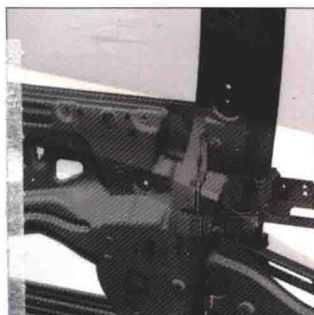
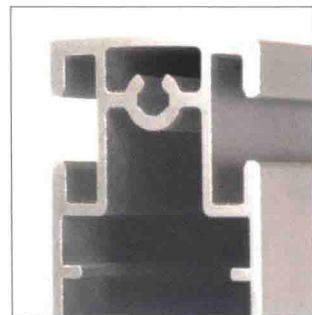


Manufacturing and Design

understanding the principles
of how things are made



Erik Tempelman
Hugh Shercliff
Bruno Ninaber van Eyben

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Understanding the Principles of How Things Are Made

First edition

by

Erik Tempelman

Hugh Shercliff

Bruno Ninaber van Eyben



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Erik Tempelman, Hugh Shercliff, Bruno Ninaber van Eyben
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Preface

TEACHING MANUFACTURING AND DESIGN

In teaching manufacturing, the classic starting point is to group all processes into categories, starting with their primary functions (shaping, joining, surface treatment). Shaping processes tend to be subdivided by material class (metal, polymer, etc.) or the material state (solid, liquid, powder): hence, metal casting, metal forming, polymer molding, and so on. All processes within one category then have certain aspects in common, making understanding easier. However, for teaching and learning, this approach has its limitations if applied too rigorously. On the one hand, processes within one category can still be worlds apart when it comes to putting them in a *design context*, technically, economically, or both. On the other hand, there are useful parallels between processes that fall superficially into different categories, meaning that educational opportunities can be missed—for example, at the level of the mechanism of metal removal, machining has things in common with metal forming. For similar reasons, categorizations are poor at dealing with new processes: for instance, thixomolding lies somewhere between deformation and casting, whereas additive manufacturing, also known as “3D printing,” is something else altogether. In summary, categorizing processes is only a starting point for teaching and learning about manufacturing and design.

This book provides an alternative, based on a division between the hierarchical levels of the *principle*, the *method*, and the *equipment* used for manufacturing, and based on a distinction between the attributes of processes with respect to *function*, *quality*, and *cost*. This structuring of thought processes around manufacturing has proven to be very useful for a design setting, especially because it invites a gradual choice for manufacturing processes during the product design process, moving steadily down the hierarchy while going from conceptual design to product detailing—all the time striking trade-offs between attributes of function, quality, and cost in all their forms.

A second novel aspect of the book is its selective nature, as it covers only those processes that the suggested readers are most likely to encounter during their careers. This makes it very different from the conventional “encyclopedia” textbooks—and, consequently, much more manageable. The book also gives guidelines for how to build up knowledge on the processes not covered here, encouraging a philosophy of lifelong learning.

Furthermore, we have opted to address the “how” of the selected processes just as much as the “what” by presenting the underlying physics and material science. This is something that works especially well at the level of the manufacturing principle, although again we have been selective by focusing on the main concepts and terminology. Mixed with the right respect for practical considerations, this science-led approach allows the reader to distinguish what is (im)possible in principle from what is (im)possible in practice, and this is a vital skill for professional designers in their interaction with the manufacturing industry. It also invites readers to explore generally applicable concepts, to discover ways to make simple models of complex phenomena, and to forge a strong connection between manufacturing and materials science.

The book has a final innovation: exercises do not appear the end of chapters but are embedded in the main text itself, at strategic locations, and they are deliberately open-ended. Furthermore, full solutions are not provided, although hints and examples are (in the online appendix). This setup might seem strange at first sight, but it has already proven itself to be effective in encouraging students to become

active learners. Overall, we expect that professionals, teachers, and students alike will appreciate the novel approach to teaching manufacturing processes for product design that is taken in this book.

READERSHIP

This book is written primarily for bachelor's-level students of industrial design, design engineering, and general mechanical engineering (including manufacturing, materials, aerospace, and automotive), as well as their teachers. It will also prove to be worthwhile for students of other disciplines relating to design and engineering, as well as for design art school students who are not put off by a few equations. Basic high school physics and mathematics are required, as is some acquaintance with materials science. *Manufacturing and Design* can also be recommended for people working as professionals in the fields of materials, manufacture, or design, for whom it may serve as a fresh-up course or even as inspiration for solving production-related design problems.

THE CHANGING WORLD OF MANUFACTURE

Until the 1980s or so, dealing with manufacturing during product design was comparatively easy. Most designers worked either for original equipment manufacturers (OEMs) that had in-house manufacturing facilities or for design agencies that had, through their OEM clients, strong ties to those facilities. So all necessary knowledge and experience could be found either in-house or right around the proverbial corner. Moreover, the manufacturing specialists were “on the same team” as the designers. Apart from those organizational and communicational benefits, the world of manufacturing processes was not changing too rapidly, and product life cycles were comparatively long, leading to design processes we would now consider to be relaxed.

Today's designers have no such luxuries. Many OEMs have outsourced their manufacturing facilities, often to faraway countries, and knowledge and experience are hard to come by. And when designers finally meet the specialists, these individuals are no longer on the same team and now have all the reason to use the difference in knowledge to their advantage. Development times are short, leaving little opportunity to reflect. Even more crucially, the world of manufacturing is changing faster than ever, making it ever more likely that real chances are missed to deliver the same functionality with better quality, or against lower cost, or to find another road towards market success. Any one of these factors alone forces designers to reconsider what they think they know about manufacturing, let alone the force of all of them together!

This book presents a way out. By tackling the vast and dynamic field of manufacturing processes from a fresh, different angle than existing approaches, as well as by being very selective, it allows you to make the most out of the increasingly limited time that students, teachers, and professionals have available. It gives designers the knowledge needed to not only create optimal designs, but also to understand where the supplier is coming from, so that together, they can search through the manufacturing options and find the best compromise.

Ultimately, this book aims to raise our level of thinking and take manufacturing and design into the 21st century. As long as one does not forget about practicalities, understanding the physics behind the processes is key to understanding what is possible and what is not, but for too long this topic has been ignored or made incomprehensible in university textbooks. *Manufacturing and Design* aims to change this situation.

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Introduction

CHAPTER OUTLINE

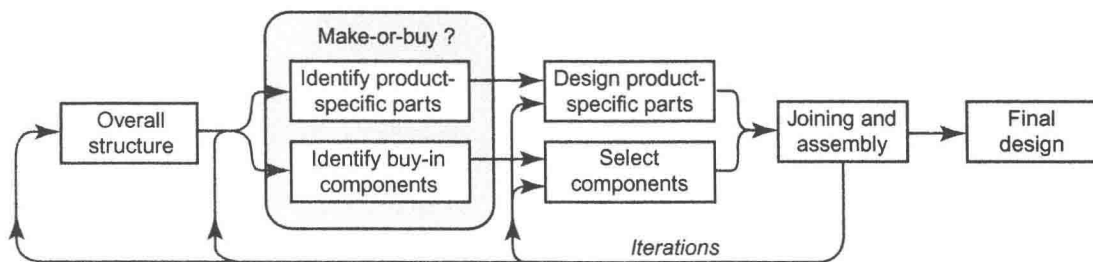
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1.1 MANUFACTURING: THE ROLE OF THE DESIGNER

All products you see around you, from the simple disposable coffee cup in your hand to the hugely complex aircraft overhead, have been *designed*. They have also been *manufactured*. Without exception, successful mass-produced products have been designed to be not just functional and pleasing to use but also affordable to make, striking the right balance between the conflicting product requirements of functionality, quality, and cost. In the design process, whose role is it to ensure that products *can* in fact be manufactured well? Before answering that question, let's look more closely at what it involves.

In design for manufacture, the first major decision typically concerns the overall structure of the new product—its layout, or architecture if you wish. The iterative process of choosing the material starts soon afterwards. Next comes the 'make-or-buy decision': deciding which components to buy in from stock and, conversely, which parts to design specifically for the new product. (Increasingly, products share components among different versions as well as generations, and this complicates both the choice of product layout as well as the decision to make or buy.) The product-specific parts are then designed in detail, which involves choosing the right manufacturing processes and is intimately linked to material selection. This is also the time to consider assembly: how will all parts and components be joined together into a working product? More often than not, it will become apparent along the way that certain design choices do not combine well with decisions made earlier. The solution is to trace back one's steps and explore alternatives before converging onto a satisfying solution. That, in a nutshell, is what design for manufacture entails (Figure 1.1). It is a difficult, complex, and time-consuming process that nevertheless lies right at the heart of design. It can also be very rewarding, especially when choices for manufacturing processes not only realize but actually *improve* the initial design ideas.

So whose role is it to take on this challenge? That, dear reader, is *your* role. Regardless of whether you are an industrial designer, mechanical engineer, aerospace engineer, or similar creator, your job is to do design for manufacture, just as you should address functionality, aesthetics, and any other requirement that your product must meet. Suppliers will gladly help you to ensure that the parts you design are feasible to make, or that parts and components are easy to assemble. But selecting a supplier means

**FIGURE 1.1**

Key steps in design for manufacture. (For color version of this figure, the reader is referred to the online version of this chapter.)

selecting a process first, at least at the top level of the manufacturing principle—for example, choosing between injection molding or thermoforming for a plastic part, or between casting or forging for metals. Although suppliers know their own process very well, they often have a limited view of alternatives and a vested interest in their own. They cannot therefore be relied on to guide such process choices—that is your job. Also, they will happily help your competition as well, so if you listen too much to suppliers, your design will not stand out from the crowd. Finally, the manufacturing industry tends to steer you in the direction of what has been done before, not of what could one day be, resulting in conservative designs that may be easy to make but that are not innovative. How can you avoid this trap? The answer: by building up a solid background of what manufacturing processes can and cannot do. That is what this book will help you to do.

1.2 PRINCIPLES, METHODS, AND EQUIPMENT

Industrial manufacturing practice comprises a vast number of processes, each of which can be encountered in numerous variations. Every process—often every piece of manufacturing equipment that a supplier has available—has its own possibilities and limitations. Understanding requires in-depth knowledge, but how can you acquire this knowledge when the number of process variants is so large and your time for learning is always limited?

The first step of the solution provided by this book is careful *selection*. After consulting a number of design professionals from various fields and product categories, a list was drawn up of processes that—with few exceptions—every designer should aim to know and understand. Next, these selected processes were ordered into an effective *hierarchy*, bringing processes together that not only have strong similarities in terms of the underlying physics and material science but also represent distinct industry branches. This leads to the hierarchical level of the *manufacturing principle*, and that of the *manufacturing method*. As parts and products eventually need to be made on a real piece of machinery, a third and final level to identify here is that of the *manufacturing equipment*.

Figure 1.2 presents an example for the group of casting processes for metals. Sand casting, low-pressure (LP) die casting, and so on are all methods under the same principle, and underneath each of these methods are all kinds of specific equipment. What may be a limitation of certain machinery (e.g., size, accuracy) need not be a restriction for other equipment; conversely, there can be

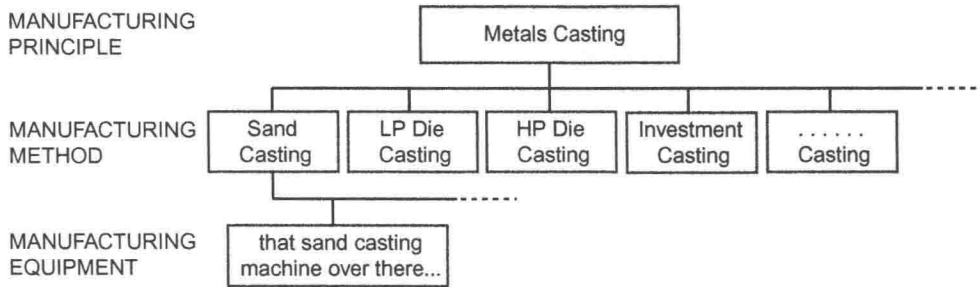
Table 1.1 Manufacturing Principles and Methods Covered in This Book

Ch.	Principle	Methods
1	Introduction	
2	Product disassembly studies	
3	Shape casting of metals	Sand casting, gravity die casting, low- and high-pressure die casting, investment casting
4	Sheet metal forming	Bending, roll bending, roll forming, panel beating, deep drawing, matched die forming, sequential die forming, rubber forming, hydroforming
5	Extrusion of metals	Hot direct extrusion of aluminum, hot direct extrusion of other metals
6	Forging of metals	Open-die forging, closed-die forging, pressure forging, net shape forging, cold heading, coining
7	Machining	Turning, drilling, milling, integral machining
8	Injection molding	Compact molding, insert/outsert molding, gas injection molding, molding with in-mold decoration, 2K molding
9	Thermoforming	Free forming, standard forming, pre-stretch forming, plug-assisted forming, twin-sheet forming
10	Resin transfer molding (RTM)	Pressure-controlled RTM, volume-controlled RTM, resin infusion, light RTM
11	Additive manufacturing	All seven sub-principles as classified by the American Society for Testing and Materials (ASTM) in 2012
12	Joining and assembly	Welding, soldering, adhesive bonding, mechanical fastening, joining using form closures, line versus cell assembly
13	None of the above	Ten additional processes
14	Recycling	
15	Manufacturing process choice	

at all. Chapter 14 covers the basics of recycling, which is, in many ways, the reverse of manufacturing processes (products go in, materials come out). Finally, Chapter 15 draws many threads of the text together by summarizing the considerations for making well-balanced choices regarding manufacture during the product design process.

In the core chapters, most of the attention goes out to the principle. Once more, the book is selective, digging no deeper than strictly necessary. Each principle is explained by using a small number of key concepts and introducing only essential terminology. The aim is not tell you all there is to tell, but instead to focus on those things you need to know to make a difference. However, even with a limited discussion of the theory underlying the various principles and by showing how it can be applied to the methods under them, you will build up the right knowledge and insights—making the most of your limited time.

In some books, this physics-based approach can tend to distance readers from the actual nuts and bolts of the subject matter. Chapter 2 aims to prevent this from happening by showing instructive examples of the real world of manufacture, and inviting readers to literally take products apart themselves. Also, each core chapter starts with an exercise that encourages you to find and study parts made under each principle. With this initial exploration of products, the focus on underlying physics immediately has a context and shows its key benefits. Instead of keeping the “black box” of manufacturing closed

**FIGURE 1.2**

Levels of abstraction—principle, method, equipment—as applied to casting processes. (For color version of this figure, the reader is referred to the online version of this chapter.)

requirements that certain methods may find hard to meet or that are even inherent limitations of the principle itself.

To summarize, the resulting process hierarchy distinguishes among the following characteristics:

- What is possible in *principle* (as determined by physical law)
- What is possible in practice—that is, the *methods* under that principle (as determined by industrial state-of-the-art)
- What is possible with the *equipment* used for that method (as determined by what a certain supplier has available)

1.3 SCOPE AND CONTENT OF THE BOOK

This book deliberately does not aim to be comprehensive. Its focus, to start with, is on *shaping* processes for parts and products, with limited space for joining and assembly, and even less for finishing. So the emphasis is on product-specific parts rather than on standard bought-in components and semi-finished stock material. It also restricts itself to those mass manufacturing processes that you are most likely to encounter, with only limited attention to less common processes. Likewise, prototyping and one-off production are only addressed briefly, whereas some processing areas (such as fabrics and textiles, or the micro-manufacture of electronic devices) are not covered at all. So what you have in front of you is a *selective* book indeed.

Table 1.1 summarizes the contents of this book. Chapters 3 to 12 form the core of the book. Each of these chapters deals with one particular manufacturing principle, explaining how it works and how it can be described and understood in physical terms. Each chapter ends with hands-on information on the various methods commonly found under that principle, as well as pointers for further study. These chapters have been written as independently as possible from each other and can therefore be read in any order or number. The remaining five chapters complement the core, as follows. Chapters 1 and 2 are scene-setting chapters that introduce the book, show what several common products are made of, and identify which processes were used to make them. Readers are invited to perform such “product disassembly studies” for themselves and to reflect on why these particular materials and processes were used. Chapter 13 contains brief descriptions of 10 additional processes, including product finishing, as well as guidance for gathering information and building insight into processes not covered in this book