Project 3: Life Cycle and Cost Modeling

Zach Selzman

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Dr. Joel Galos

Nomenclature

m = mass (kg)
C_m = manufacturing cost (assume all costs are in USD)
U_m = material utilization fraction (fraction of material that ends up in part)
n = batch size (number of parts/year)
C_t = tooling cost
$\dot{n}$ = batch rate (parts/hour)
$\dot{C}_{oh}$ = overhead cost
C_c = capital cost
L = load factor (fraction of time manufacturing equipment is used)
d = discount rate
t_{wo} = capital write-off time (hours when in denominator, years when in exponent)
ρ_C = density cost

Introduction

This paper documents the methodologies used to recommend a material and manufacturing process choice for a 10-inch-long kitchen spatula given cost and environmental considerations. The spatula is used to stir and dispense foods, in which consumers primarily value functionality, then appearance and environmental impact, respectively. The materials of interest were provided as follows: silicone rubber with a 5-15% fumed silica additive and homopolymer, unfilled, molded, and extruded polyvinylidene fluoride (PVDF). Granta Edupack (sustainability level three) was used to guide the selection of optimal manufacturing processes for each material and to assess their respective ecological impacts. Additionally, a qualitative environmental analysis was conducted using a streamlined life cycle analysis table (SLCA). Cost modeling was completed to determine the relative affordability of the material and process combinations. Following the initial selection, proposed improvements targeting cost and ecological performance were implemented to assess the robustness of the chosen solution.

Process Selection

To determine manufacturing processes for both Silicone and PVDF, Granta Edupack was used to conduct the selection in three stages: material constraint, shape and process constraints, and plotting the production rates of each process to yield two to three candidate processes. The first step was to complete a tree constraint for Silicone (VMQ, heat cured, low hardness, 5-15% fused silica) and PVDF (homopolymer, molding and extrusion). Thus, the range of manufacturing processes was then restricted to those compatible with each material. Subsequently, to narrow down the list of applicable processes, they were constrained to be able to produce a solid 3-D shape and to be a discrete primary shaping process.

These constraints were implemented because the spatula's shape eliminates ineffective processes such as rotational molding—to use Silicone as an example. Moreover, a spatula is a non-continuous product formed from scratch, hence the process constraints, which eliminated thermoforming from PVDF's potential processes, for instance. The remaining processes were then plotted with respect to production rate. This stage could be interpreted as a preliminary cost constraint, in which the processes yielding high production rates were considered because of the parameter's influence on the overall cost. The plots for both materials are shown in Figure 1 and Figure 2.

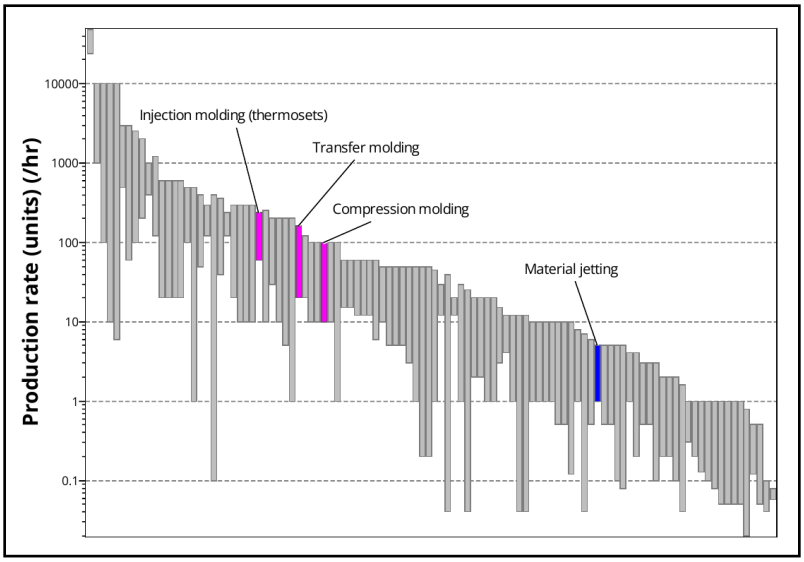


Figure 1: Plot of Silicone processes with respect to production rate

In Figure 1, it is clear that Thermoset Injection Molding, Transfer **Molding,** and Compression Molding boast orders of magnitude larger production rates relative to Material Jetting. Given cost considerations and financial assumptions (spatulas are a common household product, implying that they must be made at low-cost and in large quantities), the molding processes were selected as potential candidates.

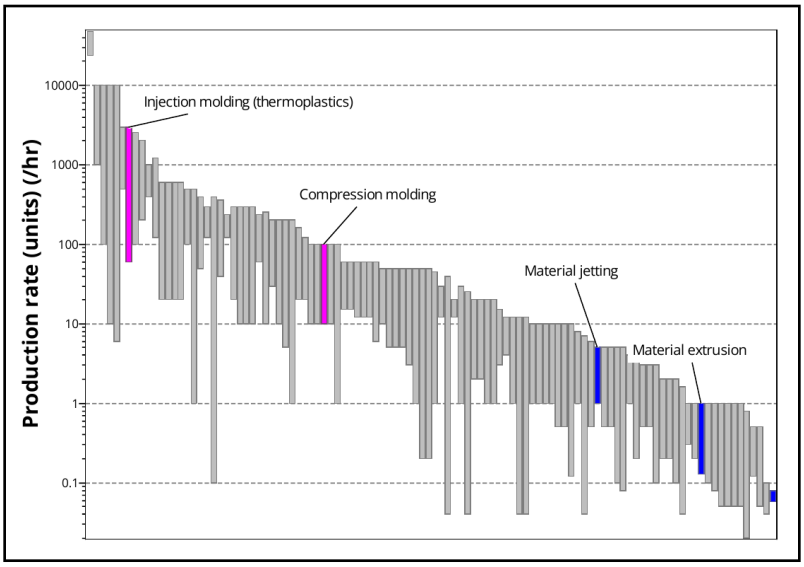


Figure 2: Plot of PVDF processes with respect to production rate

In the case of PVDF, the molding processes far much better than the material processes similar to Silicone, with Compression Molding and Thermoplastic Injection Molding demonstrating clear dominance over Material Jetting, and Extrusion[1]. Thus, the results of the process selection are consequently: Thermoset Injection, Compression, and Transfer Molding for Silicone; Thermoplastic Injection, and Compression Molding for PVDF.

Given the streamlining of manufacturing processes to within three for both materials, additional analysis is required to further differentiate the processes on the basis of cost. Despite large

[1]It is worth noting that the small blue bar in the bottom right corner of Figure 2 is a reference to the Ballistic Particle machining method. Granta Edupack characterizes this process as “obsolete”, hence it was omitted from consideration.

relative production rates (arguably the most significant cost parameter considering the high-volume spatula business), other contributors to overall cost need to be considered such as machining (tooling) cost, capital, and overhead costs. To continue the optimization of processes, a comprehensive cost model was conducted with the candidates derived from the process selection.

Cost Modeling

To provide a holistic cost analysis, all cost parameters have to be addressed. Fortunately, they are encapsulated in a digestible form in Equation 1:

$$\underbrace{C}_{\text{Total Cost}} = \underbrace{\left[\frac{mC_m}{U_m}\right]}_{\text{Material Cost}} + \underbrace{\frac{1}{n}[C_t]}_{\text{Tooling Cost}} + \underbrace{\frac{1}{\dot{n}}\left[\dot{C}_{oh} + \frac{C_c}{Lt_{wo}}(1+d)^{t_{wo}}\right]}_{\text{Capital + Overhead Cost}} \tag{1}$$

This equation was then used to model how the overall cost of each material and process combination is subject to fluctuations as a function of batch size n. To do so, data was accumulated through either Granta Edupack averages (if provided a range) or from Dr. Galos.[2] The tables for the respective values are shown below in Table 1 and Table 2:

[2]Dr. Galos provided that the manufacturing factory will produce 1,000,000 spatulas per year, the write-off time is 5 years (43,800 h), the load fraction is 1.0, and that indirect cost rates are $60/h.

	Thermoplastic Injection	Compression
Material mC_m	1.18	1.18
Overhead Rate $\cdot$ $(C)_{oh}$	60	60
Load Factor L	1	1
Capital Write-Off t_{wo}	43800	43800
Discount Rate, d	0.1	0.1
Material Utilization Fraction U_m	0.75	0.875
Tooling Cost C_t	49035	10395
Capital Cost C_c	442850	65950
Batch Rate $\cdot$ n	1530	55
Years t_{wo}	5	5

Table 1: Cost Values for PVDF

	Thermoset Injection	Transfer	Compression
Material mC_m	0.23	0.23	0.23
Overhead Rate $\cdot$ $(C)_{oh}$	60	60	60
Load Factor L	1	1	1
Capital Write-Off t_{wo}	43800	43800	43800
Discount Rate, d	0.1	0.1	0.1
Material Utilization Fraction U_m	0.75	0.735	0.875
Tooling Cost C_t	49035	31130	10395
Capital Cost C_c	442850	103950	65950
Batch Rate $\cdot$ n	150	90	55
Years t_{wo}	5	5	5

Table 2: Cost Values for Silicone

For the sake of calculation, some assumptions were required, namely material cost mC_m. To estimate the value, the spatula volume was estimated to be $5.5 * 10^{-5}$ m^3. Then, using Equation 2, in which ρ_C was provided by Granta Edupack, the material cost was calculated by multiplying the estimated volume with the density cost to get the mass material cost.

$$mC_m = \rho_c V \tag{2}$$

Despite the volume being an estimate, it is a constant multiplied with Granta's density value. Thus, it is a consistent material cost for both Silicon and PVDF relative to each other. The complete cost analysis, which iterates through discrete batch sizes n is shown in Table 3 and Table 4.[3]

Batch Size	Thermoset Injection	Transfer	Compression
1	49035.82	31131.02	10396.4
10	4904.32	3114.02	1040.9
100	491.17	312.32	105.35
1000	49.85	32.15	11.80
3000	17.16	11.4	4.86
10000	5.72	4.14	2.44
30000	2.45	2.06	1.74
100000	1.31	1.33	1.50
1000000	0.86	1.05	1.41
10000000	0.82	1.03	1.40

Table 3: Silicon Cost Analysis

Batch Size	Thermoplastic Injection	Compression
1	49036.62	10397.48
10	4905.12	1041.98
100	491.97	106.43
1000	50.66	12.88
3000	17.97	5.95
10000	6.53	3.52
30000	3.26	2.83
100000	2.11	2.59
1000000	1.67	2.49
10000000	1.63	2.48

Table 4: PVDF Cost Analysis

From Equation 1, both material cost and capital overhead cost are constant, and are referred to as fixed costs (different for each material). Thus, tooling cost is the only parameter that changes as a

[3]It is worth noting that the analysis continues until $n = 10{,}000{,}000$, despite information that the factory is producing up to $n = 1{,}000{,}000$. This was done for additional clarity for Figure 3 and Figure 4.

result of a varying batch size. This is because as the batch size increases, the fixed costs are distributed between more product units, thus, the cost assigned to each spatula decreases. However, the fixed costs are not negligible, as demonstrated in Table 3 and Table 4:

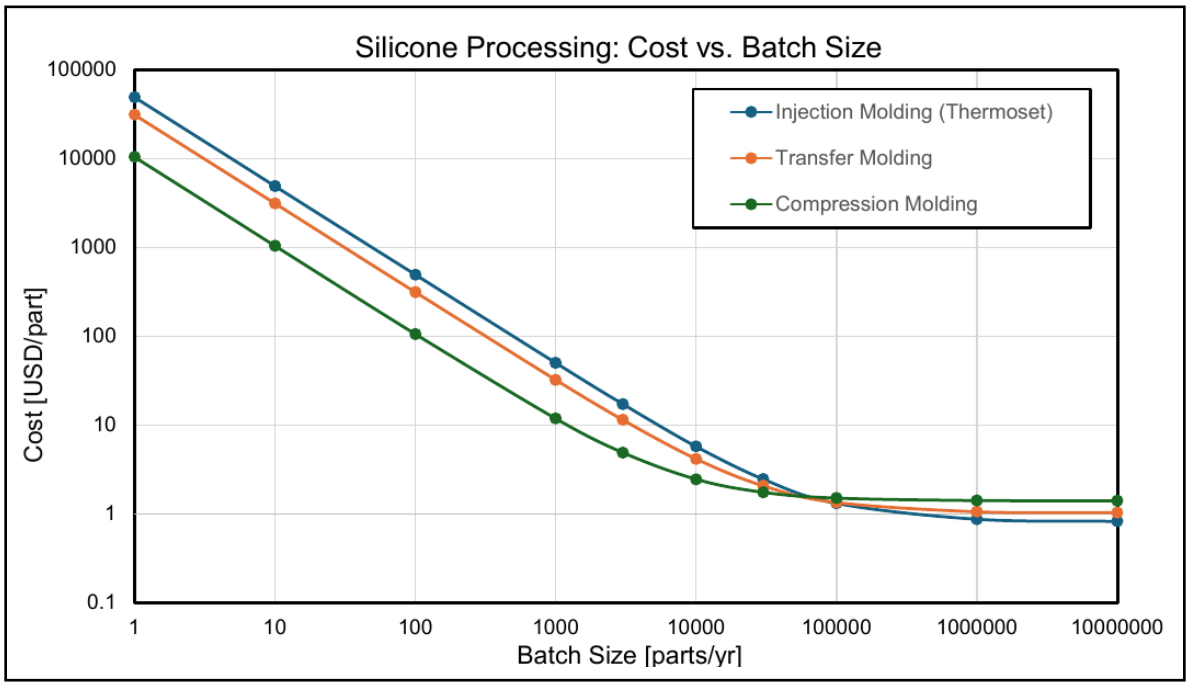


Figure 3: Plot of Silicone process costs as a function of batch size

The region of interest is the "cross-over" point, in which the cost ranking of the processes changes as a result of tooling cost being weighted higher than the fixed costs. For example, for Silicone Processes shown in Figure 3 show Thermoset Injection more costly than both Transfer and Compression as a result of capital and overhead costs.[4]. However, once the batch size approaches the range $\in [30{,}000, 100{,}000]$, Thermoset Injection becomes cheaper than the other processes, as its tooling cost is initially larger (tooling cost has a higher proportional contribution, thus it is more responsive to changes in batch rate).

Most notably, for the production of a million spatulas, Thermoset Injection Molding is the cheapest option. Transfer and Compression molding perform relatively well, however, the

[4]The fixed costs are material, capital, and overhead (capital and overhead are grouped together in Equation 1) However, when analyzing the processes with respect to a singular material, material costs are constant between processes. Thus, capital and overhead costs are the only relevant differentiating fixed cost.

difference is somewhat significant, with Transfer being $0.19 and Compression being $0.55 more expensive per spatula than Thermoset Injection. For a shipment of a million spatulas, the cost difference would accrue severely, implying that Thermoset Injection is the optimal process —excluding ecological implications, which are discussed in the following section.

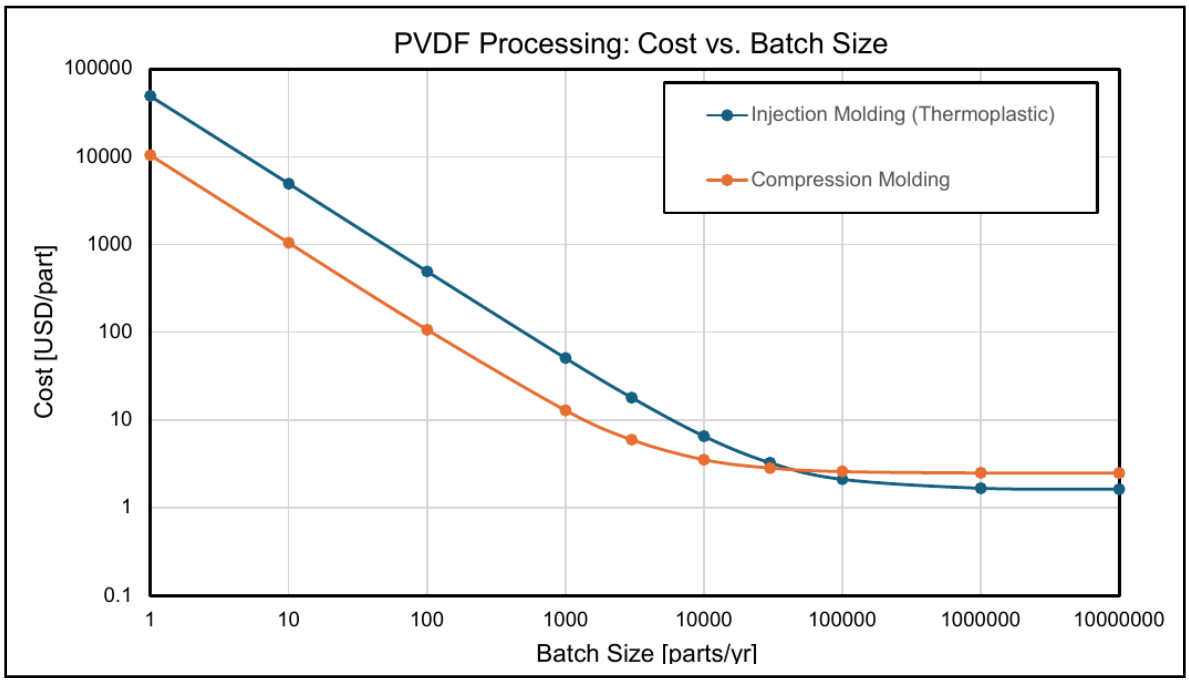


Figure 4: Plot of PVDF process costs as a function of batch size

The cost model for PVDF shown in Figure 4 illustrates similar behavior to Figure 3, although with additional clarity given only two process candidates. In a similar fashion to Silicone, there is a clear "cross-over" in the range $\in$ [30,000, 100,000], in which Thermoplastic Injection develops a cost advantage over Compression. Despite a much larger initial cost, at a full shipment of a million spatulas, it would be $0.82 more expensive per spatula to implement Compression molding as the manufacturing process of choice—except if there is a significant ecological advantage to Compression (similar situation with Silicone).

Comparing the cheapest processes for the two materials, Silicone Thermoset Injection has a $0.81 per spatula advantage over PVDF Thermoplastic Injection—a significant difference which ultimately yields a $810,000 difference at a full batch size. The customer is stated to value both cost and environmental impact, however, with a slightly larger emphasis on cost. Because the

cost difference between the materials at the full batch rate are so significant, it is reasonable to provide a preliminary suggestion of a spatula made out of Silicone via Thermoset Injection Molding. However, additional analysis is required to address the consumer's ecological concerns.

Environmental Impact

Streamlined Life Cycle Analysis

To analyze the ecological impacts of each material and manufacturing combination, a Streamlined Life Cycle Analysis (SLCA) matrix can be used to qualitatively address the product's environmental stressors throughout the phases of its life. For each entry in the matrix, the cell is subjectively assigned a proportional value ranging from $[1, 4]$, in which the larger numbers imply a low ecological impact, and vice-versa. The complete set of SLCA tables are shown below:

Life Stages	Materials Choice	Energy Use	Solid Residues	Liquid Residues	Gaseous Residues	Total
Premanufacture	2	3	2	1	2	10
Manufacture	3	2	2	2	2	11
Product Delivery	2	2	2	4	2	12
Product Use	3	4	4	4	4	19
Disposal	2	3	0	4	4	13
Total	12	14	10	15	14	65

Table 5: Silicone Thermoset Injection

Life Stages	Materials Choice	Energy Use	Solid Residues	Liquid Residues	Gaseous Residues	Total
Premanufacture	2	3	2	1	2	10
Manufacture	3	2	2	2	2	11
Product Delivery	2	2	2	4	2	12
Product Use	3	4	4	4	4	19
Disposal	2	3	0	4	4	13
Total	12	14	10	15	14	65

Table 6: Silicone Transfer Molding

Life Stages	Materials Choice	Energy Use	Solid Residues	Liquid Residues	Gaseous Residues	Total
Premanufacture	2	3	2	1	2	10
Manufacture	3	3	2	2	3	13
Product Delivery	2	2	2	4	2	12
Product Use	3	4	4	4	4	19
Disposal	2	3	0	4	4	13
Total	12	15	10	15	15	67

Table 7: Silicone Compression Molding

Life Stages	Materials Choice	Energy Use	Solid Residues	Liquid Residues	Gaseous Residues	Total
Premanufacture	2	2	2	2	1	9
Manufacture	3	1	2	2	1	9
Product Delivery	2	2	2	4	2	12
Product Use	3	4	4	4	4	19
Disposal	2	3	2	4	4	15
Total	12	12	12	16	12	64

Table 8: PVDF Compression Molding

Life Stages	Materials Choice	Energy Use	Solid Residues	Liquid Residues	Gaseous Residues	Total
Premanufacture	2	2	2	2	1	9
Manufacture	3	1	2	2	1	9
Product Delivery	2	2	2	4	2	12
Product Use	3	4	4	4	4	19
Disposal	2	3	2	4	4	15
Total	12	12	12	16	12	64

Table 9: PVDF Thermoplastic Injection

The matrix values were derived from various scoring considerations. The cell differentiators of note are primarily related to material residues and the disposal life stage. From Granta Edupack, Silicone is more water-intensive (liquid residue) to manufacture, however, PVDF requires fluorination (gas residue) to produce. Both materials use coolant during the manufacturing phase, and dispose of all scrap material in the landfill. Moreover, PVDF is petroleum-based, which decreases its overall Premanufacturing values. Furthermore, Compression Molding for both Materials use less energy and release CO_2 overall, however, for PVDF, energy and carbon production remain relatively elevated.

In terms of delivery, the analysis was conducted with a few key assumptions. Most notably, the spatulas are manufactured in China, then shipped to California in standard plastic packaging (consistent for all combinations). For use, the parameter was also constant between combinations, with an assumed lifespan of five years (seemed appropriate for a spatula). Silicone is not recyclable, whereas PVDF does have some limited recycle potential. However, for this first iteration, it was assumed that the consumer may not recycle or dispose of the spatula properly (unfortunately a common practice in the U.S.).

Ultimately, the SLCA qualitative analysis points to Silicone Compression Molding as the least environmentally intensive combination. Despite the recyclability of PVDF, it has a significant resource demand throughout the premanufacture and manufacturing phases. Moreover, among the Silicone processes, Compression Molding developed a slight advantage over the other two as

a result of lower energy use and impact during the manufacturing phase. Yet, given the qualitative and subjective nature of the SLCA matrices, the results need to be corroborated with Granta Edupack, which pulls data to proportionally rank the combinations using the Eco-Audit tool.

Eco Audit

The Granta Eco-Audit tool was used to rank the material and process combinations objectively using the existing database. To complete the audit, the same assumptions from the SLCA were implemented. Distance was assumed to be covered in three discrete steps: transport via cargo plane from China to California (10,081 km), transport from the airport to a warehouse using a 16-32 ton Euro 4 truck (100 km), and transport from the warehouse to a store using a 3.5-7.5 ton truck (50 km). Lifetime use also remained consistent for the combinations at five years. Thus, the primary distinguishing parameters were mass, which was calculated via $m = \rho V$, and material utilization fraction.

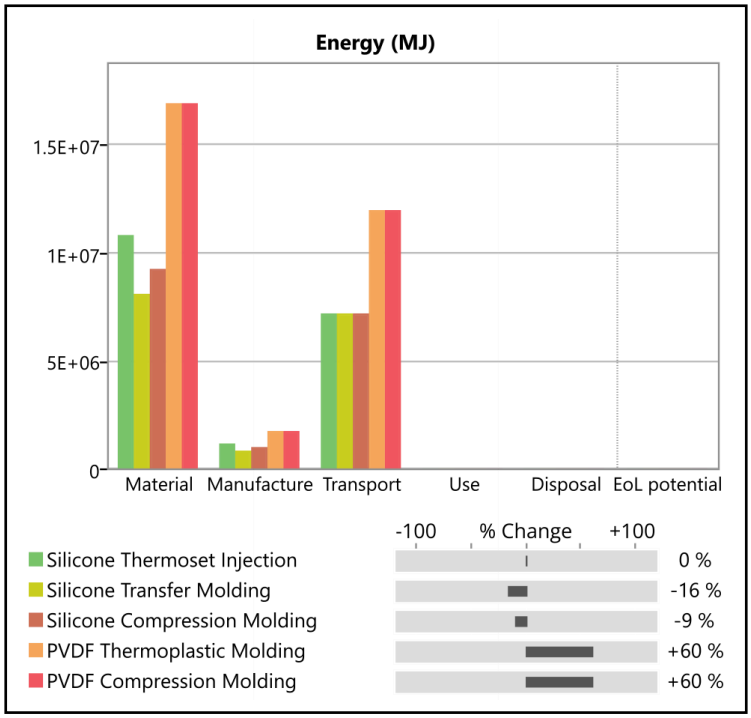


Figure 5: Eco-Audit for Energy

From the Eco-Audit, there is a clear difference between PVDF and Silicone processes. This is a result of a Silicone and PVDF spatulas having masses of 0.0583 kg and 0.0976 kg, respectively. However, there are some key differences from the results found using the SLCA method, primarily revolving around the key success of Transfer molding over the other Silicone processes. This is likely a result of the slightly larger material removal rate, although, it does appear somewhat dubious. However, the difference of note is the order of magnitude change between Silicone and PVDF, which provides evidence for the choice of Silicone, as it is both cost and environmentally effective. This relationship is further evidenced by carbon dioxide production, in which PVDF is *multiple* orders of magnitude greater than Silicone. This is shown in Figure 6 below:

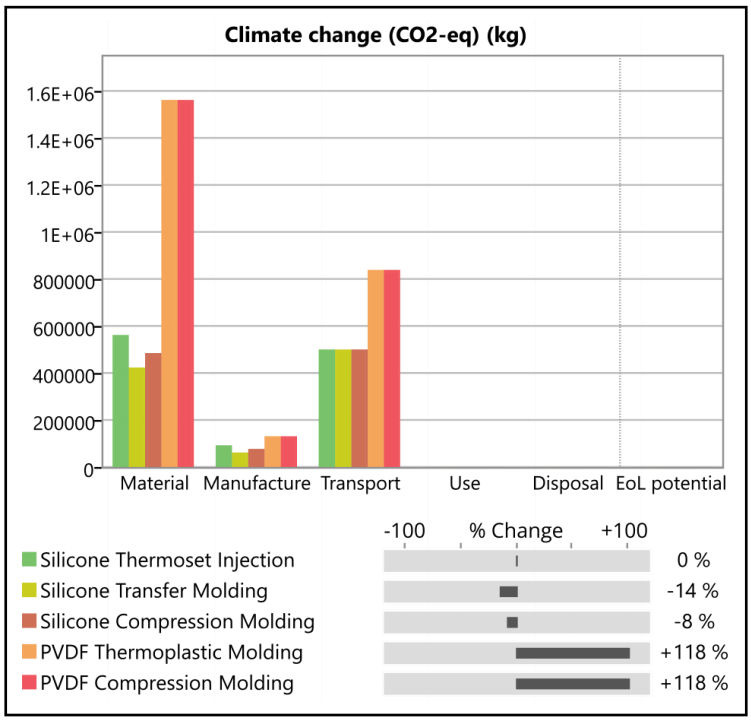


Figure 6: Eco-Audit for Carbon

Summary and Improvements

After the SLCA and Eco-Audit analysis, a more-holistic assessment of the material and process combinations can be made. Relevant observations from the previous section include relatively similar values from the SLCA (range $\in [64, 67]$). Moreover, the Eco-Audit largely favored Silicone-based processes for both energy and carbon dioxide criteria. Thus, the selection likely narrows to one of the Silicone processes. However, this analysis was performed roughly without consideration for an ideal situation. For instance, it was assumed that consumers would not recycle at all, and that the product would embody a suboptimal life cycle. Yet, the analysis results may suggest differently than above. Thus, to evaluate the stability of the completed analysis, it is necessary to compare the current process with an improved, more-ideal life cycle. To do so, the weaknesses of the current process can be rectified. For example, assume that users completely recycle PVDF, and perhaps combust (yeesh!) Silicone to recover as much energy from the material as possible. The transportation path can be changed as well, considering that air travel is expensive and energy intensive. Additionally, the manufacturing process can be refined to be more precise (slightly larger material utilization rate) and with better packaging—not to mention cost reduction by increasing the number of machines. The improvements to the environmental impacts are further explained in the following sections. Alternatively, it is necessary to determine the rigorousness of the cost model previously used, which is explored in the next section.

Improved Cost Model

With the proposed improvements under consideration, it is necessary to reiterate the analysis completed in previous sections, including the cost model. To amend the model, key parameters need to be changed accordingly. One assumption for improvement is an increase in the material utilization fraction U_m as a result of more careful machining—this is a minor improvement, but will slightly impact the material cost term.[5] Moreover, to account for the proposed increase in

[5]This was derived by taking the maximum of the range provided in Granta Edupack as opposed to the average.

production line count, the batch rate is scaled by three (three production lines) with a corresponding increase in Capital cost (need to pay for the machines). Thus, the improved tables are as follows:

	Thermoplastic Injection	Compression
Material mC_m	1.18	1.18
Overhead Rate $\cdot$ $(C)_{oh}$	60	60
Load Factor L	1	1
Capital Write-Off t_{wo}	43800	43800
Discount Rate, d	0.1	0.1
Material Utilization Fraction U_m	0.90	0.95
Tooling Cost C_t	49035	10395
Capital Cost C_c	442850	65950
Batch Rate $\cdot$ n	4590	165
Years t_{wo}	5	5

Table 10: Improved Cost Values for PVDF

	Thermoset Injection	Transfer	Compression
Material mC_m	0.23	0.23	0.23
Overhead Rate $\cdot$ $(C)_{oh}$	60	60	60
Load Factor L	1	1	1
Capital Write-Off t_{wo}	43800	43800	43800
Discount Rate, d	0.1	0.1	0.1
Material Utilization Fraction U_m	0.90	0.97	0.95
Tooling Cost C_t	49035	31130	10395
Capital Cost C_c	442850	103950	65950
Batch Rate $\cdot$ n	450	270	165
Years t_{wo}	5	5	5

Table 11: Improved Cost Values for Silicone

The overall cost model is also changed. Most importantly, the Capital and Overhead cost term is multiplied by the number of production lines (three in this instance). However, the batch rate increases proportionally, indicating that the Capital and Overhead cost is linear and invariant

with an increase in production lines. Yet, the batch size also increases by the number of production lines. Thus, the tooling cost is divided by three. This significantly improves cost from the iterative analysis completed in the previous sections. The tables documenting the cost modeling are shown below:

Batch Size	Thermoset Injection	Transfer	Compression
1	16345.76	10377.61	3466.38
10	1635.26	1038.61	347.88
100	164.21	104.71	36.03
1000	17.11	11.32	4.84
3000	6.21	4.41	2.53
10000	2.40	1.98	1.72
30000	1.31	1.29	1.49
100000	0.93	1.05	1.41
1000000	0.78	0.96	1.38
10000000	0.77	0.95	1.38

Table 12: Improved Silicon Cost Analysis

Batch Size	Thermoplastic Injection	Compression
1	16346.36	3467.38
10	1635.86	348.88
100	164.81	37.03
1000	17.71	5.84
3000	6.81	3.53
10000	3.00	2.72
30000	1.91	2.49
100000	1.52	2.41
1000000	1.38	2.38
10000000	1.36	2.38

Table 13: Improved PVDF Cost Analysis

From Table 12 and Table 13, there is a clear cost reduction as a result of the decrease in tooling cost. Interestingly, the overall cost behavior as a function of batch rate remains relatively consistent with the previous iteration. This is largely because the reductions in tooling cost were

invariant between each material plot. For instance, see the Figure 7 and Figure 8:

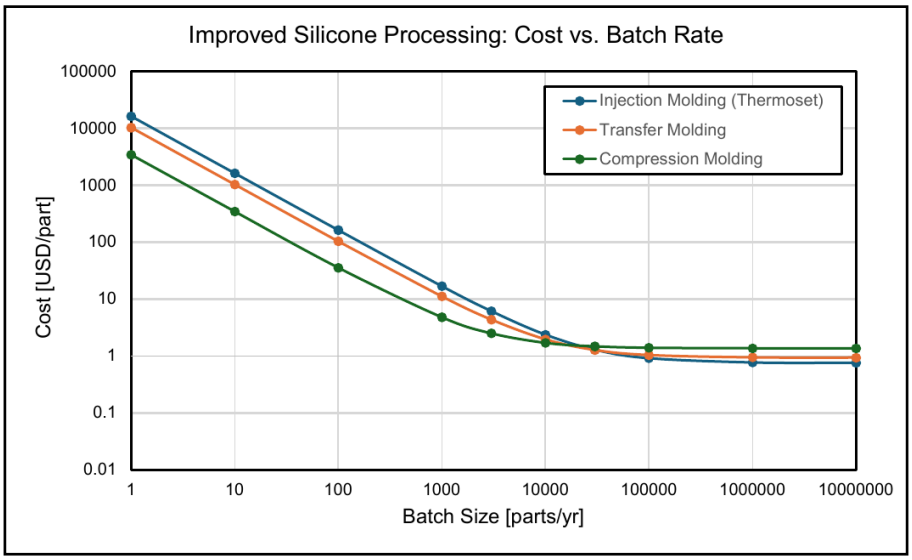


Figure 7: Plot of Silicone process costs as a function of batch size after optimization

From the Silicon plot, there is a similar cost behavior to the non-improved iteration. More specifically, the respective ordering of the processes remains largely invariant, with a similar "cross-over" point. However, there is slightly more convergence in this iteration due to optimized material utilization values. The same generally holds true for PVDF, shown below:

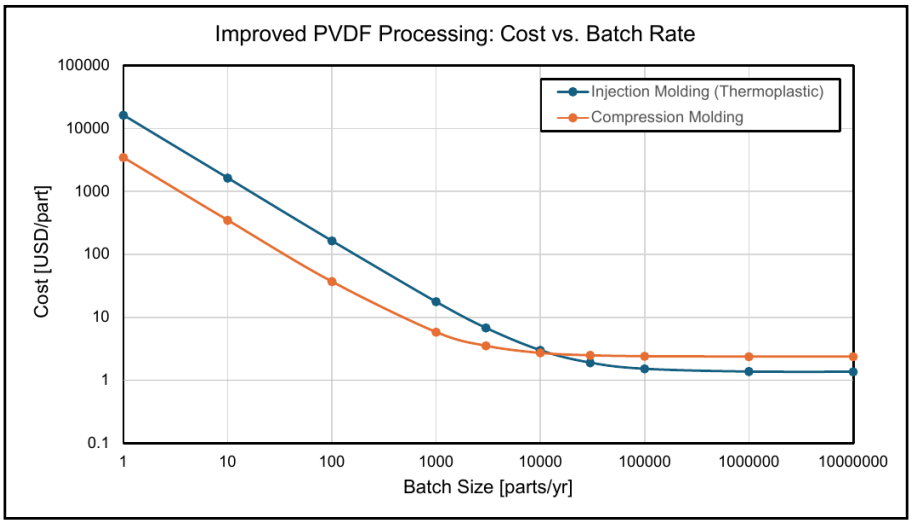


Figure 8: Plot of PVDF process costs as a function of batch size after optimization

Yet, when the most cost-effective combinations are compared (Thermoset and Thermoplastic Injection), it is apparent that Silicone retains a cost advantage over PVDF, with a margin of $0.6 per spatula. Overall, this implies that the improvement process decreased the total cost disparity between the two materials by around $0.2. When comparing the most cost effective between iterations (Silicone Thermoset Injection for both), the process improvements resulted in a $0.08 per spatula saving. From the cost modeling iterations, the model and suggestions were stable—demonstrating no change to the cumulative cost-effective ranking previously established. However, increasing the number of production lines and the material utilization fraction worked to drastically lower cost for all combinations, despite the optimal combination's rank remaining unaffected.

Environmental Impact for the Improved Process

Streamlined Life Cycle Analysis

Using the same methodology in the previous SLCA section, matrices were filled out to account for ecological improvements to the spatula's life cycle. The improvements implemented are as follows: moving manufacturing from China to Mexico to reduce product delivery impact (no cost loss as well, interestingly), more environmentally-conscious packaging (assuming recycled) to reduce energy use, reuse of coolant to reduce liquid residue, assuming the consumer recycles the PVDF spatula and combusts Silicone (to reduce disposal energy losses).[6] The SLCA table list for these improvements are shown below:

[6]It was assumed that the PVDF can be 100% recycled. This is likely not the case, especially in the U.S. with limited recycling centers for difficult plastics. It's likely that most recycling plants will dispose of the spatula, or only partially recycle.

Life Stages	Materials Choice	Energy Use	Solid Residues	Liquid Residues	Gaseous Residues	Total
Premanufacture	2	3	2	1	2	10
Manufacture	3	2	2	3	2	12
Product Delivery	3	3	3	4	3	16
Product Use	3	4	4	4	4	19
Disposal	2	3	0	4	4	13
Total	13	15	11	16	15	70

Table 14: Silicone Thermoset Injection

Life Stages	Materials Choice	Energy Use	Solid Residues	Liquid Residues	Gaseous Residues	Total
Premanufacture	2	3	2	1	2	10
Manufacture	3	2	2	3	2	12
Product Delivery	3	3	3	4	3	16
Product Use	3	4	4	4	4	19
Disposal	2	3	0	4	4	13
Total	13	15	11	16	15	70

Table 15: Silicone Transfer Molding

Life Stages	Materials Choice	Energy Use	Solid Residues	Liquid Residues	Gaseous Residues	Total
Premanufacture	2	3	2	1	2	10
Manufacture	3	3	2	3	3	14
Product Delivery	3	3	3	4	3	16
Product Use	3	4	4	4	4	19
Disposal	2	3	0	4	4	13
Total	13	16	11	16	16	72

Table 16: Silicone Compression Molding

Life Stages	Materials Choice	Energy Use	Solid Residues	Liquid Residues	Gaseous Residues	Total
Premanufacture	3	2	2	2	1	10
Manufacture	3	1	3	3	1	11
Product Delivery	3	3	3	4	3	16
Product Use	3	4	4	4	4	19
Disposal	2	3	2	4	4	15
Total	14	13	14	17	13	71

Table 17: PVDF Thermoplastic Injection

Life Stages	Materials Choice	Energy Use	Solid Residues	Liquid Residues	Gaseous Residues	Total
Premanufacture	3	2	2	2	1	10
Manufacture	3	1	3	3	1	11
Product Delivery	3	3	3	4	3	16
Product Use	3	4	4	4	4	19
Disposal	2	3	2	4	4	15
Total	14	13	14	17	13	71

Table 18: PVDF Compression Molding

As mentioned, the critical differences between iterations are primarily in the Disposal parameter because of the PVDF recycling assumption. However, Silicone Compression Molding benefited from the reduction of liquid residue, thus elevating it marginally above the PDVF processes, which are then slightly less environmentally intensive than the remaining Silicone processes. The tables also reflect the universal changes, particularly with respect to less energy use in the Delivery and Manufacturing stages. Thus, the SLCA process is stable with respect to improvements, with an invariant ranking of the combinations. Thus, there is additional evidence for the elimination of PVDF as a candidate material, although, the objective Granta Eco-Audit is required to establish certainty.

Improved Eco Audit

Another Eco-Audit was conducted to evaluate the stability of the improvements with respect to Granta's objective database. The notable differences between iterations includes a change to the transport path: trucking from Mexico to a California warehouse (2619 km) using a >32 ton Euro 4 truck, then from the warehouse to the store using a 3.5-7.5 ton Euro 4 truck (50 km). Moreover, this audit accounted for the improved material utilization fraction, and ideal disposal behavior.[7] The results are shown below in Figure 9 and Figure 10.

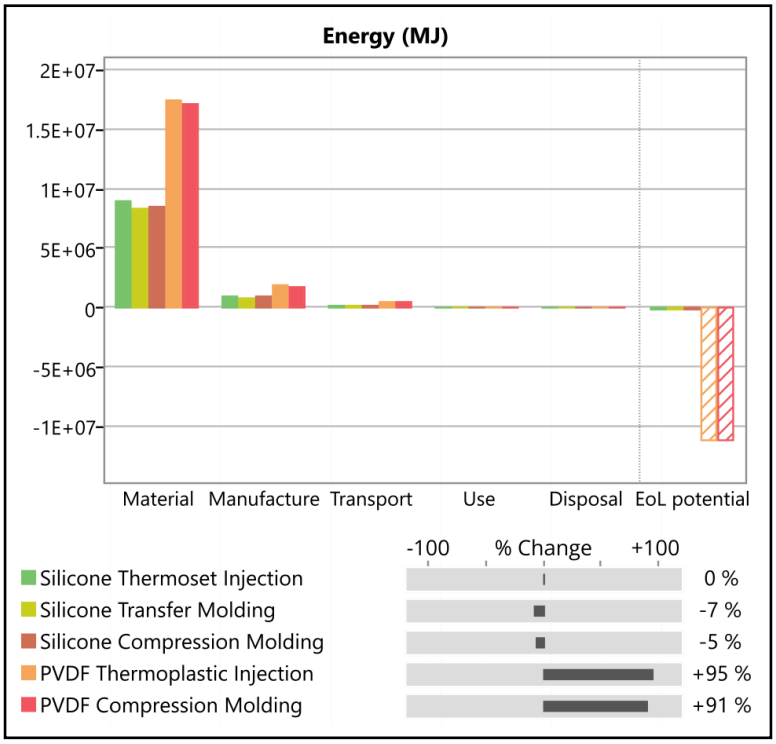


Figure 9: Plot of PVDF process costs as a function of batch size after optimization

Evident in Figure 9, the Eco-Audit results for the improved processes are stable, with PVDF being orders of magnitude more energy intensive than Silicone. However, the end-of-life potential for PVDF is significant, given the 100% recyclability assumption. The shaded bars below the axis represent the potential energy return for each combination. Although, there is an

[7] Assumed 100% recyclable in the case of PVDF, and 30% energy return in the case of combusting Silicone (reasonable value from the internet).

emphasis on *potential*, as complete or significant energy recovery is unlikely. A similar relationship is observed in Figure 10, highlighting the significance of the end-of-life parameter on the overall audit ranking

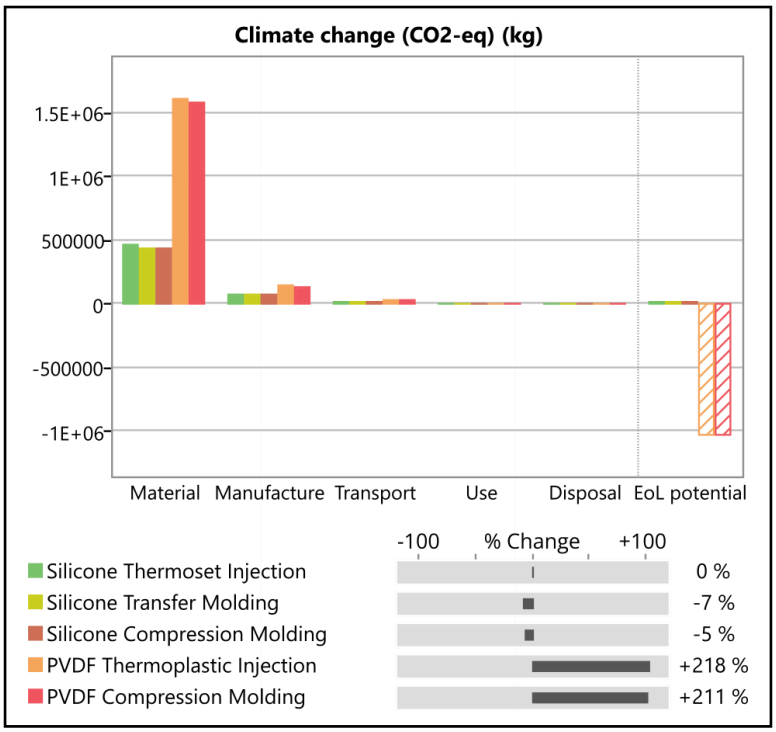


Figure 10: Plot of PVDF process costs as a function of batch size after optimization

Ecological Summary

The evaluation process used above characterizes the proportional rankings of each material-process combination. From the initial SLCA, it became apparent that PVDF had a marginally larger environmentally impact than the Silicon processes as a result of poor ranking with both gaseous residue, and the premanufacturing and manufacturing stressors. Because PVDF is petroleum based, it often requires fracking or drilling to extract (dependent on the global oil market), as opposed to Silicone which is present in abundant minerals such as quartz. PVDF's weaknesses became additionally apparent in the Eco-Audit, in which the relatively high weight contributed to significant energy requirements and carbon production throughout the material

phase. However, in the second iteration, analysis was conducted to determine how the combinations rank given more precise machining, improved transport routes, and additional production lines. The SLCA verified the efforts of the improvements, and PVDF was slightly lagging behind Silicon Compression.

The Eco-Audit introduces a similar perspective, which centralized around PVDF's potential to regain energy through recycling. Of course, it is unrealistic to assume that all spatulas would be recycled, although doing so would frame PVDF as the least environmentally intensive material (no significant change between processes). The uncertainty present in the end-of-life benefits for PVDF imply the need for additional analysis in Granta. A potential method for implementing this is shown in Figure 11.

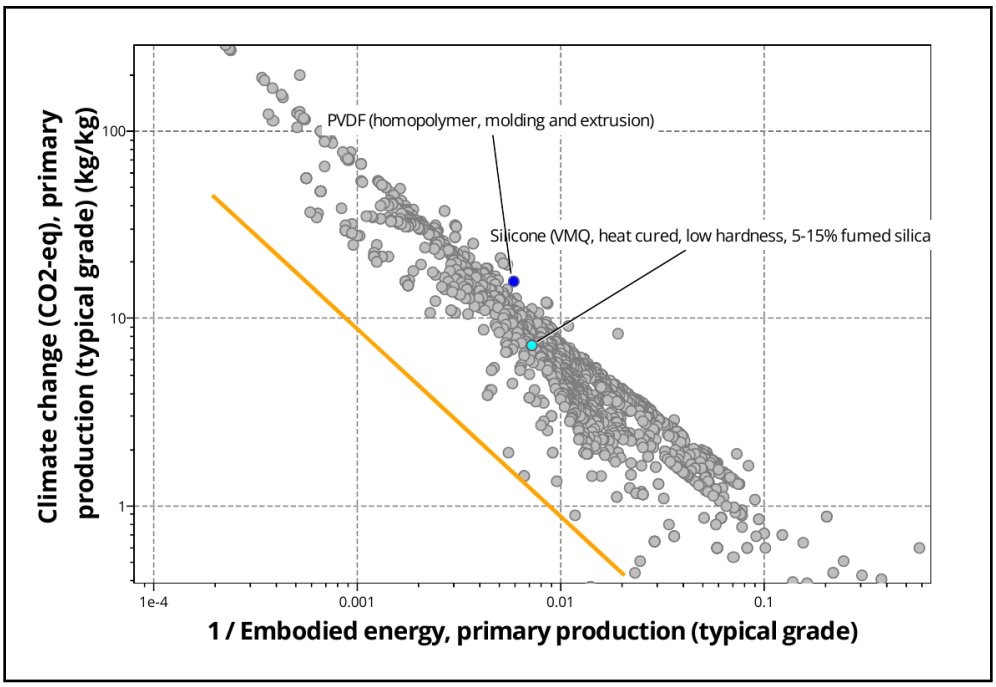


Figure 11: Plot of PVDF process costs as a function of batch size after optimization

From Figure 11, Silicone features a better ratio between embodied energy and carbon dioxide. In other words, Silicone outputs less carbon dioxide than PVDF for the same amount of energy spent in overall production. Thus, for PVDF to somewhat ecologically competitive with Silicone,

it requires ideal recycling and energy recuperation processes, and consumer behavior. Because this is unrealistic, the Silicone process family is recommended.

Distinguishing between the Silicone processes is more challenging, with roughly equivalent calculated impacts from both the SLCA and the Eco-Audit (for both iterations). Thus, determining the specific process is a matter of cost.

Final Recommendation

This report outlined the strategies used to provide a cumulative recommendation for the spatula's process and material selection. Granta's Eco-Audit and charting tools were used to provide evidence for selecting a Silicone spatula as a result of orders of magnitude smaller energy demand and carbon production. PVDF does have the benefit of being recyclable. However, that fails to offset its higher carbon to embodied energy ratio and larger mass—not to mention, a realistic end-of-life benefit is likely much lower than what was calculated in the Eco-Audit for the improved process. Moreover, PVDF fails to compete with Silicone on the basis of cost. Even for the improved process, it would cost an importer at best (excluding 1000% tariff), $600,000 more for a PVDF spatula.[8]

To determine the best process to use within the Silicone candidates, cost is the critical parameter —especially considering that the consumer emphasized the paramount importance of cost, with environmental impact as a secondary concern. From both the standard and improved cost models, at the full requested batch size of one million spatulas, Thermoset Injection Molding was the clear winner. In the slightly more convergent (smaller differences a result of changes to the material utilization fraction) improved model, Thermoset Injection Molding beat the Transfer Molding (the second cheapest) by $0.18 per spatula—translating to an $180,000 difference at a full batch size. Moreover, Compression Molding lagged even farther with a deficit of $0.6 per spatula. Thus, even with Thermoset Injection Molding featuring slightly sub-optimal ecological

[8]Derived from the improved process cost model, in which the best Silicone process remained $0.6 cheaper per spatula. The cost deficit quickly adds up, especially for batch sizes approaching 1,000,000.

impact (lagging behind in both the SLCA and Eco-Audit), the difference is within an order of magnitude, indicating that the ecological benefits of the other processes do not offset the cost deficit. Therefore, my final recommendation is to produce spatulas made out of Silicone rubber with a 5-15% fumed silica additive using a Thermoset Injection Molding process.

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