ullman 1992: 8)". Regardless of the product being designed –whether it is an entire system or small subpart of a larger product- the customer and management always want it cheaper, better and faster.

There is a continuous need for new, cost-effective, high-quality products. It has been estimated that 85% of problems with new products are not working as they should (quality), taking too long to bring to market (time), and costing too much, as the results of poor design processes.

The decisions made during the design process have the greatest effect on the cost of a product for the least investment. Design decisions directly determine the materials used, goods purchased, parts to be assembled, shapes of those parts, product sold, and, in the end, the scope of management.

It is clear that quality cannot be built into a product unless it is designed into it. Quality definitions of the customers also indicate the responsibilities of the design engineer: works as it should, lasts a long time, easy to maintain, looks attractive, incorporates latest technology, has many features, and etc.

#### 3.3.2.1. Descriptive Models

There have been many attempts to draw up maps or models of the design process. Some of these models simply describe the sequences of activities that typically occur in designing; other models attempt to prescribe a better or more appropriate pattern of activities.

Descriptive models of the design process usually identify the significance of generating a solution concept early in the process, thus reflecting the solution-focused nature of design thinking.

***Cross's Model:***

As shown in Figure 3.21, Cross developed a simple descriptive model of the design process, based on the essential activities that the designer performs. The end-point of the process is the communication of a design, ready for manufacture. Prior to this, the design proposal is subject to evaluation against the goals, constraints and criteria of the design brief. The proposal itself arises from the generation of a concept by the designer, usually after some initial exploration of the ill-defined problem space. Putting these four activity types in their natural sequence, we have a simple four-stage model of the design process consisting of: exploration, generation, evaluation and communication.

Assuming that the evaluation stage does not always lead directly onto the communication of a final design, but that sometimes a new and more satisfactory concept has to be chosen, an iterative feedback loop is shown from the evaluation stage to the generation stage.

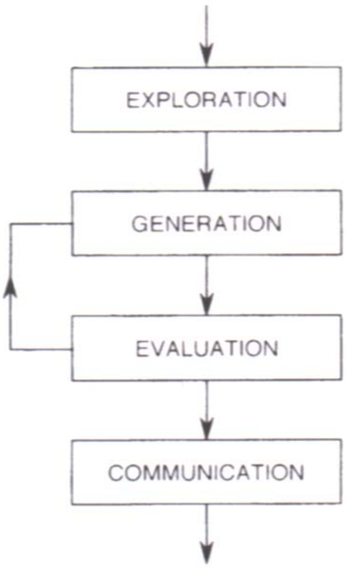



Figure 3.21 A simple four-stage model of the design process (Cross 2000: 30)

***French's Model:***

French (1985) has developed a more detailed model of the design process, shown in Figure 3.22, based on the following activities: analysis of problem, conceptual design; embodiment of schemes; detailing. In the diagram, the circles represent stages reached, or outputs, and the rectangles represent activities, or work in progress.

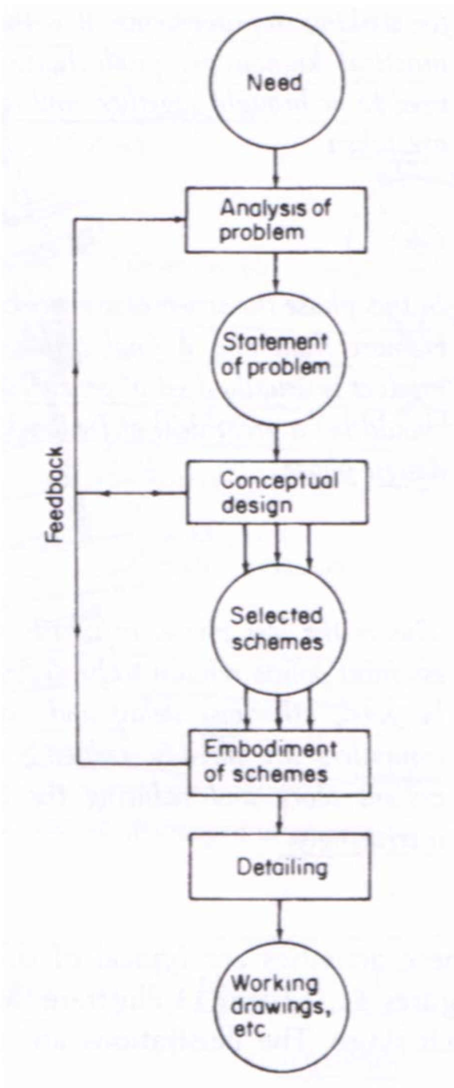



Figure 3.22 French's model of the design process (Cross 2000: 31)

The process begins with an initial statement of a need, and the first design activity is analysis of the problem.

- Analysis of Problem: The analysis of the problem is a small but important part of the overall process. The output is a statement of the problem, and this can have three elements, which correspond to the goals, constraints and criteria of the design brief:
    - a statement of the design problem proper
    - limitations placed upon the solution, e.g. codes of practice, statutory requirements, customers' standards, date of completion, etc.
    - the criterion of excellence to be worked to.

- Conceptual Design: This phase takes the statement of the problem and generates broad solutions to it in the form of schemes. It is the phase that makes the greatest demands on the designer, and where there is the most scope for striking improvements. It is the phase where engineering science, practical knowledge, production methods and commercial aspects need to be brought together, and where the most important decisions are taken.

- Embodiment of Schemes: In this phase the schemes are worked up in greater detail and, if there is more than one, a final choice between them is made. The end product is usually a set of general arrangement drawings. There is (or should be) a great deal feedback from this phase to the conceptual design phase.

- Detailing: This is the last phase, in which a very large number of small but essential points remain to be decided. The quality of this work must be good, otherwise delay and expense or even failure will result; computers are already reducing the drudgery of this skilled and patient work and reducing the chance of errors, and will do so increasingly.

#### 3.3.2.2. Prescriptive Models

These models are concerned with trying to persuade or encourage designers to adopt improved ways of working. They usually offer a more algorithmic, systematic procedure to follow, and are often regarded as providing a particular design methodology.

Many of these prescriptive models have emphasized the need for more analytical work to precede the generation of solution concepts. The intention is to try to ensure that the design problem is fully understood, that no important elements of it are over-looked, and that the real problem is identified.

These models have therefore tended to suggest a basic structure to the design process of analysis-synthesis-evaluation. These stages were defined by Jones (1984) in an early example of a systematic design methodology, as follows.

***Jones's Model:***

- Analysis: listing of all design requirements and the reduction of these to a complete set of logically related performance specifications.
- Synthesis: finding possible solutions for each individual performance specification and building up complete designs from these with least possible compromise.
- Evaluation: evaluating the accuracy with which alternative designs fulfill performance requirements for operation, manufacture and sales before the final design is selected.

This may sound very similar to a conventional design process, but the emphases here are on performance specifications logically derived from the design problem, generating several alternative design concepts by building-up the best sub-solutions and making a rational choice of the best of the alternative designs. Such apparently sensible and rational procedures are not always followed in conventional design practice.

***Archer's Model:***

A more detailed prescriptive model was developed by Archer (1984), and is summarized in Figure 3.23. This includes interactions with the world outside the design process itself, such as inputs from the client, the designer's training and experience, other sources information, etc. the output is, of course, the communication of a specific solution. These various inputs and outputs are shown as external to the design process in the following diagram, which also features many feedback loops.

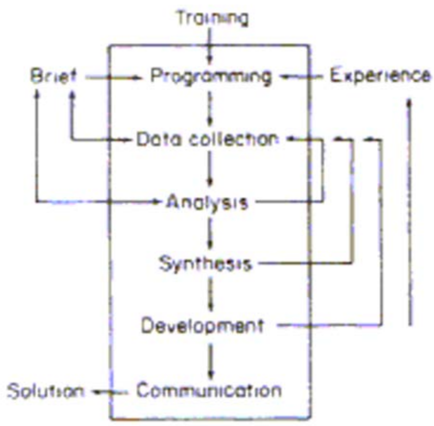



Figure 3.23 Archer's model of the design process (Cross 2000: 35)

Within the design process, Archer identified six types of activity.

- Programming: establishing crucial issues; propose a course of action.
- Data collection: collect, classify and store data.
- Analysis: identify sub-problems; prepare performance (or design) specifications; reappraise proposed program and estimate.
- Synthesis: prepare outline design proposals.
- Development: develop prototype design(s); prepare and execute validation studies.
- Communication: prepare manufacturing documentation.

Archer summarized this process as dividing into three broad phases: analytical, creative and executive (Fig. 3.24). He suggested that:

> One of the special features of the process of designing is that the analytical phase with which it begins requires objective observation and inductive reasoning, while the creative phase the heart of it requires involvement, subjective judgment, and deductive reasoning. Once the crucial decisions are made, the design process continues with the execution of working drawings, schedules, etc., again in an objective and descriptive mood. The design process is thus a creative sandwich. The bread of objective and systematic analysis may be thick or thin, but the creative act is always there in the middle (Cross 2000: 36 quoted Archer).

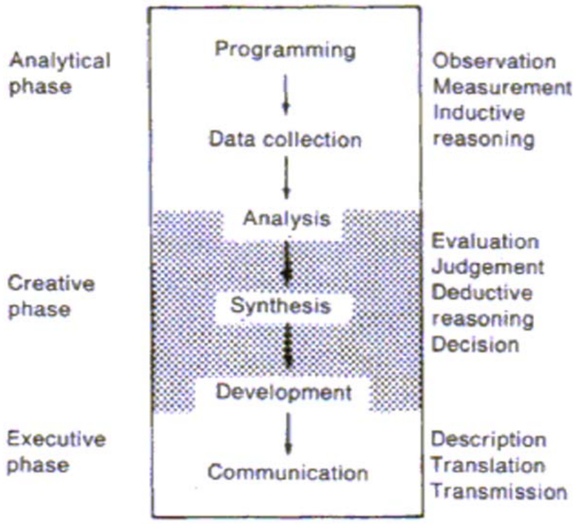



Figure 3.24 Archer's three-phase summary model of the design process
(Cross 2000: 36)

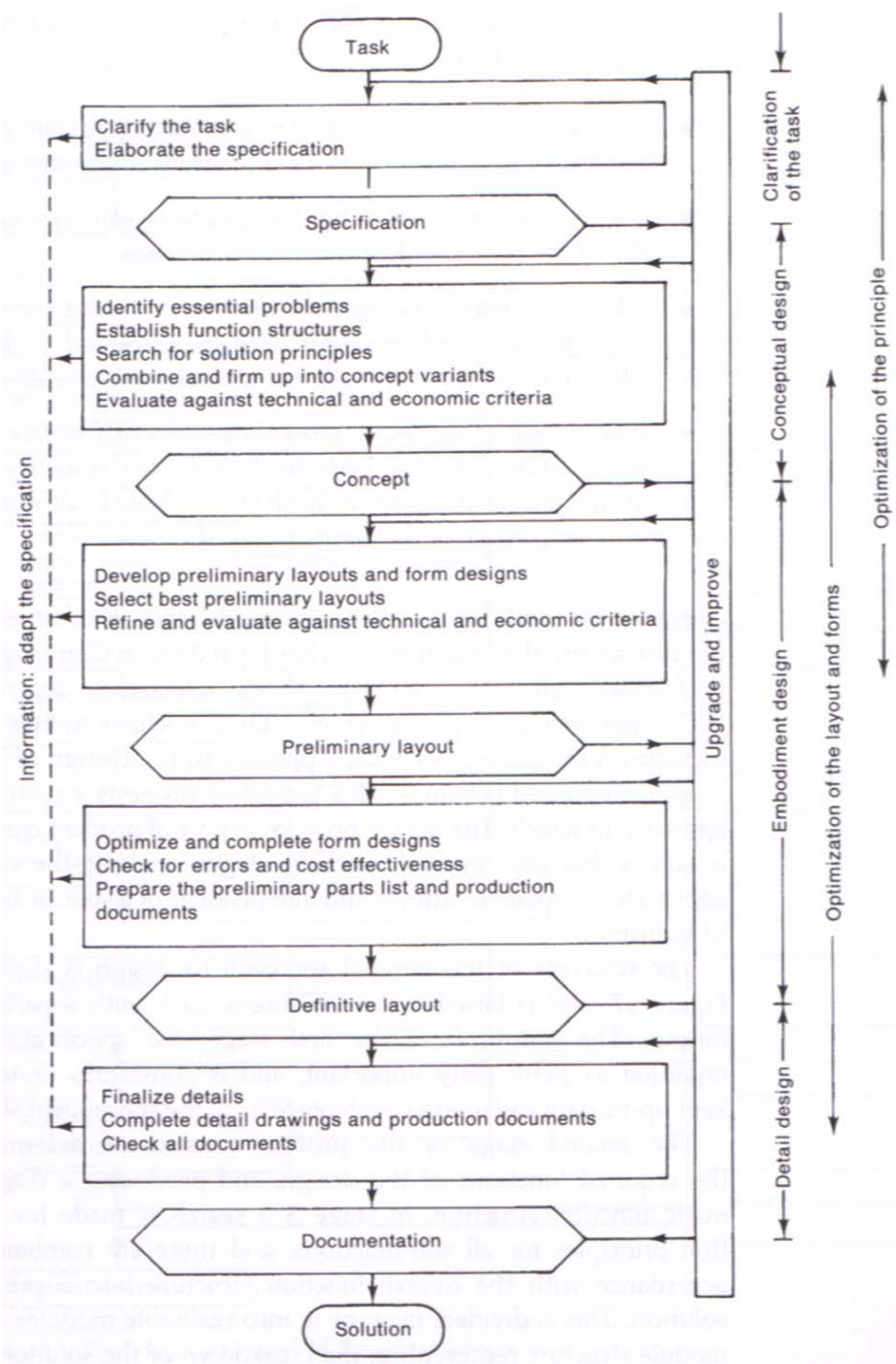



Figure 3.25 Pahl and Beitz's model of the design process

(Cross 2000: 37)

***Pahl & Beitz's Model:***

Some much more complex models have been proposed, but they often tend to obscure the general structure of design process by swamping it in the fine detail of the numerous tasks and activities that are necessary in all practical design work. A reasonably comprehensive model that still retains some clarity is that offered by Pahl and Beitz (1984) (Figure 3.25). It is based on the following design stages:

- Clarification of the task: collect information about the requirements to be embodied in the solution and also about the constraints.
- Conceptual design: establish function structures; search for suitable solution principles; combine into concept variants.
- Embodiment design: starting from the concept, the designer determines the layout and forms and develops a technical product or system in accordance with technical and economic considerations.
- Detail design: arrangement, form, dimensions and surface properties of all the individual parts finally laid down; materials specified; technical and economic feasibility re-checked; all drawings and other production documents produced.

***March's Model***

A more radical model of the design process, which recognizes the solution-focused nature of design thinking, has been suggested by March (1984) (Figure 3.26). He argued that the two conventionally understood forms of reasoning - inductive and deductive – only apply logically to the evaluative and analytical types of activity in design. However, the type of activity that is most there is no commonly acknowledged form of reasoning. March drew on the work of the philosopher Peirce to identify this missing concept of abductive reasoning. According to Peirce

Deduction proves that something ***must be***; induction shows that something ***actually*** is operative; abduction suggests that something ***may be***.

It is this hypothesizing of what may be, the act of synthesis, that is central to design. Because it is the kind of thinking by which designs are generated or produced, March prefers to call it productive reasoning. Thus his model for a rational design process is a 'PDI model': production-deduction-induction.

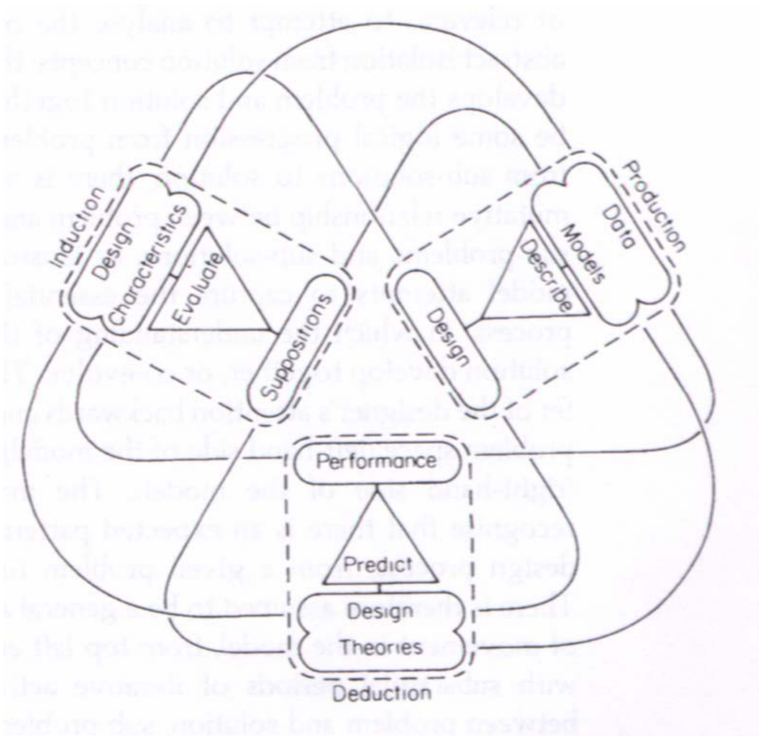



Figure 3.26 March's model of the design process (Cross 2000: 41)

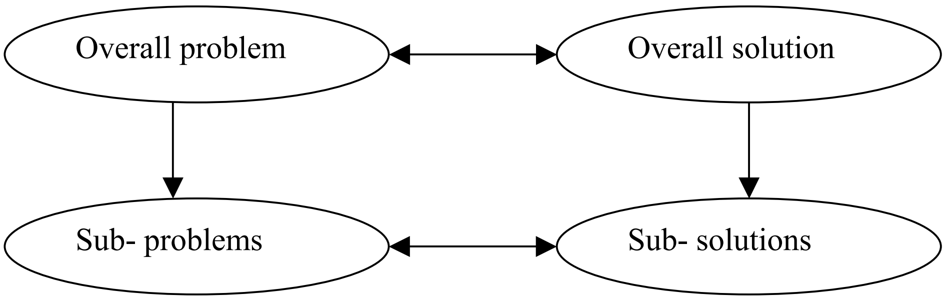



Figure 3.27 The symmetrical relationships of problem / sub-problems / sub-solutions / solution in design (Cross 2000: 42)

In this model the first phase, productive reasoning, drawings on a preliminary statement of requirements, and some presuppositions about solution types in order to produce, or describe, a design proposal. From this proposal and established theory (e.g. engineering science) it is possible deductively to analyze, or predict, the performance of the design. From these predicted performance characteristics it is possible inductively to evaluate further suppositions or possibilities, leading to changes or refinements in the design proposal.

### 3.3.3. Design Methods

#### 3.3.3.1. New Design Procedures

There is a need to improve on traditional ways of working in design. There are several reasons for this concern to develop new design procedures. One is the increasing complexity of modern design. A great variety of new demands is increasingly being made on the designer, such as the new materials and devices (e.g. electronics.) that become available and the new problems that are presented to designers. Many of the products and machines to be designed today have never existed before, and so the designer's previous experience may well be irrelevant and inadequate for these tasks. Therefore a new and the more systematic approach is needed, it is argued.

A related part of the complexity of modern design is the need to develop teamwork, with many specialists collaborating in and contributing to the design. To help coordinate the team, it is necessary to have a clear, organized approach to design, so that specialist's contributions are made at the right point in the process. Dividing the overall problem in to sub-problems in a systematic procedure also needs that the design work itself can be subdivided and allocated to appropriate team members.

As well as being more complex, modern design work often has very high risks and costs associated with it. For example, many products are designed for mass manufacture, and the costs of setting up the manufacturing plant, buying-in raw materials, and so on, are so high that the designer cannot afford to make mistakes: the design must be absolutely right before it goes into production. This means that any new product must have been through a careful process of design. Other kinds of large, one-off designs, such as chemical process plants, or complex products such as aeroplanes, also need to have a very rigorous design process to try to ensure their safe operation and avoid the catastrophic consequences of failure.

Finally, there is a more general concern with trying to improve the efficiency of the design process. In some industries there is a pressing need to ensure that the lead-time necessary to design a new products kept to a minimum. In all cases, it is desirable to try to avoid the mistakes and delays that often occur in conventional design procedures.

The introduction of computers already offers one way of improving the efficiency of the design process, and is also in itself an influence towards more systematic ways of working.

### 3.3.3.2. What is Design Method?

One of the most significant aspects of this concern to improve the design process has been the development of new design methods. In a sense, any identifiable way of working within the context of designing can be considered to be a design method. The most common design method can be called the method of design-by-drawing.

Design methods can, therefore, be any procedures, techniques, aids or “tolls” for designing. They represent a number of distinct kinds of activities that the designer might use and combine into an overall design process. Although some design methods can be the conventional and normal procedures of design, such as drawing, there has been a substantial growth in new, unconventional procedures that are more usually grouped together under the name of design methods.

The main intention of these new methods is that they attempt to bring rational procedures into the design process. It sometimes seems that some of these new methods can become over-formalized, or can be merely fancy names for old commonsense techniques. They can also appear to be too systematic to be useful in the rather messy and often hurried world of the design office. For these kinds of reasons, many designers are still mistrustful of the whole idea of design methods.

The counter-arguments to that view are based on the reasons for adapting systematic procedures, outlined above. For instance, many modern design projects are too complex to be resolved satisfactorily by the old conventional methods. There are also to many errors made with conventional ways of working, and they are not very useful where teamwork is necessary. Design methods try to overcome these kinds of problems, and above all they try to ensure that a better product result from the new design process.

Some design methods are new inventions of rational procedures, some are adapted from operational research, decision theory, management sciences or other sources, and some are simply extensions or formalizations of the informal techniques that designers have always used. For example, the informal method of looking of manufacturer's catalogues or seeking advices from colleagues might be formalized in to an information search method; or informal procedures for saving costs by detailed redesigning of a component can be formalized into a value analyses method. Different design methods have different purposes and are relevant to different aspect of and stages in the design process.

The new methods tend to have two principles features in common. One is that they formalized certain procedure of design and the other is that they externalized design thinking. Formalization is a common feature of design methods because they attempt to avoid the occurrence of oversights, of overlooked factors in the design problem and of the kinds of errors that occur with informal methods. The process of formalizing a procedure also tends to widen the approach that is taken to a design problem and to widen research for appropriate solutions; it encourages and enables you to think beyond the first solutions that comes into your head.

This is also related to other general aspects of design methods, that they externalize design thinking, i.e. they try to get your thoughts and thinking process out of your head and into the charts and diagrams that commonly feature in design methods. This externalizing is a significant aid when dealing with complex problems, but it is also a necessary part of team work, i.e. providing means by which all the members of the team can see what is going on and contribute to the design process. Getting a lot of systematic work out of your head and onto paper also means that your mind can be more free to pursue the kind of thinking it is best at: intuitive and imaginative thinking.
Design methods therefore are not the enemy of creativity, imagination and intuition. Quite the contrary: they are perhaps more likely to lead to novel design solutions than the informal, internal and often incoherent thinking procedures of the conventional design process. Some design methods are, indeed, techniques specifically for aiding creative thought. In fact, the general body of design methods can be classified into two broad groups: creative methods and rational methods.

#### 3.3.3.2.1. Creative Methods

There are several design methods, which are, intend to help stimulate creative thinking. In general, they work by trying to increase the flow of ideas, by removing the mental blocks that inhibit creativity, or by widening the area in which a search for solutions is made.

***Brain Storming:***

The most widely known creative methods is brain storming. This is a method for generating a large number of ideas, most of which will subsequently be discarded but with perhaps a few novel ideas being identified as worth following-up. It is normally conducted as a small group session of about 4-8 people.

The group of people selected for a brain storming session should be diverse. It should just not be experts or those knowledgeable in the problem area, but should include a wide range of expertise and even laypeople if they have familiarity with the problem area. The group must be non-hierarchical, although one person does need to take an organizational lead.

An important prior task for the leader is to formulate the problem statement used as a starting point. If the problem is stated too narrowly, than the range of ideas from the session may be rather limited. On the other hand, a very vague problem statement leads to equally vague ideas, which may be of no practical use. The problem can often be usefully formulated as a question, such as “how can we improve on x?”

In response to the initial problem statement, the group members are asked to spent a few minutes-in silence-writing down the first ideas that come into their heads.

The next, and major, part of the session is for each member of the group, in turn, to read out one idea from his or her set. The most important rule here is that no criticism is allowed from any other member of the group. At this stage, the feasibility or otherwise of any idea is not important: evaluation and selection will come later.

What each group members should do in response to every other person's is to try to build on it, to take it a stage further, to use it as a stimulus for other ideas, or to combine it with his or her own ideas. For this reason, there should be a short pause after each idea is read out, to allow a moment for reflection and to write down further new ideas.

The group session should not last more than about 20-30 minutes, or should be wound up when no more ideas are forthcoming. The group leader, or someone else, then collects all the cards and spends a separate period evaluating the ideas. A useful aid to this evaluation is to sort or classify the ideas into related groups; this in itself often suggest further ideas, or indicates the major types of idea that there appear to be. If principle solution areas and one or two novel ideas result from a brainstorming session then it will have been worthwhile.

The essential rules of brainstorming are as follows (Cross 2000: 50):

- No criticism is allowed during the session.
- A large quantity of ideas is wanted.
- Seemingly crazy ides are quite welcome.
- Keep all ideas short and snappy.
- Try to combine improve on the ideas of others.

***Synectics:***

Creative thinking often draws on analogical thinking, on the ability to see parallels or connections between apparently dissimilar topics.

The use of analogical thinking has been formalized in a creative design method known as synectics. Like brainstorming, synectics is a group activity in which criticism is ruled out, and the group members attempt to build, combine and develop ideas towards a creative solution to the set problem. Synectics is different from brainstorming in that the group tries to work collectively towards a particular solution, rather than generating a large number of ideas. A synectic session is much longer than brainstorming, and much more demanding. In a synectic session, the group is encouraged to use particular types of analogy, as follows:

Direct Analogies: these are usually found by seeking a biological solution to a similar problem. For example, Brunel's observation of a shipworm forming a tube for itself as it bored trough timber is said to have led him to the idea of a caisson for underwater constructions; Velcro fastening was designed on an analogy with plant burrs.

Personal Analogies: the team members imagine what it would be like to use oneself as the system or component that is being designed. For example, what would it feel like to be a motorcar suspension unit; how would I operate if I were a computerized filling system.

Symbolic Analogies: here poetic metaphors and similes are used to relate aspects of one thing with aspects of another. For example, the "friendliness" of a computer, the "head" and "claw" of a hammer, a "tree" of objectives, the "Greek key pattern" of a housing layout.

Fantasy Analogies: these are impossible wishes_for things to be achieved in some magical way. For example, "what we really want is a door keeper who recognize each system user". "We need the bumps in the road to disappear beneath the wheels."

A synectics session starts with the problem as given: the problem statement as presented by the client or company management. Analogies are then sought that help to "Make the strange familiar", i.e. expressing the problem in terms of some more familiar (but perhaps rather distant) analogy. This leads to a conceptualism of the problem as understood: the key factor or elements of the problem that need to be resolved or perhaps a complete formulation of the problem. The problem as understood is then used to guide the use of analogies again, but this time to "make the familiar strange". Unusual and creative analogies are sought which may lead to novel solution concepts. The analogies are used to open up lines of development, which are pursued as hard and as imaginatively as possible by the group.

***Enlarging the Search Space:***

A common form of mental block to creative thinking is to assume rather narrow boundaries within which a solution is sought. Many creativity techniques are aids to enlarging the "search space".

Transformation: one such technique attempts to transform the search for a solution from one area to another. This often involves applying verbs that will transform the problem in some way, such as magnify, minify, modify, unify, subdue, subtract, add, divide, multiply, repeat, replace, relax, dissolve, thicken, soften, harden, roughen, flatten, rotate, rearrange, reverse, combine, separate, substitute, eliminate.

Random input: creativity can be triggered by random inputs from whatever source. This can be applied as a deliberate technique, e.g. opening a dictionary or other book and choosing a word at random and using that to stimulate thought on the problem in hand. Or switch on a television set and use the first visual image as the random input stimulus.

Why? Why? Why?: another way of extending the search space is to ask a string of "why?" question about the problem, such as "why is this device necessary?" "Why can not it be eliminated?", etc. each answer is followed up, like a persistent child, with another "why?" until e deed end is reached or an unexpected answer prompts an idea for a solution. There may be several answers to any particular "why?", and these can be charted as a network of question and answer chains.

Counter-Planning: this method is based on the concept of the dialectic, i.e. pitting an idea (the thesis) against its opposite (the antithesis) in order to generate a new idea (the synthesis). It can be used to challenge a conventional solution to a problem by proposing its deliberate opposite, and seeking a compromise. Alternatively, two completely different solutions can be deliberately generated, with the intention of combining the best features of each into a new synthesis.

**The Creative Process**

The methods above are some techniques, which have been found useful when it is necessary for a designer or design team to “turn on” their creative thinking. However, creative, original ideas can also seem to occur quite spontaneously, without the use of any such aids to creative thinking. Is there, therefore, a more general process of creative thinking which can be developed?

Psychologists have studied accounts of creative thinking from a wide range of scientists, artists and designers. In fact, as most people have also experienced, this highly creative individuals generally report that they experience a very sudden creative insight that suggests a solution to the problem they have been working on.

This creative “ah-ha!” experience often occurs when the individual is not expecting it, and after a period when they have been thinking about something else. This is rather like the common phenomenon of suddenly remembering a name or word that could not be recalled when it was wanted.

However, the sudden illumination of a bright idea does not usually occur without considerably background work on a problem. The illumination or key insight is also usually just the germ of an idea that needs a lot of further work to develop it into a proper, complete solution to the problem. Similar kinds of thought sequence occur often enough in creative thinking for psychologists to suggest that there is a general pattern to it. This general pattern is the sequence: recognition – preparation – incubation – illumination - verification.

- Recognition is the first realization or acknowledgement that a problem exists.
- Preparation is the application of deliberate effort to understand the problem.
- Incubation is a period of leaving it to mull over in the mind, allowing one’s subconscious to go to work.
- Illumination is the (often quite sudden) perception or formulation of the key idea.
- Verification is the hard work of developing and testing the idea.

This process is essentially one of work-relaxation-work, with the creative insight (if you are lucky enough to get one) occurring in a relaxation period. The hard work of preparation and verification is essential. Like most other kinds of creative activity, creative design is 1% inspiration and 99% perspiration.

The sudden illumination is often referred as a creative leap, but it is perhaps not helpful to think of creative design as relying on a flying leap from the problem space into the solution space. The creative event in design is not so much a leap from problem to solution as the building of a bridge between the problem space and the solution space by the identification of a key solution concept. This concept is recognized by the designer as embodying a satisfactory match of relationships between problem and solution.

**3.3.3.2.2. Rational Methods**

More commonly regarded as design methods than the creativity techniques are the rational methods, which encourage a systematic approach to design. Nevertheless, these rational methods often have similar aims to the creative methods, such as widening the search space for potential solutions, or facilitating teamwork and group decision-making. So it is not necessarily true that rational methods are somehow the very opposite of creative methods.

Many designers are suspicious of rational methods, fearing that they are straitjackets, or that they stifle creativity. This is a misunderstanding of the intentions of systematic design, which is meant to improve the quality of design decisions, and hence of the end product. Creative methods and rational methods are complementary aspects of a systematic approach to design. Rather than a straitjacket, they should be seen as a lifejacket, helping the designer-especially the student designer- to keep afloat.

Perhaps the simplest kind of rational methods is the checklist. Everyone uses this method in daily life, for example, in the form of a shopping list, or list of things to remember to do. It externalizes what you have to do, so that you do not have to try to keep it all in your head, and so that you do not overlook something. It formulizes the process by making a record of items, which can be checked-off as they are collected or achieved until everything is complete. It also allows teamwork or participation by a wider group, e.g. all the family can contribute suggestion for the shopping list. It also allows sub-division of the task (i.e. improving the efficiency of the process) such as allocating separate sections of the list to different members of the team. In these respects, it is a model for most of the rational design methods. In design terms, a checklist may be a list of questions to be asked in the initial stages of design, or a list of features to be incorporated in the design, or a list of criteria, standards, etc., that the final design must meet.

There is a wide range of rational design methods, covering all aspects of the design process from problem clarification to detail design. The selected set is detailed below, with the stage in the design process shown on the left, and the method relevant to this stage on the right.

- Clarifying objectives
    - Method: Objectives tree
    - Aim: Clarify design objectives, and sub-objectives, and the relationships between them.
- Establishing functions
    - Method: Function analyses
    - Aim: Establish the functions required, and the system boundary, of a new design.
- Setting requirements
    - Method: Performance specification
    - Aim: to make an accurate specification of the performance required of a design solution.
- Determining characteristics
    - Method: Quality function deployment
    - Aim: Set targets to be achieved for the engineering characteristics of a product, such that they satisfy customer requirements.
- Generating alternatives
    - Method: Morphological chart
    - Aim: to generate the complete range of alternative design solutions for a product, and hence to widen the search for potential new solutions.

- Evaluating alternatives
    - Method: Weighted objectives
    - Aim: Compare the utility values of alternative design proposals, on the basis of performance against differentially weighed objectives.
- Improving details
    - Method: Value engineering
    - Aim: to increase or maintain the value of a product to its purchaser while reducing its cost to its producer.

These seven stages of design and their accompanying design methods should not be assumed to constitute an invariate design process. However, Figure 3.28 suggests how they related to each other and to the symmetrical problem solution model. For example, clarifying objectives (using the objectives tree method) is appropriate both to understand the problem solution relationship and to develop from the overall problem into sub-problems.

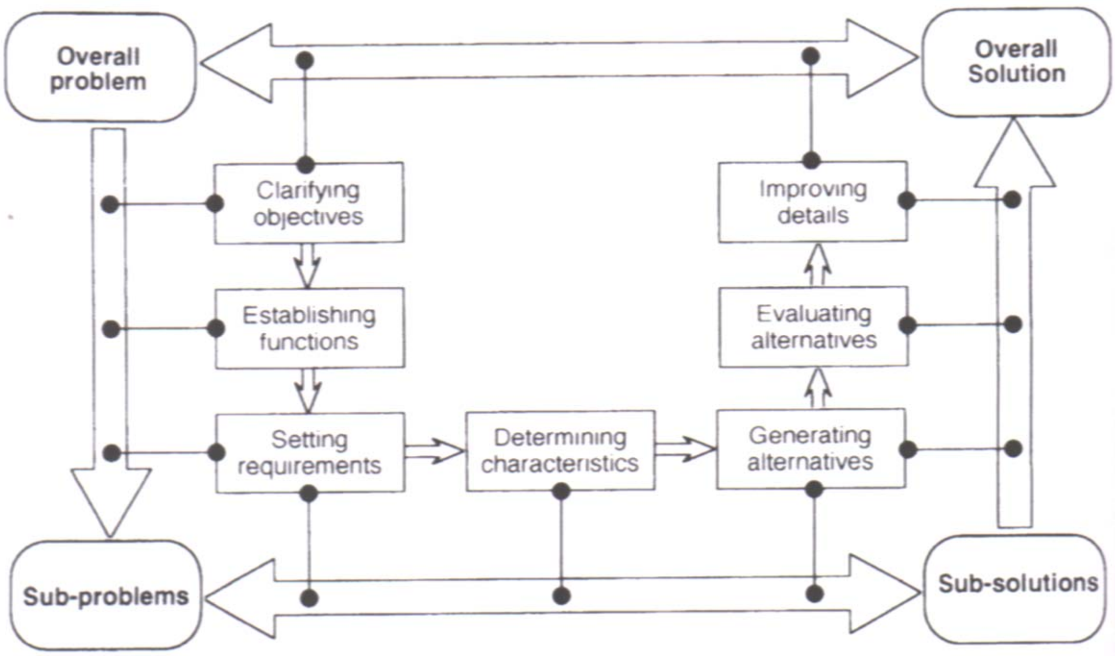



Figure 3.28 Seven stages of the design process positioned
within the symmetrical problem / solution model (Cross 2000: 58)

This model of designing integrates the procedural aspects of design with the structural aspects of design problems. The procedural aspects are represented by the sequence of methods (anti-clockwise, from top left), and the structural aspects are represented by the arrows showing the commutative relationship between problem and solution and the hierarchical relationships between problem/sub-problems and between sub-solutions/solution. Such methods are often adapted to suit the particular requirements of the task in hand. Although it is important not to follow any method in a slavish and unimaginative fashion, it is also important that an effort is made to follow the principles of the method with some rigour. No beneficial results can be expected from slipshod attempts at “method”.

# Chapter 4

# A CASE STUDY IN BICYCLE DESIGN

## 4.1 Introduction to Bicycles

### 4.1.1. Mysterious Bicycle

#### 4.1.1.1. The Origin

Baron Karl von Drais, who is called an engineer by Burrows (2000: 11), took the most remarkable first step in the evolution of the bicycle, when he discovered that a vehicle with a pair of in-line wheels does not necessarily do the obvious and fall over. For all the significance of the subsequent innovations, they were all logical and inevitable steps like cranks, chains, etc. What von Drais did, on the other hand, went far beyond logic and evolution. There was no precedent in nature, no natural forerunner to be improved upon. His running machine was as original as possible.

It is inconceivable that anyone would have theorized the bicycle into existence. There is no natural predecessor for the bicycle, unlike cars that are horseless carriages, airplanes that are iron birds, and even the helicopter, which has the humble sycamore seed as a logical starting point. “This is a case where, necessity was the *daughter* of invention, for we certainly could not do without the bicycle now (Burrows 2000: 14)”.

Despite having no natural forerunners, it had to come from somewhere. There were at the time four-wheeled vehicles in use, both animal and human powered. The French Celerifere, often misquoted as a bicycle, was one of these. It is usually suggested that one of these devices, built by von Drais, was the starting point for the bicycle. But this is not seeing with an engineer’s (Drais’s) eye. An engineer is a relatively logical person and knows perfectly well what would happen if he took two of the four wheels off his vehicle – it would fall over. But, an engineer can see the advantage in adding another wheel to one wheel. The best known one-wheeler in this era was the child's hobbyhorse. Several authors accept this as a starting point, while Burrows (2000: 12) thinks of wheelbarrows, although they are not mentioned in the history of bicycles. The Chinese have used wheelbarrows in sixteenth century which, Burrows thinks European would have known about and adopted. For there must have been a great need for cheap specialized transport in Europe at this time especially for artisans and craftspeople. This would have resulted in an enormous variety of handcarts developed.

Von Drais had worked for a while in the forestry industry, and at the time was teaching the trade to others. He was also an 'inventor'. Such a man would surely have looked at ways of getting timber out of the forests without using expensive horses. It could be a single-track vehicle (Fig. 4.1). It seems logical that, having added steering it would not have taken long for an inventor and a group of students to discover the secret of the balance without which the bicycle is impossible.

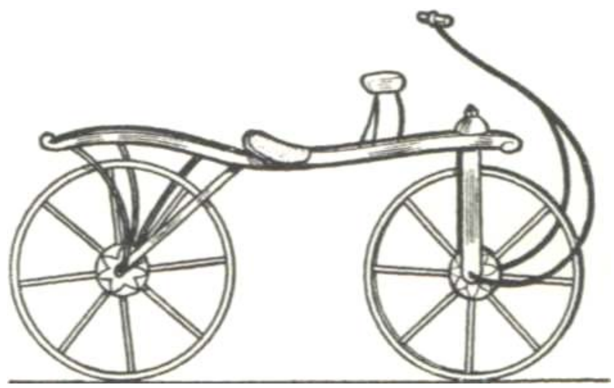


Figure 4.1 Hobby Horse by Baron Karl von Drais, 1817 (Ballantine 2001: 11)

The other great name that is always mentioned in connection with the origins of the two-wheeler is Leonardo da Vinci (as was mentioned in Chapter 2). The reason he is always mentioned is the famous sketch of *something*, shown in Figure 4.2. However, no serious historian has ever claimed that the sketch was by da Vinci, and no cycling historian has ever claimed it was bicycle. Burrows thinks that this might be the creation of the media and he adds that, "the original confusion arises from the sketch's superficial similarity to a bicycle. This has caused people to assume that it was at least an elevation or side view of something. I would argue, as an engineer and one who has *dealed with similar things*, that this is actually a plan view, looking down on something, *and not a bicycle that had fallen over*" (2000: 13-14).

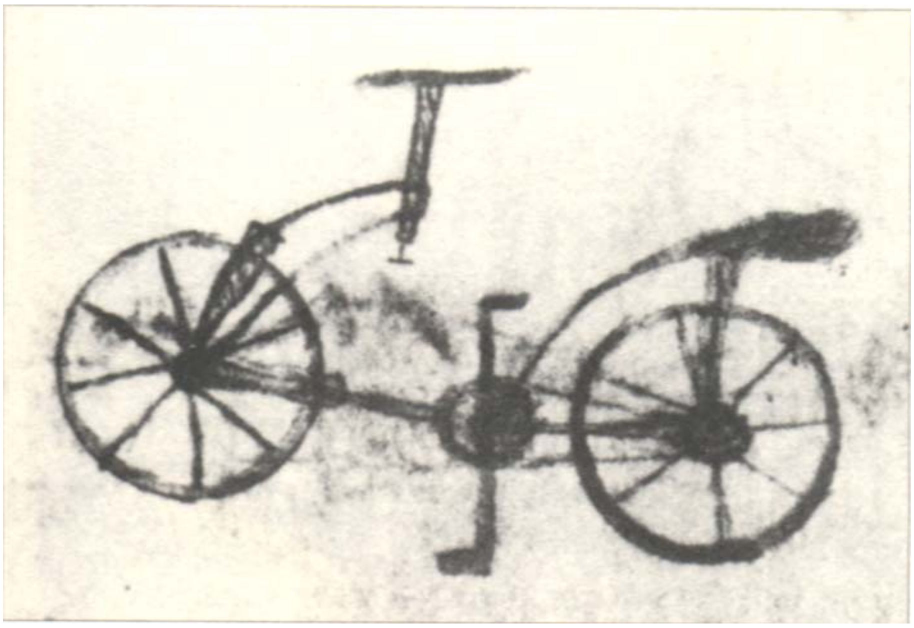


Figure 4.2 (Perry 1995: 7)
Leonardo da Vinci's Codex Atlanticus Bicycle, from Biblioteca Ambrosiana, 1493

But whichever way it came about, and whether it was genius or luck, it started a chain of events that led the modern cycle in all its forms. Seen by many as the "wallpaper" of the transport world, the bicycle is in fact one of the finest examples of engineering design of all time. It uses so little in the form of material or resources to produce; yet it does so much so efficiently with cheap healthy transport, enjoyable leisure, exciting sport and no harmful side effects.

On the other hand, it makes sense that (as the figures and facts have been available for a long time through Archibald Sharp's book *Bicycles and Tricycles*, first published in 1896), what affects the performance of a bicycle by now is a 180-year-old device.

However, the subject still remains as mysterious as the dark side of the moon since a manufacturer's claim that his bicycle is made from a remarkable new thermoplastic titanium alloy cannot be questioned. The manufacturer seems to have supernatural powers, as he says he can feel the difference between various grades of steel tubing, even though there is no instrument yet can do this.

#### 4.1.1.2. Balancing

An object is balanced by standing on -at least- three points with the center of gravity being in the middle. However, bicycle is against this rule because of its structure while balancing with two points in motion. Even tricycles are not balanced as well as two-wheelers in motion, especially in rounding a corner position where the bicycle cannot lean in order to balance the centrifugal forces in the proper direction.

"The bicycle is too unique to have been invented – it must have been a chance discovery (Ballantine 2000: 9)". Describing the dynamics of how a bicycle in motion remains upright, involves fourth-order, non-linear, partial differential equations with variable coefficients, and complex calculations that cause problems even for evolved computers. Yet it is almost impossible to make a bicycle that will not work. Build a frame, attach two in-line wheels, one of them with steering, set the thing in motion, and with someone or something aboard to "steer", the vehicle can be made to stay upright. In fact, it is possible to build a bicycle that so long as it is rolling will stay upright by itself, without a rider.

Once a bicycle is seen, it all seems incredibly obvious. A bicycle in motion does not fall down because it is constantly moving from out of balance into balance; motion resolves the yes/no issue of balance into dynamic equilibrium. It seems simple, but the process is physically unique, and there is no possibility to imagine it in the abstract. No creature in nature, nor any mechanical process, will serve model for the bicycle. "The only analogy for the bicycle I can imagine is life itself. Ecosystems operate just like a bicycle. Responding to environmental change, elements in an ecosystem increase or decrease, constantly moving the entire ecosystem from an out of balance state toward equilibrium (Ballantine 2001: 9)."

Motion is fundamental to the operation of a bicycle, and the complexity of the balancing process is probably why it works so well despite many variables. Those *fourth-order,* *non-linear,* etc. equations for how a bike stays upright have never been completed, because the permutations are infinite.

Any script about the bicycle was originally developed is pure conjecture, but it is interesting to note that if you try to teach people to ride a bike by explaining how to do it and then just send them off, they are likely to go down in a tangle or head straight for the nearest tree. If you remove the pedals and ask them to use their feet to scoot along, they will learn mystery of balance within seconds (Ballantine 2001: 10).

The bicycle is a 100 percent kinetic machine, i.e. its equilibrium depends on motion, and almost certainly was a hands on discovery intended for some other idea.

### 4.1.2. Significance of the Bicycle

The invention of the bicycle started a chain of events that led the modern cycle in all its forms that is seen by many historians as the "wallpaper" of the transport world.

"The bicycle was the first widely available means of individual transportation, and it began the era of high-speed, long-range personal transport. It has had enormous social and technological impact, providing freedom of travel to ordinary people and contributing to a host of social transformations (McMahon & Graham 1992: 1)". It led directly to the automobile beginning in 1885 when Gottlieb Daimler produced a motorized bicycle, shown in Figure 4.3. Karl Benz independently unveiled a motorized tricycle the next year, shown in Figure 4.4, and the U.S. auto industry began in 1896 with Henry Ford's bicycle-derived vehicle.

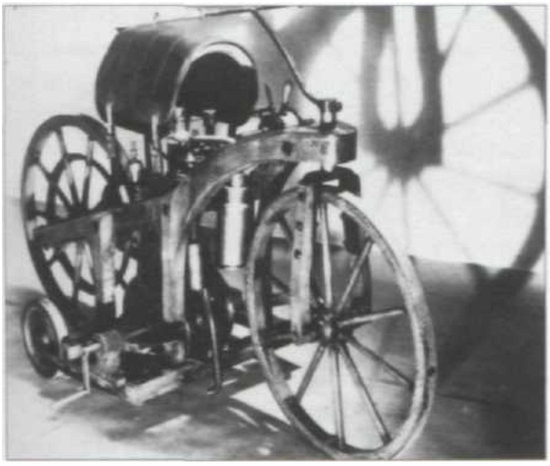


Figure 4.3 Daimler's first vehicle
(McMahon & Graham 1992: 1)

Figure 4.4 Karl Benz's first vehicle
(McMahon & Graham 1992: 1)

The preceding fifty years of bicycle development yielded a number of inventions that made these automotive precursors possible, many of which are still found in motorcars today. These include:

> …the pneumatic tire, the differential gear (which allows two side-by-side wheels to turn at slightly different speeds when a vehicle is rounding a corner), the tangent-spoked wheel (in which the spokes brace the rim against the torque applied during acceleration and deceleration), the perfection of ball bearings and the bush-roller chain for power transmission, the concept of gearing, gear ratios, and free-wheeling (in which the driving wheels are allowed to rotate free of the driving mechanism), and, of course, various braking systems, which were made necessary by the introduction of free-wheeling (McMahon & Graham 1992: 2).

Many features of today's automobiles are direct descendants of bicycle technology. The free-wheeling concept is used in clutch assemblies, and the derailleur is used in transmissions. The timing-chain that turns the camshaft is a sometimes bicycle-type bush-roller chain, and both drum and caliper-disc brakes were bicycle developments. It is no mystery how this technology was transferred so rapidly, since a great number of the early auto manufacturers got their start making and repairing bicycles. Of course, one of the most important contributions of the bicycle pioneers was the development of methods for mass production of intricate, highly reliable and easily repairable machines.

> A number of advances in materials technology stem from the development of the bicycle. These include the processing of thin-walled, seamless drawn-steel tubing, brazing, electric welding, heat treatment

and case-hardening of steel, and the use of fibers for reinforcement (which was necessary for the pneumatic tire) (McMahon & Graham 1992: 2).

It may be less obvious that the airplane is the other major offspring of the bicycle. However, a careful look at the early flying machines of the Wright brothers and Glenn Curtiss shows the genealogy quite clearly. The Wrights were in the business of bicycle manufacturing, and Curtiss was a bicycle racer. The Wrights were familiar with the technology needed for minimizing weight in a high-strength, stiff structure, and they employed a framework of drawn-steel tubing, braced like a bicycle frame, along with bicycle wheels and the cabling used on bicycles for brakes and gears to manipulate their control panels. With this they used the lightweight motors that came from motorized bicycles. An example of an early airplane is shown in Figure 4.5.

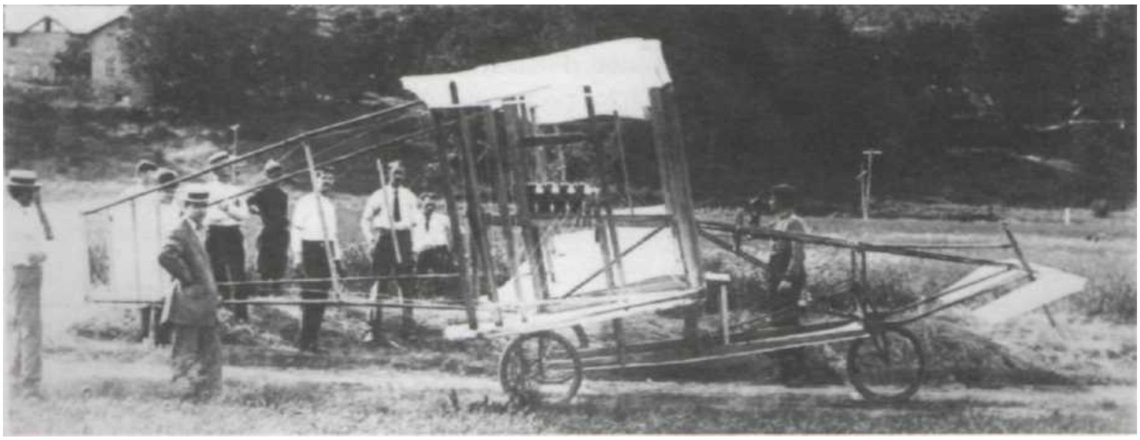


Figure 4.5 Glenn Curtiss's "June Box", 1908 (McMahon & Graham 1992: 3)

Most of the early pilots got started with bicycles.

Curtiss edged out the Wrights in getting the first U.S. pilot license. Orville Wright, who along with Wilbur invested the flying machine, ironically received the second license. Both Curtiss and Orville Wright had also raced bicycles. In France, the Farman brothers, also bicycle racers, took up flying and became airplane manufacturers. The same thing happened in Germany, where August Euler (German pilot license no.1) established the first airplane factory there. German license no. 2 went to Hans Grade, also a bicycle racer. Helene Dutrieu of Belgium was a bicycle racer and daredevil stunt rider who became one of the first women to fly in Europe. Alessandro Anzani a professional Italian bicycle sprint champion became a pioneer in airplane-engine manufacture (McMahon & Graham 1992: 3).

None of this was accidental; the same skills needed for balancing a bicycle and banking it on turns, practiced to the point where they become instinctive, could be transferred directly to flying. For the leading cyclists of the early 20th century, flying was a logical extension of cycling.

### 4.1.3. Evolution of the Bicycle


Figure 4.6 Velo development (Perry 1995: 11)

Baron Karl von Drais of Germany, in 1817, introduced a running machine that is still popularly known as a hobbyhorse. The vehicle consisted of a body set above two wheels, and was powered by the rider pushing his feet alternately against the ground. Crucially, the front wheel could be steered.

The hobbyhorse (Fig. 4.1) was crude and uncomfortable, but it was fast; on a good road a hobbyhorse rider could beat a horse. In a fashion craze, hobbyhorses rapidly appeared throughout Europe and even in America, primarily as objects of curiosity. But the newfangled machines were physically hard on riders, and they were not always liked by the general public. Therefore, the popular interest in hobbyhorses ebbed.

Technological improvement was needed, and in subsequent years, a number of backyard inventors devised two-wheel machines with pedal drive transmissions. Especially notable was a Scottish blacksmith, Kirkpatrick Macmillan, who around 1839 built a bicycle with rear wheel drive via a treadle transmission (Fig. 4.7). Technically advanced, Macmillan's velocipede (what a bike was called back then) was capable of a sustained average speed of eight mph. Macmillan made no effort to market or manufacture his bike, and the original machine has not survived, although many copies were made.

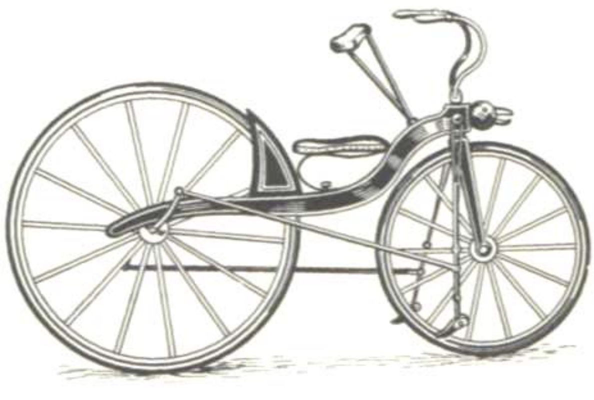


Figure 4.7 McMillan type bicycle built by McCall, 1860
(Ballantine 2001: 11)

Another technically advanced rear wheel drive velocipede similar to Macmillan's was made around 1842 by Alexander Lefebvre of France. In 1860 or 1861 Lefebvre moved to California, taking his original machine with him; “it now survives as the world's oldest existing bicycle (Ballantine 2001: 11)”.

There were other attempts at pedal drives, but now, achieving widespread popularity for a bicycle design or innovation depended on achieving successful commercial manufacture, marketing, and sales. This was the accomplishment of one Pierre Michaux, a French cabinetmaker and locksmith, who, with his son Ernest, organized workshops in Paris and in 1861 launched a bicycle with pedals and cranks attached directly to the front wheel. The first machines were crude and not very comfortable (the vehicle was known in Britain as a boneshaker), but in 1866 a new model was introduced, with a curving wrought-iron frame, a larger front wheel, and various other refinements. Astutely, Pierre supplied French royalty with finely crafted, upmarket versions of the new edition. The aristocracy was entranced, and played with their new toys in the streets of Paris, sparking a vogue for velocipedes. Suddenly, in all the best places, cycling was the thing to do (Ballantine 2001: 11-12).

As demand for velocipedes soared, an overwhelmed Michaux factory was refinanced and relocated by the Olivier Brothers, who took over the business in 1869. The new regime marketed vigorously, advertising top range machines in "enamelled, polished and damascened steel, polished or engraved aluminum bronze. Wheels of West Indian hardwood, amaranth, makrussa, hickory, ebony or lemon tree. Handlebar grips of sculpted ivory." Until 1867, Michaux had produced a few hundred machines a year; under the Olivier Brothers, production was claimed to be 200 machines a day - and they were only one of some 75 manufacturers of velocipedes in France (Ballantine 2001: 12).

France led the world in bicycle design. In 1869, in a development eventually crucial for the efficiency and performance of all types of machines throughout the world, Jules Suriray patented and produced ball bearings (accepted as the atoms of machine age were first developed for the bicycle) for bicycle wheel hubs. Other innovations featured that same year at the Paris Velocipede Exhibition were metal spoked-wheels, solid rubber tires, a four-speed gear, and a free wheel. In 1870 the Franco-Prussian War broke out, and the bicycle industry was all ruined.

Fortunately, the passion for velocipedes had spread throughout Europe and across the Atlantic. In America, the craze was short lived, but in Britain, the velocipede found an enduring home. Firms in the Midlands counties of England, producing sewing machines, firearms, and other machinery took up the manufacture of velocipedes, first as a sideline and eventually as a principal activity. Coventry, in particular, became the epicenter for the continuing evolution of the bicycle.

With pedals and cranks attached directly to the front wheel, the speed of a boneshaker was a function of wheel size; the larger the diameter of the driving wheel, the faster the rider could go. The limiting factor was rider leg length, and through the 1870s the boneshaker quite literally grew into the famous, elegant high wheel bicycle (Fig. 4.8), a machine that often stood as tall as a man.

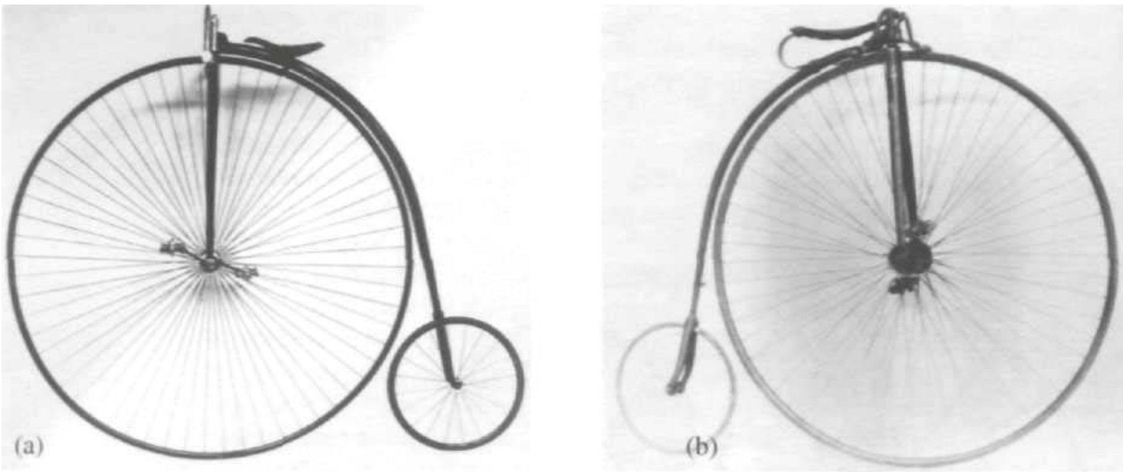



Figure 4.8 The Humber “Genuine Beeston” Racing Ordinary, 1886
(McMahon & Graham 1992: 6)

The high wheel bicycle (known as “Ordinary”) was an athletic sporting machine extremely fast, and quite dangerous to ride. The large driving wheel gave speed, but since the most effective riding position was almost straight above the wheel, the center of gravity was very high, and finely balanced. This made the bike unstable and when under way, encountering a chance stone, stick, or rut could, and often did, cause the bike to cartwheel, pitching the rider over the handlebars in a horrendous forward fall known as "coining a cropper." The instability of the bike also prohibited any possibility of serious braking. A spoon brake (which worked by rubbing against the front tire) fitted to many machines was only a wishful hope, because overzealous application of this puny device, or even just backpedaling too hard could also tilt the bike and send the rider flying (Ballantine 2001: 15).

In the 1880s, designers and inventors were experimenting with an enormous variety of pedal powered machines: monocycles, dicycles, tricycles, quadricycles, swimming machines, flying machines, and innumerable cycle-related mechanisms, devices, and accessories. One strong line of investigation was the quest for what would later be called a "safety" bicycle, a machine stable enough to be ridden without the likely possibility of an upset.

The deficiencies of the Ordinary led to a decline in its popularity and the demand for the "safety" bicycle, which was introduced by Starley in 1885: he called it the "Rover." (Fig. 4.9) It had a diamond frame, a chain-and-sprocket drive to the rear wheel, wheels of almost equal size, and a seat for the rider that was so far to the rear that the risk of a "header" was all but eliminated (McMahon & Graham 1992: 6).

Figure 4.9 The Rover safety bicycle by J K Starley of England, 1885
(McMahon & Graham 1992: 7)

The Rover utilized the 1879 advances of Lawson, who had also equalized the wheel sizes and introduced rear-wheel chain drive, but apparently prematurely for the market.

Starley also benefited from the bush-roller chain, introduced by Renold in 1880, which greatly reduced the friction and wear that plagued earlier chain designs.

The final major advance in this "golden age of the bicycle" came in 1889, when John Dunlop, a veterinary surgeon from Belfast, patented the pneumatic tire. The present-day configuration of the bicycle was set by 1890 with the Humber, with its straight-tube diamond frame (Fig. 4.10). Both the pneumatic tire and the safety bicycle displaced their predecessors entirely in a rather short period of time (McMahon & Graham 1992: 7).

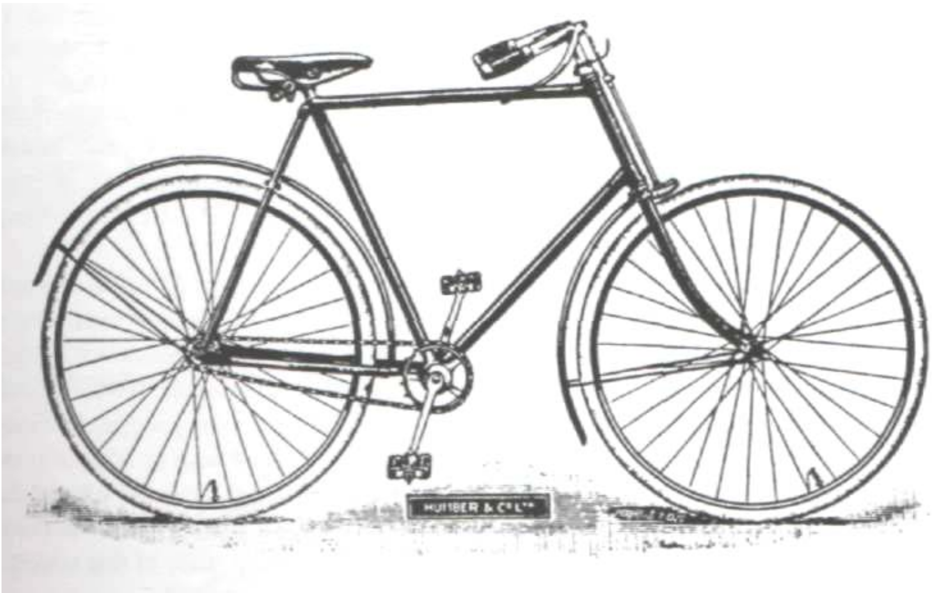


Figure 4.10 The Humber, 1890 (McMahon & Graham 1992: 7)

By 1910 most present-day bicycle equipment had been introduced, including the freewheel mechanism, caliper and drum brakes, derailleur-type gears, and the hub gear. With the introduction of the safety, the popularity of the bicycle grew explosively. By 1899 there were several hundred factories in the U.S. producing close to one million bicycles per year (McMahon & Graham 1992: 8).

The success of the bicycle in creating widespread demand for a private mode of transportation and stimulating the paving of roads and highways finally led to the shift in public attention to motorcycles and automobiles. Thus, the evolution of the bicycle came to a standstill soon after the turn of the century. It was not until the relatively recent spin-off of materials developed for aerospace applications, including high-strength aluminum and titanium alloys and fiber-reinforced composites that the excitement returned to bicycle technology. Since the story of the bicycle parallels that of the development of structural materials over the last century and a half, it can be thought that it is in many ways the ideal vehicle for the study of that subject.

### 4.1.4. Types of the Bicycle

Once there were three basic kinds of bikes: sport bikes with drop handlebars and derailleur gears, roadster bikes with flat handlebars and hub gears, and rugged single speed paperboy bikes. Sport bikes were divided into lightweight racers with no frills, and more strongly built tourers equipped with pannier racks and fenders. Roadsters were heavy and usually featured a chain guard, fenders, carrier rack, and possibly built in lights and a kickstand. Paperboy (now cruiser) bikes were really heavy, and had wide tires and a single pedal-operated coaster brake. Only a glance at a bike was needed to understand its genre and purpose.

Today there are more general categories and sub-types, and the distinctions often blur; a mountain bike designed and equipped for touring, for example, may be similar to a road touring bike in all but small details. A roadster city bike with hub gears may be a quality lightweight well able (other things being equal) to show its heels to a sport bike. Cruisers have sprouted alloy frames and wheels, and multi-speed gears. Then there are human-powered vehicles (HPVs), a category covering a range of designs, from sleek, high speed streamliners to large, four wheel quadricycles made to carry freight or passengers (Ballantine 2001: 27).

Despite their many different forms, most cycles have a clear primary purpose, and fit fairly firmly within a category. Two important things should be mentioned here, before revealing the types of bicycles are: weight and gear.

- Weight: Bike weight is fundamental so that, if a bike is heavy, it cannot be made to go. Here, the limiting factor is the human power.

- Gear: The transmission converts energy input at the pedals into power at the driving wheel. Different size gear ratios allow the rider to maintain an even match between work rate and terrain. Low gears produce more power but less speed by requiring more turns of the cranks for every turn of the driving wheel; high gears produce more speed but less power by requiring fewer turns of the cranks for every turn of the driving wheel.

First of all bicycles can be divided into two broad categories that are safety, or upright, bicycles and recumbent cycles. This classification depends on how bikes are built and how they look, rather than how they are used (Ballantine 2001: 31). As recumbent cycles are not subject of this study, they are not going to be mentioned here.

Full size upright or safety bicycles sort out into four basic groups (Ballantine 2001: 31): (1) roadster and style bikes; (2) commuter and city bikes; (3) road sport bikes; and (4) mountain bikes.

**4.1.4.1. Roadster and Style Bikes**

Cruisers are tough and durable, and are the ubiquitous mount for local deliveries, and rental fleets in parks. Cruisers are simple and need little mechanical care, fitting comfortably with a casual, laid back approach to life. Some models are available with alloy wheels, which greatly improve riding ease and enjoyment.

- Beach Cruiser (Fig.4.11): It is the modern reincarnation of the classic American paperboy bike. Heavy, robust steel frame, 26-inch steel wheels with hefty 2-inch wide tires, single speed hub with a pedal operated coaster brake, wide handle-bars, and mattress saddle. Beach cruisers are about style rather than performance and are usually done up in bright, cheerful colors.

- BMX Cruiser (Fig. 4.12) (and BMX Free style): This off-beat category generally features a compact frame, 24-inch wheels with wide, knobby tires, a single speed gear, and straight forks. BMX cruisers are basically BMX for bigger boys and girls, or smaller adults. BMX freestyle bikes are made and equipped for performing tricks and stunts and have also become quite popular as local ride around machines.

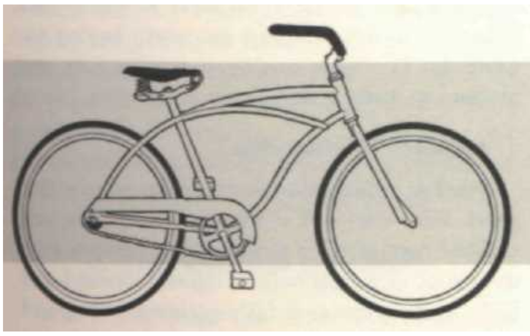


Figure 4.11 Beach Cruiser

Figure 4.12 BMX Cruiser

(Ballantine 2001: 31)

- Heavy Roadster (Fig. 4.13): Steel frame and 26- or 28-inch wheels, 1.5-inch wide tires, single speed or 3-speed hub gears are used. A proper classic version will have 28-inch wheels and roller lever rim brakes. Fully enclosed chain guard, kickstand, stout rear carrier, and built in lights. At around 50 pounds this is the European version of the paperboy bike, sometimes called an "Africa" model because of its popularity in developing countries like China. Many "Old Faithfuls" are still trundling out decades of service, and new machines continue to be produced by a few manufacturers. Heavy roadsters with a rear hub brake are imported from the Netherlands from time to time. The bikes are well made and pretty, with rustic charm, and they ride steadily and gracefully as long as the terrain is flat.

- Light Roadster (Fig. 4.14): "Light roadster" as a description could embrace several kinds of bikes, including some very up market models. A *traditional* light roadster, however, is a more sprightly version of a heavy roadster, and features a steel frame. 26-inch steel wheels with 1.375-inch wide tires, long reach side pull calliper rim brakes, 3-speed hub gears, half chainguard, and steel or plastic fenders are used. With a weight of around 35 pounds, a light roadster is more than a bit of work to pedal, and steel wheels mean grossly inadequate braking in wet weather.

Figure 4.13 Old Faithful    Figure 4.14 Light Roadster

(Ballantine 2001: 32)

- Modern Roadster Bike (Fig. 4.15): Steel or cro-mo alloy frame, alloy wheels, hub gears, fully enclosed chainguard, hub brake rear, calliper cantilever or V-brake front are used. Hub gears and fully-enclosed chainguard slant this type toward regular everyday urban use, with a minimum of attention and maintenance – a transport machine, but one that goes nicely — a smooth good clothes bike. A modern roadster is fairly heavy, but handles well and, unlike a traditional light roadster, it has serious brakes.

Figure 4.15 Pashley Paramount    Figure 4.16 Commuter

(Ballantine 2001: 33)

### 4.1.4.2. Commuter and City Bikes

The distinctions between a commuter bike, a town bike, and a city bike are quite fine, and are readily mixed by manufacturers in their catalogs. The basic concept, though, is a bike, which is a proper lightweight with a cro-mo, or aluminum frame and full size 26-inch or 700C alloy wheels, fitted with a semi-mattress saddle and flat handlebars for a fully upright riding position. These bikes generally weigh 25 to 30 pounds and have a pleasantly brisk performance, and can cope with day rides and light touring (25 to 35 miles), as well as regular commuting and local utility use.

- Commuter Bike (Fig. 4.16): Derailleur gears, part chainguard, 700C wheels with fairly light 1.125-inch wide tires, calliper V-or cantilever brakes, fenders, carrier rack, and possibly, built in lights. The slant here is towards the performance of a fast road sports bike, and a primary use for regular journeys of some distance, 7 to 8 miles or more. A good model should be 26 pounds or less. Some manufacturers have tried producing really high quality commuter models, with a carbon fiber or other high tech lightweight frame and very light wheels, for a weight of 23 pounds and less. Such machines are a real treat, but they are expensive and not enough demand has developed for them to become available on a regular basis.

- City Bike: It is similar to the commuter bike, but with 26-inch wheels and 1.5- or 1.75-inch wide tires - a seemingly small but significant difference. Where the commuter bike is kin to the fast road bike, the city bike is clearly derived from the tough, go-anywhere mountain bike, and can cope more ably with the jagged surfaces and deep pot holes of mean urban streets. A city bike has firm, stable handling. A city bike can also be just fine in the countryside. With smooth city tires and close fitting fenders, it cannot cover the same spectrum of rough terrain as a true cross country mountain bike, but it will handily take to paths, trails, and the open countryside and, with a little skill, can be pushed surprisingly far in more extreme conditions.

- Cross or Hybrid Bike: It is cross between a mountain bike and a road bike, with 700C wheels and flat handlebars. Hybrid bikes are available in many specifications, from plain to full suspension. Some manufacturers offer hybrid city bikes, with fenders, a rack, and lights. Most models, though, lean toward off-road sport and are fairly sparse. The larger 700C wheels are a little faster on the road than 26-inch wheels, a bit of an advantage for longer journeys or touring, but not important over short distances. A hybrid is a highly flexible all rounder. Depending on the tires and equipment Fitted, it can manage, say, 45-

mile tours in comfort, tackle all but extreme off-road riding conditions, or serve ably as a quick and durable urban commuting machine. Weight varies according to quality, and can range from around 23 or 24 pounds up to 28 pounds.

#### 4.1.4.3. Road Sport Bikes

- Sport Bike: It is modeled after road racing bikes, sport models feature a lightweight frame, steel or alloy components. 700C 25/32 tires, calliper rim brakes, derailleur gears, narrow saddle, and drop bars are used. Weight is around 28 to 30 pounds, sometimes more. Sport bikes vary a great deal in quality. At the low end, the machine may be nothing more than an ordinary mild steel roadster frame fitted with derailleur gears, drop handlebars, and "go faster" stripes for a racy appearance. At the high end, the machine may be a genuine lightweight with a fairly lively performance. In general, however, most quality sport bikes are function-specific models identified as fast touring, training, triathlon, racing, and so on. Sport bikes have modest performance and easy, predictable handling. Better models with alloy components (unless steel models) are fine for general riding, commuting, light touring, and moderately hilly terrain.

- Touring Bike, road version (Fig. 4.17): A full on road touring bike follows the general outline of a sport bike, but the frame geometry or configuration is arranged to provide a more comfortable ride and stable, predictable handling even when laden with baggage. Panniers are positioned so that they neither foul the rider, nor induce instability in handling because they are too far away from the bike. There are front and rear pannier racks, full-length fenders, and a profusion of mounting points for water bottle cages. The derailleur gearing is wide range, with ample low ratios for easier hill climbing, and the brakes are stout and strong - calliper cantilever or V-brake, or possibly hydraulic calliper. Wheels and tires are 700C or, in some cases, smaller and stronger 26-inch or 650B. Full on touring bikes can be used for commuting and day rides, but their proper activity is daily touring in the 50 to 100 mile range. Some models are claimed to weigh as little as 24 pounds, but, with a comprehensive equipment specification, 27 to 32 pounds is more likely.

- Fast Touring/Sport Touring (Fig. 4.18): A touring bike tweaked with lighter wheels and narrow 1- or 1-1.25-inch wide tires, and stiffer frame geometry, or a racing bike beefed up with heavier wheels and tires, and a more relaxed frame geometry - either way, a quick machine that can still manage light touring loads. This best of both worlds approach is popular for general use and commuting, as well as for weekend and holiday touring. Gearing is often a group of high, closely spaced ratios for speed, and a handful of low ratios for long climbs. There is provision for mounting slim fenders and a rear carrier rack. Compact side pull calliper brakes are used and its weight is 23 to 28 pounds.

Figure 4.17 Touring

Figure 4.18 Fast touring

(Ballantine 2001: 35)

- Fast Road/Training Bike: Fast-touring bikes can be quick, but are still rooted in touring and carrying things. Fast road or training bikes are derived from racing bikes, and the emphasis is on performance. The frame is close clearance, with no room or provision for fenders or a carrier rack, and is designed for quick handling and rapid acceleration. Shod with narrow profile 1- or 1.125-inch wide tires, a fast road bike typically has a stiff ride over rough surfaces. Glose ratio gears, compact side pull calliper brakes are used and its weight is 21 to 26 pounds.

- Triathlon (Fig. 4.19): Bikes made for triathlon (swimming-running-cycling) events are similar to fast road models, but the frame geometry has a tight back end, for fast response to pedal input, while the front end is more relaxed, to help guide tired riders through the bends. Profile bars for an aerodynamic riding position and lots of water bottle mounts are usually standard. Its weight is 21 to 25 pounds.

- Road Racing (Fig. 4.20): Strong, tight, close clearance frame for taut responsiveness and crisp, quick handling. Close ratio gears, and sprint wheels with sew up tubular tires. Mass start road racing in a pack of riders is often rough and tough, and the bikes are made to be light but strong and reliable. Weight is usually 20 to 22 pounds, but can pare down to 18 pounds. With sprint wheels and tubular tires a racing bike is strictly for competition. The trend with road racing bikes is toward compact frames with a sloping top tube, as pioneered by the TCR from Giant.

Figure 4.19 Triathlon

Figure 4.20 Giant TCR

(Ballantine 2001: 36)

- Time Trial (Fig. 4.21): A time trial (TT) bike is similar to a road-racing bike, but more lightly built. In a time trial, riders race on their own against the clock. The object is to go as fast as possible, and TT machines are set up according to course requirements, for example as a single speed, if the course is flat. A classic TT bike can be a study in painstaking effort to shed every ounce of excess weight, with cranks, chainrings, and other components drilled with hundreds of holes. A modern TT bike concentrates on aerodynamic efficiency, with a smooth, sculpted frame and profile bars.

- Track Bike (fig. 4.22): Made for racing on wooden tracks, these are stark greyhounds with a single fixed gear (the wheels turn when the cranks turn and vice versa), no brakes, and a weight of 16 to 17 pounds.

Figure 4.21 Short distance TT

Figure 4.22 Track

(Ballantine 2001: 37)

#### 4.1.4.4. Mountain Bikes

The mountain bike has changed the definition of what a bicycle is. Mountain bikes began as machines for off-road downhill racing, but then quickly evolved into many different forms covering a broad range of functions.

In essence, mountain bikes represent a fresh, no holds barred approach to bike design, and the use of new materials, to come up with bikes that do what people want. This innovative approach has rewritten the design rules for creating bikes of all kinds, from roadsters through to flat out speed machines. Diamond framed road-racing bike, which is a perfect synthesis of design and technology for the goal of speed, is now a classic. Modern racing bikes, built with ideas derived at least in part from mountain bike design and technology, are better and faster.

Mountain bikes offer a range of options in transmissions, brakes, controls, saddles, and handlebars; how these are mixed and matched has a big effect on the nature of a bike. A feature almost exclusive to mountain bikes, however, is suspension, which can be for the front or the back wheel, or both. Briefly, suspension improves bike control and rider comfort, but adds weight and mechanical complexity. For a downhill racing bike, the benefit of suspension is well worth the extra weight. In the case of a cross-country machine that must go up as well as down, weight is a significant performance factor, so there may be front wheel suspension only, or none at all.

- Mountain Bike, Standard or "Classic" (Fig. 4.23): It is a simple non-suspension mountain bike of good enough quality to be worth riding off-road. Bikes of this sort are suitable for general transport and moderate off-road riding.

- Mountain Bike, Cross Country: As the name suggests, cross-country mountain bikes are designed for both climbing and descending, and in between. There are many different specifications. It's common to have front suspension for comfort but, to save weight, not back. On the weight count, many racing mountain bikes do not have any suspension at all. However, as suspension systems steadily become lighter, cross-country bikes with dual suspension are becoming more popular.

- Technical/Trials Mountain Bike: Technical and trials mountain bikes are built for handling extreme terrain and obstacles. The idea with trials is to ride "clean." without the feet touching the ground, and so the bottom bracket is high to provide clearance over obstacles. The frame geometry is tight, for precise control. These are skill bikes and people use them to ride over cars, clamber over 5-foot diameter logs, and perform other incredible stunts. Technical riding is also popular in cities.

- Freestyle Mountain Bike: At one level, freestyle is about simply messing around with more flash and catching air (jumping). Trials bikes generally do not have suspension, freestyle bikes often do. At a competitive level, freestyle is wild and woolly. The action is fast and furious, with lots of air and spills.

- Downhill Mountain Bike (Fig. 4.24): Downhill mountain bikes axe made to do just one thing: blast along as fast as possible. Deep travel, dual suspension is a requirement, and as suspension systems become better and speeds rise ever higher, the bikes are becoming bulkier and stronger. A full on downhill racer with a bomb proof frame and massive 3-inch wide tires resembles a motorcycle more than a bicycle. It's so heavy that no one ever thinks about pedalling one of these *up* a mountain. Fast downhill riding and racing is wildly exciting, but the latest advances in suspension systems are pushing speeds to extreme levels.

Like rock climbing and sky diving, downhill bike racing is a sport that should be approached with respect.

- Touring Mountain Bike: A touring mountain bike is similar to a road-touring bike, but has 26-inch rather than 700C wheels, and flat instead of drop bars. Otherwise the concept is the same: wide range gears, powerful brakes, pannier racks front and rear, and an abundance of water bottle mounts and other accoutrements for comfortable long distance travelling.

Figure 4.23 Classic

Figure 4.24 Downhill: fast

(Ballantine 2001: 38, 39)

### 4.1.5. Elements of a Bicycle

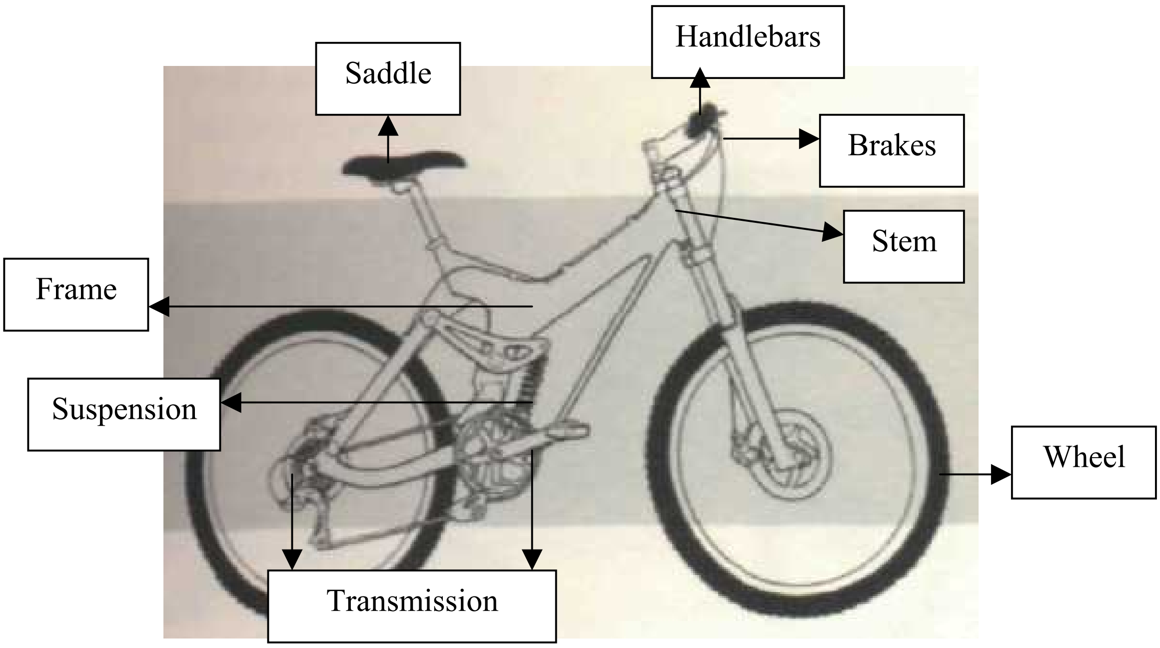



Figure 4.25 Downhill mountain bike (Ballantine 2001: 39)

A bike consists of the:

- frame;
- suspension (optional);
- wheels (hubs, spokes, rims, tires);
- transmission (pedals, chainset, gear changers, chain, freewheel);
- brakes;
- handlebars, stem and saddle (Fig. 25).

Some bicycle manufacturers make their own frames (brand names like Trek. Giant, Fisher, Cannondale, etc.), others buy them from outside builders, and many do both. Frames vary in quality from crude to ultra-fine, and are produced by firms that range from lone builders through to huge factories.

The components of the bicycle are known as the *specification.* Components are supplied by specialist companies, in various designs and quality grades. Some firms produce specific components such as rims or brakes: others produce *group sets* containing the components of a complete specification. Group sets are identified by a name or model number, as in Campagnolo Chorus or Shimano 105, and are ranked by design and quality, or cost. Sources of components are diverse, but volume sales to bike manufacturers are dominated by the Japanese firm Shimano (Ballantine 2001: 44).

### 4.1.5.1. Frame

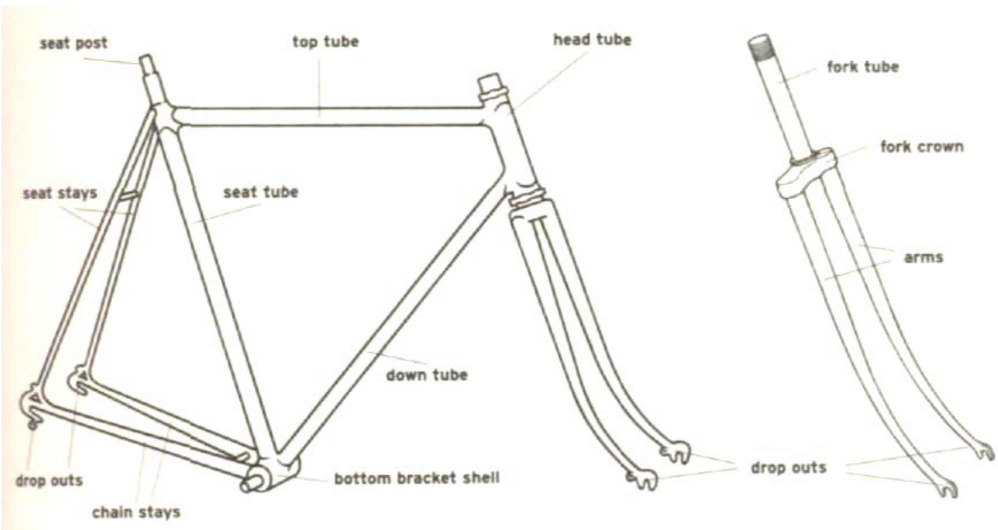



Figure 4.26 Diamond frame

The frame, separately shown in Fig. 26, is the heart and soul of a bicycle. It translates pedal effort into forward motion, guides the wheels in the direction selected, and helps to absorb the road shock. How well the frame does these various jobs is determined by the materials from which it is built, the design, and the method of construction. There is no way to work around or upgrade a cheap frame. Components such as wheels are easily changed, but the frame endures and should be the first focus of attention when considering a bike.

Weight in a bike is pretty well everything, and the most fundamental factor in this department is the frame. The better the frame, the lighter the weight for the same or even greater strength. Related to this are two qualities. The first is resiliency, twang, or flex, which gives better bikes springiness and vitality. This is inherent in the materials from which the bike is made, and is exactly the dynamic difference between heavy, unyielding cast iron and light, flexible tempered steel. The second quality is stiffness, which is related to materials and geometry as well as weight. In a nutshell, a frame with too little stiffness will bend and twist too much, and a frame that is too stiff will not have enough give for comfort. Strength shouldn't be confused with stiffness: a frame made of heavy, weak tubing can be stiff, and a frame made of light, very stiff tubing can be weak. Essentially, frame design consists of trying to strike the best balance between strength, stiffness, and weight (Ballantine 2001: 39).

#### 4.1.5.2. Wheels

After the frame, the wheels - tires, rims, spokes, and hubs - are the most important components of a bike. The frame is the vitality, the wheels the point of translation into motion. Their effect on performance and comfort is enormous. Once completed, a bike frame is unlikely to go back to the torch or glue pot for changes and modifications. Wheels, however, are easily altered, and offer a range of options regarding performance, durability, and suitability for different conditions.

A traditional metal-spoked bicycle wheel is one of the strongest engineering structures in existence. The spokes are in tension rather than compression - the weight of the bike hangs from the spokes rather than stands on them - and this is why a well-built wheel can support a rolling weight of up to a ton or more. Wheels are made to be as light as possible because weight has a greater effect on a wheel than anywhere else on a bike.

To appreciate the truth of the old saying, "an ounce off the wheels is worth a pound off the frame," hold a bicycle wheel by the axle ends and move it around in the air, and then do so again while spinning the wheel. The faster the rotation, the greater the "weight," or inertia, and the harder it is to move the wheel into a new plane of rotation. Bicycle wheels are built with spokes and rims to keep weight to the minimum and thereby reduce both the force of gyroscopic inertia, and energy required for acceleration or braking.

Another force that operates on wheels is aerodynamic drag. At speed, ordinary spokes churn the air like an eggbeater and disrupt its flow. This is of little consequence for everyday riding, but is significant when racing. Deep rim spoked, molded one piece, and disc wheel designs all increase the surface area of the wheel to smooth the flow of air and improve aerodynamic efficiency, at some cost in weight.

Wheels operate on a simple spectrum: light wheels are quicker and more fragile; heavier wheels are slower and more durable. The type of bike, rider, and conditions determine the balance of priorities. Wheels for racing on smoothly surfaced roads are lighter and slimmer than wheels for touring with heavy loads on dirt tracks.

A wheel is a package where the components -tire, rim, spokes, and hub - tend to follow suit in weight and quality. Stout tires, wide rims, and thick spokes go with touring and mountain bikes. Light tires, narrow rims, and slender spokes go with road racing bikes. Generally, heavier wheels are better able to cope with bumps, potholes, and rough surfaces. Much depends on the rider. "Comfortable" for a beginner usually means a wheel stable enough to not skitter at the sight of a pebble. An experienced cyclist, however, is likely to be happier with a lighter, more responsive wheel (Ballantine 2001: 61-63).

### 4.2. Bicycle Design: Frame Design

Designing a bicycle frame looks like designing clothes in the means of fitting of designs (bicycles or clothes) on humans body. As the tailor designs clothes for a person, there are bicycle designers like tailors that design bicycles specialized for a person. On the other hand, in the means of ready-made clothing industry, there are bicycle designers and manufacturers that design and produce for the bicycle industry. They design and/or buy standard components for building the bicycles. As this study is concerned with industrial product design, it is more included in the second area; however, the designer should have an idea of both of these areas in order to improve him/herself in designing bicycles.

Designing a frame carries two important complementaries that are: geometric parameters and materials. As a general rule in bicycle design, where the performance of the bicycle increases, the comfort of the bicycle decreases. Therefore, the frames of race bikes are designed through the geometric parameters and materials in a way that they are fast and light, but uncomfortable. On the other hand; in roadster, style, and city bikes, comfort becomes more important than the performance that their geometric parameters and materials differ from the race bikes.

### 4.2.1. Geometric Parameters

The design or geometry of a bicycle frame with an upright riding position varies according to its intended purpose and the type and weight of rider. The two fundamental types of bikes are road and off-road, and within each category there is a similar basic choice: going quickly and responsively, or more slowly and evenly. Generally, performance bikes have quick pedal response and handling, while bikes made for general riding are more stable.

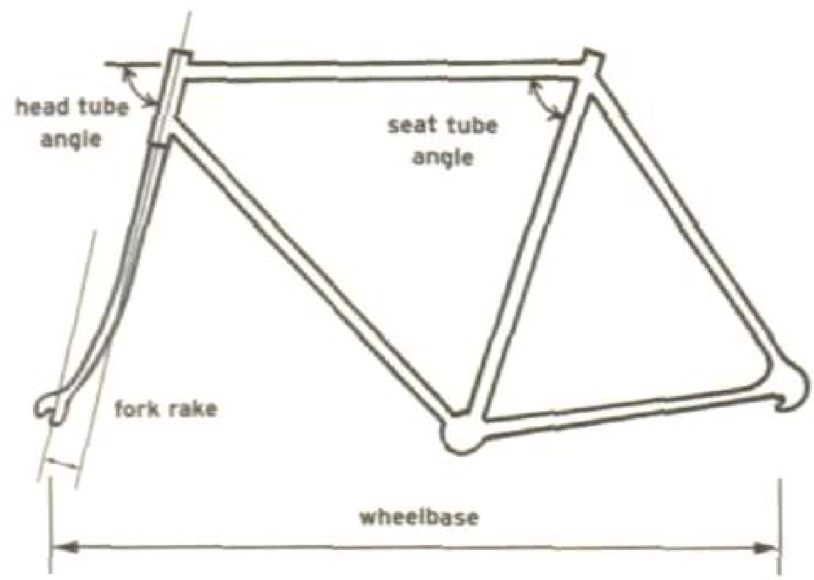



Figure 4.27 Geometric Parameters

The first crude indication of a bike's character is the wheelbase (Fig. 4.27), the distance between the wheel axles. On road bikes this ranges from 38.5 inches for racing models to around 42 inches for touring models. On mountain bikes the range is from around 41 inches to 45 inches. Wheelbase is an additive function of the relative angles at which the frame tubes are joined, and their length. Tightly built, short wheelbase frames are often described as "stiff," and long wheelbase frames as "soft." These terms give the misleading impression that tight frames have a harsh ride compared to relaxed frames. In fact, wheelbase makes only a slight difference to ride comfort, more important are the type of wheels and tires. Frame design variations are for performance characteristics, degree of stability, and room for mounting panniers.

The design and character of a bike is often described as a function of the angles to horizontal formed by the head and seat tubes (Fig. 4.27). While it is broadly true that a classic "soft" touring bike might be 72° parallel, and a more responsive "stiff" racing bike might be 74° parallel, frame angles depend on the length of the frame tubes and not the other way round. For example, women generally have less reach than men, and short women in particular have limited reach. A correctly proportioned frame will have a top tube of a length that requires steepening the seat tube angle to 75° or even 76°. Despite having a supposedly "stiff" geometry, such a bike will be comfortable to ride (Fig. 4.28).

| **Seat Tube Angle** | **Rider Position** | **Recommended Uses** |
|---|---|---|
| Shallow (< 73.0 º) | Relaxed | Road race, century, ultra |
| Normal (73.0º-74.0) | Neutral | Road race, criterium |
| Steep (74.0º-75.0º) | Aggressive | Criterium, time trial, triathlon |
| Extra steep (>75.0º) | Aerodynamic-aggressive | Time trial, triathlon |

Figure 4.28 Seat tube angle’s affects

The stiffness of a frame in a vertical (up and down) plane has little if anything to do with the seat tube angle. Even a very whippy frame with a lot of torsional (twist) and lateral (side to side) movement, will have very little vertical compliance. It's a structural thing, seen everywhere in large four-sided farm gates with a single diagonal cross brace.

The gate may rock, and sway in the breeze, but so long as the cross brace is adequate, the up and down position won't change. On a bike, in a vertical plane, the forks move but the rest of the frame pretty much stays put. Vertical compliance of a frame is a function of height and length, or wheelbase. A longer or shorter wheelbase does make a difference, but only a very small one (Ballantine 2001: 50, 51).

The important point is that position on a bike is a function of saddle and handlebar position. This provides the question: why the diamond frame?

#### 4.2.1.1. The Diamond Frame

The diamond pattern frame with a level top tube evolved over 100 years ago and is a perfect design for road bikes and the kinds of alloy steels used through the 1970s. This combination of steel tube and diamond frame has proved to be very enduring that it gives anyone setting out to design a better (rigid safety bike) a bit of problem. For it makes the situation different from that of many other mechanical devices –cars, food-mixers and the like- where there are numerous design variations and opportunities for improvement. "With the bicycle there is one absolute and totally defined shape handed down by generations of frame-builders. And not only the shape, but also the size of the tubes, has been institutionalized (Burrows 2000: 55)".

A profound economic advantage of a dropped top tube is that to fit different riders it is no longer necessary to make frames in a range of perhaps ten or more different sizes. Small, medium, and large will cover the lot. Precision fit for individual riders is achieved through different size seat posts and stems. In a mass-production bike, this is a huge economy, not just for the manufacturer, but also for the stores, which only have to stock three sizes instead of ten or more, with lower retail prices (Ballantine 2001: 53).

#### 4.2.1.2. Alternatives: the Moulton, the Burrows Monocoque and the New Trends

Although the 1890s manufacturers such as Thomas Humber had clearly got the frame right (diamond frame), there have been many designers trying to change it. Two of these alternatives deserve to be mentioned here, as being successful.

The Moulton: Figure 4.29 shows Alex Moulton's small-wheel/suspension approach, using (firstly) monolithic cruciform and (later) multi-tube geodesic frame construction. Many subsequent small-wheel designs stem from Moulton's 1960 original. It is, if not a better bicycle, at least a viable alternative offering some real advantages over the traditional format (Burrows 2000: 56).

Figure 4.29 The Moulton (Burrows 2000: 56)

The Burrows Monocoque: The other and most recent alternative is Mike Burrows's moulded monocoque racing design, shown in Figure 4.30. It is again not a better bike, but offering the racing cyclist at least some advantage over 'iron sticks' Figure 4.30 Burrow's Monocoque (Burrows 2000: 57).


Figure 4.30 The Burrows Monocoque -1 (Burrows 2000: 76).

The New Trends: Many designers try to change the 130 years old diamond structure. Recognition of the new materials makes them dream wide (beyond iron sticks), as shown in Figure 4.31. These examples need to be solved with rational – engineering - knowledge, since they seem to be easily broken and destroyed with only stylish thinking.


Figure 4.31 Stylish design of bicycles

### 4.2.2. Materials

Once the geometry parameters are determined, it is time for deciding on the materials. Nowadays, high performance racing bicycles constructed of steel and aluminum as well as more sophisticated materials such as carbon fiber and titanium are all widely available. Moreover, the aerospace-derived titanium and carbon fiber are not as astronomically priced as they once were.

<u>• Steel</u>

Steel is the most versatile material and can be drawn, machined, shaped, and alloyed with other metals to accommodate a wide variety of strength and performance requirements. The result is an impressive array of strong, comfortable, excellent handling, and inexpensive frames built of steel alloys. The one drawback to steel is that it is much heavier than newer materials.

• Aluminum

Aluminum is a popular material because it is extremely lightweight, produces strong tubing and framesets, and yet is remarkably inexpensive. Aluminum's major disadvantage is that it lacks the durability or damage and fatigue resistance of either steel or titanium.

• Titanium

Titanium is as strong as steel at half the weight, and free from corrosion and fatigue. Fabricating titanium is difficult, and the cost of tooling (making machines to work it) is high, which makes titanium frames expensive. Still, they are truly beautiful, and regarded by many as the ultimate.

• Metal Matrix Composites

Metal matrix composites (MMC) are metals with the addition of small, hard particles. This mixture has improved strength and fatigue resistance, but weld quality goes down, and the material is difficult to machine or work into various forms, such as tubes. Basically, it is more suitable for components than for frames.

• Magnesium

Very, very light, but the stuff is better for parts than frames. Magnesium works best in bulky shapes, and not very well in fine, drawn out shapes.

• Plastic

It should be possible to build nice bicycles with injection molded plastics such as nylon, but major research is needed to understand what bicycle designs will work in plastics. The first successful plastic bicycle will probably be a recumbent design, as this configuration is more sympathetic to the use of new materials.

• Carbon Fiber

Carbon fiber is the lightest of all frame materials. Since it can be layered and reinforced, it produces some of the stiffest and strongest frames available. Additionally, it can be molded and sculpted into aerodynamic forms without sacrificing strength, making it a top choice of triathletes. Carbon fiber's one disadvantage is that in the event of cracking or damage the frame is not repairable and must be replaced. Also, a poor quality carbon fiber frame may be brittle and lack the shock absorption of top quality carbon fiber frames.

In mass-production, frames for cheap bikes are made with heavy, inert mild steel; for entry level, basic quality bikes, much better hi-ten steel is used; for midrange bikes, cromo and other lightweight alloy steels are used; and for top-range bikes, aluminum or composites. Fine alloy steels, aluminum; titanium, and composites such as carbon fiber and aramid are used for hand built frames. With modern materials, a dropped or sloping top tube is practical even for racing bikes and, since it has many advantages, will soon be standard. The future for frames, whether for crafting exotic racing machines or mass-producing inexpensive, is in composite materials and one-piece monocoque designs.

**4.2.2.1. Composite Materials**

Steel and aluminum as frame materials work best in tubular form. Both metals are isotropic, equally strong in all directions. However, the new cutting edge in frame materials, composites, are anisotropic - i.e., composed of fibers strong in specific directions - and the builder can decide which way they go. This means a radical change in design approach.

Composites consist of fibers bound by glue or resin, or by a substance such as nylon. The most common type for bikes is carbon fiber, which in pure form is as strong as the finest steel, never fatigues, and yet is only two-thirds the weight of aluminum. Carbon fiber is somewhat brittle, so frames and components made in this material are overbuilt by a generous margin. They are nonetheless still ultra lightweight, yet can withstand more abuse than steel. Frames are also produced in aramid, the material for bulletproof shields and armor and better known by the trade name Kevlar™. Aramid is not as strong as carbon fiber, but is much tougher.

A number of manufacturers produce traditional tubular design frames in composite materials. The tubes are glued together via lugs, made either from cast aluminum alloy or molded carbon. Because a material such as carbon fiber is so light and strong, it has considerable advantages even when shaped into tubing. Replicating the form of a metal bicycle, however, is not the best way to use composites.

One big asset of composites is the ease with which they can be worked and shaped into various forms. This allows strength, flexibility, and other characteristics to be placed and added precisely where required. The most efficient configuration for composites is monocoque, the entire frame as a single piece, with the means to hold the wheels, cranks, forks, saddle, and everything else in one cohesive unit. Monocoque means that chassis and body, or skin, are one; more than a few of the slick-looking frames currently labeled as monocoques are in fact glued together assemblies of bits and pieces.

#### 4.2.2.2. Monocoque Designs

Monocoque designs (Fig. 4.32) are aerodynamic, light and strong, look great, and are fun to ride. The frame has a decided shape and form, and the large surface areas open up almost limitless graphic and decorative possibilities. There are monocoques just as beautiful as the finest paintings. They are easy to enjoy: while a regular bike has a lot of nooks and crannies and can be a bit of chore to keep clean, a few swipes with a rag and a monocoque is shining.

Monocoque designs are limited to racing and very high-end bikes. Yet composite materials and monocoque construction hold enormous potential for producing not just competition machines with precise performance characteristics, but also a range of general use and utility bikes of better quality and design at lower cost. Realizing this potential, however, is nothing like as easy as rolling off a log. Volume production in composites requires a huge investment and, up until now, few if any bike designers have created monocoques that are much more than aerodynamic, fast, and good looking. There's still a lot of expensive, computer aided design research and development to be done, and as well, considerable production engineering to, work out the best manufacturing techniques. Then, too, currently available components are designed for stick bikes: monocoque designs have different needs.

Figure 4.32 The Burrows Monocoque –2 (Burrows 2000: 57).

Somebody can design something that looks very pretty, having some sense of how and where to build for strength and flex and so on, but even he/she is a leading bike designer, from a technical point of view the final product is likely to lag behind a well-crafted frame in steel or aluminum. The reason is so little about monocoque construction for bicycles is known, but there is a rich fund of experience of building with tubes.

Composite materials are already well established and monocoque designs, with greater aerodynamic efficiency, are faster than traditional stick design bicycles. As builders learn more about composites, particularly in volume production, monocoque bikes will become increasingly commonplace. It can't happen too soon. For example, using monocoque construction it is feasible to create a bicycle with everything but the pedals and the wheels completely self-contained and sealed. No external lights, cables, brakes, gears, or chain. All the mechanical bits run in constant lubrication protected from dirt and will last almost forever.

### 4.2.3. Engineering and Industrial Design of Bicycles

The bicycle can be accepted as one of the finest examples of engineering design of all the time. It uses so little in the form of material or resources to produce; yet it does so much so efficiently with cheap healthy transport, enjoyable leisure, exciting sport and no harmful side effects.

#### 4.2.3.1. Positioning Bicycles according to Industrial Design and Engineering Priorities

Product range of industrial design and engineering design, and their weighing in products are shown in Figure 4.33. According to this figure, and the given examples in the figure, bicycles can be positioned in the middle. However, as bicycle has been accepted as a mature design for along time, the basic design that the Humber carries did not change until 1970s. The incredible variety related to demands, creates a broad design area today, in the means of both engineering and industrial design.

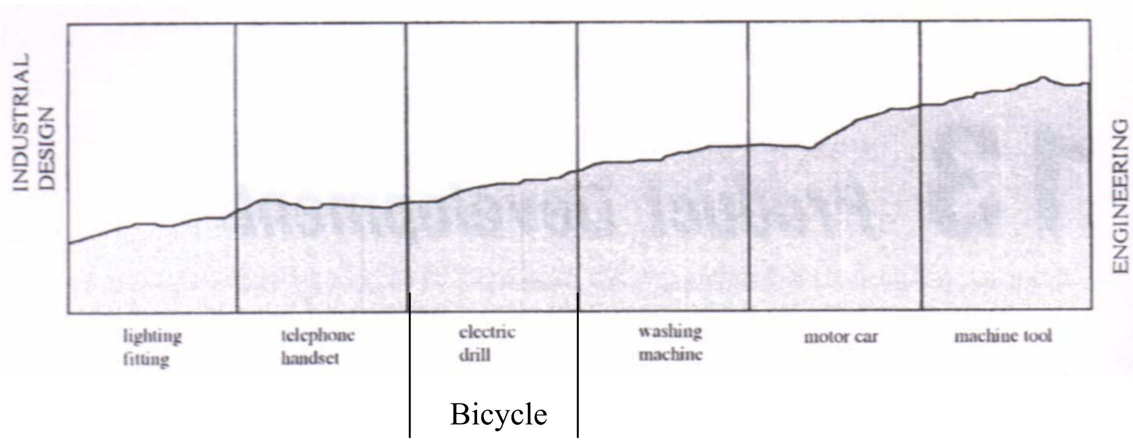



Figure 4.33 Position of bicycles in the product range
(Figure at top is from Cross 2000: 198)

The industrial designer acts through concepts of quality, quantity, identity and method that, he/she determines the qualities (materials, construction, mechanism, shape, color, surface finishes and decoration) of objects, which are reproduced in quantity by industrial methods, and their relationship to people and the environment. In doing so, he/she deals with a lot of criteria (that were mentioned in Chapter 2):

- Functional Criteria
    - Physiological Criteria
    - Environmental Criteria
    - Communicational Criteria

- Psychological Criteria
    - Perceptional Criteria
    - Socio-Cultural Criteria
    - Sensitive Quality (Criteria)
    - Explanatorily Criteria

- Technological Criteria
    - Material Criteria
    - Production Criteria

- Economical Criteria
    - At the Consumers' Level
    - At the Producers' Level
    - At Macro-Level

The bicycle provides an example of technology, which applies to many different areas of science. The basic principles of physics, mechanical engineering, materials, and design are all included in determining how a bicycle is built. In addition human physiology, physical education, and kinesiology [study of the principles of mechanics and anatomy in relation to human movement (Merriam-Webster Authority & Innovation 2000: Version 2,5)] are also represented in the basic way that bicycles are designed. Even psychology becomes important in acceptance of a design. For example, mountain bikes are the primary type of the bike sold in the United States, even in Kansas and Nebraska, which haven't seen any mountains for a few million years. As we look at bicycles from different countries and see how their designs differ, we see how science and technology evolve within the local cultural context. In addition to the content of science, technology and culture the bicycle also offers a way to teach various types of skills related to science and technology. The process of science can be developed by trying to understand why these designs are preferred. This process can develop problem solving skills, the process of science skills, and an understanding of the design process of engineers.

#### 4.2.3.2. Frame as an Engineered Structure

From the standpoint of structural engineering, the most important component of a bicycle is the frame. It is also the most interesting component with regard to materials engineering. To consider frames properly, it is necessary to know how to analyze stress and deformation in a loaded structural member of a bicycle and then to see how the stresses can be accommodated by intelligent choices of frame geometry, materials, and joining methods.

The evolution of frame design has led to the so-called diamond frame, shown in detail in Figure 4.34.

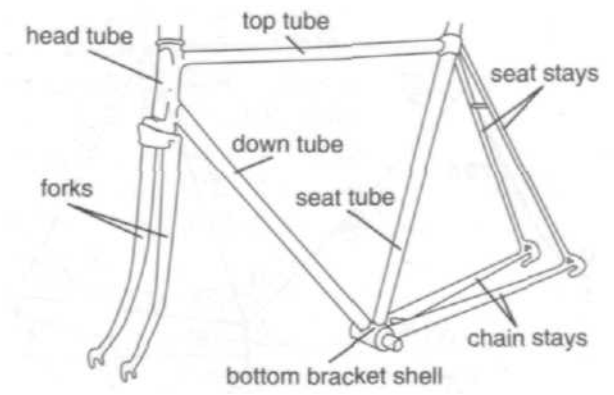



Figure 4.34 The complete frame of a conventional diamond-frame bicycle

Stresses in the various parts of such a frame due to the static weight of a rider can be estimated fairly easily, and they turn out to be rather small. However, stresses arising from some dynamic loads can be much larger and must be given serious attention. The important kinds of loading are indicated schematically in Figure 4.35.

The potentially large loads depicted in Fig. 4.35 can cause permanent deformation, or even catastrophic fracture, of the bicycle, or they can lead to fatigue cocking. In addition, the response of the frame to vertical forces from a bumpy road (Fig. 4.35.a) affects riding comfort. A frame that distorts elastically by a relatively large amount (for a given set of forces) is said to be more compliant than one that distorts less. The more compliant the frame, the more comfortable the bicycle is to ride. However, this kind of flexing wastes energy, because the work done by the rider in distorting the frame is not used in forward propulsion. For this reason, a racer opts for a frame that is elasticity stiff, rather than compliant.

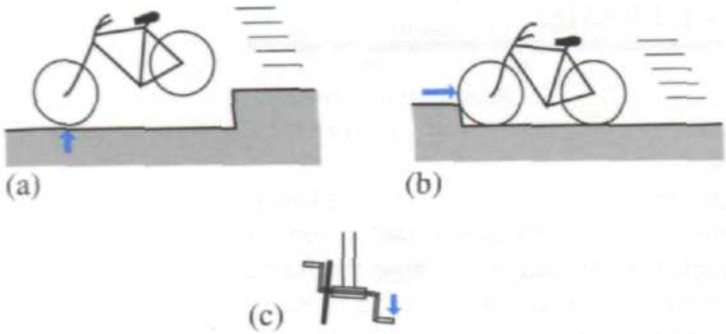



Figure 4.35: Schematic representation of the types of loading that must be withstood by a bicycle as a result of: (a) a vertical drop after passing over a large bump, (b) an impact from a frontal barrier, and (c) the force of pedaling by a strong rider, e.g., when climbing a steep hill.

### *Forces in a Bicycle Frame; Basic Definitions and Rules*

The analysis of forces employed here will be fairly elementary but require some explanation of the methods of engineering static, which involves the applications of Newton's laws to bodies at rest. That is, only the equilibrium of a stationary bicycle in response to the applied forces will be considered; dynamics of the moving bicycle will not be treated here. To begin, only the forces that act in the plane of the frame will be considered; later the important out-of-plane forces due to the pedaling action and to the off-center pull chain on the rear wheel spindle will be examined briefly. To make an approximate analysis of the forces on the members of a frame, a typical version of a touring bicycle has been selected. The basic geometry is as shown in Figure 4.36.

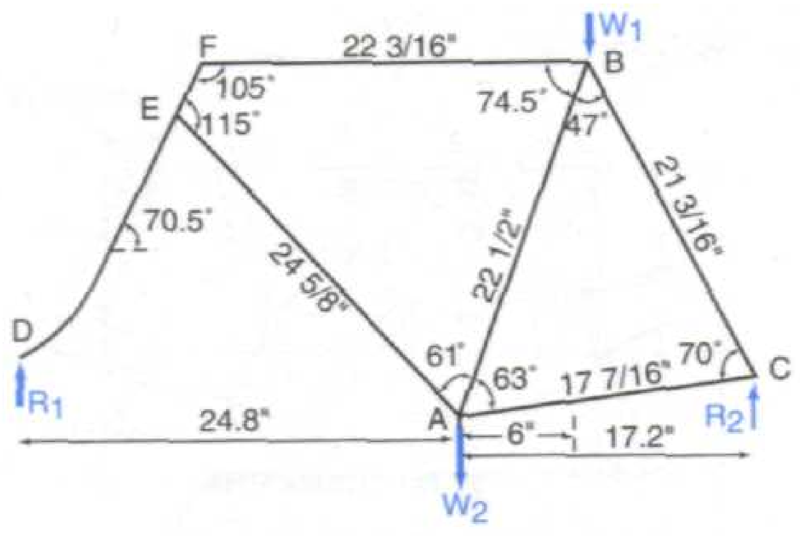



Figure 4.36: A model of the frame of a common touring bicycle frame, showing the downward caused by a rider on the seat, $W_1$, and pedals, $W_2$, and the upward (reaction) forces transmitted wheel axles, $R_1$ and $R_2$.

Before the forces in this frame can be analyzed, one must first know simple rules of static's:

**1.** A force is a quantity that has both direction and magnitude; therefore, it is a vector quantity. By use of a system of rectangular (i.e., x, y) coordinates, a force vector can be resolved into two components, each of along one of the coordinate axes.

**2.** Newton deduced that any force on a body at rest must be opposed by an equal and opposite force. That is, there can be no net force on a body at rest. The presence of a net force would cause a body to be accelerated, according to the famous Newtonian law: $F = ma$, or force equals mass times acceleration. This law is applied to the pinned joints on the bicycle frame, resolving forces applied at the joints into $x$ and y components and setting the sums of the vertical and horizontal components equal to zero.

**3.** This law of Newton applies not only to transnational motion, i.e., motion of a body from one place to another, but also to rotational motion of the body about some axis. Thus, Newton's law states that, for a body at rest, there must be no net moment. That is, the sum of all moments must be zero.

#### 4.2.3.3. What is a Good Bike?

With a good bike, design materials, and construction are well balanced and suit the intended purpose and cost of the machine. An ultralight, aerodynamic time trial bike made for the Tour de France and built with advanced composite materials, and a crude cargo bike made for hauling bananas to market in Nicaragua and built with crude mild steel, can both be good machines. In the Tour de France, the stakes are high and scores of consultants, designers, scientists, and technicians from several companies may work together on creating a bike especially for the event. High cost is axiomatic. In Nicaragua, the average yearly income is less than many people in America earn in a week, and the typical bike building resource is one person equipped with a hacksaw and a simple gas welder. Low, low cost is essential. For the Tour contender, exotic design, space age materials, and high tech construction; for the banana carrier, a simple design, easily worked mild steel, and rudimentary joinery.

A good bike is honest. It does the job it sets out to do, makes efficient use of materials, and stands up. In Nicaragua, most of the rural bike builders have a pretty fair idea of what they are doing. They have to. The bikes they build to earn their bacon must work well and be reliable, or else the builder goes hungry. Similarly, high tech racing bikes must deliver performance; excuses do not win races.

Figure 4.37 Modern day cruiser: Silver Bullet by Sparta (Burrows 2000: 79)

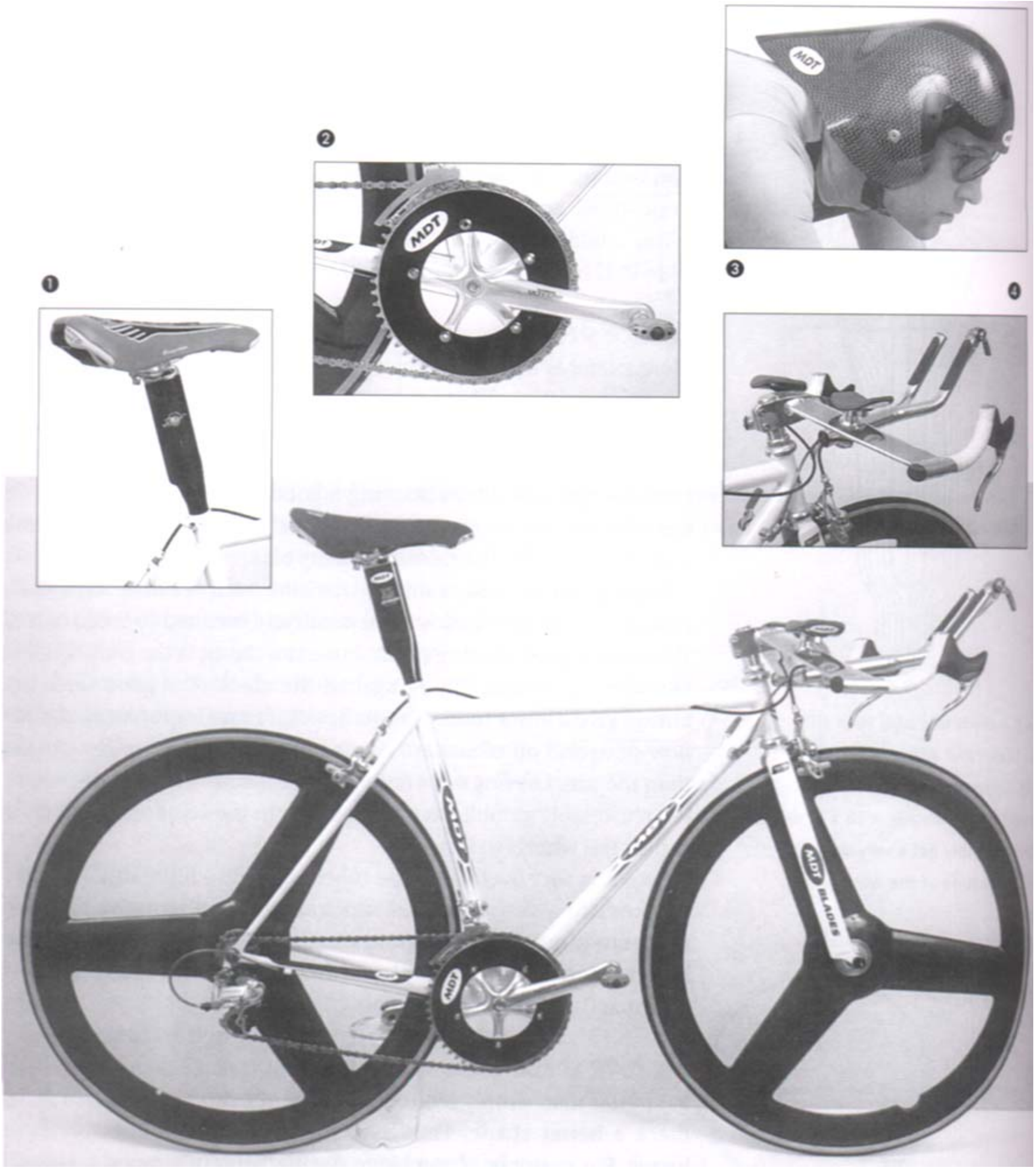



Figure 4.38 Aero-race bike (Burrows 2000: 72)

| Design features of Figure 4.37 | Design features of Figure 4.38 |
| --- | --- |
| Stylish | Race |
| Fashionable | Aerodynamic |
| Comfort | Performance |
| Heavy | Light |

## Chapter 5

## CONCLUSION

Today, industrial product design has become one of the most important strategic elements of competitive advantage in industrial context, because of the increase in “designed” demand of objects and the requirement of teamwork in designing complex objects of the new world.

Since industrial product design deals with a lot of criteria, like physiological, environmental, communicational and technological criteria, borrows concepts and methods from other disciplines, and the industrial designer behaves like the team synthesist between other professions such as engineers, sociologists, marketers etc. in order to determine the formal qualities of objects produced by industry. Unless being in a design team, the industrial designer still acts through concepts of quality, quantity, identity and method that, it determines the qualities (materials, construction, mechanism, shape, color, surface finishes and decoration) of objects, which are reproduced in quantity by industrial methods, and their relationship to people and the environment.

Industrial product design field, because of dealing with a lot of criteria, considered by some authors as an interdisciplinary activity in research context. However, as industrial product design field can be stretched to other fields easily, and other fields can be welcomed in the field easily, interdisciplinary approach causes conflicts in developing industrial product design knowledge. Referring to Cross, industrial product design should be taken as a field of design discipline that accumulates and develops its own design knowledge. With this approach, industrial product design might create and strengthen its place among other trespassing fields and disciplines.

Designing is a multidisciplinary activity with the participation of disciplines such as design, engineering, sciences, and humanities acting toward the same purpose. Industrial product design borrows concepts and criteria from other disciplines throughout this activity. Engineering, as the subject of this study, is one of the most important features of industrial product design in the means of bringing design to an end product that is sold in the market. Industrial product design intersects with engineering criteria, given below, and deals with engineering professions related to these criteria throughout the design activity.

The intersecting criteria of engineering and industrial design in a product are:

- Functional Criteria
    - Physiological Criteria
    - Environmental Criteria
- Technological Criteria
    - Material Criteria
    - Production Criteria
- Economical Criteria
    - At the Producers' Level
    - At Macro-Level

By revealing these criteria and comparing industrial product design with related engineering professions, human-centered aspect and synthesis approach of industrial product design, and on the contrast, material-centered aspect and analysis-synthesis approach of engineering design, which is the chosen engineering field as being close to industrial product design field, are indicated.

Synthesis of experience and analysis of materials and forces of the nature in engineering discipline causes the engineer act like an artist (designer) as well as a scientist in the expansion of the engineering knowledge. In these means, engineering design field, where engineering and scientific knowledge is applied to products, processes, systems, and etc., uses some design methods, techniques, or procedures. Scientific methods and design methods are not different at the most immediate level, which is revealed in the last part of Chapter 3. Industrial designer, who provides from these intuitive and non-intuitive methods in the means of scientific design ["Scientific Design refers to modern, industrialized design –as distinct from pre-industrial, craft-oriented design- based on scientific knowledge but utilizing a mix of both intuitive and non-intuitive design methods (Cross 2000: 44)”], and combining these with his/her own abilities of:

- Creativity and intuition
- Recognition that problems and solutions in design are closely interwoven
- The need to use sketches, drawings, or models of various kinds as a way to explore the problem and solution together; becomes successful.

“From studies of a number of industrial and engineering designers, Fricke (1996) found that designers following a ‘flexible-methodical procedure’ tended to produce good solutions (Cross 2000: 27)”. These designers worked reasonably efficiently and followed fairly logical procedure, whether or not they had been educated in a systematic approach. In comparison, designers either with a too-rigid adherence to a systematic procedure (behaving ‘un-reasonably’ methodically), or with very unsystematic approaches, produced mediocre or poor design solutions.

In this study,

**1.** Non-intuitive and intuitive concepts and methods used in industrial product design field is searched for in order to try to put a milestone in developing industrial product design knowledge in design discipline

**2.** The advantages of providing from non-intuitive methods are revealed.

**3.** Intersecting criteria between industrial product design and engineering fields, as an advantage of these professions both in industrial and educational contexts are given.

**4.** Approaches of scientists, engineers and designers to the design problems, as another advantage of observing the artifacts in order to design, are given.

**5.** Focusing on products, the engineering and the design criteria are revealed in the bicycle examples, as a case of this study. Change in design priorities are indicated on different types of products, using the advantage of variety in bicycles.

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