

SYSTEMS AND INDUSTRIAL ENGINEERING SERIES



Applied Mechanical Design

Ammar Grous

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Preface

This book is designed for students in specialized schools and in science and technology universities, and also for professionals in the industrial sector. Its content is based on case studies with given solutions, which are targeted and discussed. This content is drawn from the author's own classes in applied mechanical design. It gives an overview of all the necessary elements of knowledge, and the methods for analyzing and selecting materials. The book is written as a didactic tool to guide readers in their approach to design, making heavy reference to industry.

The construction of the book is founded primarily on intuition where Arts and Industry are concerned. University courses in Technology offer solutions to the problems arising in design, but do not always present an exhaustive list of the numerous steps that need to be followed at the implementation stage. Sometimes, solutions put forward in mechanical design refer to diagrams without saying anything of the “how”, the “why” or the “where”... The thought process surrounding design is far more subtle, much deeper and, in many respects, considerably more complex than it might, at first glance, appear to be. The approach to design must begin with concise methods which enable us to:

- clearly set out the problem (or problems) at hand;
- compare succinct analytical solutions;
- make informed, and duly documented, choices and selections.

In this book, we examine a protocol which qualifies and quantifies the requirements, beginning with a clearly written set of Functional Specifications (FS). The methods and analyses herein aim to satisfy the expressed need.

In particular, it is absolutely crucial to have, at our disposal, mathematical and physical tools to calculate the mechanical resistance of materials. Knowledge of how

materials behave is fundamentally important to enlightened design; in other words, the results of calculations, even fairly accurate, constitute simple pedagogical mathematical exercises which have no bearing on the final decision taken on a project. The case studies presented here are the result of the author's research and targeted work in mechanical design. They are taken directly from the author's teaching materials which have, in turn, given rise to manuals and a wide range of publications, including manufacturer catalogs on an international scale.

At the end of the book, readers will find case studies which have previously been discussed in the author's classes, with a view to finding solutions. They are invited to make use of these materials for an appropriate illuminating study, in keeping with the workshop tools and lab tools available to them. In applied mechanical design, there is no single solution, but instead a range of possible solutions in view of the means and methods being used.

Ammar GROUS
December 2017

Introduction

In design, modeling is an indispensable step. In the preliminary stages of a design project, it is essential to make sketches (outlines), and combine these with a rough graphic-analytical model. When the preliminary sketches appear viable, we move on to other factors of progressive design. The principles of the calculations include combinations of properties to find the best possible performances that the project can deliver. The mathematical model is founded on exact values of the stresses at work, and of the strains undergone by the components, bounded by the operational limitations. In this book, we present concrete examples with different geometrical properties, under stress from a variety of types of loading. Beams, bars, discs and cylinders (to mention only a few classic forms) already have working hypotheses concerning their use, set out in specialized publications. It is wise to draw upon this pre-existing body of work in putting together real-world projects. The important thing is to be aware that the information is out there, and that judicious use can be made of it. The formulae presented herein are taken from the specialist literature, cited in the bibliographies at the end of each chapter. The tables, standards, formulae and other are presented here as an illustrative guide. Under no circumstances should this book be thought of as exhaustive; readers must refer, for more detailed information, to the aforementioned specialized publications.

Historically, the design of products such as mechanisms and machines has been at the heart of engineering sciences and techniques. The development of computer tools and computer-aided design (CAD) has greatly contributed, with the help of the standards brought into force, to better presentation of the graphical results of sketches of definitions and products. Optimization methods, new workflow schemes and mathematical tools employed in mechanical construction can easily be used by project designers. On the basis of a clear set of technical specifications, the designer can achieve their objectives in the shortest possible time and with the lowest possible material cost. A clearly presented preliminary project is a good guarantee for the production of a safe, well-documented design.

There is no reproducible, prefabricated “recipe” for a good design of mechanical systems. Instead, there are step-by-step, incremental methods which are optimized to deliver the desired results. The current book is founded on experience both in industry and in teaching. It discusses indispensable tools which orientate and guide designers in their search for solutions. It uses a skill-based pedagogical approach, and thus presents the target vectors, including:

1) *Methodology*: Readers of this book will follow the steps, from needs analysis to the hunt for mutually acceptable solutions (agreed between the client and the designer), right through to the presentation of the documented preliminaries for the project. Technical specifications, creative design methods (including FAST: Function Analysis System Technique), Gantt charts and FMECA (Failure Modes, Effects and Criticality Analysis) are used here.

2) *Principles behind the calculations*: The elements of analysis and calculations traditionally employed in construction are the preserve of the mathematical and applied physics tools. The novel aspect of this book is that it brings in a clearly documented pedagogical approach. The analytical approach follows the principles of the calculations. The materials and processes, which are subjects close to mechanical systems, are clearly documented.

3) *Graphical-analytical tools*: The graphical and/or analytical methods discussed herein are used in such a way that engineers, technicians and students can, themselves, use them or draw inspiration from them for their own projects. Logically, the fundamentals of computer-assisted design are examined using the software tools recommended in the industry.

4) *Pedagogical and industrial case studies*: The solved examples given here are taken from the author’s own experience in industry and in a university setting. These examples cover a wide range of fields in manufacturing industry (recreational equipment, lifting devices and forms of transport, pedagogical demonstrative mechanisms, etc.). The studies also look at how to make the right choice of materials and structures for the projects at hand.

This book, which is devoted to applied mechanical design, draws on case studies taken from the author’s own experience in the professional and university spheres. It is based on a methodology and pedagogical approach which are deliberately painstaking, because they are being used instead of pure mathematics and applied physics to present the subject. It is an arduous task to present a mechanical design book, owing to the multidisciplinary of the field and the computer tools which are crucially important to run the design calculations quickly. Design is not a singular subject: a complete design project will inevitably require the coming together of a multitude of technical, scientific and technological disciplines, in addition to clarity in the drafting of the dossiers making up the studies.

The first chapter discusses the organization of workflow for projects. Its purpose is to guide the projector–designer through the entire organizational process, from the first general overview sketch to the launch of the idea based on the technical specifications. This part tackles the search for practical solutions which can orientate the projects. This, in a manner of speaking, is the art of conducting a design project.

Chapter 2 sets out the main design tasks, with emphasis being placed on the judicious use of materials and geometric form. Throughout the book’s eleven chapters, we present case studies with worked solutions as a didactic approach.

Next, the third chapter presents the principles underpinning the calculations for the elements of machines, materials and structures. It is here that calculation tools prove indispensable for the design analysis. This chapter discusses the need for process analysis and materials analysis. It is also at this stage that the issue of sizing comes into play, and that geometry (GPS: Geometrical Product Specifications) takes on its demonstrative part. We also look at the theory of Hertz contact stress.

Chapter 4 is given over to the particular geometric forms used in applied mechanical design: profiled and incurvate parts (we look at the NURBS method: Non-Uniform Rational Basis Spline).

We move on, in our fifth chapter, to the appropriate use of the principles of calculations for the elements of machines employed in mechanical construction. We touch upon cases of material resistance and give further case studies, with solutions, which can serve as concrete examples to be used in tutorials and other applied mechanical design workshops.

The sixth chapter presents case studies devoted to the noise and vibrations produced by mechanical elements and machine supports. The solution sets demonstrated here could be used to devise other projected cases for tutorials.

Chapter 7 offers further context about a number of cases commonly encountered in welded structures, and presents the calculations used to determine the fatigue of stationary parts and bearings.

The eighth chapter then presents case studies on the brakes and clutch systems used in applied mechanical design.

In the ninth chapter, we discuss bolted mechanical structures, such as spring washers and axles.

Chapter 10 is devoted specifically to the principles underlying the calculations for machine elements made of plastic materials.

The eleventh chapter presents concrete projects that have actually been tackled in the author's classes and tutorials, and the resulting commentated sets of solutions also offered.

The Conclusion and Appendix provide a brief summary, containing a glossary, and tables of reference pertaining to the standards in force in construction and mechanical design. Having come to the end of the above sections of the discussion, this final chapter presents a number of recommendations regarding the drafting and final presentation of projects.

This book is specifically targeted at problem-solving in mechanical design. Its purpose is absolutely not to lay out the fundamental concepts used in mechanics, but it does draw upon those concepts (discussed in depth in other works) to put forward succinct, practical solutions. That is where its strength as a tool for teaching and training lies. Users can refer to an illuminating set of commentated solutions.

Case Study-based Design Methodology

1.1. Methodology for designing a project product

“Methodology” should be taken to mean the preparation of an exhaustive file of the steps that must be followed at a research center. That file will contain the data defining the product, right down to the expression defining the need for it.

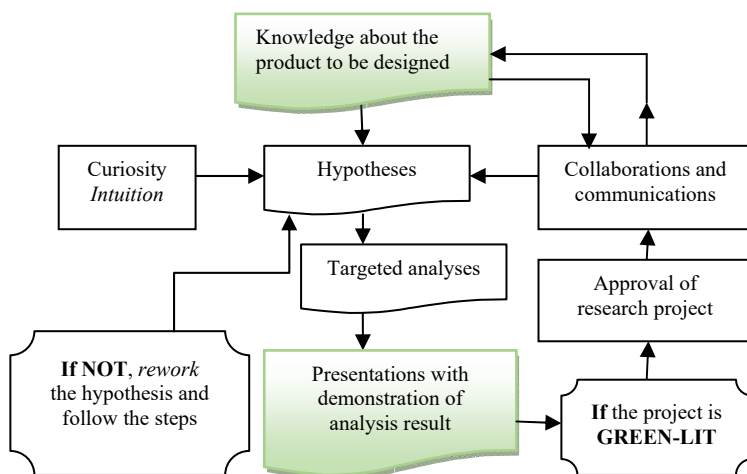


Figure 1.1. *Scientific approach to design*

The scientific approach is named as such because of the dissatisfactions pertaining to fields not explored by the core sciences. If the subject is unique or original, in collaboration between multiple disciplines, new hypotheses may be formulated and patented. Thus, the state of the art will be enriched.

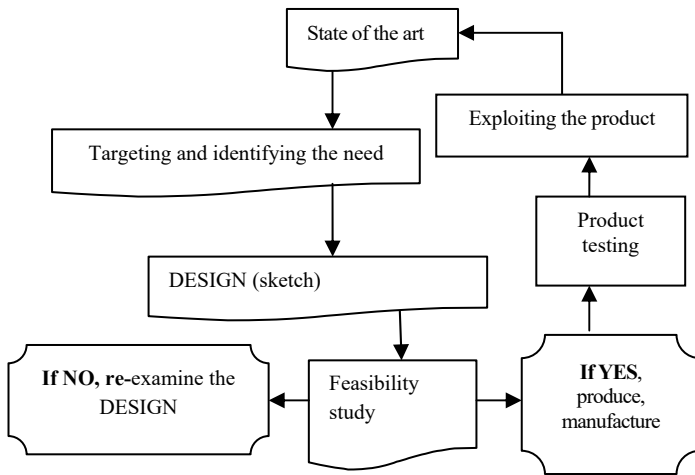


Figure 1.2. *Process of a design project*

Given the multi-disciplinarity (fields of mechanics, pneumatics, hydraulics, electronics, etc.) of subjects which encapsulate design and vast domains of application (the manufacturing industry, agriculture, civil and/or military construction, biomechanics, automotive engineering, aeronautics, etc.) in this book, we present examples found in systems in mechanical and civil engineering. The mathematical foundations are common to the two domains, but the behavior of the materials and structures sometimes differ.

We can already see that design is hugely complex. A designer must have good knowledge of numerous branches of science and technology, in addition to a keen sense of the dual organization of good intuition. The project approach is less stressful because the client will have clearly expressed their requirements at the outset. Solutions will be put forward with the aim of satisfying the requirements, in connection with the technical and economic feasibility. Once the designer has accepted the project to conduct manufacturing studies, tests will be carried out. If the result is a conclusive approval, then the product will be made and potentially released to the public.

1.2. Main players involved in the design process

Design projects are studied in a research hub (RH). Thus, the RH is an entity which is often complex, the size of which is subject to variation from one company to another. The teams employed at RHs are multi-disciplinary, complementary and

diverse. The tasks are often trivial and overseen by: the study *engineer*; the study *designer* and the *projector*.

The research engineer is the head of the research project, but delegates some of the work to the projector. In addition to the calculations for which s/he is responsible for (graphic design, core sciences and applied sciences), the research engineer acts as an interface between the administrative and financial management teams.

The study designer, despite what the title suggests, actually deals with more than just designs. His/her role is to finalize the defining designs and drawings in the preliminary stage of the project.

The projector, as the etymology indicates, assists the research engineer in projecting technical tasks, including the defining design drawings. Depending on the structural organization of each company, the projector may sometimes deal with clients, with suppliers and with all the company's separate departments. In addition to the tasks of computer-aided design (CAD), the projector is indispensable in a research center, because the research engineer trusts projector and relies upon him/her for all the work needing to be done.

Specific publications on company structure offer fuller definitions of these hierarchical roles. This book, for its part, is intended to be an instructional design-support tool: sketches, calculations, tests, measurements and checks.

The design workspace evolves around the projector. The below diagram illustrates what we mean by this:

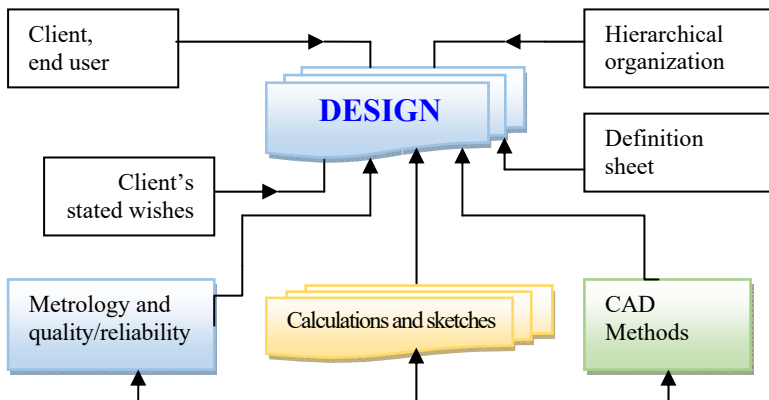


Figure 1.3. *Diagram illustrating the work environment*

The projector is in charge of the needs analysis, the feasibility study for the requirement and the execution of the preliminary (“pre-project”) stage. It is worth bearing in mind that there are multiple possible combinations to create a product. The organigrams offered here are simply a few illustrative examples. The staff at the research hub, drawing upon their relevant experiences, would choose possibilities which fit in with their own working methods.

1.3. Conceptualization and creativity

At the initial stage of the design, it is wise to begin with proposals of ideas to help bring the product to life. The team then take an initial overall view of the adopted solutions to lay the foundations for the task of design.

Criteria behind principles of construction		
Human factors	Production	Reliability
Calibration function	Standards	Maintenance
Settings	Materials	Maintainability
Connections	Recycling	Environment
Setups	Components	Handling
Safety/security	...	Applied quality control
Accessibility	etc....	Applied metrology

Table 1.1. *Main construction criteria in design*

1.4. Functional analysis in design: the FAST method

The method known as FAST – Function Analysis System Technique – is a workflow organization method which offers a logical and explicative diagram illustrating the operational and technical functions.

- *Why* does the function need to be performed?
- *How* does the function need to be performed?
- *When* does the function need to be performed?

It is an interrogative method, the answers to which will guide a designer in their choices and methods. Function Analysis System Technique, known by its acronym FAST, is used in functional analysis either to describe (descriptive FAST) or to create (creative FAST). FAST is said to be descriptive if the design solution already exists. This method is used, for example, to carry out a critical study of how a product’s technical and/or economic functions are served. The process is as follows:

Prepare for the analysis → Gather and collate the technical functions → Sort the technical functions → Construct a FAST diagram (How? and/or When?) → Write up the technological adopted solution.

Creative FAST is used as follows: Prepare for the analysis → Search for and collect ideas (brainstorming, or “Kaizen”) → Order the ideas → Construct a FAST diagram (How? and/or When?) → Write up the technological adopted solution.

Simplified example of a FAST approach in manufacture by machining

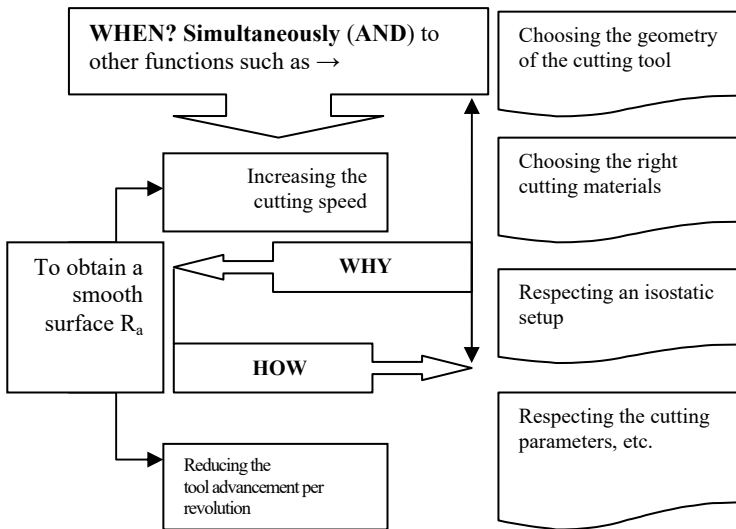


Figure 1.4. FAST in machining manufacture

1.4.1. Decision-support tools in design

Although decision-support tools can be very helpful if used properly, it is advisable not to blindly accept the accuracy of the proposed solutions. These tools are used at the end of the creative sessions that are an integral part of the preliminary design phase of a project. The purpose of using them is to stabilize the choice of solutions – in other words, to check the validity of the decision and to create a commented decision dashboard.

Validity of the decision: The questionnaire is designed to extract the true requirements of the product. It then becomes a question of explaining the advantages and disadvantages weighing toward the maintaining of the solution.

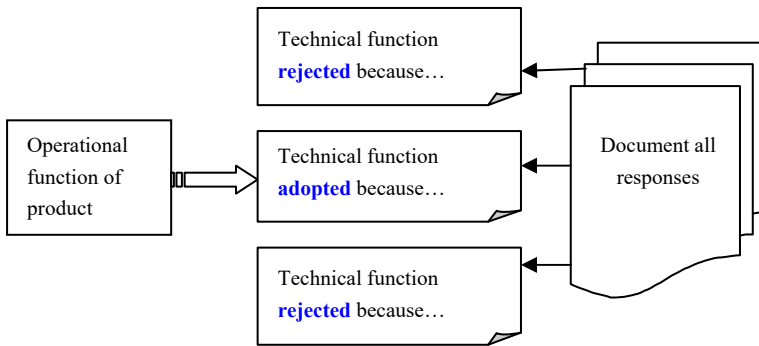


Figure 1.5. Decision-support system (expert system)

For example: why use one material instead of another? Why choose that environment? etc. The assessment criteria justify and support the characterization of the product's operational function. Of course, it is crucial to also take account of criteria such as cost, maintenance and even esthetic appearance, etc.

A so-called Bayes table (named after the Scottish statistician Thomas Bayes, 1702-1761), is a multi-criterion table used to formalize a decision. To draw up a Bayes table, we insert the factors contained in relation [1.1], below, in accordance with the following seven steps:

- 1) Define the objective of the decision to be made
- 2) Collate the proposed solutions (Sol₁; Sol₂; ... Sol_j)
- 3) Collate the criteria (Criterion₁; Criterion₂; ... Criterion_j), assigning each a score between 1 and 3, depending on the case study
- 4) Weight the criteria (κ_i) with weight scores ranging from 1 to 5
- 5) Find the value structure for each criterion
- 6) Carry out an overall evaluation (calculate the total sum)
- 7) Analyze the results to produce the best solution(s) as a function of the highest weighted score.

Decision dashboard relating to three solutions

$$Score_{Solj} = \sum_{i=1}^n N_i \times \kappa_i \quad \text{where} \quad \left\{ \begin{array}{l} \kappa_i \text{ is a weighting coefficient } (1 \leq \kappa_i \leq 5) \\ Score_{Solj} \text{ is the score for solution } sol_j \\ N_i \text{ is the criterion score } (1 \leq N_i \leq 3) \\ i \text{ is the criterion number } (1 \leq j \leq n) \end{array} \right\} \quad [1.1]$$

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