1 Plastic Parts

This chapter compares the special features of plastic parts with alternatives made of metal or other materials. There are design rules that are directly justified by the manufacturing process. The information provided here is intended to give the designer a rough overview.

1.1 General Information

Difference between metal and plastic parts

Injection molded components differ from their metal counterparts in interesting ways.

- Plastic parts have a different shape for the same function.
- Often a conventional assembly can be realized in one plastic part, i. e. many functions can be implemented directly in a single component.

For example, consider compressor bars made of metal, plastic, and material combinations (Figure 1.1). First, it is important that the requirements are met. The question as to which material is better or worse is not possible until clear evaluation criteria have been established.

Figure 1.1 Metal and plastic compressor bars for ring binders

General requirements

In any event, the requirements for the compressor bars are:

- Function: Clamping force
- Economy (manufacturing costs).

The clamping force is generated by the deformation of a wire in the elastic range in the case of the metal variants and by the deformation of the plastic in the all-plastic variant. Due to the considerably lower modulus of elasticity of plastic, the plastic variant is only suitable for small forces and should not be used for very thick ring binders.

Manufacturing costs of injection molded parts are only favorable for large production runs

Manufacturing costs consist of the costs of material, production equipment (machine and mold) and labor. Roughly speaking, material costs constitute half of the manufacturing costs. Material costs range from 2 to 4 $/kg. In the all-plastic variant, the costs are very low because the product is created in a single process step. Although the machine and tooling costs are very high, if the expected number of pieces exceeds the limit of about 10,000 the tooling costs per part are low. And if many injection molded parts can be produced per hour with one machine, the machine costs per part are also low.

Functional integration leads to simpler production

The metal compressor bars consist of several elements that must be joined together. Basically, the fewer process steps that are necessary, the lower is the risk of failure in production. This should also be considered when compiling manufacturing costs.

1.1.1 Comparison of Designs (Conventional vs. Plastic)

Rethinking the design when using plastics

The use of plastics requires a fundamental design rethink. The example of a clothespin shows that the older product made of wood is cheaper than a similar plastic clamp (Figure 1.2). Both variants consist of two clamp elements that are pressed together by a metal spring. The wooden clamp can be cut very quickly from a profile-milled board. The corresponding plastic clamp is more expensive to manufacture and has inferior properties, because it can become brittle and break due to weathering.

A well-designed plastic clamp will consist of only one element, and that eliminates the need for assembly. In principle, plastic components can incorporate many functions. This is referred to as functional integration.

Cast structures can have very freely formed surfaces

A plastic component can have a very complex design if it is manufactured by injection molding. Due to the molding process used for production, the design of a plastic component can feature any type of free-form surface. In conventional components, the individual parts are predominantly milled and turned from the solid, with the result that simple shapes predominate here.

Considering a comparison to conventional products, the following generalization can be made:

Conventional components often consist of various individual parts that form an assembly. By contrast, good plastic components often consist of a single part (Figure 1.3).

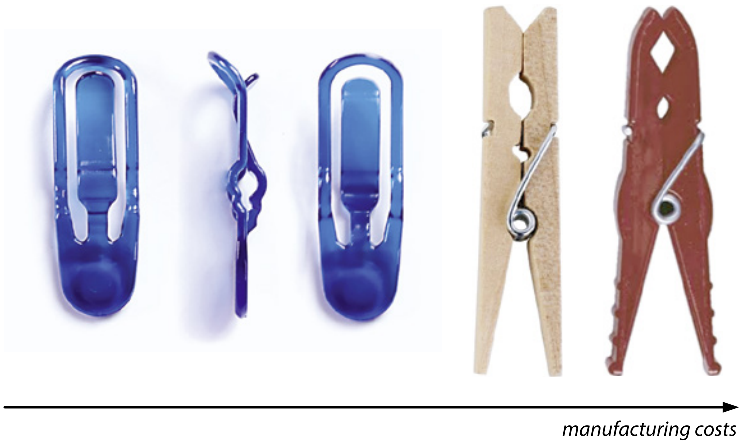

Figure 1.2 Manufacturing costs of clothespins of different designs

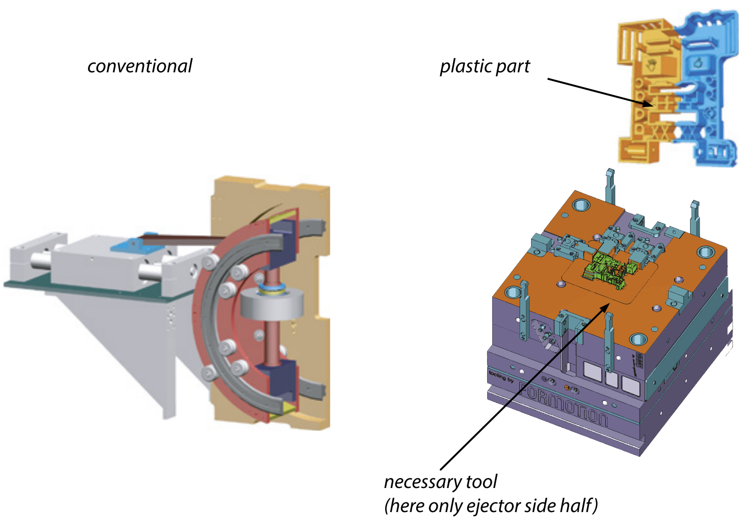

Figure 1.3 Comparison of a conventional assembly consisting of different individual parts and a plastic component, along with the mold required for production [image source: Ziebart/FH-Bielefeld, Ritter/HS-Reutlingen]

Good designs in plastic consider the feasibility of using injection molds

During the development of a plastic component, consideration must be given to the mold at the design stage, because it limits the design freedom to a certain extent. In any event, the designer of an injection molded part should be aware of the possibilities afforded by mold technology, because slight changes in the shape of a plastic component can have a very large effect on the cost of a mold. Molds consist of many individual parts and are in turn very complex assemblies. The molds must perform different tasks (Figure 1.4). The actual mold cavity has to be filled with melt and the heat of the melt needs to be dissipated (cooling) so that the plastic part will become solid and stable and can be demolded via an ejector system.

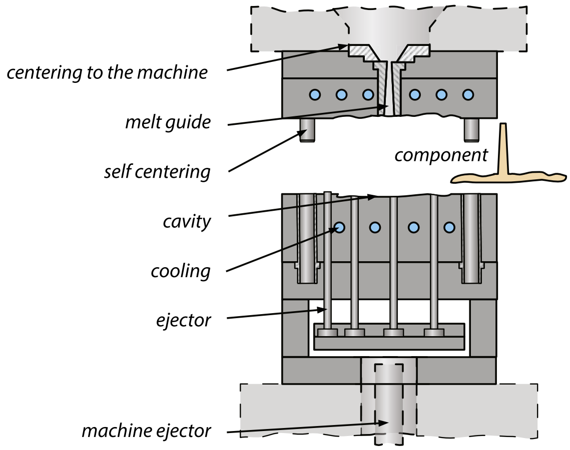

Figure 1.4
Design and functions of a simple injection mold

Demonstration mold shows effect of good component design on the mold

For demonstration purposes, the "Polyman" plastic component shown in Figure 1.3 is poorly designed on the left side and well-designed on the right side. This assessment of the design relates to the mold implementation. For the various lateral openings, three sliders are required on the poorly designed side to demold the undercuts (Figure 1.5). With a few minor changes to the shape, the well-designed side can dispense with sliders completely. This makes the mold less expensive and less susceptible to faults during production or requires less maintenance.

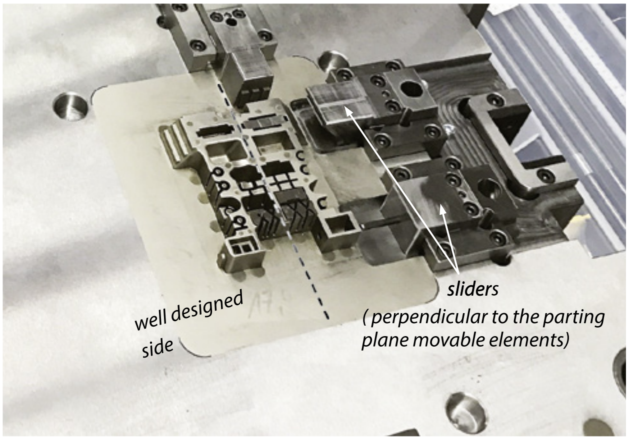

Figure 1.5
Ejector side for the Polyman demonstration part [image source: Ritter/HS-Reutlingen]

1.1.2 Special Features of Plastics

The biggest advantage of plastics is their low melting point

The most important property is the melting temperature of plastics, which is only about 1/10 that of metal (Figure 1.6). This makes it possible to cast plastics in steel molds of very complex shape. The precision of the steel molds can be transferred to the plastic component largely without the need for reworking and can be repeated almost as often as required. However, the complexity and expense of such molds render this production barely suitable for small production quantities. Plastic parts manufacture is thus almost always a mass production process.

A distinction needs to be made between melt temperature and transition temperature. In processing, the melt temperature is always much higher than the transition temperature from the solid to the melt state. Strictly speaking, only semi-crystalline plastics can melt, because melting entails the liquefaction of crystalline areas. Amorphous plastics, therefore, merely soften. This may not become clear until Chapter 5, where specific material properties and characteristic temperatures are discussed.

Temperature of the plastic melt

1.1.2.1 Comparison of the Properties of Plastics and Metals

Further comparison with metals reveals major differences in properties. Thus, specific applications may only be feasible in one of the two materials.

Mechanical properties of plastics are not as good as those of metals

Table 1.1 Comparison of Metals and Plastics

Property	Metal	Plastics
Young's modulus	high	low
Tensile strength and yield strength	high	moderate
Density/weight	high	low
Young's modulus	no	possible

- The modulus of elasticity of metals and especially steels is approx. 1000 times higher than that of plastics. Applications subject to high load requirements are therefore largely limited to metals. Plastic components would deform too much in such cases.
- Metals are stronger than plastics. The issue here is that of component failure. This can be both a fracture and an unacceptable permanent deformation.
- Young's modulus and the strength of plastics are strongly dependent on temperature. For applications involving high temperatures, which can be as low as 50 °C, particular care must be exercised in the choice of material subject to long-term loads.

Young's modulus for plastics is temperature-dependent and therefore not constant

- The density of plastics is only approx. 1/7 that of steel. Applications that require a certain weight (e. g. pendulums for clocks or curtain weights) cannot easily be made in plastic.
- Some plastics are transparent.

A close comparison of different materials reveals further advantages and disadvantages.

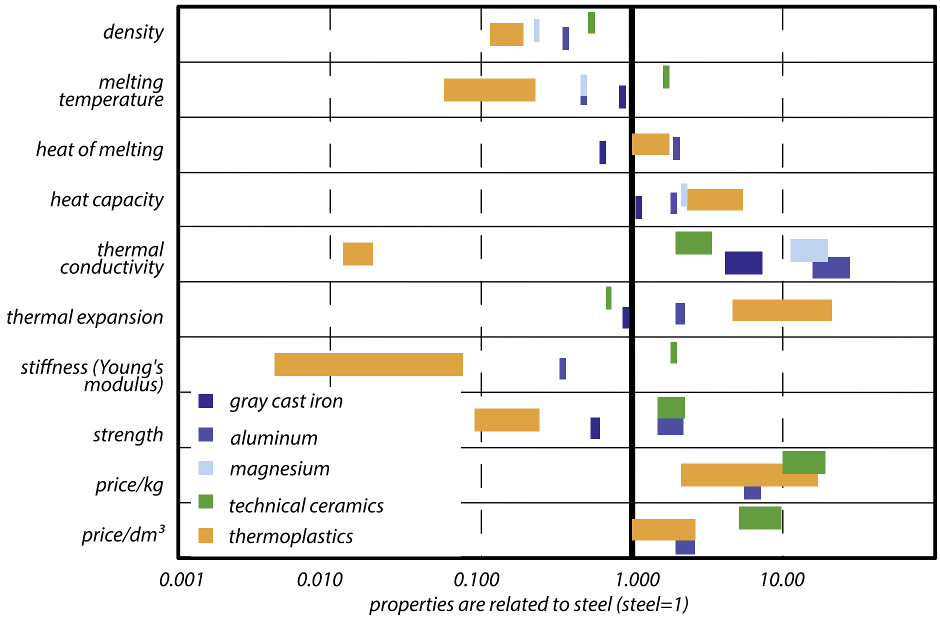

Figure 1.6 Comparison of thermoplastics with steel [source: WAK-Kunststofftechnik]

With regard to production, the low thermal conductivity of plastics makes it difficult initially to dissipate the heat of the melt from inside the component to the mold. The thicker a component is, the longer the cooling process will take. For this reason, plastic parts are thin-walled wherever possible. Jumps in wall thickness are unfavorable.

Low thermal conductivity enables precision injection molding of fine structures

The low thermal conductivity, however, also makes it possible to fill long, thin flow paths in a controlled manner. Plastic components can thus be considerably finer structured than cast metal components.

Plastics are usually more expensive per kg than metals

It is often assumed that plastics are inexpensive, but this is not the case. Especially those plastics that are intended for use at elevated temperatures can cost more than $10 per kilogram. When expressed in terms of weight, the outcome is the specific raw material price, which is given in $/kg. This is comparable to that of metals.

1.1.2.2 Special Mechanical Behavior

Metals have a definite failure limit (yield strength)

Metals are atomic in structure, i. e. they are composed of individual atoms that form crystals in regular repetition during cooling. When a load is applied, the atoms move slightly away from each other, returning to their original state after the load is removed. This elastic behavior is linear, i. e. the deformation increases in proportion to the load. Above a load limit R_p, entire atomic layers shift; when the load is removed, the deformation remains (Figure 1.7).

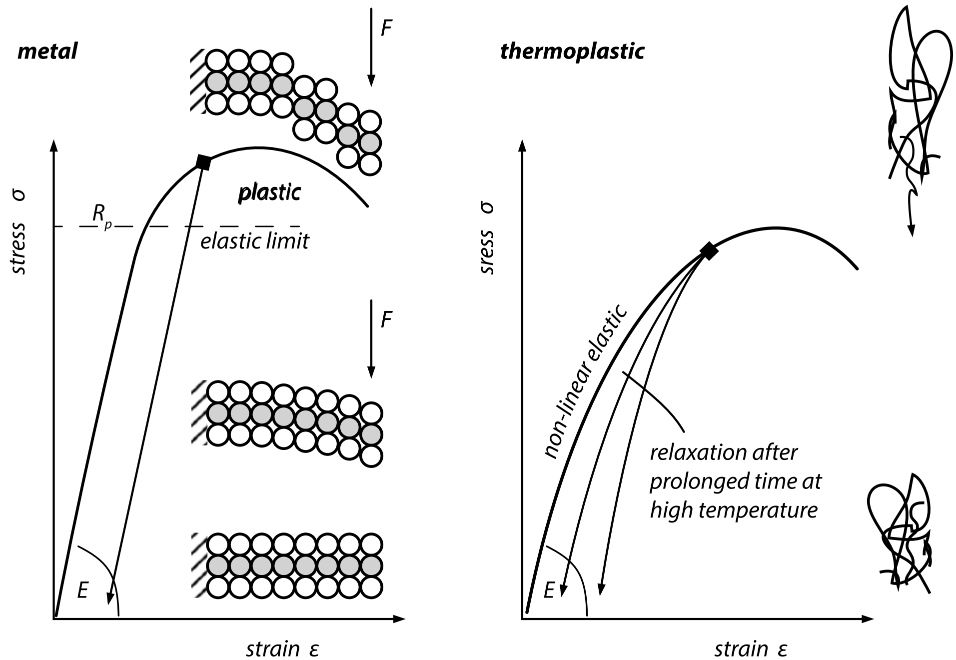

Figure 1.7 Elastic and plastic deformation of metals and plastics at different load levels

Plastics have a molecular structure, which can be imagined as a collection of tangled spaghetti. The entire tangle of molecules is initially elastic under load. At low temperatures, the molecular chains "stick" to each other; at higher temperatures, they are able to slide off each other. The deformation behavior is not linearly elastic, i. e. at high loads, the deformation becomes increasingly greater. The extent to which a load allows complete recovery of deformation depends strongly on its duration. A brief load is often elastic, while a load applied for a long time causes irreversible viscous deformation.

Mechanical failure of plastics is time- and temperature-dependent (viscous)

For accuracy, the deformation of plastics should not be called plastic, but viscous. Plastic deformation always describes an irreversible deformation; in metals, this occurs through the sliding of planes of regularly arranged atomic layers. Plastics, however, consist of tangled long molecules which, under load, can deform as a whole bundle and can partially recover their deformation. Viscous deformation is said to occur when the permanent deformation that cannot be recovered is time-dependent.

Difference between plastic and viscous deformation

The different plastics each have a specific molecular structure. There are two groups (Figure 1.8): crosslinked and non-crosslinked. Thermosets and elastomers belong to the crosslinked plastics. During processing, chemical bonds form between the molecular chains, preventing them from melting even at high temperatures. The following pages deal almost exclusively with non-crosslinked

Thermoplastics can soften or flow at higher temperatures thermoplastics. A distinction is made between amorphous and semi-crystalline thermoplastics. Amorphous means that the molecular chains are entangled totally irregularly. In the case of semi-crystalline plastics, it is possible for some of the molecules to form regular arrangements in crystal form during the cooling process.

non-crosslinked plastics		*cross-linked plastics*	
amorphous	*semi-crystalline*		
loosely entangled molecules	*entangled molecules and molecules linked by crystals*	*molecules cross-linked,*	*molecules cross-linked, soft intermediate segments,*
$T_{operation} < T_{glass}$ predominantly brittle at $T > T_{glass}$ plastic formable	$T_{operation} < T_{melt}$ at $T < T_{glass}$ brittle/elastic at $T > T_{glass}$ tough at $T > T_{melt}$ formable	$T_{operation} < T_{degradation}$ predominantly brittle non-meltable	$T_{operation} < T_{degradation}$ at $T < T_{glass}$ brittle/elastic at $T > T_{glass}$ tough non-meltable
thermoplastics		*thermosets*	*elastomers*

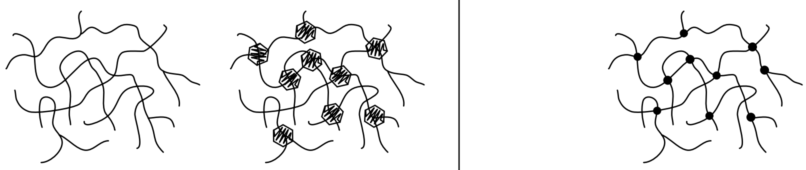

Figure 1.8 Structure and application range of plastics

Below the glass transition temperature, plastics are mostly brittle and hard

All plastics have a characteristic glass transition temperature. Below this temperature, the behavior is largely glassy, i.e. brittle. The individual molecules of the plastic are virtually frozen and cannot be displaced against each other. Permanent deformation is not possible; the plastic behaves elastically. Above the glass transition temperature, the plastic softens increasingly, turning from tough to soft. Under load, permanent deformation occurs to an extent that depends on the temperature and the duration of the load.

Above the melting temperature, crystals of semi-crystalline plastics melt

Semi-crystalline plastics have an additional characteristic melting temperature above which the crystals melt. While amorphous plastics can only be used below the glass transition temperature because, above it, they undergo noticeable viscous deformation under load, semi-crystalline plastics can be used up to the melting temperature range. The crystals hold the molecules together. Compared to crosslinked plastics, the crystals act as physical crosslinking points.

The load-bearing capacity of plastics is temperature-dependent

Mechanical behavior is strongly dependent on temperature, especially in the case of thermoplastics (Figure 1.9). At very low temperatures, all plastics are predominantly brittle and break without warning like hardened steels (behavior 1, also characteristic of thermosets). In the glass transition temperature range, slight necking occurs shortly before fracture (behavior 2); unlike metals, the maximum here is called the yield stress. Semi-crystalline plastics can deform extensively in the range between the glass transition temperature and the melting temperature. Very characteristic here is the shoulder-neck deformation (behavior 3). For actual applications, however, this behavior is of no further significance, because plastics should only be loaded up to their yield stress.

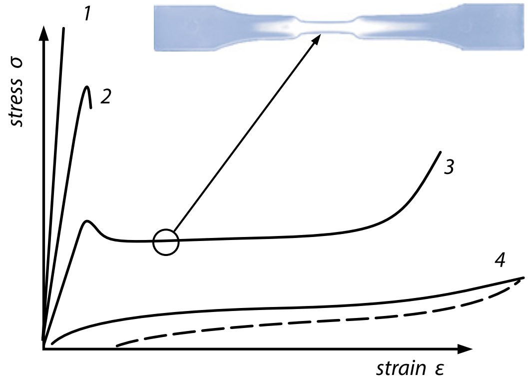

Figure 1.9 Deformation behavior of plastics under load
1: Thermoset or amorphous thermoplastic
2: Thermoplastic in the range of the glass transition temperature
3: Semi-crystalline thermoplastic above the glass transition temperature
4: Elastomer

It is interesting to note that semi-crystalline plastics in particular exhibit behaviors 1 to 3, depending on the operating temperature. Note that here the slope of the stress-strain curve becomes increasingly flat with increase in temperature, i. e. Young's modulus becomes smaller with increase in temperature.

Plastics for high-temperature use are more expensive

The molecular structure influences the glass transition temperature and, in the case of semi-crystalline plastics, the melting temperature. The heat deflection temperature characterizes the temperature up to which a plastic component still largely preserves its shape under load. This property is closely related to the raw material price (Figure 1.10).

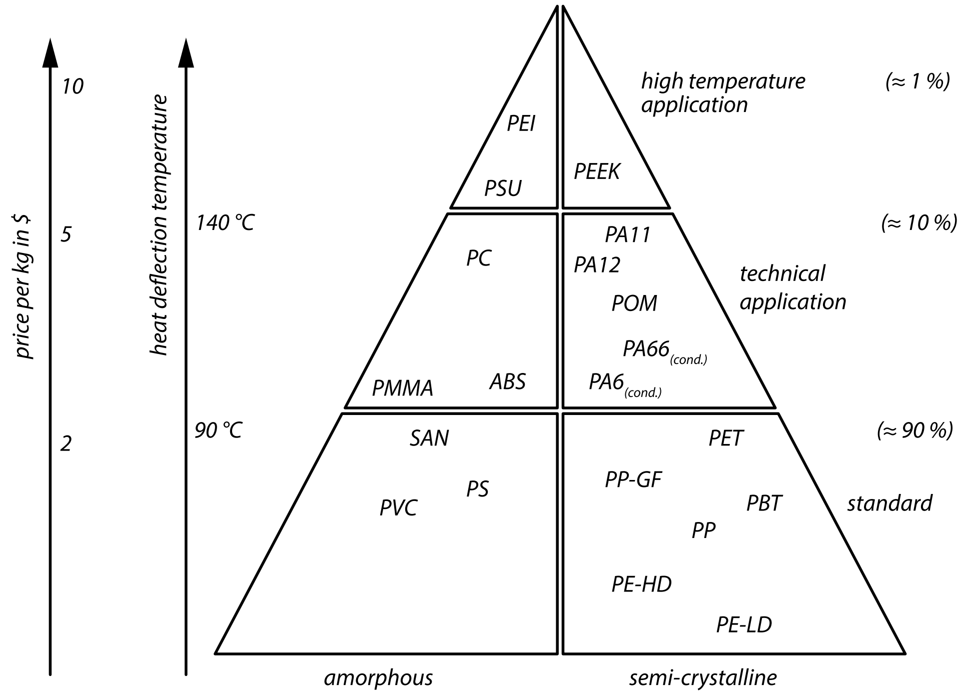

Figure 1.10 Important amorphous and semi-crystalline thermoplastics

The most important plastics are PP, PE, PVC

Even though there are very many different plastics, only a very few grades are used (Figure 1.11), with PP and PE playing a major role. This is because the properties of plastics can be modified within wide limits by means of fillers. This largely applies to stiffness (Young's modulus), which can be increased with glass fibers, for example.

Engineering plastics of high heat resistance are mainly used in the automotive sector.

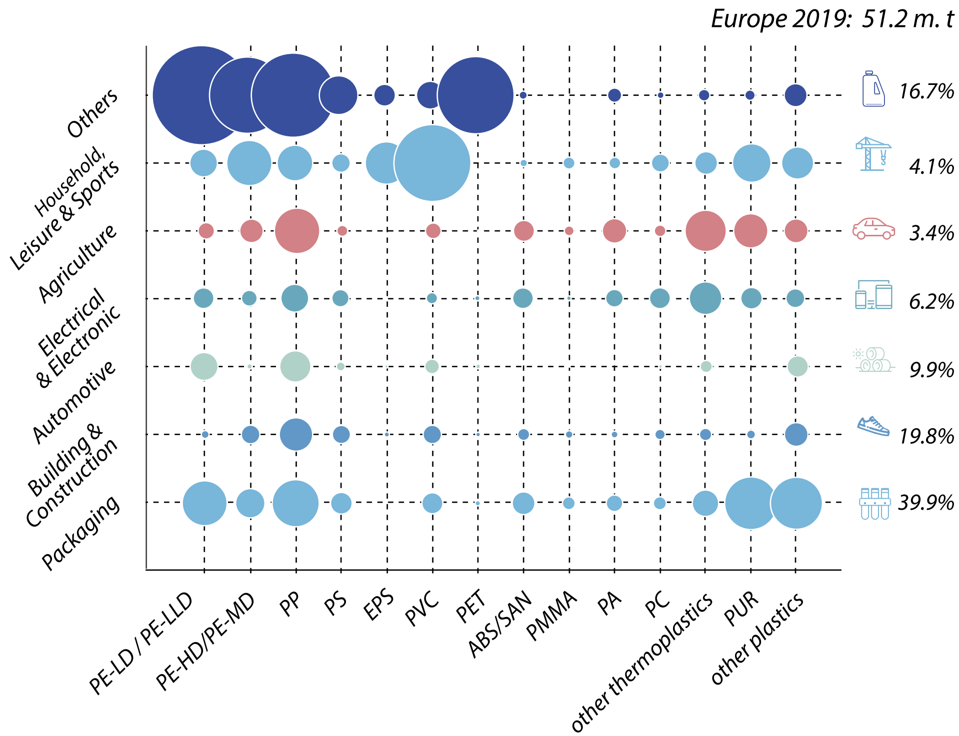

Figure 1.11 Predominantly used plastics by application [source: PlasticsEurope]

1.1.3 Reasons for Using Plastics

Plastics are chosen for a variety of reasons:

- Cost-effective reproduction
- Functional integration
- Material substitution
- Special properties
- Design
- Weight savings

Mass production requires cost-effective, repeatable production

Cost-effective reproduction means mass production. The cost of a single injection-molded component is very high because it cannot be produced without a suitable mold. Injection molds can be very expensive, with the price also depending on the complexity of the component to be produced. Complex components made of plastic are therefore always mass-produced items because the mold costs are spread over many components. Injection molding becomes an interesting proposi-

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