Life Cycle Analysis and Cost Modeling for the Manufacture of a Polymer-based Spatula

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Product Specifications and Process Selection

The product for manufacture is a 10-inch-long spatula made of one of the two following materials: Silicone rubber with 5-15% fumed silica additive (Si rubber) or homopolymer, molding and extrusion, unfilled polyvinylidene fluoride (PVDF). The volume of the spatula was estimated by approximating its design as the combination of a handle section and a thinner spatula face that total 10 inches in length. The exact shape of the spatula is not restricted in this analysis and can slightly change to best suit the manufacturing processes discussed. However, it is assumed that the section thickness of the handle should be at minimum 1 cm to ensure sufficient strength, and the face thickness should be thin (2-5 mm). The spatula should have a smooth surface finish and relatively tight tolerance to ensure the production of a desirable and effective consumer product. For both candidate materials, the spatula will be considered to be one solid part made by a single primary manufacturing process.

With these specifications and assumptions in mind, CES software[1] was used to select viable processing methods. Aside from the difference in material class (Thermoset elastomer for Si rubber, thermoplastic for PVDF), the filters used in the selection process were very similar for the two materials. The process was selected to be a primary production process capable of making a solid 3D part with a minimum section thickness of 1 cm. The processes were filtered further by limiting the roughness and tolerance of the manufactured parts. Finally, based on the data sheets for both materials, molding processes were considered due to suitability of both polymers for molding processes relative to other forming processes.

Transfer molding, thermoset injection molding, and compression molding were chosen as Si rubber processing methods for further analysis. All three are able to produce the necessary range of section thicknesses for the assumed part (~2-12 mm) and are suitable for the manufacture of Si rubber. These three molding methods are very prevalent in large batch polymer manufacturing in industry. For the same reasons as the Si rubber case, compression molding and transfer molding are suitable methods for manufacturing PVDF. Thermoplastic injection molding was not considered due to its small cross-sectional thickness. Notably, the batch rate of compression molding for thermoplastics is slower than for thermosets, which will be important in the cost modeling of these processes.

Cost Modeling

The selected processes/materials were put through a cost model in Excel to determine a single cost per part for each considered combination. The cost model used calculated material cost, tooling cost, and capital/overhead costs together as follows:

$$C = \left(\frac{mass * Cm}{Um}\right) + \left(\left(\frac{1}{n}\right) * \left(Ct * ROUNDUP\left(\frac{n}{nt}\right)\right)\right) + \left(\left(\frac{1}{ndot}\right) * \left(Coh + \left(\left(\frac{Cc}{L * twoh}\right) * ((1 + d)^{twoy})\right)\right)\right)$$

Cost values for each process/material were taken directly from the CES software and were assumed to be the average value of the range given (directly in between the minimum/maximum values) to best approximate average costs. Given that the batch size is 1,000,000 spatulas, the capital write-off time is 5 years, the load fraction is 1.0, and overhead cost rates are $60/hr, the following costs per spatula were calculated and input into table 1 below.

Table 1: cost per part

Cost Per Part for Selected Material/Process Combinations (USD)		
Process	*Si Rubber*	*PVDF*
Compression Molding	1.5964	4.2341
Transfer Molding	1.0630	2.7168
Injection Molding	0.8924	N/A

The cost model used indicated that the cheapest combination of the considered methods is the injection molding of Si rubber. A more detailed view of the effect of batch size on the cost of each production process can be seen in Appendix A.

Eco-audit and Life Cycle Analysis

The eco-audit tool on the CES software was used to analyze the life cycle costs of the polymer molding process for both materials. It was assumed that the spatulas have a lifespan of 7 years and are both made and distributed only in North America. Distribution is done via 6 axle trucks across a distance sufficient to reach any consumer in the chosen region (5000 km). It is assumed the material stock travelled the same distance to reach the manufacturing plant, such that there is no additional discrepancy in the transport impact on their lifecycle. Finally, the materials were assumed to be standard grade in terms of virgin material percent. The Si rubber was 100% virgin material, and the PVDF had a very low recycled content of 0.1%. For the first iteration of analysis, it is assumed the Si rubber ends up in a landfill at the end of its product life, and the PVDF is recycled. The estimated impact for both materials is shown below in tables 2 and 3.

Table 2: Eco-audit results for Si-rubber molding

Phase	Energy (MJ)	Energy (%)	CO2 footprint (kg)	CO2 footprint (%)
Material	7.86e+06	87.9	4.12e+05	82.9
Manufacture	8.4e+05	9.4	6.72e+04	13.5
Transport	2.33e+05	2.6	1.67e+04	3.4
Use	0	0.0	0	0.0
Disposal	1.13e+04	0.1	794	0.2
Total (for first life)	**8.95e+06**	**100**	**4.97e+05**	**100**
End of life potential	0		0	

Table 3: Eco-audit results for PVDF molding

Phase	Energy (MJ)	Energy (%)	CO2 footprint (kg)	CO2 footprint (%)
Material	9.82e+06	82.1	1.4e+06	89.8
Manufacture	1.69e+06	14.1	1.27e+05	8.1
Transport	3.88e+05	3.2	2.8e+04	1.8
Use	0	0.0	0	0.0
Disposal	6.63e+04	0.6	4.64e+03	0.3
Total (for first life)	**1.2e+07**	**100**	**1.56e+06**	**100**
End of life potential	-6.48e+06		-9.23e+05	

According to tables 2 and 3, Si rubber uses less energy and produces less CO2 emissions at every stage than PVDF when assuming standard grade material. However, PVDF has a large end of life potential if recycled that can mitigate its energy requirements for production. The total life cycle energy (subtracting EoL potential) for the PVDF is 5.52e6 MJ and is 8.95e6 MJ for the Si rubber. The total carbon emissions for the PVDF is 6.37e5 kg and is 4.97e5 kg for the Si rubber. If 100% of the PVDF is recycled, then the total life cycle energy of the PVDF process is lower, but its emissions are still higher than the virgin Si rubber. It is important to note that the assumption that 100% of the PVDF is recycled is likely not indicative of reality, as consumers might not recycle their spatulas. Additionally, the low percentage (0.1%) of recycled PVDF in circulation could indicate that that process of recycling PVDF is not common enough to assume 100% recovery of material. Despite this, the potential for embodied energy saving and recycling is important to consider in this analysis. A visual comparison of the life cycle energy and CO2 emissions are both shown below in figures 1a, 1b.

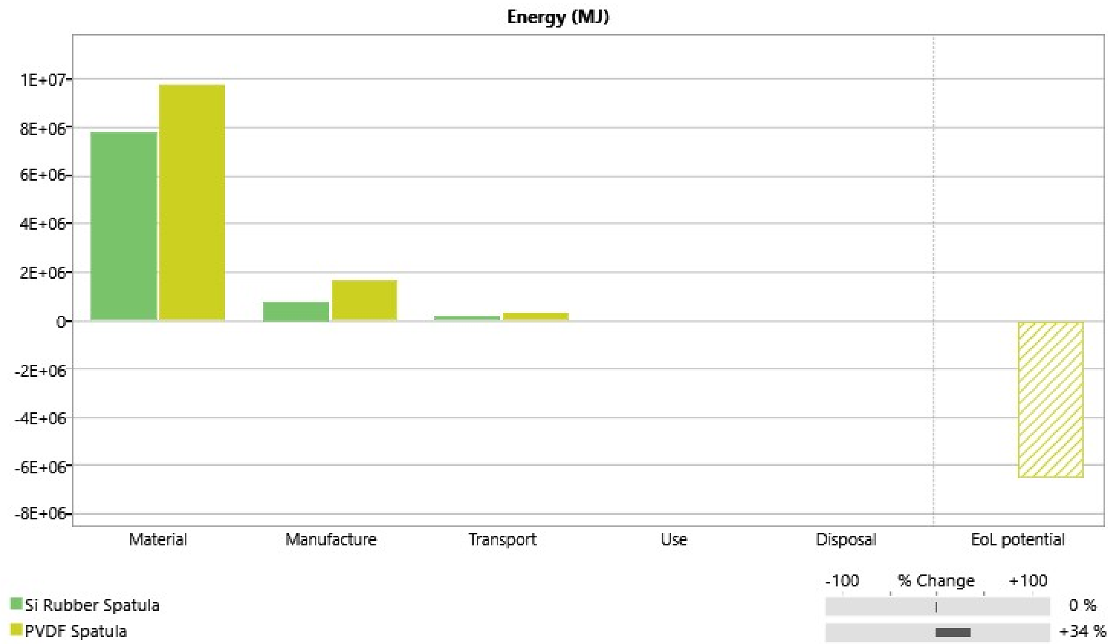


Figure 1a: Eco-audit energy use comparison for Si, PVDF molding processes

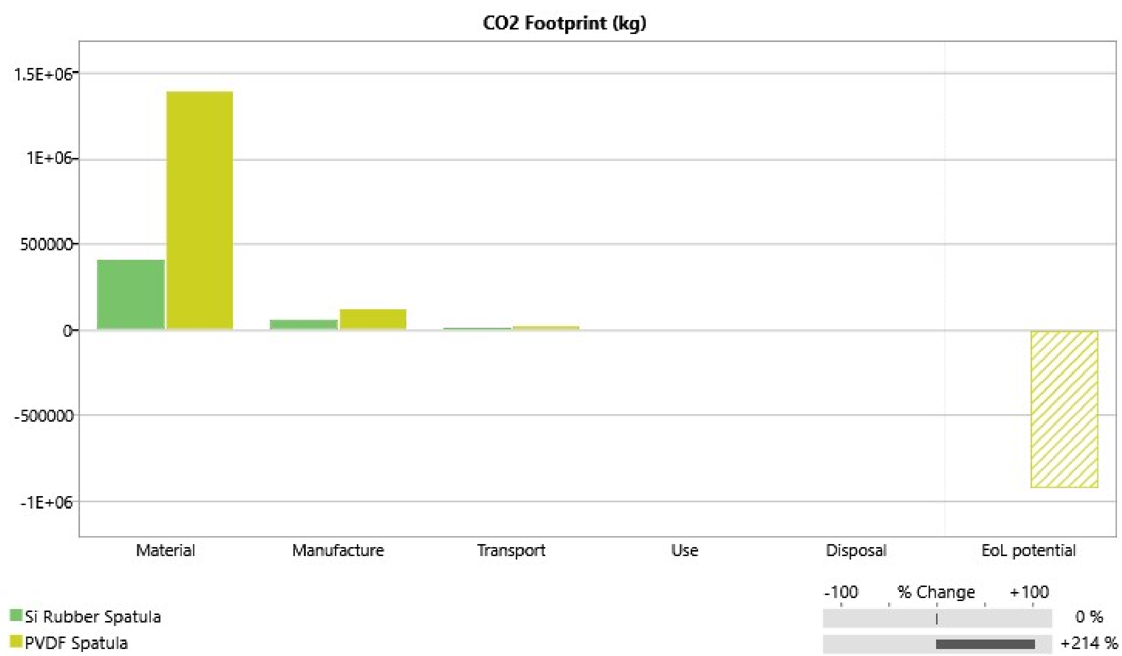


Figure 1b: Eco-audit CO2 emission comparison for Si, PVDF molding processes

A simplified life cycle analysis (SLCA) was also performed on both processes (Table 4,5) to assess life cycle costs and determine avenues for impact optimization. The life stages of the Si rubber generally had less negative impact than those of the PVDF. In particular, the premanufacture, manufacture, and delivery stages of Si rubber use less energy and produce fewer harmful byproducts than those of the PVDF. However, the inability of the Si rubber to be recycled greatly affects its end-of-life impact on the environment, as it can only be combusted to recover its embodied energy or simply put into a landfill. Both materials received the maximum score for their use stage, since using a spatula has no impact on any of the criteria.

Table 4: SLCA for Si rubber

Si rubber Molding Process SLCA						
life stage	**material choice**	**energy use**	**solid residue**	**liquid residue**	**gaseous residue**	**total**
premanufacture	2	3	3	3	2	13
manufacture	2	3	3	3	3	14
product delivery	3	3	3	3	3	15
use	4	4	4	4	4	20
recycling/disposal (end of life)	1	3	4	4	1	13
total	12	16	17	17	13	75

Table 5: SLCA for PVDF

PVDF Molding Processes SLCA						
life stage	**material choice**	**energy use**	**solid residue**	**liquid residue**	**gaseous residue**	**total**
premanufacture	3	2	2	2	1	10
manufacture	2	2	3	3	1	11
product delivery	3	2	3	3	2	13
use	4	4	4	4	4	20
recycling/disposal (end of life)	3	3	4	4	3	17
total	15	13	16	16	11	71

The SLCA performed reveals that the life stages with the largest environmental impact for the Si rubber are its end of life and premanufacture stages. A possible way to reduce the premanufacture impact would be to use a material supplier with tighter environmental control that captures the carbon emissions of rubber production and/or uses renewable energy. Burning the Si rubber at the end of its life recovers some of its embodied energy, but releases emissions, making it a less effective (though potentially still important) method for reducing environmental impact. The most environmentally critical life stages of the PVDF are its premanufacture/ manufacture stages. Since PVDF is recyclable, sourcing a higher percentage of recycled PVDF will greatly reduce its environmental cost.

Overall, the eco-audit and SLCA performed on both material/processing routes show that the standard-grade Si rubber has less of an environmental impact than the standard-grade PVDF. In general, the manufacture of the spatula using the Si rubber produced less emissions and used less energy than the manufacture of PVDF. When all life cycle costs are considered, the Si rubber has less of an overall impact.

Optimization of Cost and Life Cycle Impacts

A second iteration of both environmental and cost analysis was performed based on results from the above eco-audit/SLCA and cost modeling. For the second eco-audit, almost all of the same assumptions were used for the processing and life stage numbers. However, the Si rubber was assumed to be combusted at the end of its life to recover some of its embodied energy. Additionally, the recycled fraction of the PVDF was increased to 50% from 0.1%. Due to the low amount of recycled PVDF in the current supply chain, attaining more recycled material would likely be prohibitively expensive or difficult, which is why a 50% recycled material was used instead of a higher percentage. Table 6 and 7 below show the eco-audit results for both materials.

Table 6: Second iteration eco-audit results for Si rubber molding

Phase	Energy (MJ)	Energy (%)	CO2 footprint (kg)	CO2 footprint (%)
Material	7.86e+06	87.7	4.12e+05	82.8
Manufacture	8.4e+05	9.4	6.72e+04	13.5
Transport	2.33e+05	2.6	1.67e+04	3.4
Use	0	0.0	0	0.0
Disposal	2.84e+04	0.3	1.98e+03	0.4
Total (for first life)	**8.96e+06**	**100**	**4.98e+05**	**100**
End of life potential	-2.66e+05		7.35e+04	

Table 7: Second iteration eco-audit results for PVDF molding

Phase	Energy (MJ)	Energy (%)	CO2 footprint (kg)	CO2 footprint (%)
Material	6.58e+06	75.4	9.38e+05	85.5
Manufacture	1.69e+06	19.4	1.27e+05	11.6
Transport	3.88e+05	4.5	2.8e+04	2.5
Use	0	0.0	0	0.0
Disposal	6.63e+04	0.8	4.64e+03	0.4
Total (for first life)	**8.72e+06**	**100**	**1.1e+06**	**100**
End of life potential	-3.24e+06		-4.62e+05	

The higher percentage of recycled PVDF lowered the energy costs of the material greatly. The manufacture and transport stages of the PVDF still required more energy than that of the Si rubber, but the overall lifetime energy of the PVDF was lower (5.48e6 MJ) than that of the Si rubber even after combustion (8.694e6 MJ). However, the CO2 emissions of the PVDF (6.38e5 kg) over its lifetime are still greater than those of the Si rubber (5.715e5 kg). Since it is possible to recover embodied energy in the Si rubber while still creating less emissions than the PVDF, this audit suggests that Si rubber is still more ecologically friendly than the PVDF despite its end-of-life drawbacks. A visual comparison of the life cycle energy and CO2 emissions are both shown below in figures 2a, 2b.

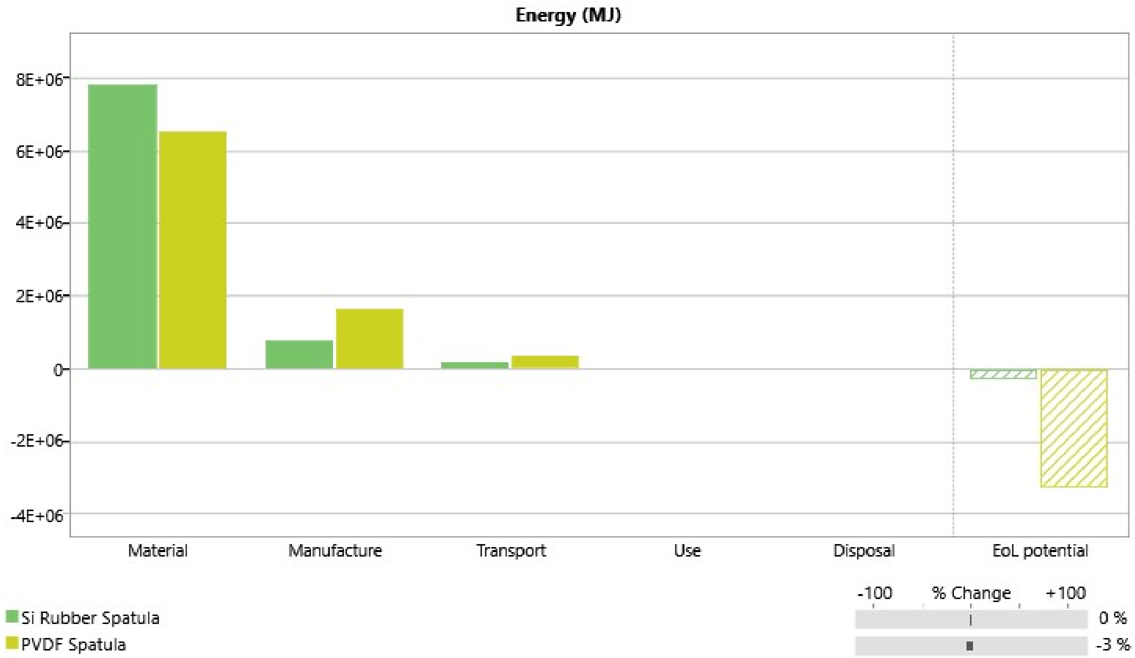


Figure 2a Second-iteration eco-audit energy use comparison for Si, PVDF molding processes

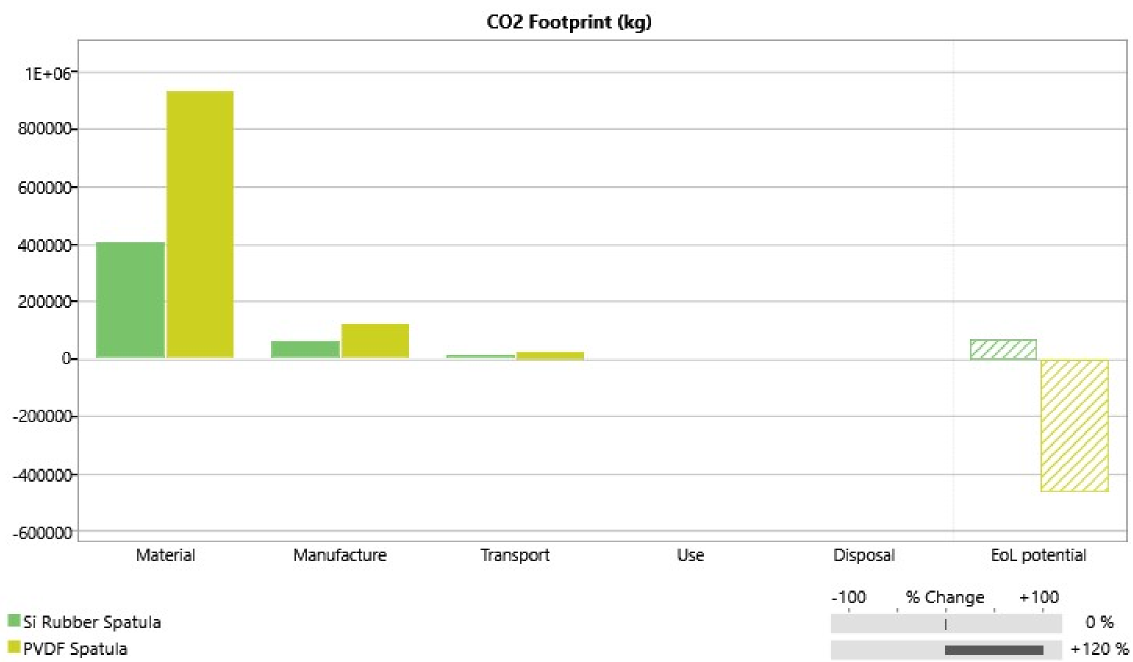


Figure 2b Second-iteration eco-audit CO2 emission comparison for Si, PVDF molding processes

The cost of the manufacturing processes can be lowered through capital investment. The most effective single factor in reducing costs is an increase in the batch rate due to the decrease in overhead and write-off costs. It is assumed that the way to increase the manufacturing production rate is to invest in more sophisticated, expensive machinery. Doing so raises capital costs, but greatly increases the production rate of the spatulas. The same cost model as before was used to explore this tradeoff using the maximum batch rate and equipment cost values from the CES software. The results of this analysis are shown below in table 8.

Table 8: Second iteration cost analysis cost per part

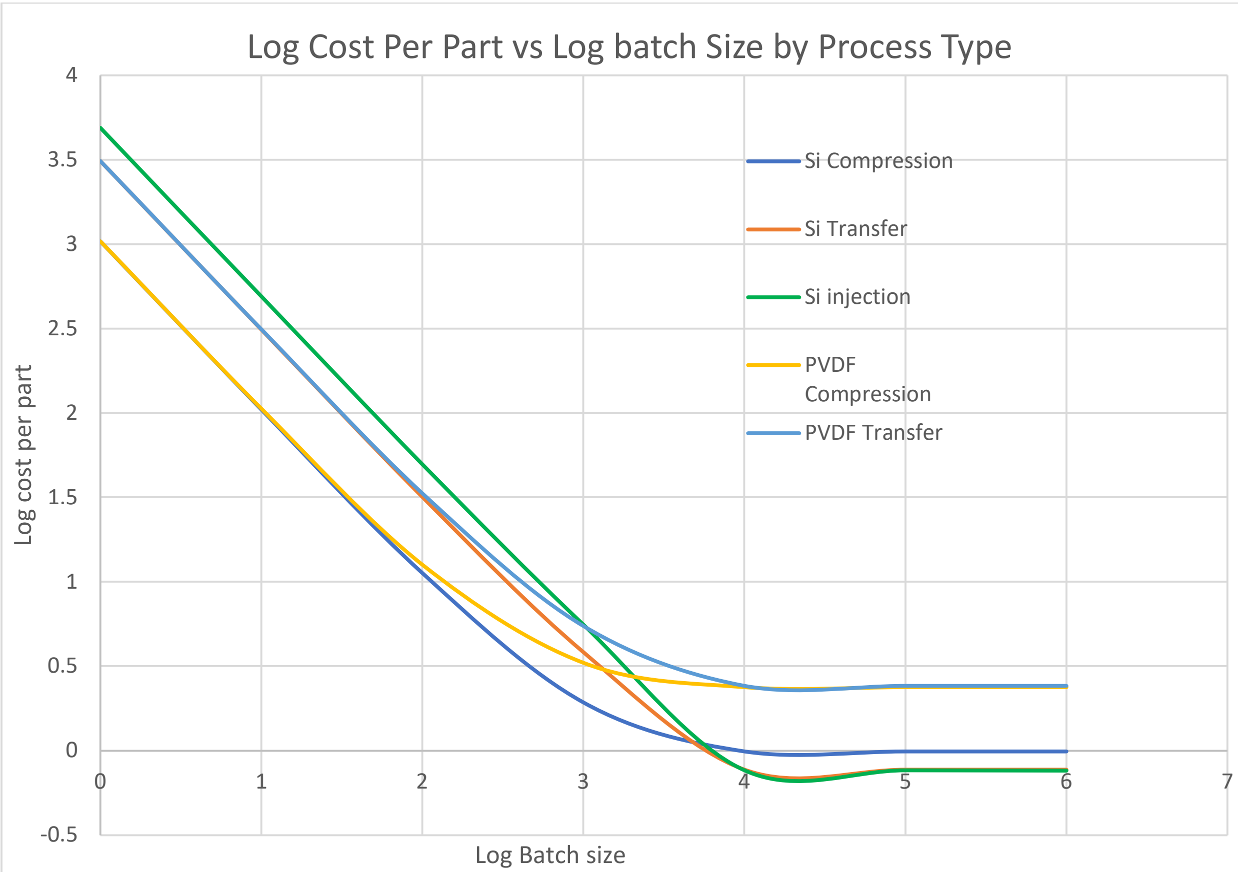
Cost Per Part for Selected Material/Process Combinations (USD)		
Process	*Si Rubber*	*PVDF*
Compression Molding	0.9894	2.3786
Transfer Molding	0.7723	2.4261
Injection Molding	0.7638	N/A

The cost of every manufacturing process is greatly decreased with a large increase in batch rate. Ideally, other process costs would also be optimized, notably tooling cost and life. However, the tooling cost cannot be decreased greatly, as cheaper, simpler molds can lower batch rate. Additionally, it may be possible that more sophisticated equipment could lengthen the life of the tooling in the molding process, though this was not considered as part of the cost analysis as the molds used were assumed to be the exact same as in the first cost model. The injection molding of the Si rubber remains the cheapest option overall for the manufacture of the spatula.

Manufacturing Recommendation

Based on all the above analysis on the selected material/process combinations, the recommended processing route is injection-molded Silicone rubber with 5-15% fumed silica additive. Besides being by far the cheapest method analyzed in terms of cost per spatula, the Si rubber had less of a lifetime impact on the environment. It used less energy in almost all life stages than even idealized PVDF and had much lower overall CO_2 emissions, which is critical to consider regarding modern environmental standards and impacts.

Appendix A: Log-Log cost/batch size curves



References

[1] "Ansys GRANTA EduPack software, ANSYS, Inc., Cambridge, UK, 2023 (www.ansys.com/materials)."