Chapter 1
The Material Selection Strategy

Abstract outlines the general principles of material selection strategy, and what happens when it is restricted to material specialists instead of being considered as a multifaceted problem managed by teams with multi-layered skills. There is an explanation of the two main approaches used in material selection strategy, the derivative and non-derivative methods, and an outline is provided of the main differences between them. Some available tools are presented.

Introduction

In the spring of 2011, a friend of mine, an engineer who works in a multinational company accepted an invitation to talk to my students who were attending a first-year course in metallurgy and materials. While he does have an engineering background, he is not a metallurgist, and he works in the field of product and market development in a highly diversified international company. He was fervent in talking to future engineers—namely engineering students—discussing competences, skills, the attitudes that people who want to modify and improve the environment and world for their own children have, but he reminded them that the world can be shaped only if everyone concerned reflects on and comes up with choices and decisions. He commented frequently on typical Monday morning business meetings, where, at the beginning at least, people from different company unit areas are sitting around the table sipping from cups of black coffee to try and wake themselves up, everyone with their smartphone in their pocket because they have been told to shut them down so they can concentrate on what is being said. They struggle for a time to keep in stride with the meeting and to participate actively, but technical discussions can often be very difficult for nontechnical people, and in the end, in the stakes between the coffee cup (for concentration) and the smartphone (distraction), it is the cup that loses out to the challenge of the phones, which get turned on again.

That day, an academic and a company manager agreed that it is very important and worrying to consider just how many parts of multifaceted problems relating to product improvement or product development processes (the latter with regard to the most challenging cases) are lost because the multidisciplinary skills of a project team are only potential, however efficiently they may be expressed. This is

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particularly true when a product (re)design process involves the choice of material or material selection process. It is easy enough to leave questions of materials to material specialists or designers, but it is by no means rare that the material potentialities illustrated by such specialists in complicated formulas, data sheets regarding the mechanical properties of on-the-shelf materials, diagrams, and in some other dramatic cases, even by chemistry are finally discarded because the material is too expensive. On the other hand, discarding a choice of the material to be used simply on the basis of its dollar-per-kilogram price is nonsense when different materials with different mass versus volume densities and different resistance limits have to be compared. A major example is what was usually commented on in the past about the use of a magnesium metal-based material as a substitute in the automotive sector. One of the main drawbacks was the higher price of magnesium against aluminum. On the other hand, it was not considered that despite the fact that raw materials are purchased by procurement in dollars per kilogram, the final optimized quantity of material in the end product depends on how much raw material a designer actually needs in order to realize part sections capable of supporting the same external loads in a baseline case.

Sometimes, material selection problems are of greater complexity. This may be the case when the project team is asked not to make a choice from among candidates of the same material class, for example, which is the best contender among alloyed steels for a motor crankshaft. The challenge might sometimes be to create an enlarged point of view. For example, what class of material is the best candidate to give the most powerful and efficient contribution to weight saving in cars, considering that the current snapshot on the average car depicts a percentage lightweight share onboard of about 29 % in 2010 (Mc Kinsey 2010). With regard to the remaining "heavy" share of the vehicle, steels and cast irons dominate.

Reducing the steel and cast iron share in the weight on board an average internal combustion engine motor vehicle is not easy, because they carry load types that make it difficult to find lightweight solutions in the substitution of materials. For this reason, it is really difficult to reduce the weight of a conventional 1400-kg vehicle even by 20–50 kg, a very low percentage. But by decreasing gear components, avoiding crankshafts, and reducing chassis elements, that is, by decreasing the number of components that cannot be made of light materials, the potential lightweight share increases. This is feasible in new battery-charged electric vehicles or fuel cell-powered cars where about 200 kg is a reasonable target.

Material specialists love to claim that materials largely contribute to product improvement and development processes. We like to consider the choice of material as a "quarterback" in several challenges, since such decisions could make a considerable impact on the entire product value chain. Thus, it is interesting to take a brief progressive look along the entire value chain, in order to understand if we are willing to bet on our quarterback, thus deciding to turn off our smartphones and rejoin the meeting we abandoned for a time.

Selection of materials is strictly linked to product manufacturing phases. That is to say, over the life cycle of a product, manufacturing covers the "cradle-to-exit gate" stage, namely acquiring raw materials, shaping them, and (if necessary) carrying out some operations to fit subcomponents and assemble the final product.

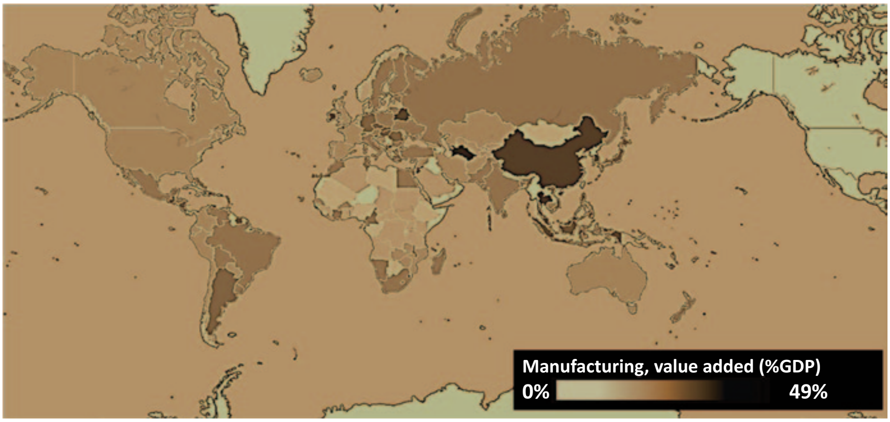

Fig. 1.1 Value added is the net output of a sector after adding up all outputs and subtracting intermediate inputs determined by the International Standard Industrial Classification (ISIC). (Source: World Bank national accounts data and OECD National Accounts data files)

Manufacturing is an essential part of economics for many developed countries. It is a fact that a nation that wishes to reach a developed status significantly increases its own proportion of gross domestic product (GDP)-related activities devoted to manufacturing.

A snapshot of the added value of the manufacturing sector per country (Fig. 1.1) depicts the recent situation—an average value of about 12 % of GDP on a world scale, about 20 % if we consider only the developed countries, with peaks of over 40 % in some developing economies. In addition, it is a fact that manufacturing must culminate in products that people need and want, if they are to act in a competitive global marketplace. And it is also a fact that countries whose offer in the manufacturing sector cannot be completely absorbed by internal demand usually create strategies in order not to shrink back to national boundaries. Thanks to the global market, products manufactured in Germany can be absorbed by larger but more competitive markets. Only high-quality products that are reliable, economical, easy to use and manufacture, and can reach the market in a short period time would have a chance for survival. A foreseeable increase in the aggregate demand of high-quality products against price and cost competitive products is an anthropologic fact, rather than an economic fact. As is well outlined by McKinsey Quarterly (2013), the relative role of low-cost products devoted to a vast, developing domestic market has been winding down since countries like China began to get rich. The income of more than half of China's urban households, calculated on a purchasing power-parity basis, will catapult them into the upper middle class—a category that previously barely existed in China. The members of this group are already demanding innovative products that require engineering and manufacturing capabilities that many local producers do not yet adequately possess. The result is that product value chains are becoming more complex, primarily because many new consumers are growing more sophisticated and demanding. The choice of materials is a key issue in the process, which leads to a rise in the complexity of a product value chain.

After the product is on the shelf, namely sold to customers or users (sometimes these can be different subjects), the usage stage starts: Some factors connected with materials can substantially influence consumers' evaluation on usability, quality, and durability. Product development follows, therefore, a two-tier approach: one is externally projected to recognize customer needs and the other is internally focused mostly on the domain of engineering in that it aims to define such key features in a product that can efficiently and powerfully translate customer needs into a success story, possibly surpassing the customers' expectations. It is not rare to find that the choice of materials constitutes the added value of a product. To the touch of the hand, the aluminum used in smartphone cases is perceived as more appealing than polymers. Superior raw material and manufacturing costs for such choices have been powerfully deployed by engineers. Aluminum, they bet, would offer more resistance per gram, and the cover case can be thinner, wider but lighter, thus suitable for a larger and more colorful screen. Apple produces a smartphone 40 % of whose weight is owed to metals (aluminum accounts for 18 %, stainless steel for 16 %) against a very low (1.8 %) weight of plastics, carefully shaping publicity in terms of saying they have created an environment-friendly life cycle for electronic goods mass production. After the usage phase, the choices made on the material to be utilized, decisions that were taken in the design phase, also determine end-of-life management since the product can be disposed of,reused, or in the best cases, recycled. During both the usage and end-of-life phases, there are some negative externalities: The choice of higher-carbon-footprint materials could impact economically on revenues if governments choose to reduce such externalities. As opposed to that, choice of recyclable materials would be a strategic decision to progressively reduce the higher cost of new metal alloys that are expensive today but have high recycling potential. Recycling reduces the impact of the cost of virgin materials.

For example, it is known that the choice of lighter materials to put on board a vehicle fueled by gasoline can contribute to reducing emissions, namely the carbon footprint of the vehicle over its life. A fuel–mass correlation factor (which Ridge (1998) sets to 1.08×10^{-4} kg CO_{2eq}/km kg) can help to point out how the linear function emissions over travel distance can be redrawn by a gentler slope as shown in Fig. 1.2. On the other hand, lighter components made of metallic materials, such as aluminum, magnesium, and titanium, are usually "dirtier" in the extraction and shaping processes, even though the direct emissions from their usage are lower than those of heavier materials. The emissions "stored" in manufacturing have, therefore, to be accounted for in the net balance between the cleaner and dirtier phases when, in order to make a decision, we compare lighter scenarios with those of the baseline.

Minimizing the consumption of energy during manufacture and use, increasing energy consumption from renewable sources, as well as maintaining water and air quality at the highest purity levels are all societal benefits when they are carefully considered in product plans and designs. While in the past relevance of such issues was devoted to sustainability consciousness of material specialists, product development engineers and designers, it has proven that today further efforts put into designing and development of sustainable products may also have positive impact onto competiveness of products.

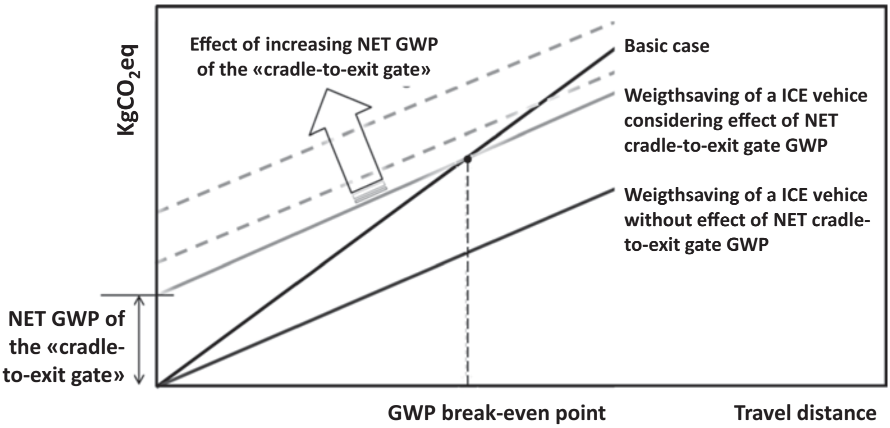

Fig. 1.2 Scheme for the assessment of positive or negative global warming potential (GWP) of lighter automotive component: seeking the GWP break-even point

Careful selection of materials may give control of the quantity and types used in the manufacturing phase, thus leading to a powerful re-think on assembly and how product functions can be maintained and repaired. As consumers attribute importance to a product's usability, among their own interests, an optimized configuration of material-manufacturing-costs is a concurrent added value that consumers recognize in competitive products.

On the market domain, reducing emissions is becoming a further added value in competitiveness. The US government is making important progress toward reducing greenhouse gas (GHG) emissions. A large number of US states and localities are implementing clean energy incentives and clean energy targets—from voluntary emission goals and green building standards to mandatory cap-and-trade laws similar to the carbon taxes of EU Directives, which give polluters a financial incentive to reduce their GHG emissions and encourage the reduction of negative externalities in their own production processes.

Scope of Material Selection

Illustrious (Farag 1989; Dieter 1991; Charles et al. 1997; Lewis 1990; Ashby 1999) and more recent milestone literature (Ashby and Brechet 2004) in the field of the selection of materials approaches the problem in terms of strategy. Thus, by introducing the term strategy, the problem of material selection is enlarged to define not just a method but plans and actions that will on a long-term basis have a substantial impact on the success of a product on the market, and consequently on the success of firms against competitive forces (Porter 1980, 2008).

What we can state at the beginning of the story is that the selection of materials is a complex and multifaceted challenge that requires teams with multidisciplinary skills. Such skills shall be completed by seeking people who may remind engineers that something which is the best is not always something that can be sold, if the customer does not perceive the difference. As well as having in the team people capable to argue for considering cheapest solution for material chosen today would make projected long-life product costs rise. And, lastly, it is a matter of fact that teams who do innovative things are made of people capable to explain technology in easy words.

Whatever the final objective or objectives of the strategy are, a material selection strategy is performed proceeding with three main consequential tasks as follows:

1. The translation of customer or user needs (i.e., external analysis) for the product, influenced by material features into technical and nontechnical requirements (i.e., internal analysis);
2. On the basis of a technical and nontechnical set of requirements, namely the *material key-features inventory*, as developed in (1), the formulation of performance *metrics* to measure how well a material matches a set of requirements;
3. A search procedure, namely a structured material selection method, in order to: (a) explore a solution space, (b) identify materials that meet the constraints, and (c) rank them by their ability to meet the requirements.

A selection strategy works by defining how it is possible to convert a set of inputs, which we call the *requirements* of the product, into a set of outputs. In other words, an effective material selection strategy shall pursue solutions capable to put into a shape customer requirements and contemporarily giving perception to users their expectations have been finally satisfied.

What does the triple-tier approach consist of in practice? That is, what do the formulation of constraints, the formulation of metrics, and the defining of search procedures mean, and what role do they play? Given that there are two different types of methodologies that we can follow, firstly it is convenient to fix the key concepts, and then, as soon as we have a hold of the main ideas, we should consider refining such concepts by discussing these two macroapproaches.

Let us consider an example.

When we go to the bike shop and look around to buy our new bike, firstly we are conscious about our budget. Our budget is obviously related to the price, but not exclusively. We consider several aspects at the same time in order to judge whether our main needs could be satisfied by the bikes we are "screening" in front of our eyes, e.g., whether they give us the right kind of feeling that they will be light and robust enough for the main type of riding we do. Weight and frame rigidity is often an issue for many bikers. A bike manufacturer knows that the targeted market segments are sensitive to this aspect, but customers are sufficiently specialized to understand that lightness must not exclude robustness and durability. All these external requirements are input requirements collected from the market (often referred as the "*Voice of Customer*" or *VOC*) but they need to be translated into technical functions. The translation process from the external or customer needs to the internal or designer requirements will be discussed in depth in Chap. 2. Here, it is enough to focus on the general process. For example, while the customer thinks about a lightweight bike, the engineer thinks of the density of construction material. Furthermore, when a biker is willing to pay $ 700 for a lightweight bike but he wants to put it under pressure by riding it off track, he will probably expect the bike to be robust enough and not to break all of a sudden. The engineers therefore think about the toughness, resistance, or resilience capability of the frame material. This process is what we call in material selection strategy the translation of needs (or external) requirements into technical (or internal) requirements. If you acute reader have gone beyond the work of the writer, you may already have identified the following crucial key point: Once engineers have translated the customer needs into measureable parameters, namely, once they have defined the *metrics*, how can they set the optimal values to target? Actually, this is the crucial question that most literature in the selection of materials tries to answer by introducing rigorous analytic methodologies, as we will discuss in the next section. At this moment, consider that engineers can define the main target for the metrics more or less precisely, namely for the technical requirements, or key factors, that can impact positively on the customer needs. Finally, the introduction of internal metrics and targets allows engineers to *rank and screen* various candidates in order then to select the one that matches the targets and respects technical and nontechnical constraints. One of the major nontechnical constraints that bike engineers fix is a target price that is not lower than marginal cost, as they are not indifferent to the budget constraints of the buyer. Other constraints are directly expressed in the technical language of engineers, e.g., how they translate the safe behavior required and expected of the bike frame when users ride down the hill. Engineers fix a minimum value of toughness resistance for the materials to screen, since they acknowledge that materials with lower values could possibly fail, leading to sudden and dangerous breakages at high speed.

What happens in every material strategy we plan is that several requirements that aim to answer customer needs will compete for fixed resources, such as the cost budgeted, the manufacturing and assembly time, and weight reduction, which contends against the strength of materials.

We have to make choices in a scarcity environment. In other words, we need to seek the optimal solution as the most efficient and powerful compromise between all the aspects we define as important, not just a high-performance solution regarding a few of these aspects. It is easy to find everyday examples of how people make purposeful choices when they are confronted with a scarcity of time or resources. If students spend all their time on metallurgy and materials, they can get full scores in the final exam, but that might mean getting a zero in machine construction. The choice made by efficient students is to balance out their time in order to get a decent grade in both subjects. This is what an economist knows well: The total amount of resources in an economy—workers, land, machinery, factories—is limited. A choice must be made.

The best way to keep in mind all the features product materials should satisfy is to consider them as various aspects of a multifaceted problem. Such a problem will be analyzed by multidisciplinary experts from the marketing area capable of hearing the customer's voice, from the procurement area for negotiating the costs of materials, from the research and development area for discussing performance targets and solutions, from the production area to mitigate impracticable solutions for the installed plant, from finance, to evaluate investments, e.g., in a new plant in order to satisfy technological breakthroughs that need introduction.

But all those people around the table need to speak a comprehensible and common language so that they can negotiate what is important and what is not, so they can decide what they are willing to discuss, make arrangements, and move toward a midway solution.

Material Selection Methodologies: An Overview

Material selection methodologies in engineering design are devoted to giving support to decisions often made in uncertainty and in the awareness that multiple conflicting criteria need to be managed and satisfied. Material selection methodologies are thus constructed to seek out the optimum choice of materials throughout a combination of certain key factors (controlled independent variables or design parameters) which permit the obtainment of a product characterized by a defined number of desired properties (dependent variables, quality response characteristics, functional requirements). The general cognitive scheme is well known in much literature in various fields (from economics to medicine and engineering) dedicated to making decisions in multiobjective optimization[1] (or MOO) problems.

A decision-making problem is defined as *multiobjective* if its solution consists of identifying multiple objectives that somehow have to be combined in order to yield one final solution. It is not likely that a single solution that simultaneously maximizes all the objectives (as we discuss in depth in Chap. 2) exists. As in the simple example of the bike development engineer, in order to realize a competitive product, engineers are generally asked to pursue some macroobjectives such as: (a) minimizing mass; (b) minimizing volume, so that less material is used (sometimes space is precious, as in mobile phones, portable computers, etc.); (c) minimizing material and manufacturing costs and increasing productivity; (d) minimizing the environmental impact, which usually involves positive impact in reduction of energy per kilogram of product, thereby reducing sources used and direct production costs.

The choice of a specific material among varieties that can simultaneously minimize mass, maximize stiffness, and minimize cost in light of all the given design constraints means that it is necessary to study the problems by considering that:

[1] Multiobjective optimization (also known multicriteria optimization) developed in the broad area of multiple criteria decision making, also known as multiple-criteria decision analysis (MCDA). MCDA is a subdiscipline of operations research methodology founded in the UK during World War II explicitly to consider multiple criteria in decision making in highly complex environments like the military. Generalizing the operational research and derivative methods further developed concerns with mathematical optimization problems involving more than one objective function to be optimized simultaneously, so that decision makers could pursue the best choice.

a. The properties of different materials are in conflict with each other and that we cannot simultaneously optimize all of them;
b. Beyond a certain trade-off, we arrive at the improvement of one feature of interest at the expense of worsening another; and
c. The search for balance is reached by optimizing the resolution of the trade-offs that exist between features and also by excluding solutions that are not respectful of constraints.

The above boundaries are typical for a multiobjective optimization problem. We discuss in the following paragraphs the two main approaches or methods that are applied to material selection strategy problems, dividing them into two macro-groups: (a) the nonderivative, or *implicit* methods, and (b) the derivative, or *explicit*, methods.

Derivative Method of Material Selection Strategy

A derivative method, or *explicit* method**,** for material selection starts from translating product requirements and needs into an objective function. For example, a reasonable objective function for the bike is minimizing the weight while still making it possible to charge the external load as the biker uses the pedals, inducing torsion and a bending state of stress in the frame tubes. The elastic deflection of the tubes caused by the biker pedaling has to be minimized, since the higher the elastic deflection during pedaling, the lower the energy transferred to gear and wheel. This is a further constraint with regard to the supporting load.

An explicit method thus starts from the objective function and expresses itself in terms of material features—e.g., density, elasticity module—and other parameters that depend on design.

Generalizing, such methods consist of writing out the *explicit* form of the objective function in such a way as to show how it depends on the material variables that can be used to rank the candidate materials.

In order to reach a better understanding of the process, let us consider the following typical classroom case of material screening among candidates.

The case consists of selecting the best candidate material to reduce weight on board a vehicle by substituting panels made of steel (as a baseline scenario), with magnesium alloy or aluminum alloy. The objective function therefore is to select out of the three screened materials the one that offers the lightest solution alternative to a real-case scenario that is defined by the following design constraints:

- Steel pan is the baseline scenario, and it accounts for about 30 kg (for the sake of simplicity, the case study considers a single large pan, while in reality 30 kg is the total weight for around five pans) onboard and have length L, width a, and thickness b as specified in Table 1.1;
- The load on the baseline pan is fixed and there is a momentum M_f that bends the pan.

Table 1.1 Comparison of weight saved on board when either conventional wrought magnesium or wrought aluminum is used to substitute a steel pan loaded in bending mode to external momentum M_f

Features	Magnesium alloy (type ZW30)	Aluminum alloy (type AA7050)	Steel (type AISI 4140)
Density (kg/dm^3)	1.81	2.74	7.87
Resistance limit (MPa)	125	220	450
Substitution factor (kg alternative/kg baseline)	0.44	0.49	1.00
a (dm)	19.49	19.49	19.49
b (dm)	0.019	0.014	0.010
L (dm)	19.49	19.49	19.49
Volume (dm^3)	7.21	5.43	3.80
Total weight onboard (kg)	13.1	14.9	29.9
Weight saved (kg)	16.9	15.0	0

Instead we conceive the redesign phase as something that will take advantage of a number of free options (namely the "free-variables" as engineers put it) left for the new component, such as:

- The thickness of the pan b, which is, however, limited to twice the baseline pan;
- The material, which means the material resistance limit.

Two real candidates are therefore considered for substituting steel pan: a wrought magnesium alloy, a commercial ZW30 series; and an aluminum alloy, a commercial AA7075 heat-treated alloy. The two material family groups, magnesium and aluminum alloys, are selected because it is known that potentially these two material classes offer advantages in weight-saving strategies because of their density, i.e., mass per volume, lower than steel. As shown in Table 1.1, the densities of magnesium and aluminum alloys are respectively 22 and 34 % that of steels.

On the other hand, 4140 steel has a higher resistance limit[2] than the two other candidate materials. This implies that we would expect to use a much greater material mass in order to realize new pan sections in either magnesium or aluminum that could support the same momentum M_f, namely the external load, as supported by the baseline steel pan.

On the other hand, due to the lower density, each kilogram of steel is expected to be substituted by a smaller mass of light alloy. This key concept in automotive sector literature that deals with vehicle weight-saving is known as the substitution factor. The meaning is: how many kilograms of a baseline scenario material can be substituted by 1 kg of a lighter material?

[2] In the case study, the resistance limit of a material is considered to be the resistance to bending fatigue, thus assuming the pan is loaded by this load type. This would not be true in a real case scenario, since the pan is not highly stressed by fatigue loading. In any case in many classroom cases, we prefer to consider some rearranged situation, reflecting on the simple shape and geometry of a component in a state of stress which would be usual in many other structural parts of the object.

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