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Facilitating the Production of 3D-Printed Spare Parts in the Design of Plastic Parts: A Design Requirement Review

Alma van Oudheusden *, **Jeremy Faludi** and **Ruud Balkenende**

Department of Industrial Design Engineering, Delft University of Technology, 2628 CD Delft, The Netherlands; j.faludi@tudelft.nl (J.F.); a.r.balkenende@tudelft.nl (R.B.)
* Correspondence: a.a.vanoudheusden@tudelft.nl

Abstract: Using additive manufacturing for spare part production can ensure that spare parts are available for a long time. However, spare parts are currently not designed for additive manufacturing. This study aimed to find how the production of 3D-printed spare parts can be facilitated in the design of plastic parts. We used a literature review and illustrative case to find how the design requirements for standard injection moulded plastic parts relate to the manufacturing capabilities of additive manufacturing for spare parts. The design requirements were defined by assigning corresponding structural and material properties. These requirements were then used to construct and evaluate the capabilities of additive manufacturing compared to injection moulding. It was found that additive manufacturing is especially suitable for requirements like Accuracy, Heat resistance, and Chemical resistance. However, to fully enable 3D-printed spare parts, certain design challenges still need to be tackled. Designers should pay careful attention to the synergies and trade-offs between design requirements and the challenges that might arise from the combination of certain requirements. Also, designers should ensure products are easily reparable before considering 3D-printed spare parts. If we target these challenges in the design phase, we can facilitate 3D-printed spare parts that enable product repairability.

Keywords: 3D printing; additive manufacturing; repair; spare parts; circular economy; sustainability

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1. Introduction

The amount of waste from consumer products is increasing at an alarming rate. There are multiple ways to prevent waste from discarded products, but one key way is to repair them [1,2]. This is mainly because of two reasons: repair slows down resource loops [3], and the required investments are lower than for other recovery options [4]. However, one of the main problems in repair is that spare parts are not always available [5,6]. If we want to enable the repair of products, spare parts should be available for most of the product's lifetime.

In Europe, there are regulations to increase the availability of spare parts. These regulations specify that spare parts should be available within 15 working days for 7–10 years after the last market release [7,8]. However, it is difficult to predict how many spare parts are needed, and storing them in warehouses can be costly [9,10]. Some of these parts might not even be used [11], leading to higher costs and more waste [12,13]. This means that manufacturers need a new way to provide spare parts.

Increasing the availability of spare parts can be achieved with additive manufacturing. This method is increasingly used in the manufacturing industry to produce plastic end-use parts [14]. Using additive manufacturing means that, instead of keeping a large inventory of physical spare parts, a digital file of each spare part can be stored online and produced on demand [15,16]. This will save costs and waste from unused parts while making them available for a longer period [17].

While this approach can be used throughout the product, it makes the most sense for product-specific parts. The standardised parts in consumer products, such as nuts, bolts, and springs, are already mass-produced by third parties and are thus always readily available. Additive manufacturing is not a suitable alternative here, as conventional manufacturing of simple parts has lower production costs and lower environmental impact per part at this scale [18,19]. Conversely, product-specific parts cannot be used outside their target products, which means they are not readily in stock from perpetual mass production. Additionally, these parts are mostly plastic parts made with injection moulding. As injection moulding is unsuitable for on-demand manufacturing [20], these parts would benefit the most from 3D-printed spare parts. Therefore, we chose plastic parts made with injection moulding as the focus of this study.

Using additive manufacturing to produce parts that were initially designed for injection moulding introduces one major challenge: translating the design from one manufacturing method to another. Both the overall product complexity and specific part requirements, such as fine details and flexibility, can make it difficult to reproduce injection moulded parts with additive manufacturing [21,22]. Moreover, redesigning spare parts for additive manufacturing after the initial production gives minimal possibilities for design changes and creates an increased workload [14,23]. In the ideal case, printed spare parts would be enabled in the original part design. This means that parts should be designed for both injection moulding and additive manufacturing. However, how can that be achieved easily and effectively?

The main research question is then as follows: how can the production of 3D-printed spare parts be facilitated in the design of plastic parts? This leads to the following research questions for this study:

RQ1. Which design requirements drive the design for both injection moulding and additive manufacturing?

RQ2. How can these design requirements be used to facilitate the design of 3D-printed spare parts?

To answer these research questions, the relationship between design requirements and manufacturing capabilities was studied. We used a literature review to identify which design requirements are relevant and to assess the capabilities of injection moulding and additive manufacturing for these requirements. Then, we performed an illustrative case to show how the results can indicate the suitability of a part for additive manufacturing. By understanding how the design requirements affect the application of additive manufacturing, designers can facilitate the use of additive manufacturing to produce spare parts.

2. Materials and Methods

Our study was set up in three parts: we created and defined a list of design requirements, assessed the manufacturing capabilities of injection moulding and additive manufacturing for these requirements, and constructed an illustrative case for an exemplary consumer product. As this was an iterative process, the methodology is not presented chronologically.

2.1. Selecting and Defining Requirements

To find which design requirements drive the design for both injection moulding and additive manufacturing (RQ1), we identified which general design requirements are needed to describe the general functioning of a product part. To do this, the design requirements from previous studies on 3D printing for repair [21,22] were merged and supplemented with an additional literature review. These design requirements were defined further by matching them to relevant structural and material properties.

The cited studies were merged by sorting the requirements into groups and rephrasing them where needed, so they all represented a neutral state. For example, the requirement of Large forces was changed to Strength. The list of requirements was then revised and updated using insights from the literature review and case. This was an iterative process in which requirements were added, removed, and rephrased. The same approach was used to match the design requirements to relevant structural and material properties.

For the supplemental literature review, literature and books on mechanical and material engineering were used. We started with the book Materials: Engineering, Science, Processing and Design [24] as this is an essential work on material engineering. Literature was added to this using requirement-specific search terms and further snowballing. For example, queries were along the lines of "Additive Manufacturing OR 3D-printing AND Strength". Literature was accepted or rejected based on whether it provided fundamental insights into the described requirements and manufacturing processes on a commercial application level. During the literature review, it was found that this field is strongly industry-driven and that companies do not often publish their findings in scientific sources. Therefore, to supplement the literature review, we used grey literature such as design rule overviews and technical datasheets (TDSs) of printing materials. These were retrieved from prominent sources: industry leaders like Hubs and Xometry, material manufacturers like Formlabs and 3DSystems, and material databases like Granta Selector.

The resulting design requirements and properties were checked, and any redundancy was removed. Finally, the design requirements and properties were presented in a table. This table was used to define which data needed to be gathered to specify the manufacturing capabilities in the next step.

2.2. Defining Manufacturing Capabilities

To find out how these requirements can be used to facilitate the design of 3D-printed spare parts (RQ2), we compared the manufacturing capabilities of injection moulding and additive manufacturing. By understanding the gap between the two manufacturing methods and adjusting the design accordingly, it becomes easier to produce 3D-printed spare parts.

We selected three additive manufacturing methods for this study: selective laser sintering (SLS), stereolithography (SLA), and fused deposition modelling (FDM). These methods were chosen as they are commonly available and generally provide good-quality parts [14]. This also means that there will be enough information available to judge the capabilities of these methods.

The manufacturing capabilities of these methods were then quantified so they could be compared. This quantification was performed by collecting data on the structural and material properties of each requirement. For the structural properties, data were gathered from manufacturing documentation, such as design guidelines and machine specifications. For the material properties, data were gathered from material databases and technical datasheets. Here, a maximum of four materials were chosen that represented the outer ends of a wider range of suitable materials. The material selection was based on the applicable material properties that were defined for that specific requirement. In this way, we could limit the amount of data while still providing a fair representation of the whole range of possibilities for each requirement.

As there were variations in data quality, each data entry in the table was marked with a data quality score. This score was determined by assessing the data quality and availability, as described in Table 1. The assessments of manufacturing capabilities based on lower data quality will be less reliable than those based on high-quality data.

Table 1. The data quality assessment.

		Data Quality Assessment	Example
1	High-quality	There are sufficient data on structural and material properties to define the manufacturing capabilities for this design requirement. The material data are retrieved from standardised testing procedures (ASTM/ISO).	SLS has an accuracy of ±0.3%
2	Medium- quality	There are insufficient data on structural properties to fully define the manufacturing capabilities for this requirement. However, a general assessment can be made using the limited material data from standardised testing methods (ASTM/ISO).	Elastic resins make parts with stretchable and rubber-like properties (50D Shore hardness).
3	Low-quality	There are insufficient data on structural and material properties to define the manufacturing capabilities for this requirement. Claims are made on material capabilities, but the available data are qualitative and unofficial.	This resilient grade of FDM nylon is highly resistant to shocks and fatigue.
4	No data	There are no data available, the requirement is rarely mentioned.	Insufficient data.

Next, we rated all the additive manufacturing methods on each design requirement to find to which degree the requirements affect the application of additive manufacturing. This was performed using the colour-coding system in Table 2. The gathered data were presented in a table where each cell was marked with the corresponding colour code. This gives a visual presentation of which requirements limit the application of additive manufacturing the most for a given part versus which requirements are easily managed. In the next step, the illustrative case shows how a designer could use this assessment process to estimate the printability of product parts.

Table 2. The colour-coding system for the assessment of additive manufacturing (AM) capabilities compared to injection moulding (IM) and the assessment of part printability.

	Capabilities of Each AM Method Compared to IM (See Section 3.2)	Printability Score for Each Part Requirement (See Section 3.3)
Green	The capabilities of the AM method are similar to or better than IM.	The part requirement can likely be met with standard materials and post-processing. Likely no design adjustments or verification steps are needed.
Yellow	The capabilities of the AM method are somewhat inferior to IM (limitations to functionality or performance, especially in the high-end range).	Meeting the part requirement requires more specialised materials and/or extensive processing. Minor design adjustments or verification steps would be needed.
Red	The capabilities of the AM method are considerably inferior compared to IM, or the requirement is impossible to achieve with this AM method.	The part requirement is (almost) impossible to achieve. Major design changes or verification steps are needed.
Grey	The manufacturing capabilities cannot be assessed as data quality or availability is too low.	The manufacturing capabilities cannot be assessed as data quality or availability is too low.

2.3. Setting up an Illustrative Case

To illustrate how the results can be applied in the design of consumer products, we performed an illustrative case. The printability of ten exemplary parts from a consumer product was assessed using the insights from the literature review. The consumer product and its parts were selected based on their illustrative properties for the analysis process and their expected printability. The printability of these parts was then assessed by comparing their part requirements against the manufacturing capabilities from the literature review. Finally, we concluded what the main points of attention would be when this part would be designed for both injection moulding and additive manufacturing.

We chose to study a high-end vacuum cleaner as the European Commission is developing new eco-design regulations for this product category [25,26]. Also, the complexity of this product will give valuable insights into the printability of consumer products and the issues that might be encountered. From this vacuum cleaner, we chose the following ten parts: the bumper, LED cover, wheel suspension frame, brush locking cap, back cable cover, hinge, wheel and brush of the floor nozzle, and the container and inlet seal of the dustbin. These parts were selected to present a variety of design requirements and part complexity. Generally, all parts could be fully disassembled to give a fair overview of the capabilities and limitations of additive manufacturing rather than of reparability. However, one submodule was selected to explore the challenges that these submodules might pose for the application of additive manufacturing.

The selected parts were analysed in more detail. First, each part was analysed on the list of design requirements using visual inspection and a calliper. The observed requirements and properties were all marked in an annotated photo of the part. This was performed to see whether all part features were covered by the design requirements table and to obtain more insight into the interaction between requirements. Then, the part material was identified through material code observation or Fourier-transform spectroscopy (FTIR) to give a representable material selection. A representative printing material was selected for each part based on the applicable requirements and the original material. For this, we used Supplementary File S1 and additional insights from the material data collection in the literature review.

We collected and structured the assessment findings in a data table for each part. The first column listed the design requirements of this study, and the three consecutive columns noted the part requirements and how likely SLA, SLS, and FDM were to meet these requirements. This was performed by comparing the requirements for each design requirement against the capabilities of the manufacturing methods from the previous step. We then visualised this assessment by applying the corresponding colour code from Table 2. Finally, the bottom two rows of the table listed the major part requirements and concluding remarks on the estimated printability of each part.

The next section will present the results of these steps. Using these results, we can define how 3D-printed spare parts can be facilitated in the design phase of the product.

3. Results

The relationship between design requirements and manufacturing capabilities was investigated through two tables. Table 3 creates an overview of the design requirements, and Table 4 defines the manufacturing capabilities for these requirements. The insights from Table 4 were then applied in a case to illustrate how designers can use the findings to facilitate 3D-printed spare parts in the original design.

Table 3. Summary of design requirements, with examples of structural and material properties, for plastic injection-moulded spare parts. "…" indicates more properties are listed for that requirement in the full version; see Appendix A for the full version of this table.

Design Requirement	Structural Properties Example	Material Properties Example
Geometry		
Shape	• Overhang • Cavities • …	• Thermal expansion rate • Linear mould shrinkage
Detail	• Minimum wall thickness • Minimum feature size • …	• Thermal expansion rate • Linear mould shrinkage
	See also: Accuracy and Tolerances	

Table 3. *Cont.*

Design Requirement	Structural Properties Example	Material Properties Example
Accuracy and tolerances	• Part tolerance • Part clearance • …	• Thermal expansion rate • Material shrinkage • Linear mould shrinkage
Configuration		
Water-/airtightness	• Wall thickness • Porosity/gaps • …	• Permeability ($O_2/CO_2/N_2$)
	See also: Accuracy and Tolerances, Surface finish	
Multi-material	• Inserts • Fastening feature/mechanical bond • Surface smoothness	• Material compatibility • Material shrinkage • …
Surface finish	• Surface finish • Surface texture	• Friction coefficient • Self-lubrication
Transparency	• Microstructure • Wall thickness • …	• Transparency • Haze • …
	See also: Surface finish	
Mechanical requirements		
Strength	• Part/feature size • Wall thickness • …	• Tensile strength • Young's modulus • …
Flexibility (bend)	• Length • Cross-sectional area • …	• Young's modulus • Flexural strength • …
Elasticity (stretch/compress)	• Length • Cross-sectional area • Microstructure	• Young's modulus • Elongation at break • …
Impact resistance	• Stress concentrators • Wall thickness (optimization) • …	• Fracture toughness • Impact strength (Izod, Charpy) • …
Abrasion resistance	• Microstructure • Surface roughness • …	• Hardness • Abrasion resistance (Tabor) • …
	See also: Surface finish	

Table 3. *Cont.*

Design Requirement	Structural Properties Example	Material Properties Example
Fatigue resistance	• Stress concentrators • Compressive surface stress • ...	• Fracture toughness • Fatigue limit at 10^7 cycles • ...
Creep resistance	• Part geometry • Stress concentrators • Fillet/chamfer radius	• Creep resistance • Glass temperature • ...
Thermal requirements		
Heat resistance	• Part/feature thickness • Part volume	• Glass temperature • Heat deflection temperature • ...
Cold resistance	• Part/feature thickness • Part volume	• Ductile/brittle transition temperature • Minimum service temperature • ...
Chemical requirements		
Water resistance	• Crevices • Porosity/gaps • ...	• Water absorption • Permeability (O_2/CO_2/N_2) • ...
	See also: Detail, Surface finish	
UV resistance	—	• UV resistance • Indoor stability • ...
Chemical resistance	• Crevices • NEMA-rating	• Chemical resistance index • Environmental stress crack index • ...
	See also: Detail, Surface finish	
Food safety	• Crevices • Corner radii • ...	• Food contact grade • Sterilizability
	See also: Detail, Surface finish, Chemical resistance	

Table 4. Summary of manufacturing capabilities for meeting the design requirements from Table 3. See Supplementary File S1 for the full version of this table. The footnotes indicate the following data quality for that requirement: [1] = High-quality data, [2] = Medium-quality data, [3] = Low-quality data, [4] = No data available.

Design Requirement	Injection Moulding (IM)	Stereo-Lithography (SLA)	Selective Laser Sintering (SLS)	Fused Deposition Modeling (FDM)
Geometry				
Shape [1]	High form freedom, draft needed.	High form freedom, but support needed. [1]	High form freedom, no support needed. [1]	Good form freedom, but support is needed. [1]
Detail [1]	Min. wall size: 0.8–1.2 mm, min. feature size: 0.4–0.6 mm.	Min. wall/ feature size: 0.1–0.4 mm. [1]	Min. wall/ feature size: 0.8 mm. [1]	Min. wall/ feature size: 1.1–1.5 mm. [1]
Accuracy and tolerances [1]	Typically ±0.25 mm, can go as low as ±0.025–0.125 mm.	Accuracy of ±0.15% (min. 0.01–0.03 mm) for industrial machines. [1]	Accuracy of ±0.3% (min. 0.3 mm) for industrial machines. [1]	Accuracy of ±0.15% (min. 0.2 mm) for industrial machines. [1]
Configuration				
Water/air tightness [1]	Water- and airtight when using the recommended wall thicknesses.	Properly printed parts are waterproof and airtight. [1]	Parts have a porous surface and need additional post-processing. [1]	Parts have a porous microstructure and need additional post-processing. [1]
Multi-material [1]	Multiple options (e.g., insert-, 2K-, and overmoulding).	Only on lab-scale. [1]	Only on lab-scale. [1]	Multiple-material extrusion is possible. [1]
Surface finish [1]	Smooth finish possible (Ra = 0.012–0.7 µm for parts with a polished finish).	Smooth finish possible (Ra ≈ 0.4–2.3 µm). [1]	Rougher finish, even after post-processing (Generally around Ra ≈ 2.3–5.7 µm). [1]	Rougher finish, even after post-processing. Large variations (Ra = 0.9–22.5 µm, side planes are roughest). [1]
Transparency [1–2]	Wide range from opaque to fully transparent	Wide range from opaque to fully transparent. [2]	All parts are opaque. [1]	Ranges from opaque to translucent. Visible layer lines, part needs post-processing. [2]
Mechanical requirements				
Strength [1]	Various high-strength polymers are available (e.g., PEI, PEK); tensile strength around 92–120 MPa. Strength is isotropic.	Generally brittle materials, but stronger resins exist (e.g., tough and durable resins), tensile strength around 61–65 MPa. Strength is near-isotropic. [1]	Generally strong materials, tensile strength around 29–69 MPa. Printed parts are not as strong as IM. Strength is slightly anisotropic. [1]	Strong materials (e.g., PEI, PC), tensile strength around 48–81 MPa. Strength is highly anisotropic due to limited layer adhesion. [1]
Flexibility [2]	Ranging from stiff plastic to hard rubber to very soft elastomer polymers; Young's modulus between 0.2–50 MPa.	Ranging from stiff polymeric to hard rubber-like to softer silicone-like materials, Young's modulus between <1–10 MPa. [2]	Stiff polymeric to hard rubber-like materials available, Young's modulus between 5.3–131 MPa. [2]	Ranging from stiff plastic to hard rubber-like to softer silicone-like materials, Young's modulus between 15.3–205 MPa. [2]
Elasticity [2]	There are various polymers with very high elongation at break (80–1780%). Stretch is isotropic.	There are resins with relatively high elongation at break (160–300%). Stretch is near-isotropic. [2]	There are powders with high elongation at break (60–500%). Stretch is anisotropic. [2]	There are filaments with very high elongation at break (150–950%). Stretch is anisotropic (risk of layer delamination). [2]

Table 4. *Cont.*

Design Requirement	Injection Moulding (IM)	Stereo-Lithography (SLA)	Selective Laser Sintering (SLS)	Fused Deposition Modeling (FDM)
Impact resistance [2]	There are various impact-resistant polymers (e.g., PAI, HIPS); notched impact strength >500 J/m.	Engineering resins (e.g., tough, durable, rigid PU) have good impact resistance; notched impact strength between 17–375 J/m. [2]	Lower impact strength due to porous surface (needs post-processing). There are various impact-resistant powders (e.g., PA11, PAx); notched impact strength between 32–71 J/m.	Lower impact strength due to bad layer adhesion. There are various impact-resistant filaments (e.g., ABS, PC-ABS); notched impact strength ranging between 32.2–241 J/m.
Abrasion resistance [3]	There are various wear-resistant (e.g., PA) and self-lubricating (e.g., UHMW-PE) polymers available.	Insufficient data. Claims of high wear resistance for durable resins. [3]	Insufficient data. Claims of good wear resistance for some materials (e.g., PA, PEEK). [3]	Insufficient data. Claims of high wear resistance for some materials (nylon, PEKK). [3]
Fatigue resistance [3]	There are various fatigue-resistant polymers (e.g., POM, PEEK). Defects (e.g., knit lines) can affect fatigue strength	Insufficient data. Claims of good fatigue properties for some materials (e.g., Accura resins). [3]	Insufficient data. Claims of good fatigue properties for some materials (e.g., PP). [3]	Insufficient data. Claims of good fatigue properties for some materials (e.g., PA, PEEK). Needs post-processing to offset layer adhesion /surface defects. [3]
Creep resistance [3–4]	There are various creep-resistant polymers (e.g., PC)	Insufficient data. Common resins may creep, but some resins (e.g., rigid ceramic resins) claim to be more creep-resistant. [3]	Insufficient data. Additives are said to give a material a higher creep resistance. [4]	Insufficient data. Claims of filaments being more susceptible to creep due to their low melting point. [3]
Thermal requirements				
Heat resistance [1]	There are multiple heat-resistant polymers available (e.g., PAI, PEEK), service temperature between 161–260 °C.	Generally low heat resistance, but there are heat-resistant resins with heat deflection temperature between 200–300 °C (might require thermal curing). [1]	All materials are heat-resistant, service temperature typically between 150–185 °C, but can go up to over 300 °C. [1]	General service temperature between 50–120 °C. More heat-resistant filaments (e.g., PC, PEI) have an HDT between 133–214 °C. [1]
Cold resistance [4]	Difficult to determine, but most engineering plastics besides PP and PET are well suited to temperatures below zero.	Insufficient data. In experimental testing, strong resin was unaffected by prolonged exposure below zero.	Insufficient data.	Insufficient data. Essentium claims their Altitude filament can withstand −60 °C.

Table 4. *Cont.*

Design Requirement	Injection Moulding (IM)	Stereo-Lithography (SLA)	Selective Laser Sintering (SLS)	Fused Deposition Modeling (FDM)
Chemical requirements				
Water resistance [1]	There are various polymers (e.g., HDPE, PP) with little to no water absorption (<0.1%).	Virtually no porosity. There are various materials with low water absorption (<0.1–0.35%). [1]	Additional finishing is required to offset surface porosity. Most powders have low water absorption (around/below 0.1%). [1]	Additional finishing is required to offset layer gaps. Various filaments (e.g., PETG, PP) have low water absorption (between 0.23–1%). [1]
UV resistance [3]	A few polymers have UV resistance of tens of years (e.g., PEI, PAI).	Insufficient data. Resins are sensitive to UV degradation (embrittlement and yellowing). [3]	Insufficient data. Claims of UV resistance for some powders (e.g., nylon, TPU). [3]	Insufficient data. Claims of UV resistance for some filaments (e.g., ASA, PVDF). [3]
Chemical resistance (household) [2]	There are various polymers with excellent chemical resistance (e.g., PEEK, PP).	Most resins have good chemical resistance for most household chemicals. [2]	Most materials (e.g., PA, PP) have good chemical resistance for most household chemicals. [2]	Most engineering filaments (e.g., PP) have good chemical resistance for most household chemicals. [2]
Food safety [1]	There are various food-grade polymers (e.g., PC, PP), parts need to adhere to strict production regulations.	Resins are not food-safe due to their toxicity. Coating is insufficient to guarantee food safety. [1]	Certified food-grade printing of PA11/12 is possible, but options are limited. [1]	Food-safe filaments are available, but there is no certified production process. Layer lines pose a risk for bacteria buildup. [1]

[1] = High-quality data, [2] = Medium-quality data, [3] = Low-quality data, [4] = No data available. The colour-coding in the cell indicates the following regarding the capabilities for each additive manufacturing method compared to injection-moulding: green = similar or better, yellow = slightly inferior, red = considerably inferior or impossible, and grey = insufficient data (quality) for assessment.

3.1. Design Requirements

The full table of design requirements that designers would use is too long to display here; it is shown in Appendix A and summarised in Table 3. Table 3 gives an overview of the selected design requirements, each with an example of relevant structural and material properties. This summary table should be sufficient to construct a general definition of the design requirements.

Appendix A, summarised in Table 3, lists a total of 20 requirements that are divided into five groups. The appendix presents a more complete overview of structural and material properties for each design requirement, including citations. To give an example, for the requirement Shape, Appendix A lists nine structural properties (Size, Wall thickness uniformity, Undercuts/overhang, Horizontal bridges, Internal channels, Part thickness/shell, Feature spacing, Pockets and cavities, and Draft angles (IM only); [27–42]) and two material properties (Thermal expansion coefficient and Linear mould shrinkage; [24,43–47]). Additionally, the cross-references in Table 3 and Appendix A indicate a larger overlap between design requirements, such as for Detail and Food safety. Using these requirements, we can define the capabilities of additive manufacturing in the next section.

3.2. Manufacturing Capabilities

The full table of manufacturing capabilities that designers would use is too long to display here; it is shown in Supplementary File S1 and summarised in Table 4. Table 4 assesses the manufacturing capabilities of injection moulding and additive manufacturing for the design requirements in Table 3. Though only a summary, Table 4 should be sufficient to compare the manufacturing capabilities of injection moulding and additive manufacturing.

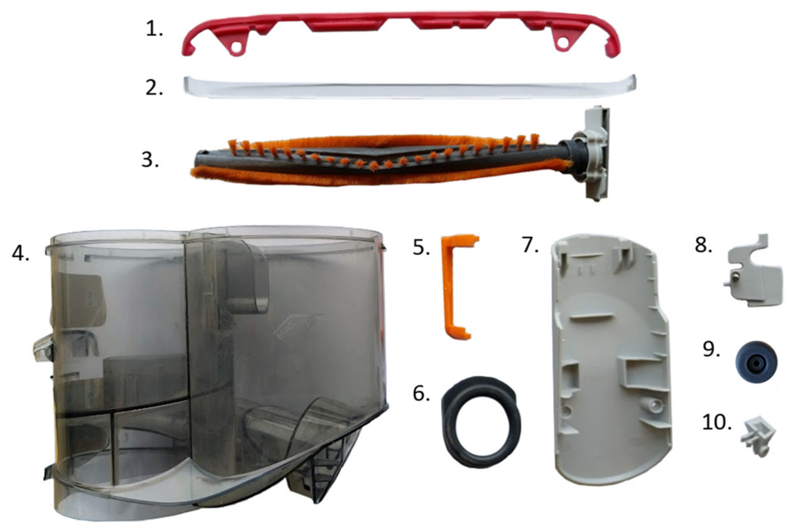
Supplementary File S1, summarised in Table 4, gives a high-level overview of which design requirements are generally achievable and which ones are more challenging for additive manufacturing. The Supplementary File presents a more detailed overview of the manufacturing capabilities for each design requirement, including citations. To give an example, for the design requirement Shape, Supplementary File S1 lists what each manufacturing method is capable of in terms of form freedom, use of support structures, corners, overhang and bridging, drainage holes, and common printing defects that affect the shape. From this analysis, we concluded that FDM printing is less capable of replicating complex geometries than injection moulding, as FDM printing is more prone to printing defects [48]. This meant that FDM printing was marked yellow for this requirement. The capabilities of SLA and SLS printing were more comparable to those of injection moulding and were, therefore, both marked green. The design requirements that were marked green for most printing methods were Accuracy, Heat resistance, and Chemical resistance. Conversely, requirements that were mostly marked red were Multi-material and Food safety.

There were variations in the data quality for the various requirements, as indicated by the footnotes in Table 4. For 16 out of 20 requirements, sufficient information was available to estimate the capabilities of additive manufacturing. This made it easy to determine the relative capabilities of additive manufacturing compared to injection moulding. Some of these requirements could be better defined with extended material data. For instance, for Flexibility, the data sheets report obscure material properties, such as Shore hardness, rather than more representative properties like Young's modulus or flexural strength. Still, the relative manufacturing capabilities for these requirements could be estimated through the available data and observation of the demonstrated material behaviour. For the remaining four requirements, the data were low-quality or not available. This was mostly the case for mechanical requirements, such as Abrasion resistance and Creep resistance. For example, Supplementary File S1 lacks citations for requirement-specific properties for Abrasion resistance, such as the wear constant or wear rate. As a result, the capabilities of additive manufacturing for these requirements could not be estimated.

The manufacturing capabilities described in Supplementary File S1 (summarised in Table 4) represent the general performance of each manufacturing method using standard operating parameters. The table should not be seen as a look-up table, nor is it depicting the ultimate performance of additive manufacturing. Instead, it helps designers to evaluate which areas require more attention during the (re)design phase. For example, while injection moulding can achieve very high accuracy, in most cases, its accuracy is comparable to that of industrial-level additive manufacturing. This means that accuracy will only be a point of attention for specific features that require high accuracy, such as press fits and snap fits. These part features can likely still be achieved with additive manufacturing, but they will need more careful design optimisation. These assumptions were verified in the illustrative case.

3.3. Illustrative Case

Figure 1 shows the ten exemplary parts of the vacuum cleaner that were selected to illustrate the use of the table. The manufacturability of these parts as 3D-printed spare parts was assessed by comparing their part requirements against the manufacturing capabilities in Table 4. The results are presented below in Tables 5 and 6. The full study on the printability for each part, which discusses the applicable requirements and printability scores in more detail, can be found in Supplementary File S2. The assessment presented below is intended to provide an overview of part printability.



1. Floor nozzle bumper
2. Floor nozzle LED cover
3. Floor nozzle brush
4. Dustbin container
5. Floor nozzle locking cap
6. Dustbin inlet seal
7. Floor nozzle cable cover
8. Floor nozzle hinge
9. Floor nozzle wheel
10. Wheel suspension

Figure 1. Parts selected for the illustrative case.

Table 5. Summary of assessments of part printability for parts 1–5. For full assessments, see Supplementary File S2.

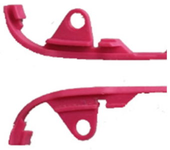
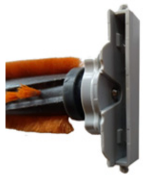
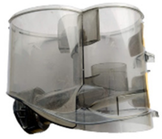
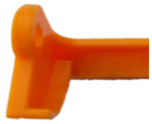
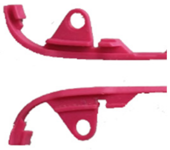
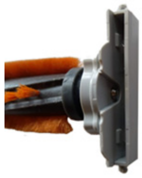
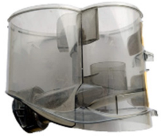
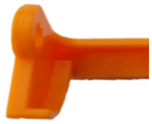
	1. Floor Nozzle Bumper 			**2. Floor Nozzle LED Cover**			**3. Floor Nozzle Rotating Brush** 			**4. Dustbin Container** 			**5. Floor Nozzle Brush Locking Cap** 		
Original Material	PP			PC			Nylon + PP + POM			Glass-Filled ABS			ABS		
SLA Material *	Durable (PP-Like) resin			Clear resin			Durable (PP-Like) resin			Clear resin			Durable (PP-Like) resin		
SLS Material	PA11			PA11			PA12			PA11			PA11		
FDM Material	ABS			Clear PETG			Nylon			Clear PC			Nylon		
AM Method	SLA	SLS	FDM	SLA	SLS	FDM	SLA	SLS	FDM	SLA	SLS	FDM	SLA	SLS	FDM
Shape															
Detail															
Accuracy and tolerances															
Water/air-tightness															
Multi-material															
Surface finish															
Transparency															
Strength															
Flexibility															
Elasticity															
Impact resistance															
Abrasion resistance †															
Fatigue resistance †															
Creep resistance †															
Heat resistance															
Cold resistance															
Water resistance															
UV resistance †															

Table 5. *Cont.*

	1. Floor Nozzle Bumper 	2. Floor Nozzle LED Cover	3. Floor Nozzle Rotating Brush 	4. Dustbin Container 	5. Floor Nozzle Brush Locking Cap 
Chemical resistance					
Food safety					
Major part requirement(s)	—	Transparency Surface finish	Multi-material Abrasion resistance	Impact resistance Shape	Strength Flexibility Accuracy
Concluding remarks	The shape, detail, and semi-rigid flexibility/flexural strength should be achievable with all printing methods.	Limited printing options as full transparency is required for technical functioning.	Part complexity is too high. The bristles are not replicable with any printing method.	The inlet cavity's complex shape combined with the transparency makes the part difficult to replicate with any printing method.	Printable, but the high flexural strength and accurate details will be difficult to achieve.

* SLA resins are thermosets but often characterised as "thermoplastic-like", e.g., durable resins are "PP-like". † Insufficient data in Table 4 to conclude. The colour-coding in the cell indicates the following regarding part manufacturability: green = likely possible with standard manufacturing and little design adjustments, yellow = could be possible with careful consideration of manufacturing and design, red = almost impossible without major design changes, grey = insufficient data (quality) for assessment.

Table 6. Summary of assessments of part printability for parts 6–10. For full assessments, see Supplementary File S2.

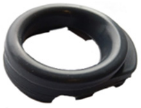
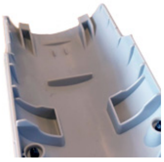
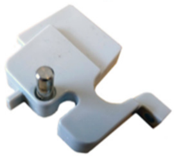
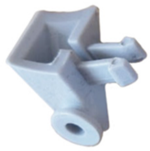
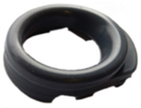
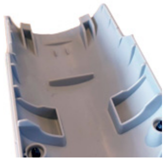
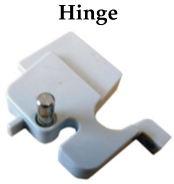
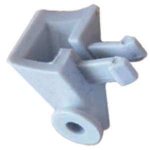
	6. Dustbin Inlet Seal 			7. Floor Nozzle Back Cable Cover 			8. Floor Nozzle Hinge 			9. Floor Nozzle Wheel 			10. Floor Nozzle Wheel Suspension 		
Original material	PDMS (Silicone)			ABS			POM + Metal Pin			PP + LDPE			PTFE (Teflon)		
SLA material *	Rebound resin			Tough (ABS-Like) resin			Durable (PP-Like) resin			Tough resin + Flexible resin			Durable (PP-Like) resin		
SLS material	TPU			PA12			PA12			PA12 + TPU			PA11		
FDM material	TPE			Nylon			Nylon 66			ABS + TPU			Nylon		
AM Method	SLA	SLS	FDM	SLA	SLS	FDM	SLA	SLS	FDM	SLA	SLS	FDM	SLA	SLS	FDM
Shape															
Detail															
Accuracy and tolerances															
Water/air-tightness															
Multi-material															
Surface finish															
Transparency															
Strength															
Flexibility															
Elasticity															
Impact resistance															
Abrasion resistance †															

Table 6. *Cont.*

	6. Dustbin Inlet Seal 	**7. Floor Nozzle Back Cable Cover** 	**8. Floor Nozzle Hinge** 	**9. Floor Nozzle Wheel** 	**10. Floor Nozzle Wheel Suspension** 
Fatigue resistance †					
Creep resistance †					
Heat resistance					
Cold resistance					
Water resistance					
UV resistance †					
Chemical resistance					
Food safety					
Major part requirement(s)	Flexibility Elasticity Strength	Accuracy Impact resistance Strength	Surface finish Abrasion resistance Multi-material	Abrasion resistance Surface finish	Strength Flexibility
Concluding remarks	The combination of part requirements for the (dis)- assembly process will be challenging to achieve, especially for SLS.	The part is printable but further testing is needed to see if the snap-fit strength and general impact strength are sufficient.	The metal pin makes the part more complex to print. For higher abrasion resistance, a different material or external lubrication might be needed.	The two different materials make the part more complex to print. Either a multi-material or multi-component part is needed.	The required flexural force and fatigue resistance for the snap-fits will be challenging to replicate for most printing methods.

* SLA resins are thermosets but are often characterised as "thermoplastic-like", e.g., durable resins are "PP-like". † Insufficient data in Table 4 to conclude. The colour-coding in the cell indicates the following regarding part manufacturability: green = likely possible with standard manufacturing and little design adjustments, yellow = could be possible with careful consideration of manufacturing and design, red = almost impossible without major design changes, grey = insufficient data (quality) for assessment.

The overview in Tables 5 and 6 presents how Table 4 has been used to identify potential tensions between the part designed for injection moulded and the 3D printed spare part (without any redesign). If a part is green for all relevant properties, 3D printing is expected to be straightforward. If a few indicators are yellow, a redesign is likely needed. Red indicates that the part cannot be 3D printed without extensive redesign. Below, a few examples of ratings are discussed to illustrate the assessment process. It should be noted that the assessments below are based on assumptions, whereas product designers would be able to make these assessments more accurately.

- For the floor nozzle bumper, the part requirements for Shape and Detail are easy to achieve. There is no overhang or other complex geometry, and the part details range between 1 and 2 mm. This is well within the capabilities of additive manufacturing, as all manufacturing methods can print a detail size of around 1 mm. Therefore, these requirements are rated green.
- For the floor nozzle brush, the part requirements for Multi-material are almost impossible to achieve. The part has numerous subcomponents made from different materials and assembled through moving connections. The brush could be printed as separate components up to a certain point, but the overmoulded bristles will be impossible to replicate with additive manufacturing. Therefore, this requirement is rated red.
- For the dustbin inlet seal, the part requirements for Flexibility and Elasticity will be difficult to achieve. The part requires the properties of a soft and stretchable elastomer, as it needs to stretch and compress during installation and removal. Both SLA and FDM printing offer soft and stretchable elastomers; however, without further testing, it is not possible to verify whether these materials can meet these specific part requirements.

- For the wheel suspension, the specific combination of part requirements will be challenging to achieve. The snap-fits require a tailored combination of strength, flexibility, accuracy, and surface finish in a localised section of the part. Conversely, the section of the part that connects to the rotating wheel axle requires very high abrasion resistance and a smooth surface finish. Even if each requirement is feasible separately, the designer should still be mindful of the trade-offs and synergies between the part requirements, as reflected in the concluding remarks.

4. Discussion

The results show that additive manufacturing has potential for spare parts production, but specific design considerations are needed for many of the requirements. Additive manufacturing is generally well-suited for requirements like Accuracy, Heat resistance, and Chemical resistance. Only a few of the identified requirements, like Multi-material and Food safety, will always be challenging with additive manufacturing. This can also be seen in the illustrative case. Although only the floor nozzle bumper printed in SLA is completely marked green, there are rarely any squares marked red. Most parts score a mix of green and yellow. This suggests that additive manufacturing is not simply a drop-in replacement for injection moulding, but most of the challenges posed by the design requirements could be overcome through careful design. For legacy parts or redesigns, it is a question of how much design time and effort the part is worth. However, for new product designs with increased design freedom, the tables can guide designers on how to facilitate printed spare parts in the design of the parts.

Table 4 highlights where specific design attention may be required. Designers can find which of the requirements for a particular spare part might need more careful design consideration by comparing the part requirements against the manufacturing capabilities in Table 4. Designing the part can go in two directions:

- The original part is designed to be suitable for both injection moulding and additive manufacturing;
- Two different yet interchangeable part designs are made, with the original part optimised for injection moulding and the spare part optimised for additive manufacturing.

How challenging the (re-)design process will be depends on the gap between part requirements and manufacturing capabilities, colour-coded green/yellow/red in Table 4.

Most of the relevant design requirements that drive the design for both injection moulding and additive manufacturing are listed in Table 3. While there are potentially an infinite number of design requirements, the illustrative case demonstrated that most requirements are covered by a limited number of requirements. Indeed, most parts in the illustrative case were driven by a small subset of Table 3's properties. This indicates that the design for 3D-printed spare parts could mostly be managed by developing design strategies for the more common design requirements.

Still, designers should consider what other requirements might be relevant to their part. It could be that specific parts have requirements that are not commonly encountered in consumer products, such as electrostatic discharge (ESD) resistivity, vibration dampening, or cleanability for sterilisation. Additionally, part requirements could go beyond the technical functioning: user experience can be equally important, especially for cosmetic parts. For example, the transparency of the dustbin, in this case, is technically not required, as the product would still work without it. However, it might affect the user experience, as users can only check the contents of the dustbin after removing it first. This is different from the transparency required by the LED cover. This cover protects an LED strip at the front of the floor nozzle, whose directional beam of light is used to reveal hidden dust and dirt. Omitting the transparency of the cover would, therefore, affect the product performance. Other experiential requirements could include certain visual or tactile experiences. In most cases, these additional requirements will be related to the properties and requirements already defined in Table 3. For example, the gloss of a part is related to the surface finish and corresponding properties such as the refractive index.

While the design requirements are listed separately in these tables, it is important to realise that a part is defined through the combination of requirements. Often, part properties are related to more than one design requirement. For example, the friction coefficient of a material is related to both surface finish and abrasion resistance. This interaction between design requirements can also be seen in the illustrative case. In this case, the snap-fits of the wheel suspension combine flexural strength and semi-rigid flexibility, and the soft-touch finish of the wheel combines surface finish, flexibility, and elasticity. Therefore, it is not sufficient if a manufacturing method has good scores for just a few design requirements. The whole range of applicable design requirements should be considered when enabling 3D-printed spare parts in the part design.

Some design requirements will be more difficult to combine than others. For example, the dustbin, in this case, requires a combination of transparency and impact resistance. Only SLA can manage near-optical transparency, but transparent SLA resins are known to be more brittle than opaque resins. So, while SLA scores relatively well on both transparency and impact resistance in Table 4, this part will still be challenging to design due to the combination of requirements. Similarly, combining food safety and fine details will be challenging, as there is no additive manufacturing method in Table 4 with high scores for both. As such, the specific combination of design requirements in a part can also influence which additive manufacturing method should be used or whether any are viable.

Future technical developments could shift manufacturing capabilities. Requirements that are difficult or (near)-impossible to achieve, such as transparent SLS printing, could become more accessible. As the capabilities of additive manufacturing expand in the future, it will become easier to facilitate 3D-printed spare parts in the design of injection-moulded parts.

Of course, if products or their major components are not practical to repair even with perfect spare parts, it does not make sense to consider additive manufacturing for the production of spare parts. Design for repair should be prioritised over 3D-printed spare parts for products that are not suitable for repair.

Limitations and Recommendations

The varying availability and quality of data on additive manufacturing methods and materials made it difficult to make an accurate comparison between additive manufacturing and injection moulding. The material properties in the technical datasheets used different data units and were not obtained by the same testing methods, testing conditions, and testing standards. Also, the information in the technical datasheets was not always sufficient to assess additive manufacturing capabilities for certain requirements. Moreover, it is not sufficient to rely on material data alone. The manufacturing process and printing settings will also influence most of the design requirements, but these insights were not always available.

More research is needed to obtain data on the capabilities of additive manufacturing for the design requirements that are currently inconclusive or have poor data quality. This will help to better determine to what extent particular design requirements can be met. Achieving this goal requires a collaboration between industry and scientific research and possibly an update of industry standards. Until more data are available, it is recommended that designers do additional testing and collaboration with material developers to overcome the lack of insight or limit themselves to well-understood solutions. Further research could also consider a broader range of materials and processes for the production of spare parts, using the insights from this study. Additionally, to make the information enclosed in this paper more directly applicable to designers, we recommend that further research focuses on creating design guidelines to help designers navigate the design challenges that were identified in this study.

5. Conclusions

The aim of this study was to find how the production of 3D-printed spare parts can be facilitated in the design of plastic parts. This study shows how additive manufacturing has the potential to produce spare parts for the plastic parts in consumer products. However, it is not a simple drop-in replacement, is sometimes impossible, and usually requires some part redesign or careful selection of the additive manufacturing method and material. To support designers, a good understanding of the design requirements and manufacturing capabilities for both methods is needed, as presented in this study. The manufacturing capabilities in Table 4 (Supplementary File S1) will help designers estimate how challenging the adaptation will be and, thus, whether it is worth their time and effort. The colour-coding in this table, which represents the differences between injection moulding and manufacturing, can also help designers to optimise their design for 3D-printed spare parts.

When designing printed spare parts, designers should always consider the trade-offs and synergies between design requirements and the challenges that could arise from trying to meet combinations of certain requirements. Rather than a single complex requirement, it will be the complexity of the design that will make it difficult to design a printable spare part. This represents a larger design challenge, where designers need to be fluent in both design for injection moulding and design for additive manufacturing to be able to adapt the design correspondingly. By realising printed spare parts for easier parts first, we can optimise the design process and find ways to make designers more familiar with the process. Moreover, designers should ensure products are easily repairable before considering 3D-printed spare parts. Considering the production of spare parts during the design process is the next step in designing a repairable product and preventing waste.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su16219203/s1, Supplementary File S1: Manufacturing capabilities of additive manufacturing compared to injection moulding, Supplementary File S2: Illustrative case. References [49–285] are cited in the Supplementary Materials.

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Below, Table A1 gives examples to illustrate the design requirements, as well as structural and material properties, that designers should need to take into account. This table does not pretend to be comprehensive, as there are too many design variables and properties that would need to be discussed. For some properties, the depth of study was limited. Especially for water tightness, it was difficult to find qualitative sources to cite, despite the common knowledge in industry. For these properties, data was selected from less rigorous sources, such as blog posts and material datasheets.

Table A1. The selected design requirements, with corresponding structural and material properties, for plastic injection-moulded spare parts.

Design Requirement	Structural Properties	Material Properties
Geometry		
Shape	• Size [27–32] • Wall thickness uniformity [28,31,33–36] • Undercuts/overhang [27–30,33–35,37–40] • Horizontal bridges [30,38] • Internal channels [29,37,39,41] • Part thickness/shell [34,36] • Feature spacing [35] • Pockets & cavities [31] • Draft angles (IM) [27,28,31,34,35,42]	• Thermal expansion rate [24,43–47] • Linear mould shrinkage [44]
Detail	• Minimum for • Bosses [28,31,33,34,36] • Ribs [28,33–36,40] • Gussets [28,33,34,36] • Radii [27,28,33,35,36] • Fillets [28,29,31,33–35,40,42] • Parting line (IM) [34,35] • Snap-fits [28,34,40] • Minimum wall thickness [27–29,31,37–42] • Wall profiles [40] • Minimum feature size [29,30,37–41] • Pin diameter [30,31,38] • Supported wires [32] • Unsupported wires [32] • Supported walls [30,32,38] • Unsupported walls [30,32,38] • Embossed/engraved detail [29,30,32,38–42] • Text [29,31,34,39,40] • Holes [30,31,38–40,42] • Gaps [31,40,42]	• Thermal expansion rate [24,43–47] • Linear mould shrinkage [44]
Accuracy and tolerances	• Part tolerance [28,30,31,33,38,40,42] • Part clearance [30,32,38,39,41] • Maximum wall thickness [41] • Hollowing [29,39] • Surface area [31,38–40] • Interlocking/single-build assembly [29,39,41] • Minimum feature size [286] • Size [286]	• Thermal expansion rate [24,43–47] • Linear mould shrinkage [44] • Material shrinkage [286]
Configuration		
Water-/airtightness	• Geometry complexity [39,287] • Wall thickness [287–289] • Surface finish [287–289] • IP-rating [290] • Interfaces [290] • Seal/gasket design [290] • Porosity/gaps [289]	• Permeability (O_2/CO_2/N_2) [44]
	See also: Accuracy and Tolerances, Surface finish	
Multi-material	• Inserts [34,291] • Fastening feature/mechanical bond [291] • Surface smoothness [291]	• Material compatibility [291] • Material shrinkage [291] • Friction coefficient/surface roughness [291] • Wear resistance [291]
Surface finish	• Surface finish [27–29,31,39–42,292] • Surface texture [292]	• Friction coefficient [43] • Self-lubrication [43]
Transparency	• Microstructure [24] • Wall thickness [24,293] • Surface finish [24,293,294] • Wall thickness uniformity [294] • Gradual transitions [294] • Release slope [294] • Geometry complexity [293]	• Transparency [44,46] • Haze [295] • Luminous Transmittance [295] • Diffuse Transmittance [295] • Refractive index [24,44,295] • Absorption coefficient [24]

Table A1. *Cont.*

Design Requirement	Structural Properties	Material Properties
	See also: Surface finish	
Mechanical requirements		
Strength	• Microstructure [24] • Hardness [24] • Cross-sectional area [24] • Stress concentrators [24] • Part/feature size [39] • Wall thickness [39,296–298] • Maximum wall/section thickness [296,297] • Rib use [296–298] • Fillet/radii use [297,298] • Gusset use [296,298] • Transition smoothness [296]	• Tensile strength [24,43–47,295,299–302] • Young's modulus [24,43–47,295,299–302] • Elongation at break [44–47,295,299–302] • Flexural strength [44,45,47,295,299,300] • Flexural modulus [44,45,47,295,299,300] • Specific strength [44] • Flexural Stress at 5% Strain [47] • Porosity [43]
Flexibility (bend)	• Length [24] • Cross-sectional area [24] • Wall thickness [39,303] • Microstructure [303]	• Young's modulus [24,43–47,295,299–302] • Flexural strength [44,45,47,295,299,300] • Flexural modulus [44,45,47,295,299,300] • Elongation at break [44–47,295,299–302] • Elongation at yield [44,46,300] • Shear modulus [24,43,44] • Hardness [45,47,295,300,304]
Elasticity (stretch/ compress)	• Length [24] • Cross-sectional area [24] • Microstructure [305]	• Young's modulus [24,43–47,295,299–302] • Tensile strength [24,43–47,295,299–302] • Elongation at break [44–47,295,299–302] • Yield strength [24,43–47,300] • Hardness [24,44–47,295,299–302] • Material-specific stiffness [24,44] • Bulk modulus [24,43,44] • Compressive modulus [44] • Compressive strength [44] • Compression set [45,302] • Poissons Ratio [24,44] • Elastic stored energy [44] • Resilience (Bayshore) [47,302,306] • Tear strength [45,47,302] • Stress at 50% elongation [47,302] • Stress at 100% elongation [47,302] • Stress at 150% elongation [302]
Impact resistance	• Part geometry [307–309] • Corner radii [307,309,310] • Stress concentrators [307] • Notch size/radius & placement [307,310] • Hole size/radius & placement [307] • Fillet radius & use [307] • Rib use [307,308] • Wall thickness (optimization) [307,308,310] • Part shape/roundness [307] • Part feature/size and location [307] • Part thickness [308] • Part internal structure [310]	• Fracture toughness [24,43,44] • Fracture strength [43] • Toughness [24,43,44,46] • Ductility index [44] • Impact strength notched [44,45,47,300,301] • Impact strength unnotched [44,47,300,301] • Impact strength (Izod, Charpy) [45,47] • Tear strength [45,47,302] • Flex fatigue (Ross) [47,302] • Resilience (Bayshore) [47,302,306] • Maximum Stress Intensity Factor (K_{max}) [301] • Work of Fracture (W_f) [301]
Abrasion resistance	• Microstructure [24] • Surface roughness [24,311] • Contact area surface roughness [24,311] • Coating/surface treatment [311] • Lubrication [24,311]	• Hardness [24,44–47,295,299–302] • Abrasion resistance (Tabor) [47] • Friction coefficient [24,43] • Archard wear constant [24,43] • (Specific) wear rate [24,43] • Self-lubrication [43]
	See also: Surface finish	

Table A1. *Cont.*

Design Requirement	Structural Properties	Material Properties
Fatigue resistance	• Stress concentrators [24] • Compressive surface stress [24] • Surface finish/roughness [24] • Wall thickness [24]	• Fracture toughness [24] • Fatigue limit/strength at 10^7 cycles [43,44] • Fatigue endurance [43] • Yield strength [24,43,44,46,47,300] • Tensile strength [24,43–47,295,299,300] • Melting point [43,44] • Notch sensitivity [312] • Porosity [313] • Isotropy [313]
Creep resistance	• Part geometry [314] • Stress concentrators [314] • Fillet/chamfer [314]	• Creep resistance [43,45] • Glass temperature [24,312] • Maximum service temperature [24] • Creep modulus [24,312]
Thermal requirements		
Heat resistance	• Part/feature thickness [24] • Part volume [24]	• Melting temperature [24,43,44] • Glass transition temperature [24,43,44,46,47,295,299–301] • Ductile/brittle transition temperature [46,315] • Heat deflection temperature [44–47,295,299–301] • Vicat softening point [44,45,47] • Continuous service temperature [46] • Maximum service temperature [24,44,46] • Thermal conductivity [24,43,44,46] • Specific heat [24,43,44] • Heat capacity [24] • Thermal expansion coefficient [24,43–47,295,300,301] • Thermal shock resistance [24,43,44] • Thermal distortion resistance [44] • Thermal diffusivity [24,43] • Flammability [24,43,44,47,295,299–301]
Cold resistance	• Part/feature thickness [24] • Part volume [24]	• Ductile/brittle transition temperature [46,315] • Glass transition temperature [24,43,44,46,47,295,299–301] • Toughness at low temperature [46] • Continuous service temperature [46] • Minimum service temperature [24,43,44,46] • Thermal conductivity [24,43,44,46] • Specific heat [24,43,44] • Heat capacity [24] • Thermal expansion coefficient [24,43–47,295,300,301] • Thermal shock resistance [24,43,44] • Thermal distortion resistance [44] • Thermal diffusivity [24,43]
Chemical requirements		
Water resistance	• Crevices [24] • Wall thickness [289] • Porosity/gaps [289] • Surface finish [289]	• Water absorption [44–47,300,301] • Water vapor transmission [44] • Permeability (O_2/CO_2/N_2) [44] • Humidity absorption [44] • Resistance to water [24,44]
	See also: Detail, Surface finish	
UV resistance	—	• UV resistance [24,44,46] • Radiation absorption/dissipation factor [316] • Indoor stability [300] • Outdoor stability [300]

Table A1. *Cont.*

Design Requirement	Structural Properties	Material Properties
Chemical resistance	• Crevices [24] • NEMA-rating [290]	• Resistance to acids [24,44,47,301] • Resistance to alkalis [24,44,47,301] • Resistance to organic solvents [24,44,47,301] • Resistance to oxidation [24,44] • Resistance to radiation [24] • Resistance to fuels [24] • Resistance to oils [24] • Resistance to alcohols and aldehydes [24] • Chemical resistance index [44] • Environmental stress crack index [44] • Oxygen index [44]
	See also: Detail, Surface finish	
Food safety	• Surface finish [317,318] • Cleanability [317] • Crevices [317,318] • Ridges [317,318] • Corner radii [318] • Screw threads [318] • Dead zones [318] • Drainability [318] • Shaft passages and seals [318] • Porosity [318]	• Food contact grade [44] • Sterilizability (ethylene oxide/radiation/steam autoclave) [44,46,47,318] • Chemical resistance [318]
	See also: Detail, Surface finish, Chemical resistance	

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