Supplementary Materials

This supplementary contains the cost and environmental impact analysis results for Scenarios 2-6 from:

An Economic and Environmental Assessment Model for Microchannel Device Manufacturing: Part 2 – Application

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1. Cost Results

1.1 *Scenario 2* cost results

In *Scenario 2*, HRUs are patterned by PCM and then bonded by diffusion brazing. As annual production volume increases from 1,000 to 500,000, the total manufacturing cost decreases, from $1,307.54 to $531.66 for many of the same reasons expressed above. Figure S1a exhibits the cost breakdown for the defined cost categories showing similar findings as above. At high production rate, raw materials and consumables become the main cost drivers, accounting for 42.3% and 40.2% of the total cost, respectively.

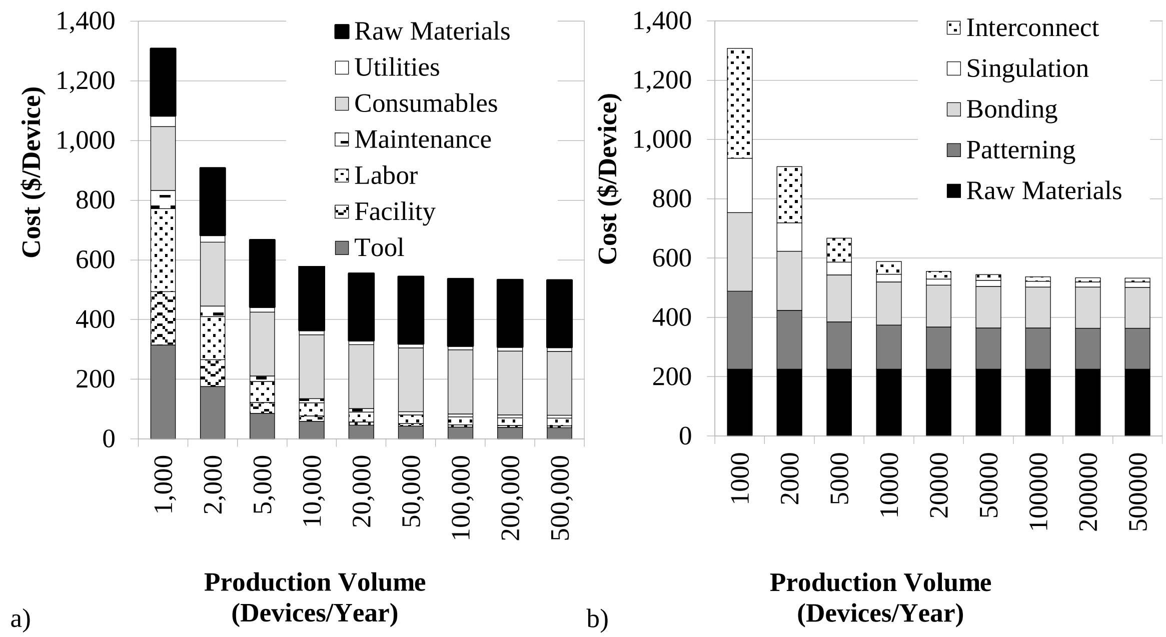

Figure S1. Cost breakdown for *Scenario 2* by a) Cost category and b) Process type and raw materials

Figure S1b demonstrates the cost breakdown by process type and raw material, where there is no difference of interconnect and singulation processes between *Scenario 1* and *Scenario 2*. Patterning cost drops from $263.49 to $138.32 as production volume increases from 1,000 to 500,000. The cost of diffusion brazing is lower than diffusion bonding for each of the nine production volumes, decreasing from $265.21 to $137.64 as the production volume increases from 1,000 to 500,000. At a production rate of 1,000, interconnect, patterning, and bonding are the top cost drivers, accounting for 28.4%, 20.2%, and 20.3% of the total cost, respectively, while at the production rate of 500,000, raw material, patterning, and bonding are the main contributors, accounting for 42.3%, 26.0%, and 25.9% of the total cost, respectively. The major reason for the reduced costs using diffusion brazing is the shorter cycle times leading to much higher equipment capacities, the need for fewer pieces of capital equipment, and lower capital equipment cost.

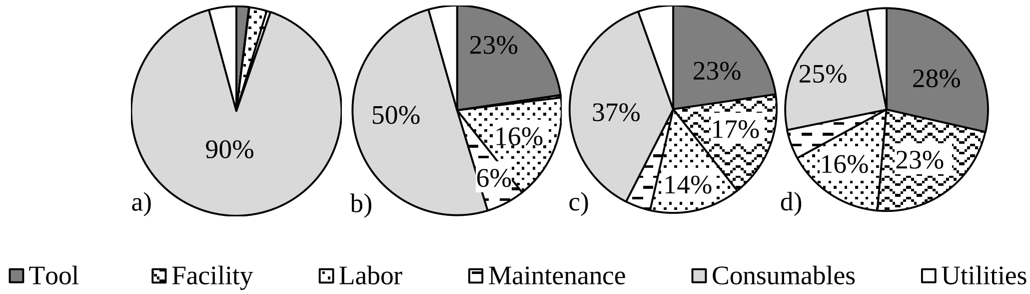

Figure S2. Cost breakdown for a) Photochemical machining, b) Diffusion brazing, c) Water jet cutting and CNC milling, and d) Electrical discharge machining processes for Scenario 2 (20,000 devices/year)

Figure S2 shows the cost breakdown by cost category at 20,000 devices per year. Distributions of cost categories are the same as *Scenario 1* for patterning, singulation, and interconnect processes since the same manufacturing processes are used. For the bonding process, consumables, tooling, and labor are the top three drivers, accounting for 50.3%, 22.7%, and 16.3% of the overall cost, respectively. The consumables cost is due to the need to add a NiP interlayer to the surface of the laminae before bonding.

1.2 *Scenario 3* cost results

In *Scenario 3*, HRUs are patterned by PCM and then bonded with laser welding. As the annual production volume increases from 1,000 to 500,000, the total manufacturing cost decreases per unit, from $1,555.64 to $707.91. Figure S3a exhibits the cost breakdown by cost category. Similar to *Scenario 1* and *Scenario 2*, the cost of raw materials and consumables are insensitive to the change in production volume compared to the other cost categories. At a low production rate of 1,000 HRUs per year, tool, raw materials, and consumables costs are top cost drivers, while at a high production rate, tool, labor, and raw materials costs are the top three cost drivers, accounting for 36.4%, 16.0%, and 14.5% of the overall cost, respectively. At a production rate of 500,000 HRUs per year, raw materials, tool, and consumables are the main contributors, accounting for 31.8%, 29.7%, and 23.2%, respectively.

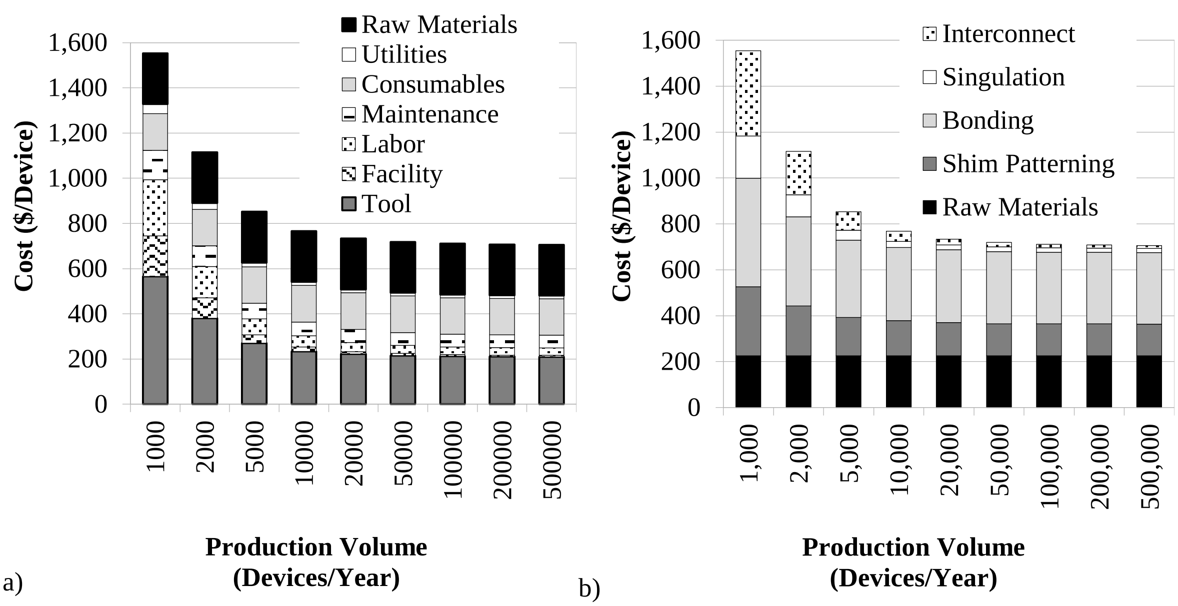

Figure S3. Cost breakdown for *Scenario 3* by a) Cost category and b) Process type and raw materials

Figure S3b demonstrates the cost breakdown by process where there is no variation in interconnect and singulation processes between *Scenario 1*, *Scenario 2*, and *Scenario 3*. The patterning process cost drops from $301.14 to $138.37

as the production volume increases from 1,000 to 500,000. The minor difference for the patterning process is because of the different process yield assumed for laser welding. The bonding process, which is performed with laser welding, is the most significant cost driver for all of the nine production volumes. Per device cost drops from $475.67 to $313.84 while the production rate increases from 1,000 to 500,000 HRUs per year.

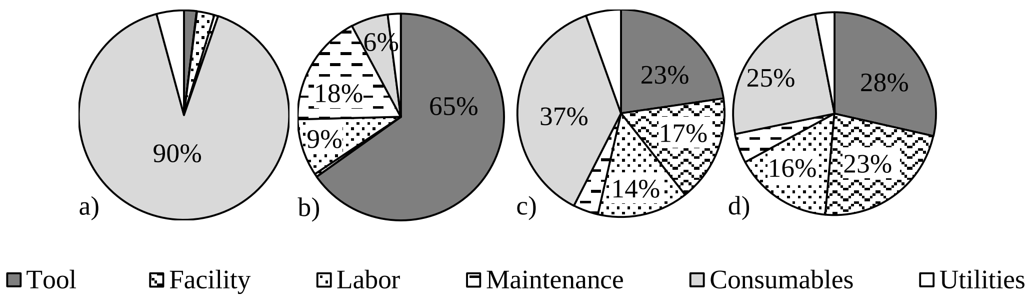

Figure S4. Cost breakdown for a) Photochemical machining, b) Laser welding, c) Water jet cutting and CNC milling, and d) Electrical discharge machining processes for Scenario 3 (20,000 devices/year)

Again, cost estimates stabilized at a production rate of 20,000 devices per year. At this point, the cost breakdown by cost category (Figure S4) shows the same breakouts for patterning, singulation, and interconnect processes as in *Scenario 1* and *Scenario 2* due to the use of the same process steps. For bonding, capital tooling is the dominant driver accounting for 64.7% of the overall cost, suggesting that the tool has a poor capacity. This is due in part to the need to weld each lamina one at a time. More importantly, the cost of laser welding is highly influenced by the length of the welding path. A longer welding path results in higher cost due to limited capital tooling capacity. Thus, the cost of laser welding will be greatly impacted by the design of shim. This may suggest opportunities to design the shim for laser welding in an effort to reduce the weld path needed per device.

1.3 *Scenario 4* cost results

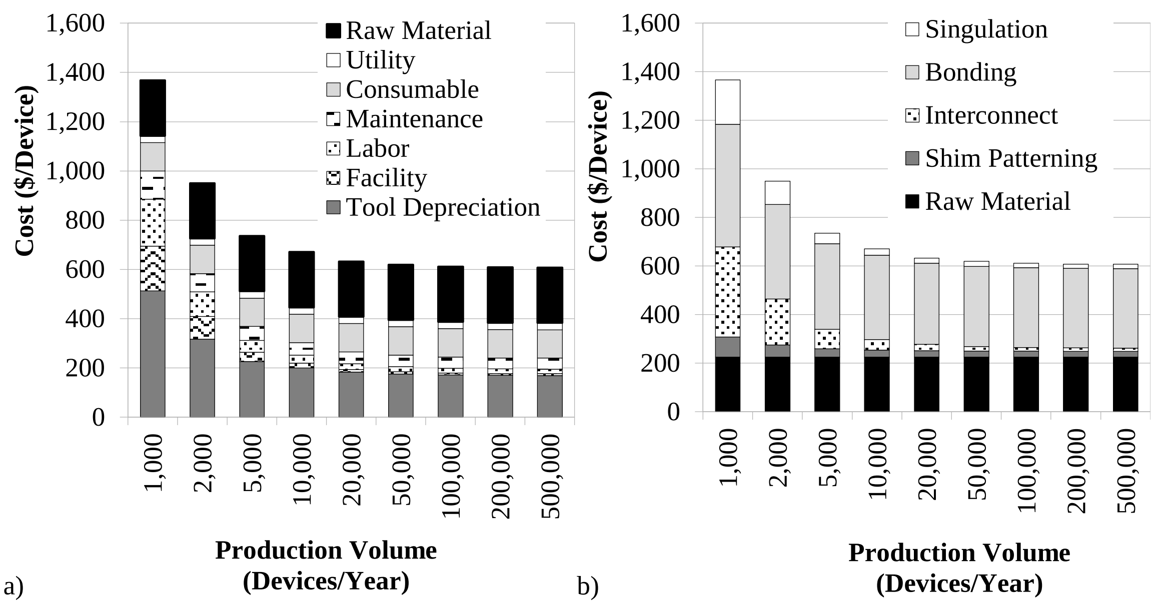

Figure S5. Cost breakdown for Scenario 4 by a) Cost category and b) Process type and raw materials

Figure S5 reports the HRU production cost estimates for *Scenario 4*, which assumes laser cutting and diffusion bonding. With the increase of annual production volume from 1,000 to 500,000 devices, manufacturing cost decreases from $1,367.28 to $607.11. Figure S5a exhibits the manufacturing cost breakdown by cost category. At a production volume of 1,000 HRUs per year, tool, raw material, and labor, account for 37.4%, 16.5%, and 14.0% of the overall cost, respectively, and are the top three cost drivers. At a production volume of 500,000 devices per year, raw materials, tool, and consumables become the top cost contributors, and account for 37.1%, 27.9%, and 19.0% of the total cost, respectively.

Figure S5b shows the cost breakdown by process types and raw materials, where the bonding process is the biggest cost driver at each production volume. As the production volume increases, cost of bonding process drops from $505.42 to $327.84. Although diffusion bonding is also used for *Scenario 1*, its cost in *Scenario 4* is slightly higher due to the nature of laser cutting, which doubles the number of shims required. Laser cutting demonstrates its excellent cost advantages as a patterning process. Compared to PCM, estimated to be from $259.49 per device at 1,000 HRUs per year to $138.28 per device at 500,000 HRUs per year, laser cutting costs are $83.03 per device at 1,000 HRUs per year and the cost decreases to $23.57 per device at 500,000 HRUs per year. There remains no variation in interconnect and singulation process results.

At 20,000 devices per year, the cost breakdown by cost category (Figure S6) shows that the bonding, singulation, and interconnect process results are the same as in *Scenario 1*. For patterning processes, consumables dominate the cost at 56.2%, mainly due to the use of nitrogen as cutting gas. Note that the laser consumables are much higher for machining than for welding. This is in part due to the higher fluences (unit energy use) in laser machining which can require more complicated optics and shorter light source life.

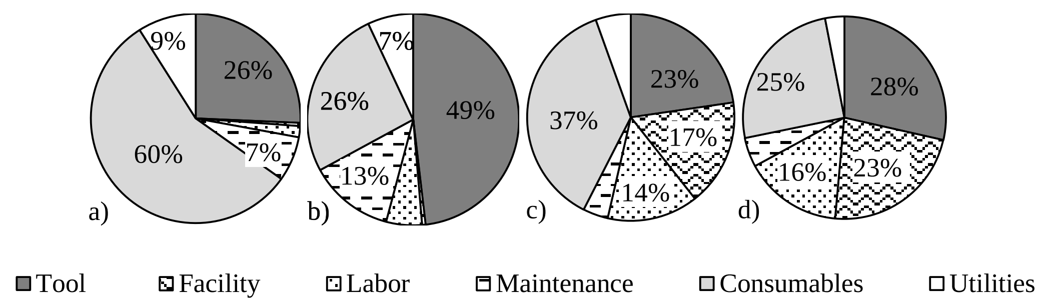

Figure S6. Cost breakdown for a) Laser cutting, b) Diffusion bonding, c) Water jet cutting and CNC milling, and d) Electrical discharge machining processes for Scenario 4 (20,000 devices/year)

1.4 *Scenario 5* cost results

As shown in Figure S7, as the production volume increases from 1,000 to 500,000 devices per year for *Scenario 5*, which assumes laser cutting and diffusion brazing, per unit cost decreases from $1,147.93 to $443.59. Figure S7a demonstrates the manufacturing cost breakdown by cost category. At a production volume of 1,000 HRUs per year, tool, raw materials, and labor, with per device cost estimates of $322.61, $225.01, and $223.06, respectively, are the top three cost drivers. At a production volume of 500,000 HRUs per year, raw materials and consumables become the top and major cost drivers, with their costs estimated as $225.01 and $112.67 per device, respectively. In Figure S7b, cost is broken down by process type and raw materials. The cost for diffusion brazing is higher in *Scenario 5* than that in *Scenario 2,* due to a doubling in the number of shims by using Design B for laser cutting. This increase in cost also accounts for additional stacking activities and consumables.

At 20,000 devices per year, the cost breakdown by cost category is shown in Figure S8. Distributions of cost categories are the same as *Scenario 2* for bonding, singulation, and interconnect processes. For patterning processes, the results are consistent with those in *Scenario 4*.

1.5 *Scenario 6* cost results

As shown in Figure S9, for *Scenario 6*, which assumes laser cutting and laser welding, manufacturing cost per device decreases from $1,666.35 to $630.31 with an increase in production volume from 1,000 to 500,000. Figure S9a demonstrates the manufacturing cost breakdown by cost category.

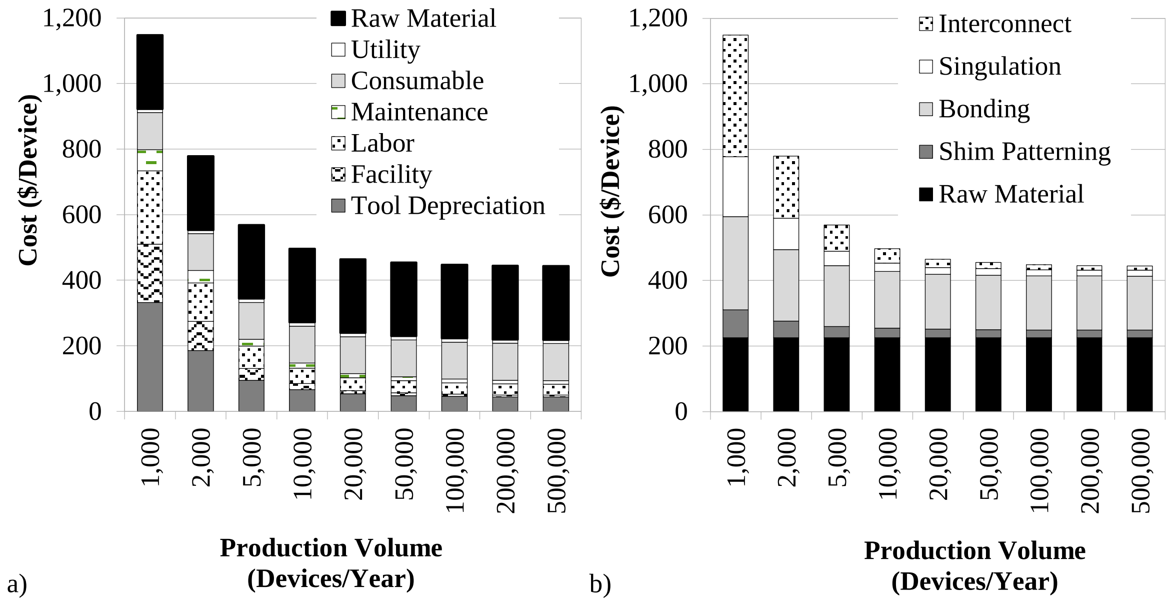

Figure S7. Cost breakdown for *Scenario 5* by a) Cost category and b) Process type and raw materials

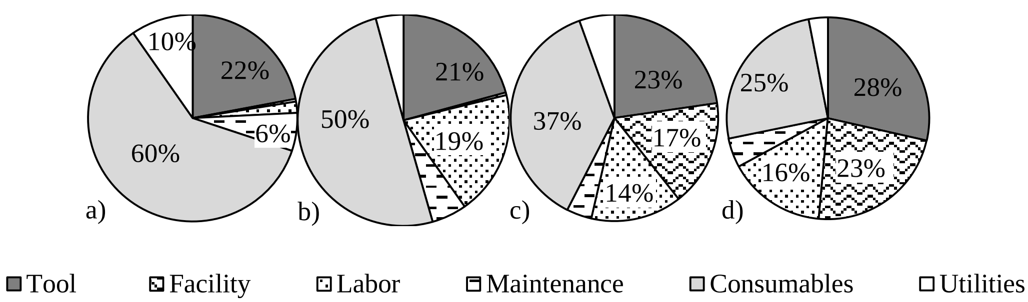

Figure S8. Cost breakdown for a) Laser cutting, b) Diffusion brazing, c) Water jet cutting and CNC milling, and d) Electrical discharge machining processes for Scenario *5* (20,000 devices/year)

At a low production volume of 1,000 HRUs per year, tool, raw materials, and labor are the top three cost drivers, with costs of $781.29, $225.01, and $201.70, respectively. At a production volume of 500,000 devices per year, raw materials and tools become the top cost drivers with costs of $225.01 and $222.93, respectively. In Figure S9b, cost is broken down by process types and raw materials. At a low production rate, the bonding process is the top cost driver, accounting for 47.0% of overall cost.

At 20,000 devices per year, the cost breakdown by cost category (Figure S10) is the same as *Scenario 3* for bonding, singulation, and interconnect processes. For patterning, results are consistent with those in *Scenario 4* and *Scenario 5*. By using laser cutting as a patterning process, the number of shims to be bonded is doubled. Thus, since the cost of laser welding as a bonding process is driven by the welding length, laser welding in *Scenario 6* is more costly than *Scenario 3*.

2 Environmental Impact Results

2.1 *Scenario 2* environmental impact results

As indicated by Figure S11a, where environmental impact score is broken down by impact category for *Scenario 2*, consumables and utilities are major contributors, accounting for 60.2% and 38.7% of the overall impacts, respectively. Figure S11b displays the environmental impact breakdown by process type and raw materials.

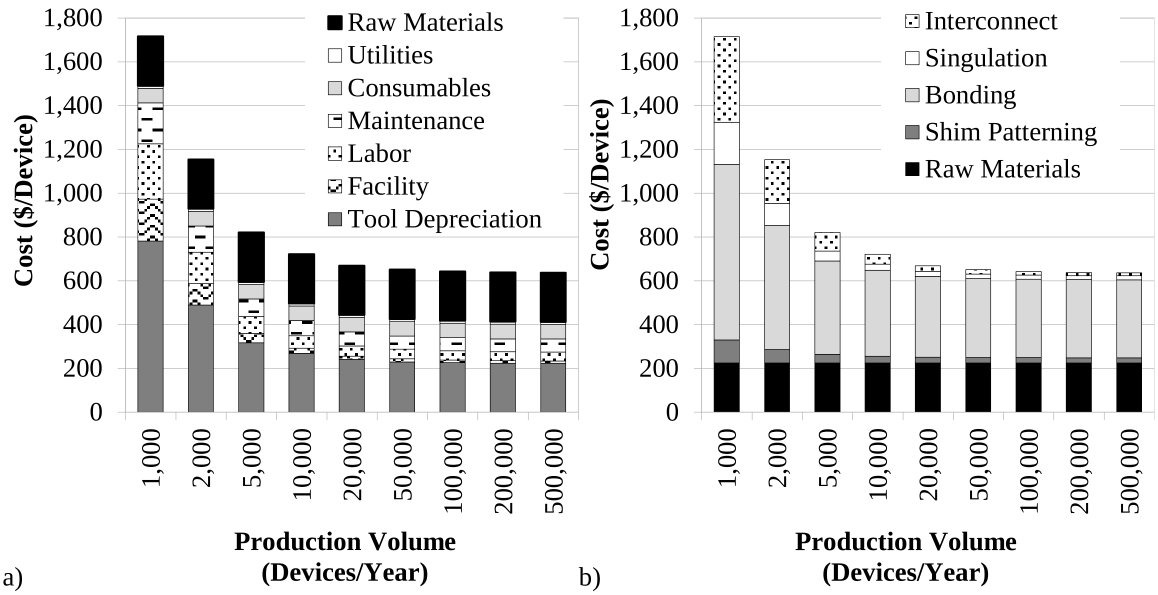

Figure S9. Cost breakdown for Scenario 6 by a) Cost category and b) Process type and raw materials

The bonding process, with an environmental impact score of 1721.24 Pts, dominates (97.5%) the total impacts. The patterning process and raw materials, with impact scores of 19.58 Pts and 19.20 Pts, account for only 1.1% each. Detailed analysis of each process is illustrated in Figure S11, where the environmental impact score for each process is broken down into the selected categories.

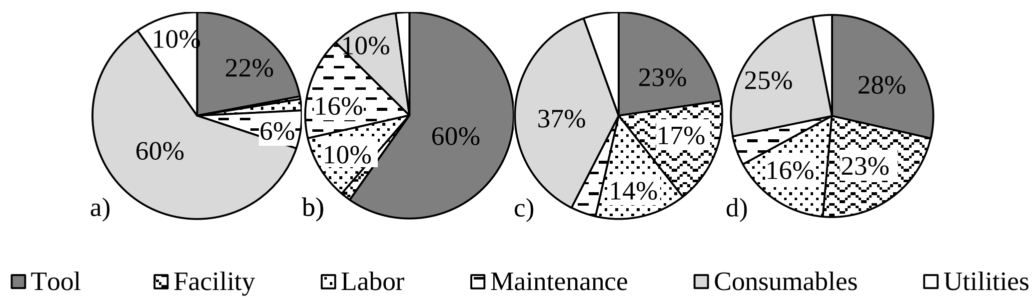

Figure S10. Cost breakdown for a) Laser cutting, b) Laser welding, c) Water jet cutting and CNC milling, and d) Electrical discharge machining processes for *Scenario 6* (20,000 devices/year)

Consistent with the results of *Scenario 1*, consumables and utilities account for 67.6% and 32.2%, respectively, of the overall environmental impacts for the patterning process. The singulation and interconnect processes have the same environmental impacts as for *Scenario 1*. For the bonding process (diffusion brazing), consumables and utilities are the major contributors to environmental impacts, accounting for 60.9% and 39.1% of the total impacts. From Figures S11 and S12, it can be seen that the major environmental driver of *Scenario 2* is the bonding process, where consumables and utilities have significant impact. It can be interpreted that although a comparatively lower bonding temperature and shorter bonding time is required for diffusion brazing, a cycle time of 25.3 hours and bonding temperature of 880°C is still significant, and consumes a large amount of water and electricity. In addition, consumables are required for each shim, which also contribute to the environmental impact.

2.2 *Scenario 3* environmental impact results

With a patterning process of PCM and bonding process of laser welding, *Scenario 3* demonstrates the lowest environmental impact compared to the other scenarios considered. As indicated by Figure S13a, consumables, utilities, and raw materials are major contributors to environmental impact, accounting for 64.7%, 28.3%, and 6.9% of the overall impacts, respectively. Figure S13b exhibits the environmental impact score by process type and raw materials. The bonding process, with an environmental impact score of 234.96 Pts, accounts for 84.3% of the total impacts. The patterning process and raw materials, with impact scores of 19.57 Pts and 19.20 Pts, respectively, account for 7.0% and 6.9% of the overall impacts. Detailed analysis of each process is illustrated in Figure S14, where the environmental impact score for each process is broken down into the selected categories.

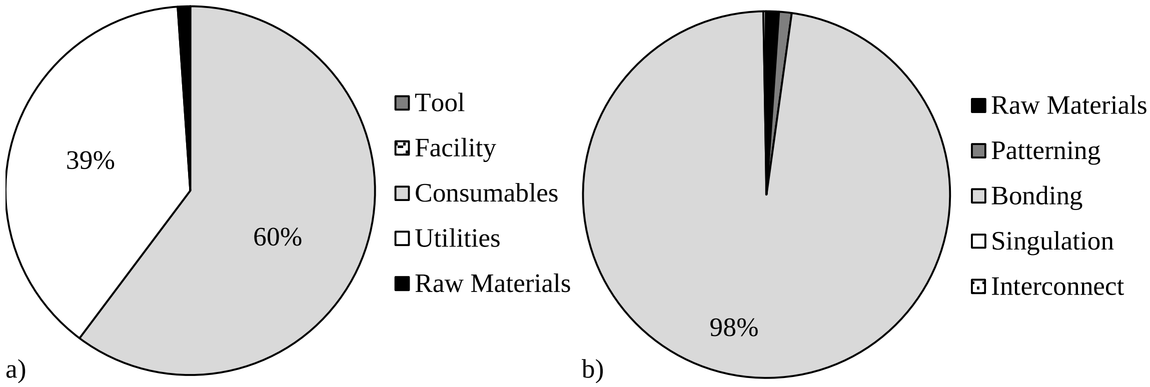

Figure S11. Environmental impact breakdown by a) Impact category and b) Process type and raw material for *Scenario 2* (500,000 HRUs per year)

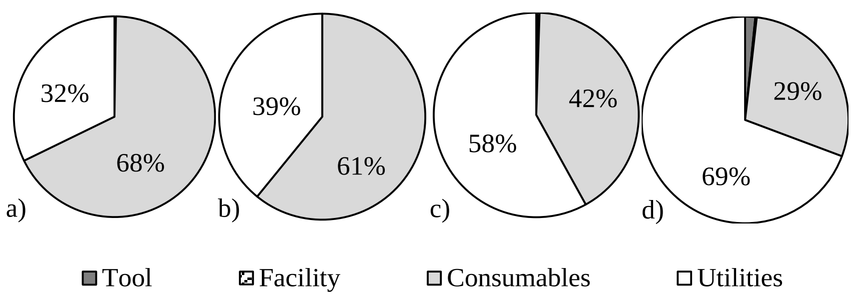

Figure S12. Categories of environmental impact for a) Photochemical machining, b) Diffusion brazing, c) Water jet cutting and CNC milling, and d) Electrical discharge machining process for Scenario *2*

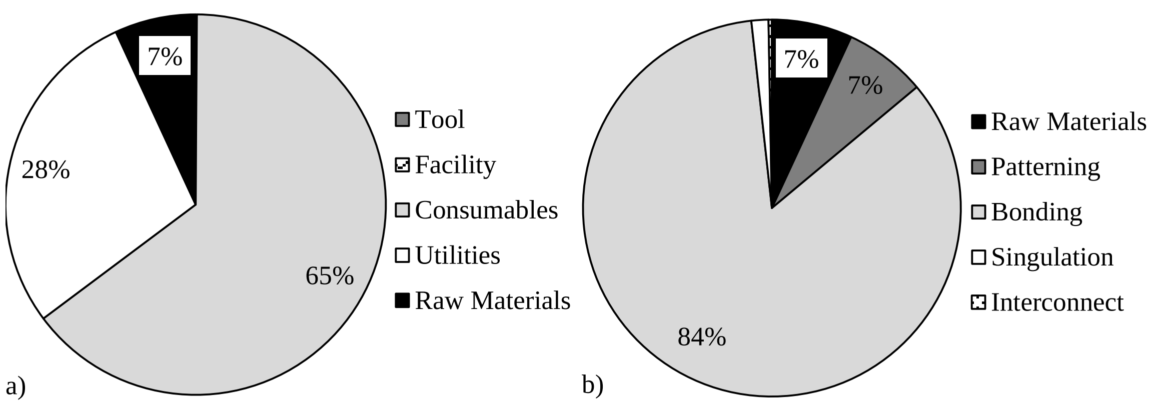

Figure S13. Environmental impact breakdown by a) Impact category and b) Process type and raw material for *Scenario 3* (500,000 HRUs per year)

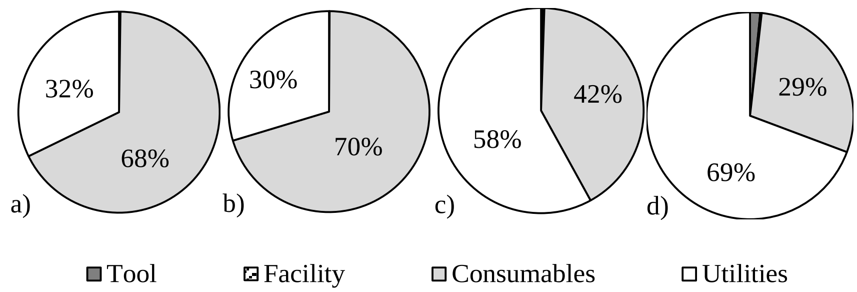

Figure S14. Categories of environmental impact for a) Photochemical machining, b) Laser welding, c) Water jet cutting and CNC milling, and d) Electrical discharge machining process for *Scenario 3*

Results for the patterning, singulation, and interconnect processes are consistent for *Scenario 1*, *Scenario 2*, and *Scenario 3* since the same manufacturing processes are utilized. Environmental impacts of the bonding process (laser welding), are primarily driven by utilities and consumables, which account for 70.3% and 29.7% of the total impacts, respectively. Figures S13 and S14 indicate that *Scenario 3* is more environmental friendly than *Scenario 1* and *Scenario 2* due to use of laser welding as bonding process.

2.3 *Scenario 4* environmental impact results

As indicated by Figure S15a for *Scenario 4*, where the environmental impact score is broken down by impact category, consumables and utilities are major contributors, and account for 87.6% and 11.5% of the overall impacts, respectively. Figure S15b displays the environmental impact score breakdown by process type and raw materials. The patterning process, with an environmental impact score of 2006.40 Pts, accounts for 87.9% of the total impacts. The bonding process, with an impact score of 253.07 Pts, accounts for 11.1% of the overall environmental impacts. The impacts of diffusion bonding are 0.6% higher in this scenario than for the same process used in *Scenario 1* because twice many shims are needed for patterning using laser cutting. Detailed analysis of each process is illustrated in Figure S16, where the environmental impact score for each process is broken down into the selected categories.

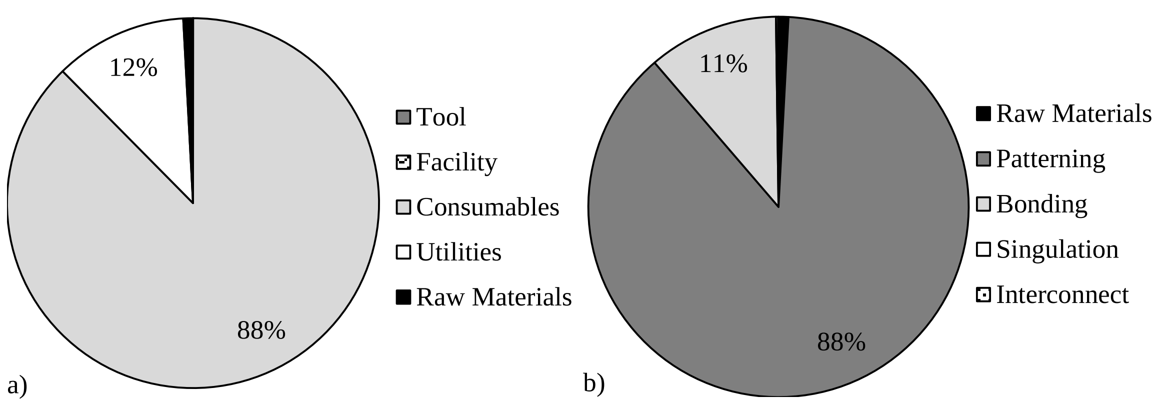

Figure S15. Environmental impact breakdown by a) Impact category and b) Process type and raw material for Scenario 4 (500,000 HRUs per year)

Results for bonding, singulation, and interconnect processes are consistent with *Scenario 1*, since the same manufacturing processes are utilized. The environmental impacts of the patterning process (laser cutting) are primarily driven by consumables, which account for 99.5% of the total impacts. Figures S15 and S16 indicate that the high environmental impact score of *Scenario 4* is mainly caused by the consumables utilized in laser cutting.

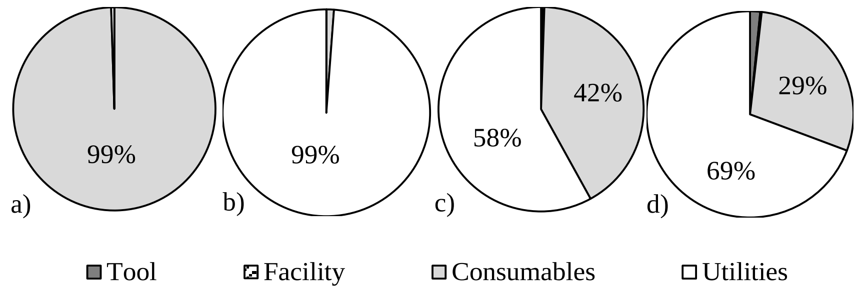

Figure S16. Categories of environmental impact for a) Laser cutting, b) Diffusion bonding, c) Water jet cutting and CNC milling, and d) Electrical discharge machining process for *Scenario 4*

2.5 *Scenario 5* environmental impact results

It can be seen from Table 6 and Figure 7 (in the paper) that *Scenario 5* has the most significant environmental impact among the six scenarios. As indicated by Figure S17a, where the environmental impact score is broken down by impact category, consumables and utilities are major contributors, accounting for 74.8% and 24.9% of the overall impacts, respectively. Figure S17b displays the environmental impact score by process type and raw materials. The bonding process, with an impact score of 3440.01 Pts, accounts for 62.9% of the overall environmental impacts. The patterning process, with an environmental impact score of 2006.39 Pts, accounts for 36.7% of the total impacts. It can be seen that the environmental impact score of diffusion brazing almost doubled compared to the same manufacturing process utilized in *Scenario 2*. This is because of Design B is used for laser cutting as a patterning process, which doubles the number of shims required. It also doubles the amount of consumables needed for diffusion brazing, resulting in more significant environmental impacts for diffusion brazing in *Scenario 5*. Detailed analysis of each process is illustrated in Figure S18, where the environmental impact score for each process is broken down into the selected categories.

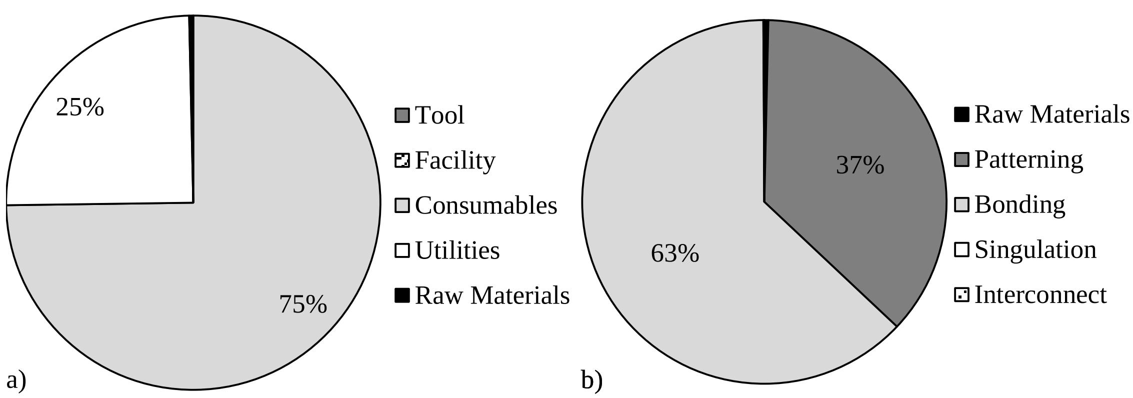

Figure S17. Environmental impact breakdown by a) impact category and b) process type and raw material for *Scenario 5* (500,000 HRUs per year)

Results for bonding, singulation, and interconnect processes are consistent with *Scenario 2*, while patterning process results are consistent with *Scenario 4* due to the same manufacturing process utilized. While the total environmental impact score of the bonding process is increased, the composition and distribution of the processes is still the same.

2.6 *Scenario 6* environmental impact results

As indicated by Figure S19a for *Scenario 6*, where the environmental impact score is broken down by category, consumables are the major contributors, accounting for 95.4% of the overall impacts. Figure S19b displays the environmental impact score breakdown by process type and raw materials. The patterning process, with an impact score of 2006.07 Pts, accounts for 88.1% of the total environmental impacts. Environmental impacts of other processes are comparatively minor.

It can be seen that the environmental impact score of laser welding increases compared to the same manufacturing process utilized in *Scenario 3*, due to the number of shims being doubled by utilizing Design B in laser cutting. This change increases the total length of welding path, thus increase its environmental impacts. Detailed analysis of each process is illustrated in Figure S20, where the environmental impact score for each process is broken down into the select categories. Environmental impact results for patterning, singulation, and interconnect processes are consistent with *Scenario 5*. The composition and distribution of bonding process in *Scenario 3* and *Scenario 6* are consistent.

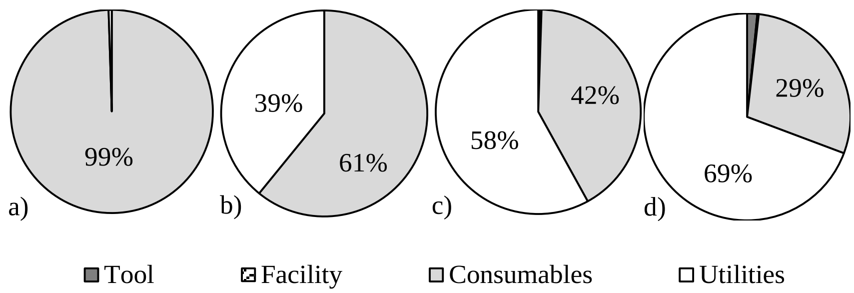

Figure S18. Categories of environmental impact for a) Laser cutting, b) Diffusion brazing, c) Water jet cutting and CNC milling, and d) Electrical discharge machining process for *Scenario 5*

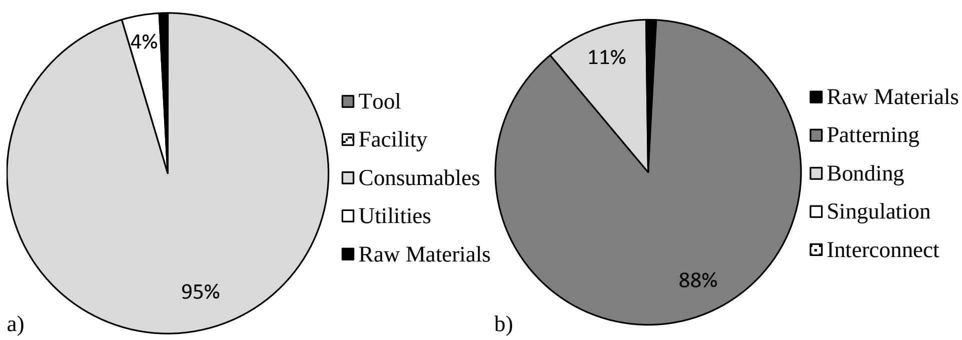

Figure S19. Environmental impact breakdown by a) Impact category and b) Process type and raw material for *Scenario 6* (500,000 HRUs per year)

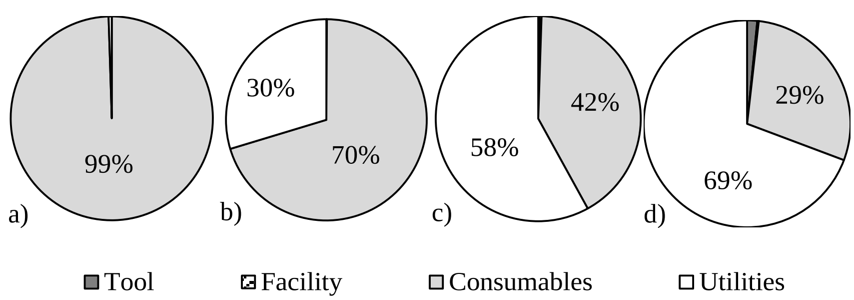

Figure S20. Categories of environmental impact for a) Laser cutting, b) Laser welding, c) Water jet cutting and CNC milling, and d) Electrical discharge machining process for *Scenario 6*

Figure captions

Figure S1. Cost breakdown for *Scenario 2* by a) Cost category and b) Process type and raw materials

Figure S2. Cost breakdown for a) Photochemical machining, b) Diffusion brazing, c) Water jet cutting and CNC milling, and d) Electrical discharge machining processes for *Scenario 2* (20,000 devices/year)

Figure S3. Cost breakdown for *Scenario 3* by a) Cost category and b) Process type and raw materials

Figure S4. Cost breakdown for a) Photochemical machining, b) Laser welding, c) Water jet cutting and CNC milling, and d) Electrical discharge machining processes for *Scenario 3* (20,000 devices/year)

Figure S5. Cost breakdown for *Scenario 4* by a) Cost category and b) Process type and raw materials

Figure S6. Cost breakdown for a) Laser cutting, b) Diffusion bonding, c) Water jet cutting and CNC milling, and d) Electrical discharge machining processes for *Scenario 4* (20,000 devices/year)

Figure S7. Cost breakdown for *Scenario 5* by a) Cost category and b) Process type and raw materials

Figure S8. Cost breakdown for a) Laser cutting, b) Diffusion brazing, c) Water jet cutting and CNC milling, and d) Electrical discharge machining processes for *Scenario 5* (20,000 devices/year)

Figure S9. Cost breakdown for *Scenario 6* by a) Cost category and b) Process type and raw materials

Figure S10. Cost breakdown for a) Laser cutting, b) Laser welding, c) Water jet cutting and CNC milling, and d) Electrical discharge machining processes for *Scenario 6* (20,000 devices/year)

Figure S11. Environmental impact breakdown by a) Impact category and b) Process type and raw material for *Scenario 2* (500,000 HRUs per year)

Figure S12. Categories of environmental impact for a) Photochemical machining, b) Diffusion brazing, c) Water jet cutting and CNC milling, and d) Electrical discharge machining process for *Scenario 2*

Figure S13. Environmental impact breakdown by a) Impact category and b) Process type and raw material for *Scenario 3* (500,000 HRUs per year)

Figure S14. Categories of environmental impact for a) Photochemical machining, b) Laser welding, c) Water jet cutting and CNC milling, and d) Electrical discharge machining process for *Scenario 3*

Figure S15. Environmental impact breakdown by a) Impact category and b) Process type and raw material for *Scenario 4* (500,000 HRUs per year)

Figure S16. Categories of environmental impact for a) Laser cutting, b) Diffusion bonding, c) Water jet cutting and CNC milling, and d) Electrical discharge machining process for *Scenario 4*

Figure S17. Environmental impact breakdown by a) impact category and b) process type and raw material for *Scenario 5* (500,000 HRUs per year)

Figure S18. Categories of environmental impact for a) Laser cutting, b) Diffusion brazing, c) Water jet cutting and CNC milling, and d) Electrical discharge machining process for *Scenario 5*

Figure S19. Environmental impact breakdown by a) Impact category and b) Process type and raw material for *Scenario 6* (500,000 HRUs per year)

Figure S20. Categories of environmental impact for a) Laser cutting, b) Laser welding, c) Water jet cutting and CNC milling, and d) Electrical discharge machining process for *Scenario 6*