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Feasibility of On-demand Additive Manufacturing of Spare Parts

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Abstract: Spare parts availability is crucial for extending the life of consumer products. However, long-term availability could lead to high stocks of spare parts, which might not be used. Instead, on-demand manufacturing of spare parts with additive manufacturing (AM) is a promising alternative. This paper presents a method to evaluate parts on their eligibility for AM spare parts. The parts evaluation is based on AM technology accessibility as well as part requirements. This method was tested by assessing all parts of the Dyson V11 broom-stick vacuum-cleaner and validated by printing and testing a selection of parts. For this, both plastic and metal spare parts were made through fused deposition modelling (FDM), stereolithography (SLA), binder jetting (BJ), material jetting (MJ), selective laser melting (SLM), selective laser sintering (SLS), and multi jet fusion (MJF), using both desktop FDM printers and off-site service providers. Based on these results, we conclude that currently only a small number of parts can be replaced by additive manufactured parts without considerable redesign efforts. AM parts can compete on price with the current stocked parts, but may be more expensive for other products. We also identified additional functional requirements for evaluating the eligibility of a spare part for AM.

Introduction

The 2014 EU circular economy strategy considers maintenance and repair important ways of preserving resources and prolonging consumer products' lifespan (Šajn, 2019). To conduct repairs, access to spare parts, tools, and information is required, which are often controlled by the original equipment manufacturer (OEM) of the product (Svensson-Hoglund et al., 2021). The spare parts inventory is normally held by an OEM or third-party service provider to fulfil warranties (Zhang, Huang, & Yuan, 2021). This means that consumers can only repair their products for a short time (typically 2 years) and only through the OEM service (Hernandez & Miranda, 2020). Spare parts may not be available when the production of the products ceases (Zhang, Huang, & Yuan, 2021). Instead, it can become more cost effective for OEMs to replace a broken product, which further affects spare part availability (Frenk et al., 2019; Van Der Heijden & Iskandar, 2013).

The 2019 EU Ecodesign regulations include reparability requirements, like increased spare part availability. Manufacturers need to ensure that specific parts are available within 15 working days for seven to ten years after the last market release (European Commission, 2019; Šajn, 2022). The European Commission is exploring the potential of implementing a repair score system based on repair, reuse, and upgrade standard EN 45554 (European Commission, 2022, p. 7).

Long-term spare part availability means that OEMs need to find cost-effective ways to keep spare parts stock for older models (Svensson-Hoglund et al., 2021). To increase spare part availability while preventing obsolete stocks, on-demand spare parts manufacturing with additive manufacturing (AM) could be used. Digital spare parts can reduce wait time, labour cost, delivery time and costs, emissions, material waste, and inventory (Attaran, 2017; Chekurov et al., 2018). Additionally, AM economics make it ideal for on-demand spare parts manufacturing (Ford, Despeisse, & Viljakainen, 2015).

However, not all spare parts can be 3D printed. Recent research has established printability requirements, especially related to part geometry (Chaudhuri et al., 2020). Van Oudheusden et al. (2023) have shown that AM is less suited to facilitate self-repair due to the redesign that is often needed to make parts manufacturable with AM at a similar mechanical performance. However, AM might be suitable in professional repair. More insight is then needed on to what extent spare parts for consumer products can be replaced by spare parts made with additive manufacturing techniques. We need to be able to evaluate the printability of product parts, based on accessibility, part functionality, and economic feasibility. Thus, the research question of this paper is, "How can we evaluate the printability of product parts based on part requirements?"

To answer these questions, we studied the accessibility of AM methods by looking at which methods are widely available, affordable, and of high enough quality, while considering both direct ownership and printing services. Then, we constructed a list of part requirements and used these in a theoretical assessment of all the parts in a household appliance. This theoretical assessment was then validated through printing and testing a selection of parts.

Method

Part printability was evaluated for a high-end vacuum cleaner Dyson V11 Torque Drive (about € 650-€700). The Dyson V11 was selected as it is an advanced household appliance offering a multitude of complex parts made from different materials. As such, it is considered an interesting case study.

The vacuum cleaner was fully disassembled using commonly available tools: PH1 (Philips) screwdriver, T8 (Torx) screwdriver, plastic prying tools, needle nose pliers, cutting pliers, flat screwdrivers, and hammer. The hammer and flat screwdrivers were used together to remove smaller parts which could only be removed with considerable force (e.g., the smaller roller wheel axles in the brush head).

The parts were mapped using the Product Breakdown Structure (PBS) method (NASA, 2016). The PBS was complemented with the part material, if identified. For further distinction, parts were only considered "eligible" for additive manufacturing if they were not standardized or commonly available parts, such as fasteners, springs, or bearings. These could likely be purchased faster, more affordably, and at higher quality than they could be printed. Parts that could not be fully disassembled were also not considered eligible. The resulting eligible selection of spare parts would need to be printable through AM.

For assessing part printability, printing methods were considered that are commonly available through service providers: fused deposition modelling (FDM), stereolithography (SLA), binder jetting (BJ), material jetting (MJ), selective laser melting (SLM), selective laser sintering (SLS), and multi jet fusion (MJF).
Printability of parts was assessed on the following eight limiting criteria, as defined by van Oudheusden et al. (2023): (1) exposure to high forces, (2) exposure to high temperatures, (3) accurate fit required, (4) fine details, (5) smooth surface or low friction required, (6) complex curvatures, (7) complex geometries, and (8) complex or inaccessible cavities. Guidelines were defined for each criterion to increase the scoring reproducibility, see Buijserd (2022). Criteria were only marked as applicable if they were essential for part functioning. For example, if a part had complex cavities required for injection moulding but without further functional purpose, the criterion did not apply. A part printability rating was calculated for each part by starting with a score of nine and subtracting one point for each applicable limiting criterion. A part failing all eight limiting criteria scores a 1. A low printability score means a part will be more difficult to print and that careful consideration is needed of the printing method, printing material, and printer settings.

Printed part affordability was evaluated by making three roughly modelled "mock-up" parts. The outer part dimensions and material volumes roughly matched the original parts, but no details were modelled. These mock-ups were submitted to service providers for a price quote, which was then compared to the original spare part cost.

Results

Parts mapping

The Dyson V11 was disassembled into 174 parts, of which 139 are unique, see Figure 1. The parts are grouped in 23 sub-assemblies, which in turn constitute six main part assemblies. Some subassemblies, like the rear dustbin seal, the motors, and the battery pack, could not be disassembled without breaking the parts or endangering the repairer. Excluding all non-eligible parts gave 67 eligible unique parts.

Figure 1. The disassembled Dyson V11.

Figure 2 shows the high-level hierarchical breakdown and the distribution of unique eligible parts over the (sub)assemblies. The brush head has the most with 26 unique eligible parts, followed by the vacuum section with 21 such parts

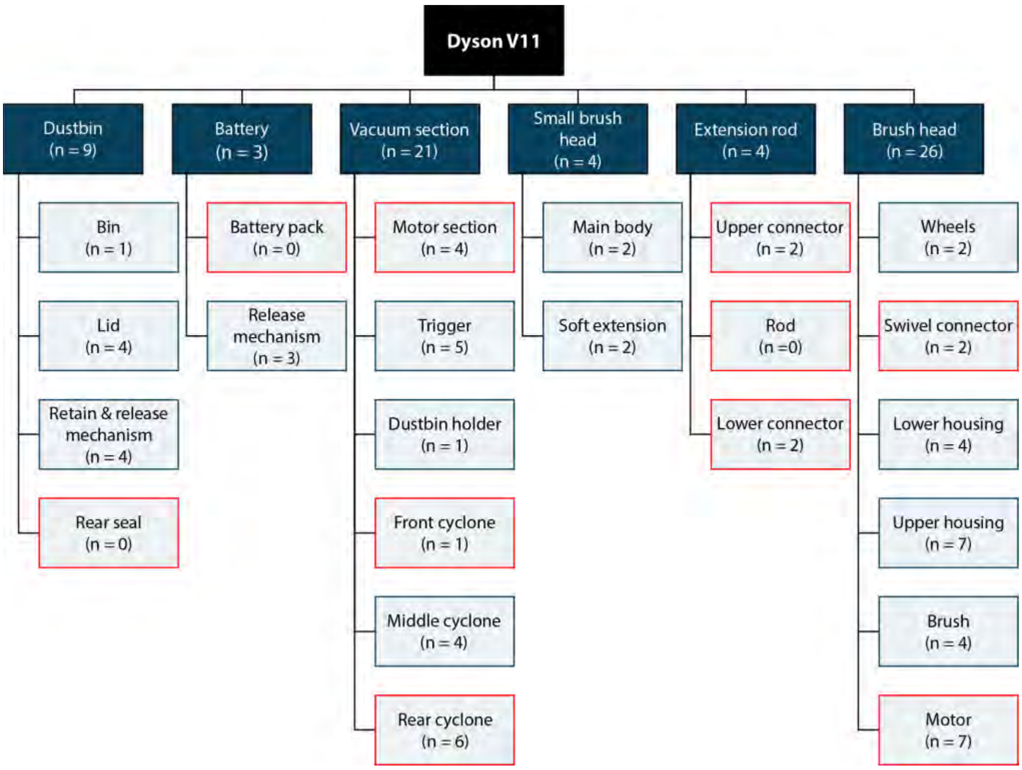

Figure 2. The Dyson V11 hierarchical breakdown. Darker boxes are assemblies, lighter boxes are subassemblies. The numbers indicate the number of eligible unique parts in each (sub)assembly. A red bevel indicates the subassembly could not be fully disassembled.

Materials

Figure 3 shows most parts are made of plastic, and that many different materials have been used. In total 25 different materials and material blends were identified, but for some materials the exact composition could not be defined. The multi-material group has the largest variety of materials, including nine different combinations.

Printability

Each part of the Dyson V11 was assessed using the eight limiting criteria mentioned in the Methods section, see for example Figure 4. Figure 5 shows the part printability scores for all eligible unique parts. Nearly all parts encounter one or more limiting criteria. Most parts encounter one limiting criterion, the lowest score was a three, and only six parts scored 9 out of 9. When assessing these high scoring parts, four of them were found to be flat foam gaskets to close part connections. These were difficult for FDM printing to match material compressibility. The other two parts could be replaced with FDM printed copies.

Still, most parts score relatively well on these criteria, and parts are usually still printable even when multiple limiting criteria apply. For example, the spring clip shown in Figure 4 had three limiting criteria but was printed successfully using SLS, SLM, and BJ.

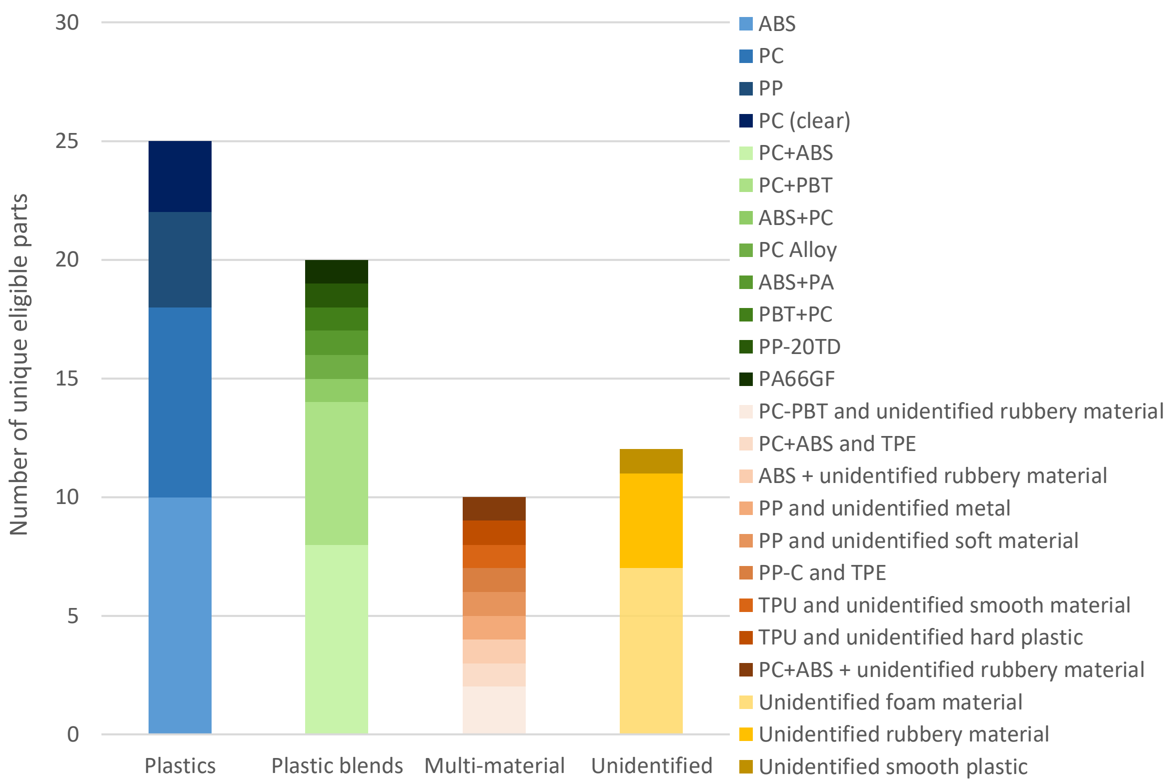

Figure 3. The material use in the Dyson V11. These materials include (blends of) acrylonitrile butadiene styrene (ABS), polycarbonate (PC), polypropylene (PP), polybutylene terephthalate (PBT), polyamide (PA), thermoplastic elastomer (TPE), PP copolymer (PP-C), thermoplastic polyurethanes (TPU), PP reinforced with 20% talc (PP-20TD), and PA 66 with glass fibre (PA66GF).

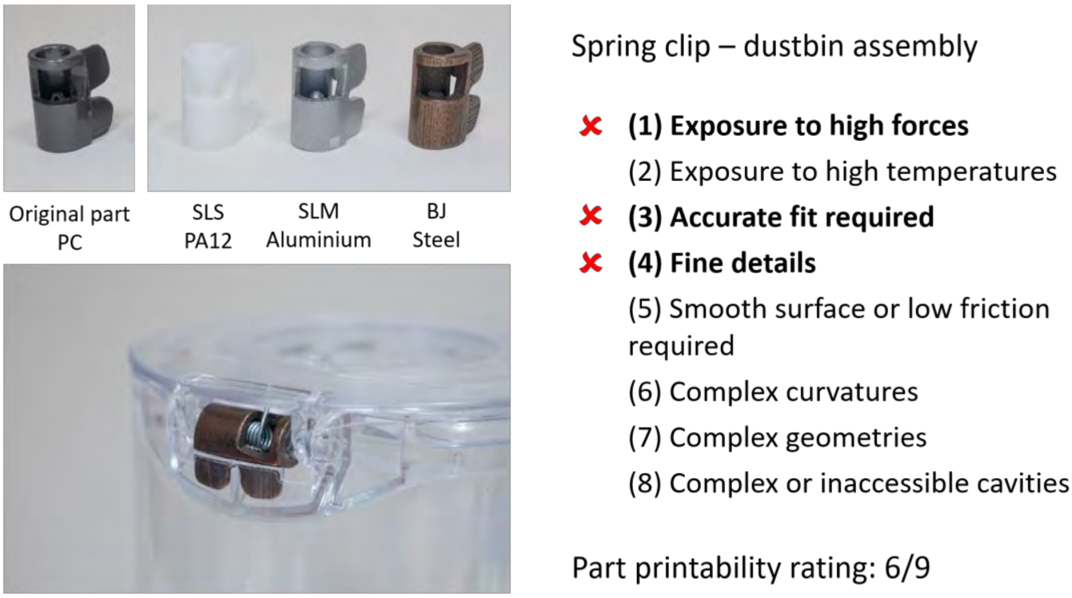

Figure 4. The spring clip printed in various materials. Limiting criteria that apply are marked with red X'es.

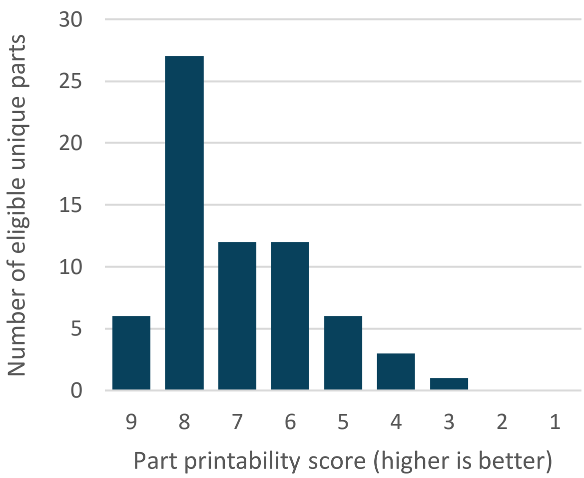

Figure 5. The Dyson V11 part printability scores.

Figure 6 indicates the occurrence of each limiting criterion. The main challenge is parts with fine details, which was marked applicable to 29 unique parts, but also other geometry related factors score high. The most frequent functional limiting factor was exposure to large forces during use.

When applying the limiting criteria, we further noticed that multiple parts of the Dyson V11 were made of flexible materials, such as rubber-like seals or soft-touch TPU parts. These materials can have properties like elasticity or flexibility beyond standard additive manufacturing capabilities. Additionally, there were multiple parts made of foam. This is not a common material in additive manufacturing, which can make it difficult to achieve the same compressibility. Other parts were multi-material parts, meaning that the materials of the part are irreversibly connected, such as a metal filter embedded in an injection moulded part. If the part cannot be replaced with a part printed in a single material, other strategies or specific printing methods are required, which are expected to complicate part production.

Affordability

The cost of spare parts for the Dyson V11 was assessed and compared with the costs of the printed replacement parts. Dyson offers a replacement for all Dyson V11 parts, but except for the HEPA filter, parts are not sold separately. Instead, consumers are required to buy and replace an entire (sub)assembly. For example, the lid can only be purchased as part of the dustbin reservoir (Dyson, 2023). Prices for original spare parts in this study therefore represent the cheapest option available for the part.

The cost of the printed replacement parts was evaluated by making three mock-up parts for the Dyson V11 and retrieving a price quote from a service provider. Figure 6 shows examples of one part. Table 1 compares the costs for printing three parts (lid, metal filter holder, and retainer clip) against the cost for the OEM replacement.

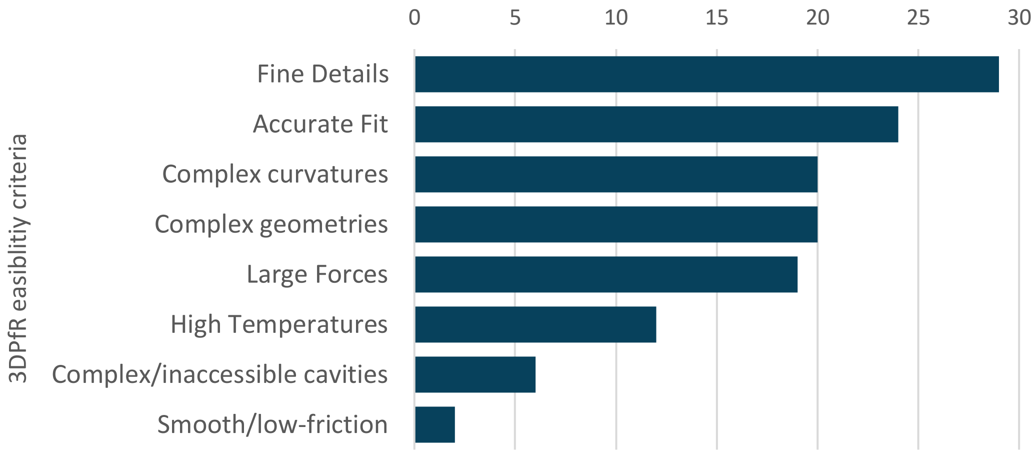

Figure 6. The occurrence of limiting criteria in the Dyson V11.

Part	Cost OEM replacement	SLS	MJF	BJT – steel	SLA – grey	FDM – ABS
Lid	€ 33.90	€ 19.07	€ 21.04	*€ 152.52*	*€ 78.92*	*€ 63.70*
Metal filter holder	€ 100.90	*€ 106.27*	€ 60.99	*€ 427.65*	*€ 139.95*	€ 52.50
Retainer clip	€ 40.00	€ 13.27	€ 13.53	€ 32.06	€ 32.43	€ 9.10

Table 1. Quoted prices for three mock-up parts of the Dyson V11. The cells marked in grey are more expensive than the OEM replacement.

Discussion

For this vacuum cleaner, 67 out of 139 unique parts were considered eligible for printed spare parts, even if a digital file is present and all printability-limiting criteria are overcome. Only 33 out of 139 parts scored very highly (8 or 9) in printability criteria. Multiple limiting criteria were encountered for most parts. Although the analysis only considered a single product, this product can be considered exemplary for many household appliances that use injection moulded plastic and multi-material parts, and that group parts in inaccessible (sub-)assemblies. Also, the multitude of materials used poses challenges to direct fabrication with AM as the manufacturing of such parts cannot be easily transposed. This implies that supplying spare parts through local AM requires either adaption in the product design to produce parts with both AM and conventional manufacturing, or that manufactures supply a digital file for AM that allows the printing of a functionally equivalent (but different) part.

Considering the method of establishing printability by assessing limiting criteria, Figure 4 shows that the criteria helped clearly distinguish between more printable and less printable parts. However, we observed that several parts were sensitive to printability issues despite a high score. This leads to additional criteria like flexibility/elasticity, compressibility, and multi-material composition (as with overmoulded parts). The highest-scoring parts were foam gaskets, which could also be produced by laser cutting sheets, so AM was not a unique enabler for their replacement.

The price of printed parts appears similar to the price of spare parts obtained through the OEM, but this is partly because the OEM requires consumers to buy a complete (sub-)module instead of just the needed part. Thus, AM spare parts are likely to be significantly more expensive than original spare parts for companies that do allow the purchase of individual spare parts. However, these economics could change for older products for which parts are rare.

Even if manufacturing AM spare parts is possible, quality guarantees will be needed. To ensure that printed spare parts are reliable, sustainable, and safe, some form of quality control and certification should be established, either through the OEM or AM service providers.

Limitations and recommendations

This study was limited by several factors. Part testing only considered the fit and short-term performance of the AM part, which makes it difficult to determine limiting criteria of long-term part performance. Also, only small parts were printed in metal, which could affect affordability for larger parts. Additionally, using an AM service provider meant that there was limited insight into the printing process, costs, and lead times. Industry can be expected to face the same challenges, but on the other hand, they can strive for more insightful collaborations.

For future research, we recommend further research into part printability to refine the current list of limiting criteria. As mentioned above, material properties like flexibility/elasticity, compressibility, and multi-material should also be considered. Additionally, research can focus on design strategies to overcome the challenges indicated by the limiting criteria. We also recommend further research to find the crossover point where AM of spare parts becomes preferable to conventional production, both environmentally and economically. To this end, we recommend that industry and OEMs focus on enabling AM of spare parts when designing the original part. Finally, additional developments in legislation and certification are needed to ensure that spare parts are safe to use.

Conclusions

Based on these results, we conclude that printed spare parts can be affordable, but that only a small selection of parts is suitable for additive manufacturing. Overall product complexity and part requirements such as fine details and accurate fit can make it difficult to reproduce parts without considerable redesign efforts. We also identified additional criteria for assessing part printability, which are elasticity and flexibility, compressibility, and multi-material. As additive manufacturing methods continue to develop and improve, it can be assumed that printed parts will become more accessible and affordable in the future.

Products should be designed for repair, and designing parts for printing on-demand can be part of this. Printing on demand means manufacturers could limit their stock of less-common parts, keep costs low, and have spare parts available long after warehoused parts would be economically prohibitive. Currently, a relatively small percentage of spare parts can be printed, but this could be fixed with redesign for printability (or if alternative printable spare parts are designed). Designing for repair is one of the many requirements to produce sustainable consumer products.

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