Materials and Processes in Mechanical Design

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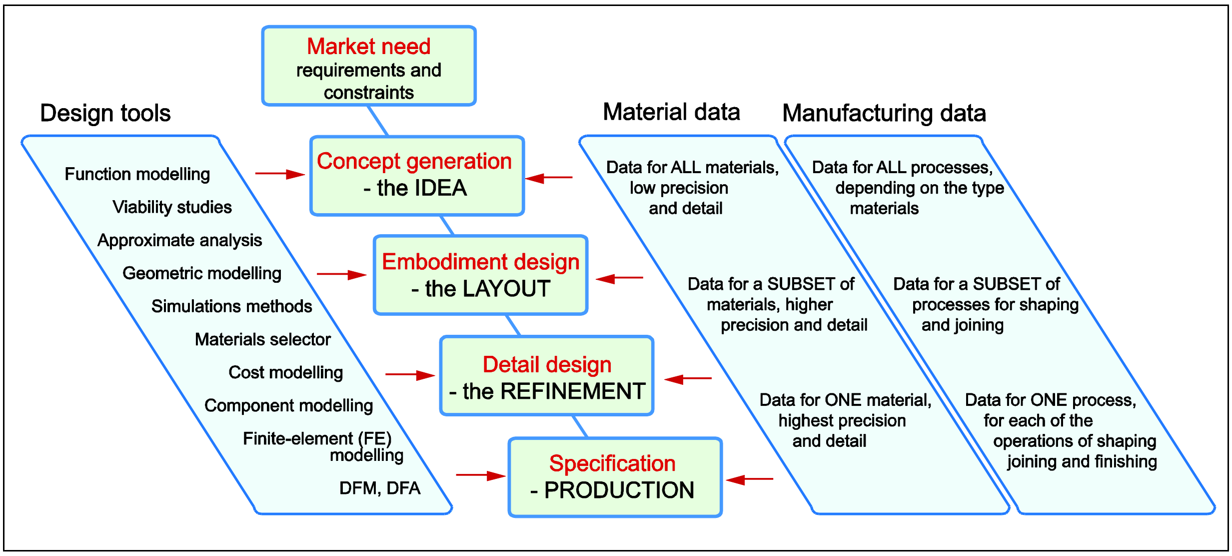

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1. Introduction

Materials create the substance of products. The process of designing products is therefore inextricably linked to that of selecting the materials with which they are made. And because the materials have to be shaped, joined and finished to make the artefact, choices of manufacturing processes are linked too. Artefacts perform one or more functions that rely on material and shape so function, shape, material and manufacturing process are coupled (Figure 1). Understanding how these interact is not an easy task yet it is something that any engineering designer does every time he or she develops a new artefact. This coupling means that the design process cannot be sequential – meaning that one cannot define shape, and then material and then manufacturing process, checking in the end whether the function requirements are met. Selecting material and process especially has to be done concurrently. The aim of this White Paper is to make the relations between material, function, shape and process explicit and explain how the CES EduPack can help in performing and teaching about it. The White paper starts by presenting modern design (Section 2) and briefly surveying creativity methods (Section 3). Sections 4 and 5 explore data-structure and organisation for materials and manufacturing processes. Section 6 examines how these data enter the design process. Sections 7 and 8 further emphasize the iterative nature of design and conclude the paper. The paper will not treat energy and sustainability explicitly, although it will always be a major concern for the designer. This topic is treated elsewhere in some depth (Ashby, Attwood and Lord 2012; Ashby, Miller, Rutter, Seymour and Wegst 2012).

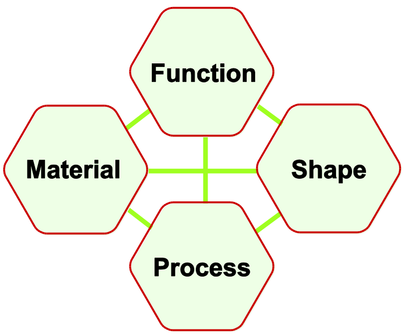

Figure 1. The interaction between function, material, process and shape.

2. Modern design methods

Design can seem mysterious. The outcome is visible, tangible. Besides function, it creates reactions, emotions. But the way the designer got there is hidden. The ability to design can seem like a gift that some people have but most have not.

The reality is rather different – "more perspiration than inspiration", designers like to say. That may be modesty, but there are ways of capturing the design methods as a set of steps. Following them is hard work (the perspiration) but there is the reassurance that, if followed long enough, a solution will emerge. Those who study the Design Process, like Nigel Cross, Karl Ulrich and many others describe the steps like this.

2.1. Zeroing-in on the problem: concept generation

The starting point of a design is an *unfilled gap* – something in the world that could be done better. The end point is the full *specification* of a product that fills that gap.

The gap is the difference between the world as it is and the world as you (or your client) would like it to be. The first task – *problem definition* – is to articulate precisely what this means – it is the "What", not the "How". The information is teased out by asking "Why?", repeatedly, like an annoying child. Why does this gap exist? Why do you want to fill it? Why do you want to do it that way? ...The answers to the sequence of Whys becomes an expression of the design requirements (see Figure 2).

Here is an example. This White Paper is written to fill a gap: Granta's White Paper series lacks one that sets out the Design Process. Here are some Whys.

- *Why fill this gap?*
  To provide Instructors of courses in Engineering Materials with necessary background for teaching Materials and Design
- *Why provide them with this background?*
  To present the ways in which the CES EduPack resources fit into, and contribute to, the Design Process.
- *Why do you want to present this information?*
  To allow Instructors to illustrate the role and importance of Materials and Manufacturing Processes in the context of Design.

Figure 2. Concept generation, as described by Ulrich (2011)

And so on. Already we have defined the problem more fully. The White Paper should show how the CES EduPack resources set the role of Materials and Process selection in the context of Engineering Design. If it fails to do this it has not filled the gap.

With this mission-statement it becomes possible to explore alternative solutions. Designers use sketching, schematics, abstraction to explore as wide a range as widely as possible, with consideration of the views of all stakeholders – those who will finance it, make it, use it, be the recipients of its use, and even those who will deal with it when it is dead. They are diverse set, often with conflicting priorities. Among the alternatives, if broadly based, are some that meet the requirements more closely than others, or those that, if combined in some way, resolve conflicts. The aim, via consultation with the stakeholders, is to identify the solution that most nearly matches the "ideal point" – the perfect closure of the gap between the world as it is and the world as you (or your client) want it.

2.2. Embodiment, detail and specification

Now we have a concept – something that, if implemented, can fill the gap.

Systematic methods for proceeding further trace their origins back to the work of Pahl, Beitz et al (2007). Figure 3 is a simplification of their flow chart, one used in various modifications by Cross (2000), Ulrich and Eppinger (2012) and many others. The chosen concept is passed to the stage embodiment design in which its layout is explored, its components sized approximately, and the first exploration of materials that will perform properly in the ranges of stress, temperature and environment suggested by the design requirements, examining the implications for performance and cost. The embodiment stage ends with a feasible layout, which is then passed to the detailed design stage. Here specifications for each component are drawn up. Critical components may be subjected to precise mechanical or thermal analysis. Optimization methods are applied to components and groups of components to maximise performance. A final choice of geometry and material is made and the methods of production are analysed and costed. The stage ends with a detailed production specification.

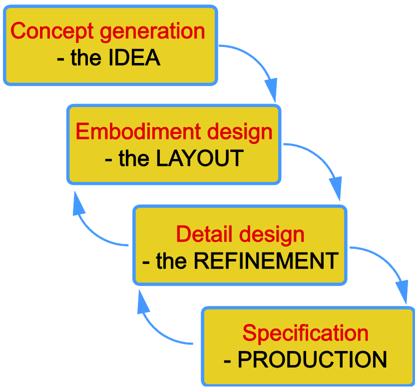

Figure 3. The further steps of the design process, simplified from the flow-chart of Pahl, Beitz et al (2007).

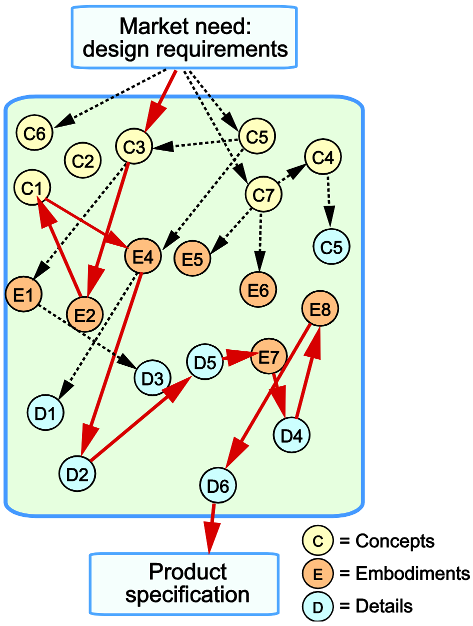

Figure 4. The non-linear nature of the design path.

All that sounds well and good. If only it were so simple. The linear process suggested by Figure 3 obscures the strong coupling between the three stages. The consequences of choices made at the concept or embodiment stages may not become apparent until the detail is examined. Iteration, looping back to explore alternatives, is an essential part of the design process. Think of each of the many possible choices that *could* be made as an array of blobs in design space as suggested by Figure 4. Here C1, C2 … are possible concepts, and E1, E2….. and D1, D2….. are possible embodiments and detailed elaborations of them. The design process becomes one of creating paths, linking compatible blobs, until a connection is made from the top ("Market need") to the bottom ("Product specification"). Some trial paths have dead-ends, some loop back.

It is like finding a track across difficult terrain – it may be necessary to go back many times if, in the end, to go forward. Once a path is found, it is always possible to make it look linear and logical (and many books do this), but the reality is more like Figure 4 than Figure 3. Thus a key part of design, and of selecting materials for it, is *flexibility*, the ability to explore alternatives quickly, keeping the big picture as well as the details in mind.

2.3. Functionality, usability, satisfaction

The pen with which this White Paper was written cost $5. If you go to the right store you can find a pen that costs well over $1000. Does it write 200 times better than mine? Unlikely; this cheap one writes perfectly well. Yet there is a market for such pens. Why?

A product has a *cost* – the outlay in manufacture and marketing it. It has a *price* – the sum at which it is offered to the consumer. And it has a *value* – a measure of what the consumer thinks it is worth. The expensive pens command the price they do because the consumer perceives their value to justify it.

What determines value? Three things. *Functionality*, provided by sound technical design, clearly plays a role. The requirements pyramid of Figure 5 has this as its base: the product must work properly, be safe and economical. Functionality alone is not enough: the product must be easy to understand and operate, and these are questions of *usability*, the second tier of the figure. The third, completing the pyramid, is the requirement that the product gives *satisfaction*: that it enhances the life of those who own or use it.

The value of a product is a measure of the degree to which it meets (or exceeds) the expectation of the consumer in all three of these – functionality, usability and satisfaction. Think of this as the character of the product. It is very like human character. An admirable character is one who functions well, interacts effectively and is rewarding company. An unappealing character is one that does none of these. An odious character is one that does one or more of them in a way so unattractive that you cannot bear to be near him.

Products are the same. The pens, one cheap, one expensive, both function well and are easy to use. The huge difference in price implies that one provides a degree of satisfaction not afforded by the other. This is a question of aesthetics, associations and perceptions. These, and the role of materials in creating them, are the subject of another White Paper on "Materials and Product Design" (Ashby, 2012), so we will leave it there for the moment.

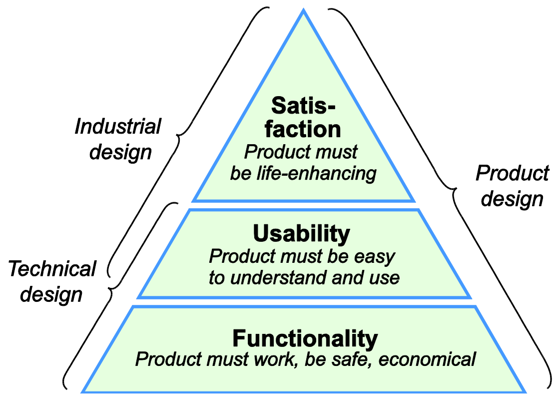

Figure 5. The design process includes consideration of functionality, usability and the satisfaction, through aesthetics, associations and perceptions, afforded to the consumer.

2.4. Types of design

Original design starts with a new idea or working principle (the ball-point pen, the compact disc). New materials can offer new, unique combinations of properties that enable original design. Thus high-purity silicon enabled the transistor; high-purity glass, the optical fiber; high coercive-force magnets, the miniature earphone, solid-state lasers, the compact disk. Sometimes the new material suggests the new product; sometimes instead the new product demands the development of a new material: nuclear technology drove the development of a series of new zirconium alloys and low-carbon stainless steels; space technology stimulated the development of light-weight composites; gas turbine technology today drives development of high-temperature alloys and ceramic coatings.

More commonly, design is *adaptive* or *developmental.* The starting point is an existing product or product-range. The motive for redesigning it may be to enhance performance, to reduce cost, or to adapt it to changing market conditions or to make it appeal to a wider consumer group. Adaptive design takes an existing concept and seeks an incremental advance in performance, enhancement of appeal or reduction in cost. It, too, is often made possible by developments in materials: polymers replacing metals in household appliances; carbon fiber replacing wood in sports equipment.

Finally, *variant design* involves a change of scale or dimension or detailing without change of function or the method of achieving it. Change of scale or circumstances of use may require change of material: small boats are made of fiberglass, large ships are made of steel; small boilers are made of copper, large ones of steel; subsonic planes are made of one alloy, supersonic of another.

2.5. Design tools

To implement the steps of Figure 2 and Figure 3, use is made of *design tools.* They are shown as inputs, attached to the left of the main backbone of the design methodology in Figure 6. The tools enable the modelling and optimization of a design, easing the routine aspects of each phase. Function-modellers suggest viable function structures. Configuration optimizers suggest or refine shapes. Geometric and 3-D solid modelling packages allow visualisation and create files that can be down-loaded to numerically controlled prototyping and manufacturing systems. Optimization, Design for Manufacturing (DFM), and Design for Assembly (DFA) and cost-estimation software allows manufacturing aspects to be refined.

Finite element (FE) and Computational Fluid Dynamics (CFD) packages allow precise mechanical and thermal analysis even when the geometry is complex, deformations are large and temperatures fluctuate. There is a natural progression in the use of the tools as the design evolves: approximate analysis and modeling at the conceptual stage; more sophisticated modeling and optimization at the embodiment stage; and precise ("exact" – but nothing is ever that) analysis at the detailed design stage.

Material and Process selection are central to the Design Process. The CES EduPack and CES Selector are examples of the kind of sophisticated tools that now exist to support this aspect of design. The purpose of this White Paper is to explain how they work concurrently with design, and we will get to that in Section 6. First, we will briefly look at creativity and how it can be enhanced.

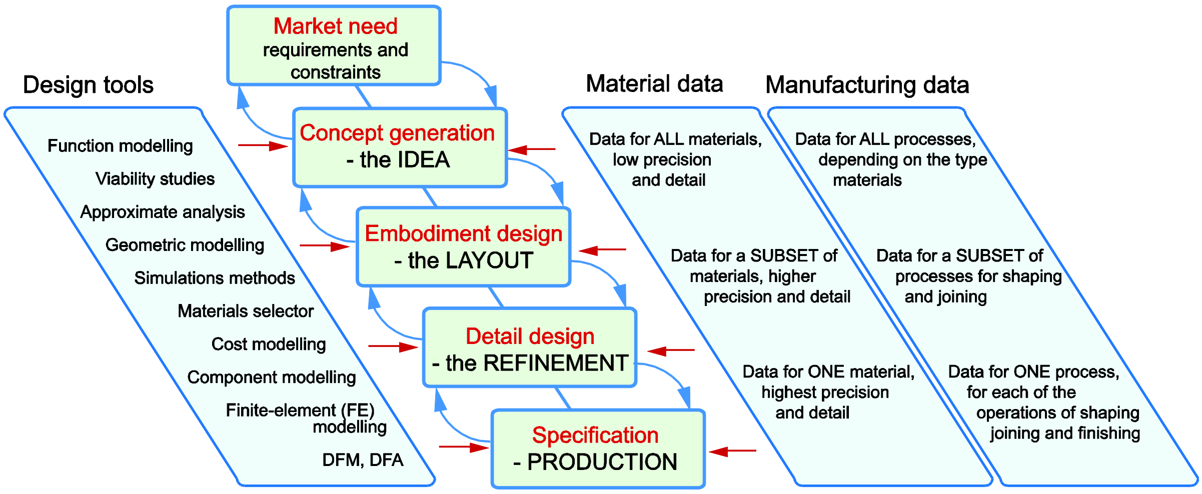

Figure 6. The design flow chart, showing how design tools and materials selection enter the procedure. Information about materials is needed at each stage, but at very different levels of breadth and precision.

3. A brief look on creativity

In the previous Section, we looked at a somewhat structured approach to develop new products, but nothing was said about creativity. The methods presented impact principally on the design *process* but not on generating good ideas. They suggest how to make a product "less bad", but not how to re-think it to make it "really good". To make more radical gains we must revisit the *embodiment* and *concept* stages, seeking tools for innovation. These are less systematic than those we use for detail design, but they are still worth exploring.

Tools for creative thinking work by breaking down barriers and forcing new angles of view. To do so, you have to escape from the view of the "product" as it is now (if there is one), seeking to see it in new ways. There are several ways of doing this, some unstructured, some, to varying degrees, structured, but they all work by breaking up the way it is viewed.

3.1. Brainstorming, mood boards, mind maps

Brainstorming relies on the group dynamics that appear when participants express their ideas, however wild, deferring all value judgment until the process is over. Humor plays a role. A joke that works relies on a creative jump, an unexpected outcome, by-passing normal reasoning. It switches the points, so to speak, deflecting thought off its usual rails onto a new track. It is the creativity of a good joke that gives pleasure, makes you laugh. Introducing it creates an environment for creative thinking. To work, brain-storming sessions must be fun and be kept short – experience suggests that one lasting more than 20 minutes ceases to be productive.

A *mood board* is a visual scrap-book, arranged on a large board placed where the designer will see it easily. It takes the form of a personalized, project-focused collection of images, objects or material samples, chosen because they have colors, textures, forms and associations that might contribute to the design. Images of products that have features like those sought by the designer and images of the environment or context in which the product will be used act as prompts for creative thinking. Many designers confronted by the challenge of creating product-character, first buy examples of other products that have a surface finish, an association, a style that might be exploited in a fresh way. The mood board acts as a trigger for ideas both about choice of materials and about their juxtaposition.

Mind-mapping is a sort of personalized brainstorming in which ideas are placed on a page and linked as appropriate; these links are used to stimulate further thinking: "light-weight materials …. wood… cells... porous solids… foams… metal foams… titanium foam…?"

3.2. More formal methods: Inductive reasoning, analogy and creativity templates

Inductive reasoning (Kolodner 1993) has its foundations in previous experience. The starting point is a set of design requirements expressed as *problem features*. A match is then sought between these and the problem features of other solved problems, allowing new, potential solutions ("hypotheses") to be synthesized and tested.

A central feature here is the library of previously-solved problems or "cases" – a "case" is a problem, an analysis of its features, a solution and an assessment of the degree of success of this solution. The challenge in assembling the library is that of appropriate indexing – attaching to each case a set of index-words that capture its features. If the index-words are too specific the case is only retrieved if an exact match is found; if too abstract, they become meaningless to anyone but the person who did the indexing. Consider, as an example, the "case" of the redesign of an electrical plug to make it easy to grip, insert and pull-out by an elderly person with weak hands. Indexing by "electrical plug" is specific; the case will be retrieved only if the "plug" is specified. Indexing under "design for the elderly" is more abstract, and more useful. Plugs are not the only thing elderly people find hard to use. Cutlery, taps, walking sticks and many other products are adapted for elderly people. Examining their shapes, materials and processes used to make them may suggest new solutions for the plug. Software shells exist that provide the functionality to create case-based systems, but, for any given domain of problems, the library has to be populated.

The use of templates to foster innovation and creativity is advocated by Goldenberg and Mazurski (2002). The evolution of a number of consumer products was studied and some evolutionary principles were extracted and put in the form of creativity templates: attribute dependency, replacement, displacement and component control attributes. These templates help in thinking of a new product by exploring links between design variables (attribute dependency), by replacing entire parts, or modules of the product with others (replacement), by eliminating entirely some parts or functions of the product (displacement) or by linking the product with its environment (component control). It is, in essence, an attempt at mechanizing creativity, based on past experience.

3.3. TRIZ and the 9-Windows Method

TRIZ (standing for Theory of Innovative Problem Solving – but in Russian) is the brainchild of the Russian patent expert Genrich Altschuller. He distilled from his study of patents 40 principles and 8 patterns of evolution for creating engineered products. There are disciples of his methods and there are non-believers. Be that as it may, one technique, the 9-windows method claimed as part of the TRIZ tool-set, finds wide use as stimulus for creative thinking. The obstacle to innovation is, often, a preoccupation of the system as it is *now*. The 9-window method forces a view of the system on different conceptual scales and at times other than the present. It takes the form of a 3 x 3 matrix of initially empty boxes[2]. The system for which creative thinking is sought is put in the central box – it can be described in words or recorded as a schematic or an image. It represents the system as it is now.

The horizontal axis is time past, present and future (it helps to make this quantitative, thus: 1 year ago, now, one year from now; or 50 years ago, now, and 50 years hence). The vertical axis is that of scale: subsystem (the components of the system) in the bottom row, above this the system scale, and above that the super-system of which the system is a part or in which it must operate. There are several ways to use the past, present and future columns. One is to ask: what are the antecedents of the system (subsystems, super-system), and what, ideally, would you like these to become in the future? Another is to ask: if you could have designed the system differently (in the past) what would you have done? What can I do now to enhance the system? What - given time – should I aim for in the future? A third is to ask: where are we now? Where have we come from over the last 5 years? Where do we wish to be 5 years from now? The idea is encourage a view of the problem from in front and behind, and from above and below, allowing a freedom to zoom in and out.

Design enterprises like IDEO, ARUP or Porsche Design develop their own in-house strategies for innovation. They are specially adapted to the context in which these companies operate and may evolve very rapidly. Some of these methods are available in the literature, but not all is said about the way in which they are implemented – that tends to be trade secret.

A fuller discussion of creativity methods can be found in the White Paper on Materials and Product Design (Ashby, 2012).

Having dealt briefly with creativity, we will now turn our attention to the data structure of materials and manufacturing processes in CES Edupack in Sections 4 and 5 respectively.

4. The Materials Universe

The CES Edupack is a teaching support tool that allows for efficient materials selection, trade-off and optimization. It encompasses a number of data-tables on materials and processes related information. The way in which the data is structured helps students to understand what unites or separates different materials. Materials that belong to the same family will share certain kinds of properties that in turn will fundamentally differentiate them in respect to other material families. The Edupack divides the materials universe into six main categories, as seen in Figure 7: Metals, Polymers, Elastomers, Glasses, Ceramics and Composites (Ashby and Cebon 2007).

Within each family, the universe is further subdivided in class, sub-class and member. As an example of what this breakdown would be for a metal, we can think of the metals family as being composed of numerous classes of alloys. One of these classes is the Aluminium alloys. Within the class of Aluminium alloys, one can find a number of standardized sub-classes that depend on the major alloying element. The 6000 sub-class would

2 Some advocates use two 9-window sets, one to analyze the problem, the other to explore solutions.

represent all the Aluminium alloys that contain Magnesium and Silicon as the major alloying elements.

Going further down from the sub-class one can find specific Aluminium alloys with specific chemical compositions and heat treatments that will define exactly the mechanical, thermal, optical, etc, properties on each of the members of this sub-class. The collection of these properties form the member's record of attributes, as seen in Figure 8.

5. The Process Universe

The Process Universe in the CES Edupack has a structure that parallels that of the Materials Universe. The data are divided into families of shaping, joining and surface treatment processes, which are sub-divided in the way shown in Figure 9. The families are further divided into classes of processes and specific processes (the members) to which a record of attributes can be assigned. Figure 9 shows an example: injection moulding is part of the moulding class that in turn belongs to the family of primary shaping processes.

Processing usually goes through a sequence of steps. Parts are given rough shapes (primary shaping) with approximate dimensions and then are trimmed to more precise tolerances or are given heat treatments (secondary shaping). They then are joined to other parts to form complex shapes (joining) and their surface is treated to cope with the environment or to perform their functions better (surface treatment). Figure 10 shows this process flow. There are parts, however, that do not need all these steps, and some others that need to cycle through those same steps several times.

The structure of the data will also help in the explanation that follows from Section 6 on the flow of information in the design process.

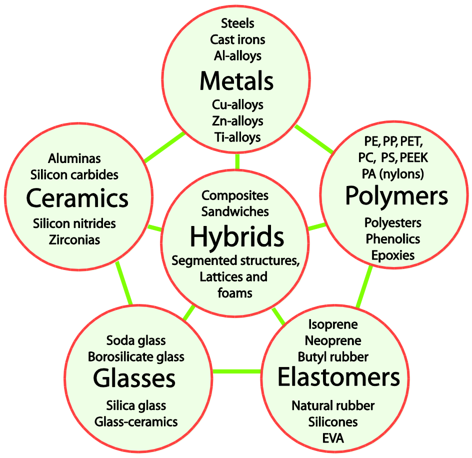

Figure 7. The materials families in the CES Edupack.

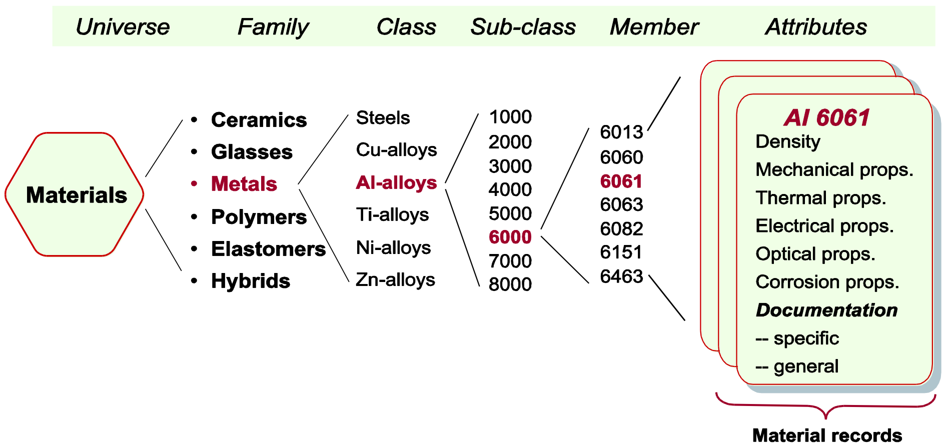

Figure 8. The Materials Universe structure in CES Edupack.

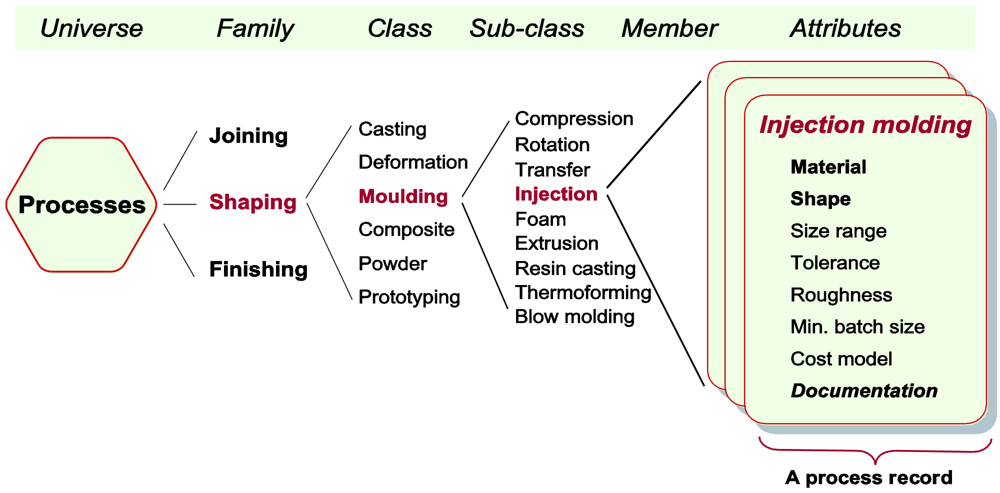

Figure 9. The Process Universe structure in CES Edupack

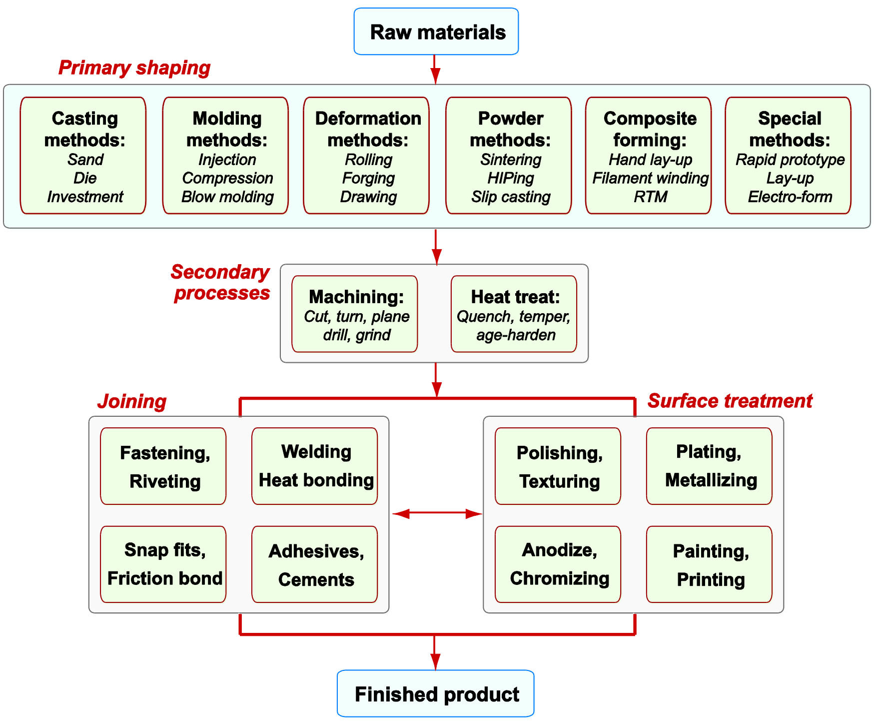

Figure 10. The processes families in the CES

6. The selection of materials and manufacturing processes

The way in which an engineering designer materializes an idea into a product is often idealized as a series of sequential activities, as it was seen in Section 2. As pointed out there, these activities often require iteration, particularly in the design of highly complex systems like automobiles or aircraft structures. Throughout the process, the selection of materials and processes plays an important, often neglected role.We will proceed with a generalized model of the engineering design process that encompasses most of the activities of design. Figure 11 shows this model – it is an evolution of Figure 3. Starting with a market need and a set of design requirements, the process goes through the phases of concept design, embodiment and detail design. We will now superimpose the activities that pertain specifically to selecting materials and manufacturing processes on each of the stages and how they contribute to the overall process (and progression) of design.

6.1. Concept design

The concept design phase is the entry point to the design process. In this phase the designer (or more often the design team) defines the primary function or functions of the product and the working principles by which they will be achieved. Ideally, these functions should be defined in such a way that they are independent of a particular solution to the problem. Some preliminary ideas for the working principles are also put forward, in a very abstract way, mostly with rough sketches and schematics. One way of doing this is to think of the product as a means of changing energy, material and information flows. The product will act upon these flows to perform the desired function, and the particular sequence and interactions among these actions roughly defines product architecture (Figure 12).

These decisions have to be taken with a limited amount of information because there is still a lot of detail missing in the early stages. The data on materials at the concept design stage is also lacking the necessary detail to perform a thorough selection, but decisions can be made at the level of material families and classes, eliminating the ones that show less promise of meeting the design requirements. Keeping a broad perspective on the types of materials to be used is crucial for innovative products. Innovation can come not only from the working principles but also from the use of new materials or the innovative use of existing materials.

A final choice of manufacturing processes is not yet possible, since the shape of each component of the product is not yet set, but again some general considerations on primary and secondary shaping can be made. One needs more detail on the working principles and layout of the system before analysing what joining methods surface finishing and treatments need to be performed. These come later in the design process.

6.2. Embodiment

The embodiment phase is one of generating or further detailing the product layout (architecture), the general form of each sub-system, the overall envelope and how the assembly of the product affect its functions, maintenance, upgrading and its end-of-life dismantling. This requires insight into what the interfaces between modules will look like, how information, material and energy will flow through the product and in what sequence, and which modules should be standard, which should be developed in-house and which should be outsourced.

Assemblies are a very important topic when designing products. One only needs to think carefully into how many times products fail at an interface between two components. Interactions between components can be predictable or incidental. Having a component near a heat source will mean that, although the component does not need to cope with high temperatures, it may need to resist them due to its particular position inside the product. Again, evaluating competing layouts is difficult because the amount of unknown variables is still large.

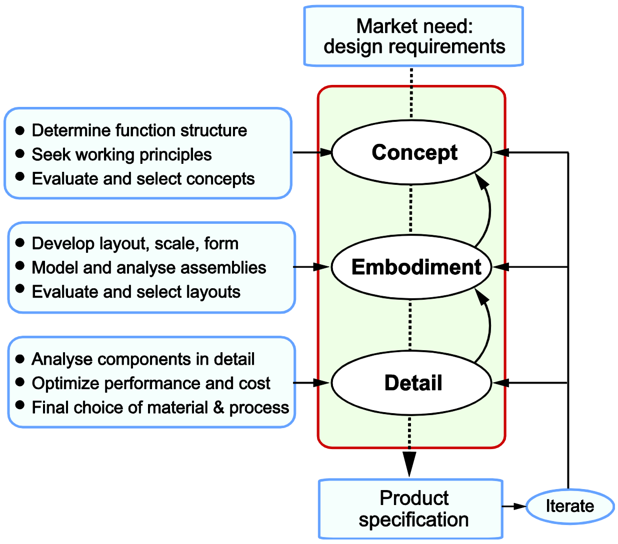

Figure 11. A generic model of the engineering design process.

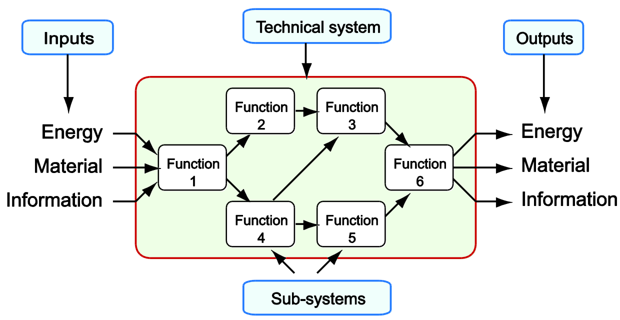

Figure 12. Setting product architecture.

Despite this, the design needs to move forward and, if needed (which is generally the case) loop-back to rethink aspects of the layout or even the concept, although in this case the ripples from the change can be far reaching. The more the design progresses, the more costly and time consuming will be any change in the design that forces a design loop to be taken. Materials and processes play an important part in this phase. They enable certain architectures and constrain others in a way that helps the design team to evaluate each architecture and keep moving forward. As the knowledge about the architecture of the system matures the need for more detailed data on materials and processes grows. A class of materials may not have enough detail, given the range of material properties within each sub-class. In some cases, particular members of each sub-class need to be identified at this stage to enable the design.

From a manufacturing perspective, the general shape of each product component is now more or less set, so decisions about the shaping of each component can now be taken. As the assembly of the components grows in importance, so the joining of parts gains prominence within the manufacturing decision making process.

6.3. Detail

In the detail phase, the components and assemblies of the product are analysed and checked for safety. Safety factors are applied to specific parts either because design codes and procedures enforce them or because the design team decides they are prudent. The loads carried by the structural parts are calculated or reliably estimated, either by hand or using computer aided tools (e.g. finite element analysis) allowing that the dimensions of the cross sections of parts or thicknesses can be set. All components are examined and designed for safety, reliability and maintainability. The shape of the parts is optimized to maximize performance and minimize cost; trade-off methods are applied to resolve conflicts between the two. One of the control-variables of cost and performance is the choice of the material to be used in the part. The ideal material in terms of performance is not, in general, the cheapest. Here is particular instance in which CES Edupack can help resolving the conflict, using penalty functions (Ashby, 2011.)

From a materials perspective, all analyses have to be carried out knowing the exact mechanical, thermal, optical or other properties of the materials used in each part. This means that the designer will be looking at a specific metal alloy, or a given polymer grade. These can only be found at the member level on the structure presented in Figure 8.

At this point a final choice of joining and surface treatment is made. Joining was probably tackled already in the previous phase, but now that a specific grade or alloy is in place, it may be revisited for verification. Surface treatment of particular parts is also important, especially where different sets of parts are in contact (functional interfaces) and specific tolerancing or surface roughness are required. Some materials acquire their final properties through heat treatment, which can only be made after all the primary shaping and joining have taken place. Painting and coating is the final step.

7. Design as an iterative process

Design in general, and mechanical design in particular are iterative activities. Iterating is, of course, time consuming and costly, but a systematic search for creative solutions early on in the process is not, in the grand scheme of things, either extremely costly or terribly time consuming and is fundamental to the design of innovative products. Having said this, the more downstream we move in the design process, iteration loops become more costly and time consuming, because each small modification affects more and more work that was already done and now needs to be redone. But sometimes it happens, and assumptions that were taken in the beginning are not realized downstream and the design needs to loop back to revise these assumptions. Figure 4 early on in this White Paper demonstrated this in a graphical way.

Robust design is a methodology that may help in taking out some of the uncertainty of design, but it will not prevent it completely. With this methodology, designers will attempt to study whether small variations in design parameters will affect the product's performance in unexpected ways. If this does not occur, than the design is *robust*. This can be done via specific statistical methods, of which the design of experiments is one, in such a way that the full range of possible variations does not need to be tested – only a subset will do. This can be quite helpful when designing with a lot of unknown variables and not enough time (or money) to test every possible configuration of the system. The method is powerful, but the choice of variables to test and whether or not they are independent can make a difference.

Back to materials and processes. The CES Edupack offers support on the selection of both materials and processes in such a way that design iteration loops are easily accommodated. All the steps of selection of material and process are reversible, and all the assumptions are easily retrieved and altered as needed, with results shown immediately.

8. Summary and conclusions

In this paper we have attempted to bridge the gap between material and manufacturing process selection and mechanical design. Along the way we looked briefly at specific tools to enhance creativity and perform detailed design tasks. We also introduced the CES range of tools that help in selecting materials and processes. We have not tried to visualize a flow of materials selection and manufacturing process decisions that is concurrent with engineering design. Figure 13 attempts to do just this. It summarizes the relative importance of materials selection and manufacturing processes selection in the design process. It depicts the design front moving from concept on the left to embodiment and detail on the right and the relative importance of material and process information dynamically changing. It shows in a very simple way the relative importance of materials decreasing with the moving design front and processes taking the most relative importance by the end. Within the materials camp, families, classes, subclasses and members are tackled sequentially, but are not compartmentalized (the frontiers between them are not vertical) and the transition is smooth. Also, shaping takes on the most relative importance in the beginning and finishing takes on the major part towards the end, but in the case of processes, the idea is that the design team never closes any of the processes – instead their parameters are refined right until the production specifications are set.

Underlying this visualization and the descriptions in Section 6 is the notion that design is performance-driven, meaning that the artefact is being designed to maximise its performance. This may not always be the case. Frequently the principal objective is to minimize cost. Then design for manufacture becomes a dominant concern. In these circumstances Figure 13 may become inverted taking the shape of Figure 14. This typically happens for incremental, or adaptive design (see par. 2.4) in which a team takes a mature design and tries to reduce its cost focusing specifically on its manufacturing processes,

Whatever the type of design, either performance driven or cost driven, materials and processes play an important role. The particular importance of materials or processes depends on the type of design. In real design problems almost nothing is strictly black or white, so one can expect a mix of performance and cost driven approaches in all designs, so selecting materials and processes becomes a question of balancing the trade-off between performance and cost.

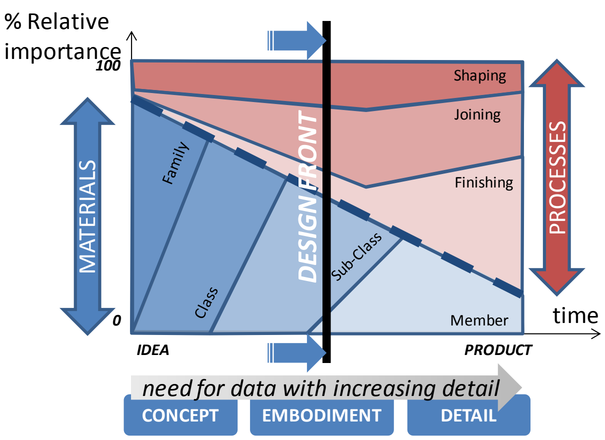

Figure 13. Relative importance of defining materials and manufacturing processes across the design process of a performance-driven artefact.

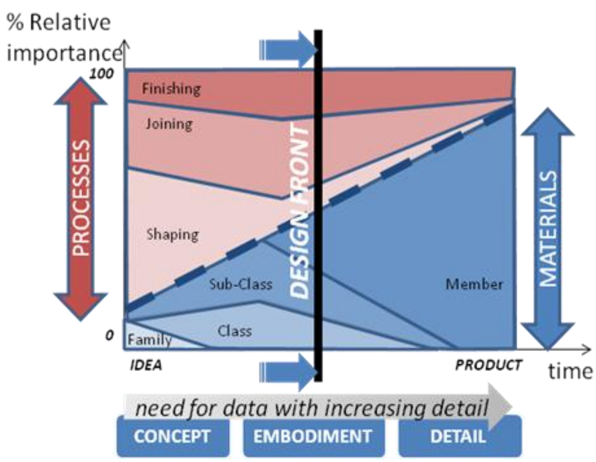

Figure 14. Relative importance of defining materials and manufacturing processes across the design process of a cost-driven artefact.

9. Further reading

A chasm exists between books on Design Methodology and those on Materials Selection: each largely ignores the other. Pahl and Beitz has near-biblical standing in the Design camp, but is heavy going. The books by Cross, Ullman, and Ulrich and Eppinger take a more relaxed approach. The short monograph by Ulrich (2011) is particularly helpful. But all of them more or less ignore Materials.

In the Materials camp, the books by Budinski and Budinski, by Charles, Crane and Furness and by Farag present the Materials case well, but are less good on design. The best compromise, perhaps, is Dieter.

Articles and texts on design methodology

Ashby, M.F. (2008) "Materials and product design, a White Paper", Granta Design, Cambridge, UK. (*One of a series of White Papers on Materials, available from* http://www.grantadesign.com/download/pdf/designpaper.pdf.)

Ashby, M., Cebon, D. (2007) "Teaching engineering materials: The CES Edupack", Granta Design, Cambridge, UK. (*Another one of a series of White Papers on Materials, available from*)

Cross, N. (2000)"Engineering design methods", 3rd edition, Wiley, Chichester UK. ISBN 0-471-87250-4. (*A durable text describing the design process, with emphasis on developing and evaluating alternative solutions*.)

Dieter, G.E. and Schmidt, L.C. (2009) "Engineering design", 4th edition, McGraw Hill, NY, USA. ISBN 978-0-07-283703-2. (*A clear introduction from authors with a strong materials background*.)

Pahl, G., Beitz, W., Feldhusen, J., Grote, K.H. (2007) Engineering design: a systematic approach. Springer, 3rd edition, translated by K. Wallace and L. Blessing, The Design Council, London, UK and Springer Verlag, Berlin, Germany. ISBN 978-1-84-628318-5 (*The Bible – or perhaps more exactly the Old Testament – of the technical design field, developing formal methods in the rigorous German tradition*.)

Suh, N.P. (2001) Axiomatic Design: Advances and Applications. Oxford University Press. ISBN 0-19-513466-4 (*Professor Suh emphasizes that design happens concurrently across different domains: the customer, functional, physical and process domains; design requirements come from the customer and flow across the functional, physical (materials) and process domains, cascading the requirements from vague concept-independent parameters to concrete physical details*.)

Ullman, D.G. (1992) "The mechanical design process". McGraw-Hill, N.Y., USA. ISBN 0-07-065739-4. (An *American view of design, developing ways in which an initially ill-defined problem is tackled in a series of steps, much in the way suggested by Figure 2 shown here*.)

Ulrich, K.T. (2011) "Design – creation of artefacts in society", The University of Pennsylvania, USA. ISBN 978-0-9836487-0-3. (*An excellent short introduction to the kind of structured reasoning that lies behind good product design. The text is available* on http://www.ulrichbook.org/)

Ulrich, K.T. and Eppinger, S.D. (2012) "Product design and development", 5th Edition, McGraw Hill, New York, USA. ISBN 978-007-108695-0. (*A readable, comprehensive text on product design, as taught at MIT. Many helpful examples but almost no mention of materials*.)

Whitney, D.E. (2004) "Mechanical Assemblies", Oxford University Press, New York. ISBN 978-0195157826. (*A book dedicated solely to mechanical assemblies and how to design and analyse them, nothing on materials*)

General texts on materials and their selection

Ashby, M. Shercliff, H. and Cebon, D. (2010) Materials: Engineering, Science, Processing and Design, 2nd edition, Butterworth-Heinemann, Oxford, UK. ISBN-13: 978-1-85617-895-2, North American Edition: ISBN-13: 978-1-85617-743-6

Ashby, M. F. (2011), "Materials selection in mechanical design", 4rd edition, Butterworth Heinemann, Oxford, UK. ISBN 978-1-85617-663-7. (*An advanced text developing material selection methods in detail*.)

Askeland, D.R. and Phulé, P.P. (2006) The Science and Engineering of Materials, 5th edition, Thomson, Toronto, Canada. ISBN 0-534-55396-6

Budinski, K.G. and Budinski, M.K. (2010) "Engineering materials, properties and selection", 9th edition, Prentice Hall, NY, USA. ISBN 978-0-13-712842-6. (*A well established materials text that deals well with both material properties and processes*.)

Callister, W.D. (2010) Materials Science and Engineering: An Introduction, 8th edition, John Wiley & Sons, New York, USA. ISBN 978-0-470-41997-7.

(*A well-established text taking a science-led approach to the presentation of materials teaching*.)

Farag, M.M. (2008) "Materials and process selection for engineering design", 2nd edition, CRC Press, Taylor and Francis, London UK. ISBN 9-781-420-06308-0. (*A Materials-Science approach to the selection of materials*)

Shackelford, J.F. (2009) "Introduction to materials science for engineers", 7th edition, Prentice Hall, NJ, USA. ISBN 978-0-13-601260-4. (*A well-established materials text with a design slant*.)

Books and articles about creativity

Altshuller, H. (1994) "The Art of Inventing (And Suddenly the Inventor Appeared)" translated by Lev Shulyak. Worcester, MA: Technical Innovation Center. ISBN 0-9640740-1-X.

Ashby, M.F. (2012) "Materials and Product Design – a White Paper", 3rd edition, Granta Design, Cambridge, UK *(A White Paper on Industrial Design that can be down-loaded from the Help file of the CES EduPack or from the Granta Design Teaching Resource website).*

Goldenberg, J. and Mazurski, D. (2002), "Creativity in Product Development", Cambridge University Press, UK. ISBN 978-0-521-00249-3. (*An attempt at explaining creativity from a combined engineering and marketing approach*)

Jacoby, R. and Rodriguez, D. (2007) "Innovation, growth and getting to where you want to go" Design Management Review, Winter 2007.

Johnson, S. (2010) "Where do good ideas come from? The natural history of innovation" Penguin Books, London, UK. ISBN978-1-846-14051-8. *(A remarkable survey of innovation across a wide spectrum of industry sectors.)*

Kelly,T. and Littman, J. (2001) "The art of innovation", Doubleday, NY. ISBN 0-385-49984-1. *(An exposition by the founder of IDEO of the philosophy and methods of his design company.)*

Kolodner J.L. (1993), *Case based reasoning*, Morgan Kaufmann Pub. San Mateo, CA. ISBN 1-55860-237-2.

Rantanen, K. and Domb, E. (2002) "Simplified TRIZ: new problem-solving applications for engineers and manufacturing specialists", St. Lucie Press, CRC Press, USA. ISBN 1-57444-323-2. *(The authors, proponents of the TRIZ method for creating thinking, introduce its used in industry.)*

Savransky, S.D. (2000) "Engineering of Creativity: Introduction to TRIZ Methodology of Inventive Problem Solving", CRC Press, USA

Other publications of interest

Ashby, M., Attwood, J. and Lord, F. (2012) "Materials for Low-Carbon Power – A White Paper" 2nd Edition, Granta Design, Cambridge, UK *(A White Paper on power generation and its implication on materials scarcity and other related topics, downloadable from the Help file of the CES EduPack or from the Granta Design Teaching Resource website).*

Ashby, M., Miller, A. Rutter, F., Seymour, C. and Wegst, U.G.K. (2012) "CES EduPack for Eco Design – A White Paper" Edition 5.1, Granta Design, Cambridge, UK *(A White Paper on selection of materials with a special attention to the environment, downloadable from the Help file of the CES EduPack or from the Granta Design Teaching Resource website).*