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Effects of carbon fibres on the life cycle assessment of additively manufactured injection moulding inserts for rapid prototyping

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Abstract

A life cycle assessment was conducted to evaluate the global warming potential and human toxicity of injection moulding processes applying newly developed tool inserts produced with vat polymerisation. The inserts were subject to increasing content of carbon fibres to improve their mechanical properties and lifetime. The additively manufactured inserts are compared to the standard materials steel, aluminium and brass. The investigated part of the production and prototyping phase considers the insert itself, the moulded part, and resulting waste material of the injection moulding process.

Additive Manufacturing Technology, Life Cycle Assessment, Fibre-reinforced Polymers, Injection Moulding

1. Introduction

Applications for Fibre-Reinforced Polymers (FRPs) in Additive Manufacturing (AM) have intensively been discussed in literature reviewed by [1]. An increased number of industrial applications includes Injection Moulding (IM) where a standardised mould manufactured from steel is equipped with a more flexible, faster, and cost-efficient IM insert manufactured from Vat Polymerisation (VP) [2-7]. Another main advance is given by the fact that tolerances are established by the VP manufacturing process. Compared to milling, the feature size especially for concave edges lies in the lower µm range and are influenced by the voxel size of the projector or laser in the printer.
Negative influence of thermal stresses result in a shorter lifetime of the inserts. Research by [2, 3] improved the lifetime performance of the inserts significantly by adding short, unseized Carbon Fibres (CFs) with dimensions of 7.2 µm diameter and 100 µm length to the photopolymer producing an insert shown in Figure 1.

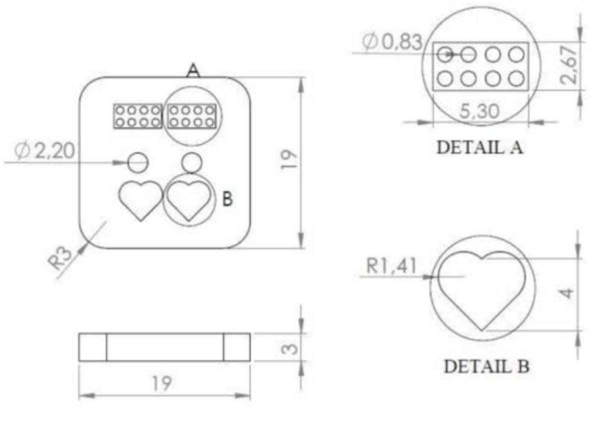

Figure 1 Geometry of the IM insert produced by VP from fibre-reinforced photopolymer. Source: [8], used with permission.

The thermoplastic polymer is injected from the back as shown in Figure 2. The polymer injection is followed by a packing phase which leads to a total time until then of 8.5 s followed by mould opening, part ejection and cooling time of 11.5 s. The cycle is continued from the beginning resulting in a total cycle time of 20 s during which the insert is exposed to temperatures between 20 C and 220 C resulting in massive thermal stresses. Metals withstand these stresses better and due to quicker cooling, are equipped with a longer lifetime.

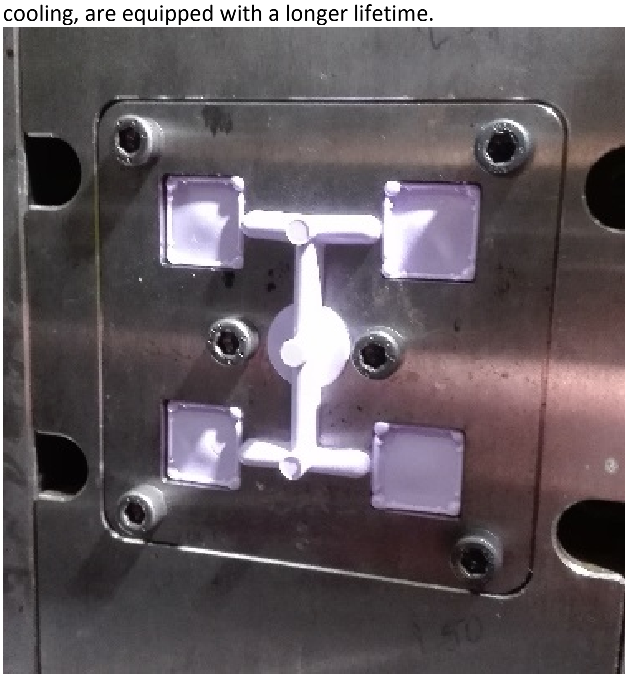

Figure 2 IM inserts and product in the conventional IM mould.

The aim of this paper is to evaluate the influence of the CFs in the IM process sketched in Figure 3 in terms of Life Cycle Assessment (LCA) previously conducted by [9, 10]. The inserts were compared to inserts made from conventional materials such as aluminium, brass, and steel though these materials have to be manufactured differently and are therefore limited by the tool diameter in shapes especially in concave corner regions.

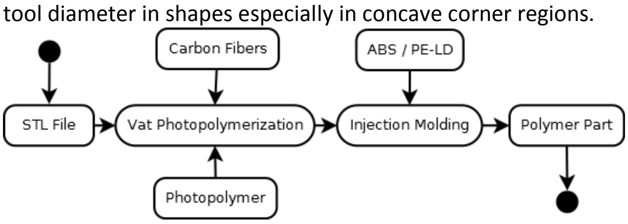

Figure 3 Process diagram of the IM process with focus on the contributors to the LCA. Source: [9], used with permission.

2. Methods

For this purpose, Global Warming Potential (GWP) and Human Toxicity (HT) were calculated for the given process according to ISO 14040/44 on screening level. Moreover, the moulded parts, made from PolyEthylen – Low Density (PE-LD) and Acrylonitrile Butadiene Styrene (ABS), were taken into consideration. The weight ratio of the moulded parts were compared to the total weight of the injected polymer including runners etc. that is responsible for approximately 60% of the produced polymer.

Inserts were produced from the proprietary photopolymer HTM-140v2 with 0% (VP 0%), 5% (VP 5%), and 10% (VP 10%) of CFs. The lifetime was considered from [2, 3] as 500 shots for VP 0%, 1300 shots for VP 5%, 2600 shots for VP 10%, and 10,000 shots for aluminium, brass and steel with 4 inserts each. Fibres were simulated according to [11, 12].

3. Results

Results of the LCA are shown in Table 1 for AM insert materials, Table 2 for metal insert materials, and Table 3 for part and waste material. It can be concluded that CF have a positive impact on the HT contribution of the inserts while their impact is still massively higher than the impact of steel as metal material with the lowest GWP and HT.

Table 1 LCA for AM insert materials. Values represent 1kg material. [9]

	VP 0%	VP 5%	VP 10%	CF
GWP in kgCO_2eq	3.118	3.769	4.419	16.127
HT in kg1,4-DBeq	621.790	596.313	570.835	112.236

Table 2 LCA for metal insert materials. Values represent 1kg material. [9]

	aluminium	brass	steel
GWP in kgCO_2eq	18.971	5.045	1.744
HT in kg1,4-DBeq	269.738	4772.948	85.757

Table 3 LCA for part and waste materials. Values represent 1kg material. [9]

	ABS	PE-LD
GWP in kgCO_2eq	3.995	1.896
HT in kg1,4-DBeq	7.057	2.486

The cumulative GWP of 4 inserts is shown in Figure 4 and Figure 5. The GWP increased at increasing CF content whereas the contributions to HT decreased. The impact of brass and aluminium on HT is significant. At the same time, the polymer scrap makes up for 60% of the weight of the injected polymer and increases the environmental impact by 33% at the first shot. The GWP of VP 10% remains below the impact of the metal insert materials as shown in Figure 4. VP 5% competes with steel at higher shot numbers.

At HT impact, the VP inserts remain between the aluminium and steel inserts for shot numbers over 5000. This makes the material suitable for prototyping and pilot production but increase the impact at larger production quantities.

In order to increase the inspected range, the entity of the injected polymer was taken into account in the LCA. This includes the final part as well as hot runners and other materials, which leave the cycle as scrap. Exemplarily, Figure 6 shows the cumulative HT impact of the mould system containing 4 inserts as well as the injected ABS polymer. Again, brass is characterised by a significant HT impact. GWP with ABS or PE-LD as well as HT with PE-LD shows similar characteristics despite the fact that the impact of PE-LD is significantly higher on HT.

Waste ratios were calculated for ABS and PE-LD scrap from hot runners and similar in relation to the entirely using the injected polymer. The ratio is shown in Figure 7 to Figure 10. Except for brass, VP 0% and VP 5%, the HT ratio converges to numbers slightly below 1 meaning that the HT impact of the inserts is negligible at higher production volumes. A similar situation occurs for ABS where the influence of the waste is even increased as compared to the impact of PE-LD waste for reasons described above.

A higher ratio is achieved for higher content of FRPs in VP due to the increased lifetime as compared to lower content of CFs.

4. Conclusion

FRPs significantly influence the lifetime of AM inserts. While AM offers significant improvement especially in terms of micro features of the surface, lifetime remains below the lifetime of metal inserts. Hence, the environmental impact needs to be considered especially for higher production quantities of parts.

The waste ratio of most materials covered by this investigation are above 0.6 after 2000 shots allowing the conclusion that the choice of materials still has potential for further improvement but only has a limited influence on the performance of the part in the LCA.

AM IM inserts proved to perform suitable for flexible prototyping and pilot production but lack at larger production quantities due to their reduced lifetime. They reduce manufacturing costs and time of the insert. CFs improve the performance not only in terms of lifetime of the insert, but also in terms of GWP and HT as compared to the photopolymer. The environmental impact of ABS supersedes the impact of PE-LD. However, the material is still chosen for its good mechanical performance.

Acknowledgements

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References

[1] Hofstätter, T. et al., "State-of-the-art of fiber-reinforced polymers in additive manufacturing technologies", Journal of Reinforced Plastics and Composites, 36(15):1061-1073, 2017.

[2] Hofstätter, T. et al., "Applications of fiber-reinforced polymers in additive manufacturing", Proceedings of the 1st CIRP Conference on Composite Materials Parts Manufacturing, CIRP, 2017.

[3] Hofstätter, T. et al., "Evolution of surface texture and cracks during injection molding of fiber-reinforced, additively-manufactured, injection molding inserts", Proceedings of ASPE Summer Topical Meeting 2016, ASPE - The American Society for Precision Engineering, 2016.

[4] Kovacs, J.G. "Construction of pre-deformed shapes for rapid tooling in injection molding", Macromolecular symposia, 239: 259-265. Wiley-Blackwell, 2006.

[5] Kovacs, J.G. et al., "Evaluation of measured and calculated thermal parameters of a photopolymer. International Communications", Heat and Mass Transfer, 38(7): 863-867, 2011.

[6] Tábi, N.K. et al., "Comparison of thermal, mechanical and thermomechanical properties of poly (lactic acid) injection-molded into epoxy-based rapid prototyped (polyjet) and conventional steel mold", Journal of Thermal Analysis and Calorimetry, 123(1): 349-361, 2016.

[7] Rahmati, S. et al., “Rapid tooling analysis of stereolithography injection mould tooling”, International Journal of Machine Tools and Manufacture, 47(5): 740-747, 2007.
[8] Mischkot, M. et al., ”Additive manufacturing for the production of inserts for micro injection moulding”, Proceedings of Euspen's 15th International Conference & Exhibition, 2015.
[9] Hofstätter, T. et al., “Integration of Fiber-Reinforced Polymers in a Life Cycle Assessment of Injection Molding Process Chains with Additive Manufacturing”, Proceedings of AMPA (Additive Manufacturing for Products and Applications) Conference, 2017.
[10] Hofstätter, T. et al., “Comparison of conventional injection mould inserts to additively manufactured inserts using life cycle assessments”, In Proceedings of Euspen's 16th International Conference & Exhibition. EUSPEN (European Society for Precision Engineering and Nanotechnology), 2016.
[11] Kreiger, M. et al., “Environmental life cycle analysis of distributed three-dimensional printing and conventional manufacturing of polymer products”, ACS Sustainable Chemistry & Engineering, 1(12):1511-1519, 2013.
[12] Song, Y.S. et al., “Life cycle energy analysis of fiber-reinforced composites”, Composites Part A: Applied Science and Manufacturing, 40(8):1257-1265, 2009.

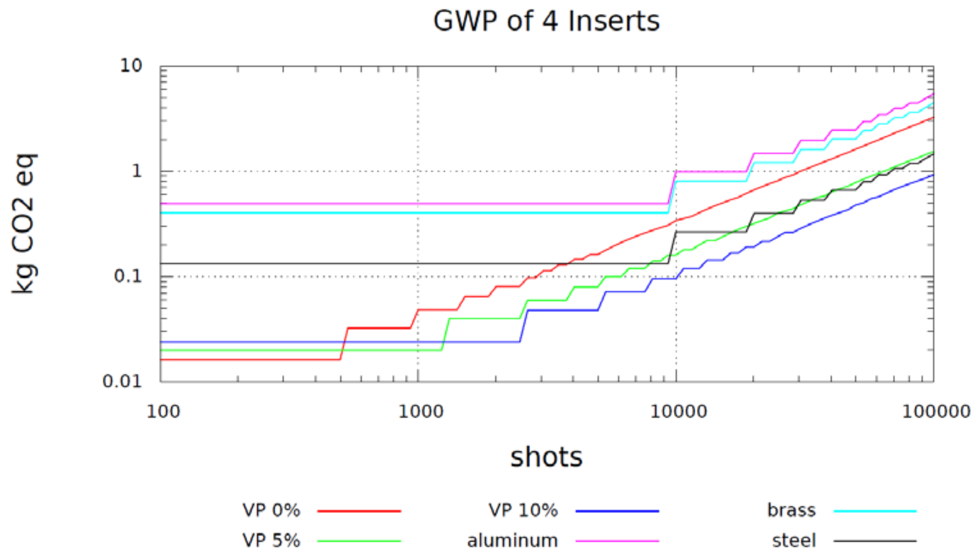

Figure 4 GWP for 4 inserts. Source: [9], used with permission.

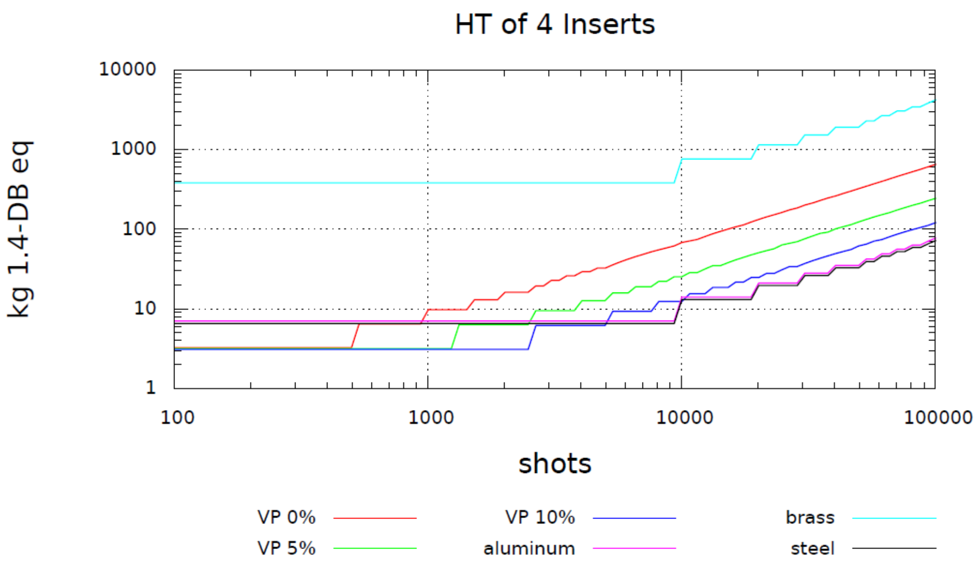

Figure 5 HT for 4 inserts. Source: [9], used with permission.

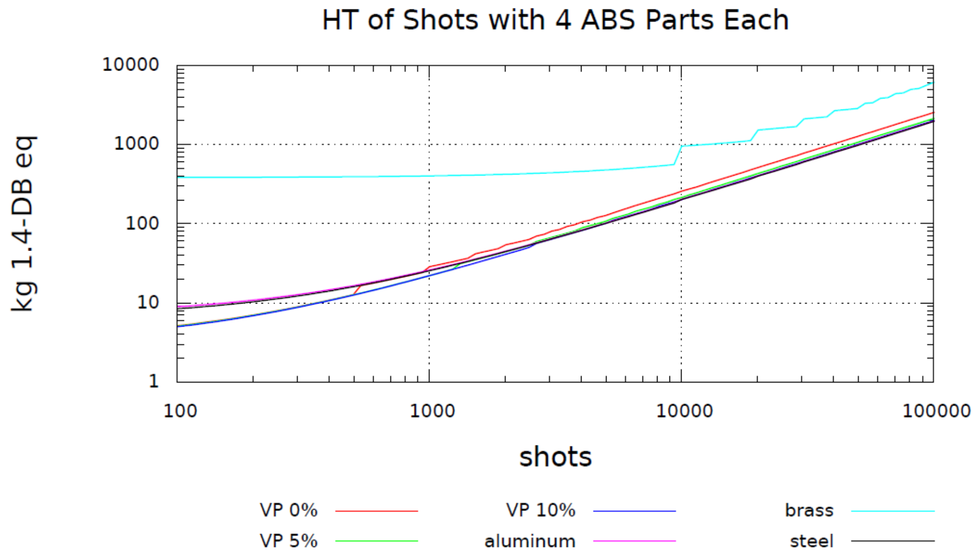

Figure 6 HT of 4 inserts with the connected ABS parts as well as ABS scrap.

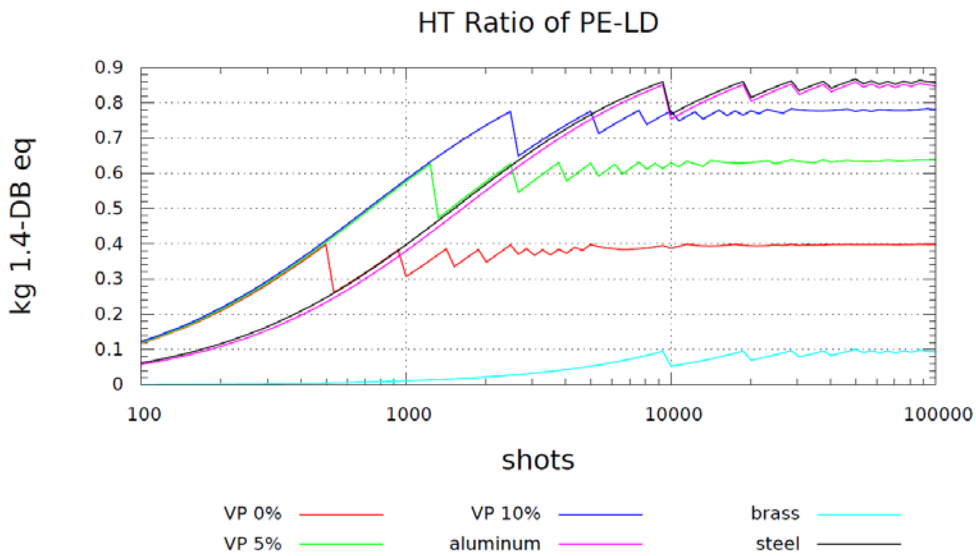

Figure 7 HT ratio of PE-LD waste on the entire process. Source: [9], used with permission.

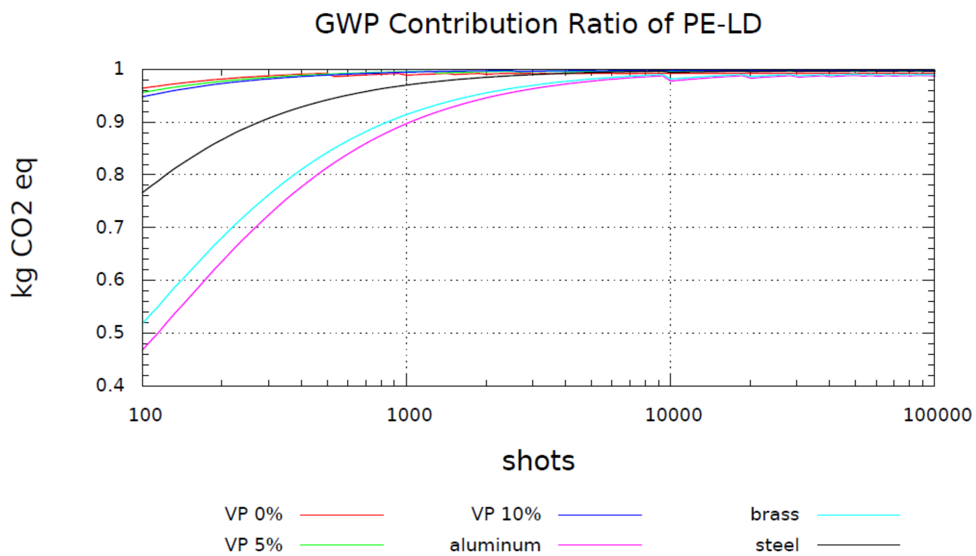

Figure 8 GWP ratio of PE-LD waste on the entire process. Source: [9], used with permission.

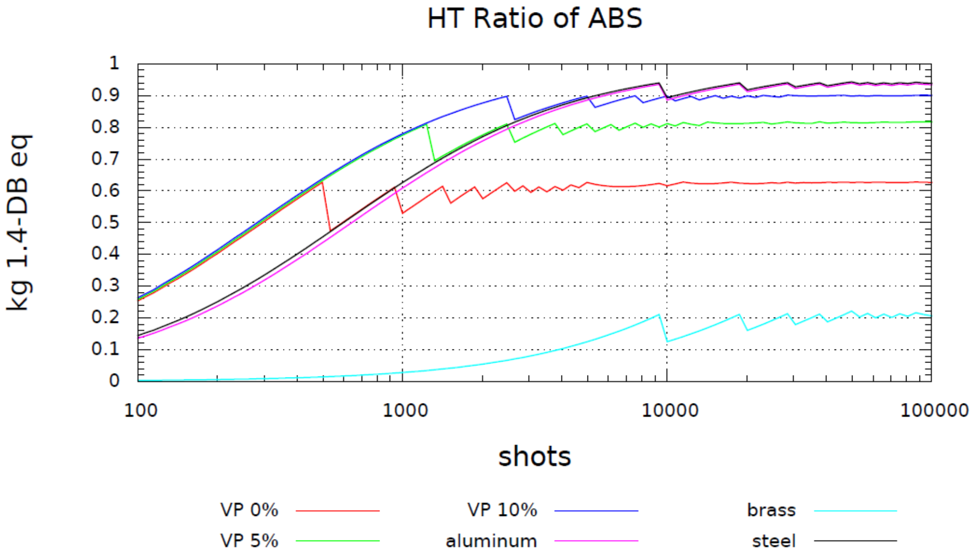

Figure 9 HT ratio of ABS waste on the entire process. Source: [9], used with permission.

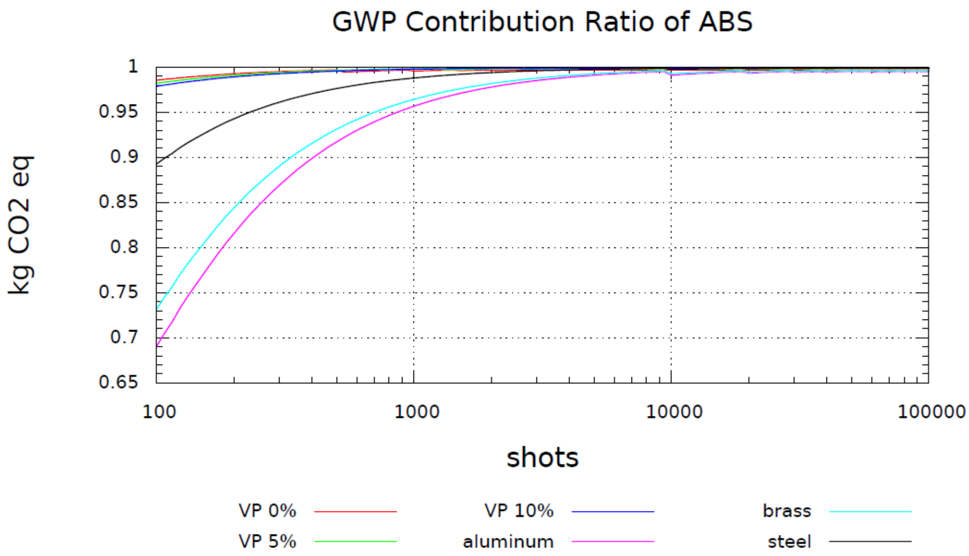

Figure 10 GWP ratio of ABS waste on the entire process. Source: [9], used with permission.