SUSTAINABILITY
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ELECTRONICS

# Bill of Attributes (BOA) in Life Cycle Modeling of Laptop Computers: Results and Trends from Disassembly Studies

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## *Introduction*

The life cycle inventory for manufacturing a product combines information about a product's attributes with supply chain data on materials use and emissions in processes. Mathematically this relationship can be written (in this example for carbon dioxide) as the dot product

$$\text{Life cycle carbon} = \text{BOA} \cdot \text{CO2/attribute} \quad [1]$$

where BOA (Bill of Attributes) is a vector of product attributes such as masses of materials, content of components and other information and CO2/attribute is a vector of supply chain emissions to deliver a unit of attribute (e.g. CO2 emitted per kg of aluminum).

BOA has been long neglected in the LCA development community. While there has been significant work to develop both commercial and public process databases, there have been no comparable efforts to characterize BOA. The implicit assumption is presumably that since the product under study is "in hand" and processes are "out there", analysts can obtain their own BOA and the need for support is on the process side. This logic is sound in principle but fails in practice.  For complex products in particular, and indeed most products in the modern economy are complex, disassembly is labor intensive and reverse engineering internal attributes such as materials content requires sophisticated equipment such as a mass spectrometer. Building BOA through gathering information throughout the supply chain is possible in principle but faces many of the same challenges as gathering process data does.

From equation [1] is it clear that reliable BOA data is as important as reliable process data in the carbon footprinting of products.  As with process data there are important methodological questions to address for BOA. What kind of data needs to be gathered? Are there useful units of aggregations of product attributes which can streamline data gathering yet still lead to reliable footprint results? When can secondary data be used versus as opposed to collecting primary data for a product?

The appropriate data structures and collections methods for BOA vary by product. Some products such as detergents the BOA changes slowly while for sectors such as information technology products both BOA and process material flows can be rapidly moving targets. The techniques and labor needed to determine BOA also vary.

This report aims to contribute to developing data and understanding of the BOA side of the equation for laptop computers. The broad goals of this study are:

- generate primary data on BOA through physical disassembly,
- characterize trends and relationships between different attributes,
- explore models relating different product attributes in order to streamline the estimation of carbon footprints.

## *Methods and case study*

In this section the discussion of BOA is elaborated for laptop computers in order to set up specific goals and tasks for this study. BOA can take many different forms but in general it can be broken into subcomponent vectors

BOA (materials, components, assemblies) [2]

These sub-component vectors are not independent, e.g. the content of silicon chips in the component affects the quantities of gold in the materials component. To discuss each component sub-vector in more detail, the materials piece is the most conceptually simple. It can be written as

materials = (mass of constituent material 1, mass of constituent material 2, …) [3]

where constituent materials are substances such as steel, aluminum, different types of plastics and precious metals. Some of these materials (e.g. steel) are relatively easy to separate and identify with disassembly while other materials such as require special processing to measure quantities or data from suppliers. Note that while [3] looks simple, the situation is complicated by different grades and combinations of materials. A more disaggregated description pulling out different grades and combinations of materials could make a significant difference in the carbon footprint, for example the purification of industrial grade materials to semiconductor production grade. Note that in the formalism one can choose to put materials processing in the materials, e.g. a separate category for purified silicon or the components part, e.g. include silicon processing in the integrated circuit piece of the BOA vector.

Note that breaking down laptops into component materials is labor intensive and depending on the targeted materials may require special laboratory equipment. Rather than undertake a materials analysis for each and every laptop studied, it is clearly desirable to find regular relationships between materials contents and other product characteristics. Given that the total mass of laptops varies substantially year to year and model to model, one avenue to explore relationships is to express the mass vector as a total mass and set of mass fractions:

mass = (total mass, mass fraction 1, mass fraction 2, ….) [4]

There are many choices for how to define bills of components and combine with process data. The central issue is that the two must match. For example, if the process data available for semiconductor manufacturing is in the form of carbon dioxide per area of silicon wafer area, in turn the BOM definition in components must reflect contained wafer area. The lack of disaggregated process data is a central driver of what component definitions are feasible. For example, while it is would presumably be more accurate to describe chip content as a list of model numbers, this would not be useful unless process data for different chip models were available. Most available process data for electronics components is highly aggregated, e.g. is of the form energy use to manufacture an aggregate mix of different types of chips, circuit boards, discrete components, etc. Until more disaggregated process data becomes available in most cases the BOA data complementing the process data will be aggregated.

As with materials, empirically measuring component aggregations to match process data can be challenging and time consuming. For example, measuring the total area of silicon wafer contained in a laptop computer requires disassembly and grinding off the epoxy packaging or special imaging techniques (e.g. x-rays). Measuring area of circuit boards or counting discrete components is less invasive, but still time consuming. It is clearly preferable to avoid such labor when possible.

The main goals are to find patterns and relationships which both simplify the collection of BOA data and clarify what forms of BOA data are most important for reliable carbon footprinting. From these goals two sub-questions emerge:

- Are there regular relationships between material and component characteristics and macro product attributes? For example, does silicon wafer content correlate with screen size of a laptop computer?
- Can easily visible component characteristics be mapped to ones more difficult to measure? For example, does the packaging area of a chip or the number of pins correlate with contained silicon wafer area?

There are clearly many possible relationships between product attributes one could test. The goal of this study is begin the process of developing BOA methods through analysis of a small subset of possible relationships. With luck useful relationships will be found, but since it feeds into future work, even failure of a hypothesized relationship provides useful information. At the least this effort will help clarify how to proceed with the BOA issue. The specific tasks undertaken here to work towards the broad goals at the end of the introduction section are:

1. Disassemble four laptops (12”, 14.1”, 15” and 17” screen sizes) manufactured in 2008, combine with prior data on a 15” model manufactured in 2001.
2. Measure masses of bulk materials, area of motherboard, and characteristics of chips on the main motherboard (number, packaging area, number of pins, and silicon wafer area).
3. Characterize trends in bulk materials and total silicon area as a function of year and screen size.
4. Determine if there are easily identifiable relationships between the packaging area, number of pins, and silicon wafer area for microchips on the motherboard.

## *Prior life cycle studies of laptop computers: BOA and process parameterization*

To set the context of this work it is worth reviewing the current availability of BOA data for laptop computers and the matching process parameterizations used. There are four laptop LCA studies which present a significant degree of data describing assumptions (Tekawa et al 1997, EPIC 2006, IVM 2007, Deng et al 2010). Of these, (Tekawa et al 1997, IVM 2007, Deng et al 2010) present data relating to BOA. Table 1 shows materials contents from the three studies normalized to a common format. It is worth noting that the IVM study, funded by the European Union, list copper, aluminum and epoxy content far lower than the other two studies. Neither (Tekawa et al 1997) or (IVM 2007) explain how the bill of materials were obtained, indicative of the general LCA practice of not documenting BOA.

Table 1: Bill of materials from prior LCA studies of laptop computers

| | **Tekawa et al (1998)** | **IVM (2007)** | **Deng et al (2010)** |
|---|---|---|---|
| Screen size | N/A | 15" | 15" |
| Year of manufacture | N/A | 2006 | 2001 |
| **Material** | **Weight (grams)** | | |
| ABS | 1,010 | 142 | 373 |
| PC | 80 | 267 | 406 |
| other plastics | 190 | 440 | 343 |
| Steel | 110 | 489 | 871 |
| Copper | 410 | 75 | 270 |
| Aluminum | 150 | 38 | 512 |
| Epoxy | 150 | 3 | 244 |
| LCD Glass | 340 | 362 | 300 |
| Gold | NI | NI | 0.36 |
| Silver | NI | NI | 1.4 |
| other metals in PCB | NI | NI | 17 |
| Other | 1,130 | 1,739 | 442 |
| **Total** | **3,570** | **3,556** | **3,779** |

The parameterization of the component level BOA and process data varies by study. (Tekawa et al 1997) count the number of microchips and discrete components and multiply by an average CO2 factor per component. (IVM 2007) use a weight normalization for integrated circuits, multiplying by energy per weight of chips, while for circuit boards they normalize per area. (Deng et al 2010) describe integrated circuits and circuit boards in terms of silicon area and circuit board area respectively.

The parameterization of component BOA/process data can substantially affect carbon footprint results. Generally speaking parametrizations seems to be chosen as a matter of convenience and there is very little analysis of what parameterizations work best for what components. Reviewing the case of semiconductor manufacturing, prior LCA studies of semiconductors have followed industry's use of normalizing per silicon area (Williams et al 2002, Boyd et al 2009a,b). The fundamental assumption here is that the life cycle impacts of chip manufacturing can be reasonable described by multiplying an aggregated value of energy use per silicon wafer by the contained silicon area (die size). (Deng and Williams 2010) provide support for this assumption by showing that a wafer area normalization of energy use of semiconductor manufacturing give similar results (~10% variability) whether using CPU specific data, firm level data or national level aggregation of the U.S. semiconductor industry all. However, given that different chips have very different numbers of layers and processing steps this insensitivity to aggregation unit is not self evident and has yet to explained analytically. We could not identify a public study that justifies the use of number of chips or mass of chips as a reasonable parameterization for use in estimating life cycle inventories.

## *Empirically finding BOA for laptop computers: Disassembly and grinding methods*

The first goal of this study is to disassemble and analyze four laptop computers (12", 14.1", 15" and 17" screen sizes) manufactured in 2008 to empirically determine BOA. This data is combined with data on a 15" model manufactured in 2001 from a prior study (Deng et al 2010). A summary of the laptops' specifications is shown in table 2.

Table 2: Summary of laptops' specifications

| Year Manufactured | 2001 | 2008 | 2008 | 2008 | 2008 |
|---|---|---|---|---|---|
| Model | OEM 1 | OEM 1 | OEM 2 | OEM 2 | OEM 2 |
| Screen | 15" | 15.4" | 12.1" | 14.1" | 17" |
| Weight | 3.39 kg | 2.68 kg | 1.74 kg | 2.41 kg | 3.45 kg |
| DVD/CD | CD Rom | DVD/CD | DVD/CD | DVD/CD | DVD/CD |
| Floppy | Included | Not Included | Not Included | Not Included | Not Included |
| Memory | 512 MB | 3GB | 3 GB | 3 GB | 3 GB |
| Processor | Intel Mobile Pentium III | Intel Pentium Dual Core | Intel Core 2 Duo | Intel Core 2 Duo | Intel Core 2 Duo |
| Hard Drive | 10 GB | 160 GB | 80 GB | 120 GB | 160 GB |
| Battery | 8 Cells Lithium Ion | 6 Cells Lithium Ion | 6 Cells Lithium Ion | 6 Cells Lithium Ion | 9 Cells Lithium Ion |

The disassembly process begins with the identification and disassembly of the laptop into major component groups. The groups were chosen based on ease of disassembly and functionality. Each component group represents one assembly that performs a specific function in the laptop. Components include hard disk, DVD-CD drive, floppy disk drive, battery, motherboard, modem module, LCD display, computer chassis, and others components. Power adapters have been excluded in this disassembly process. After identification and basic disassembly, each component group was then weighed and sorted for further disassembly and detailed inventory. Once the major components were separated, each component group was then further dismantled into individual components to be sorted by material type, weighed and cataloged. The disassembly was done using hand tools, including screwdrivers, pliers and wire cutters. Each part was completely disassembled to the level where each piece comprised of a single material. Disassembly was carried out until all materials were separated or no further mechanical separation was possible. Common materials were grouped together for cataloging if they contained a number of very small and similar parts, such as screws, wires and adhesive tape. Larger pieces were identified and weighed as a single piece. Some component groups contained more than 30 parts when disassembled. Each part was given a unique part number for the ease of recording and identification. Material types for each part were then identified by physical inspection and categorized into generalized groups. For example, all types of aluminum are considered equal. Different alloys of aluminum were not identified. A magnet was used to separate ferrous and non-ferrous metals. The items classified as magnesium were identified by an Mg symbol placed by the manufacturer. It is important to note that some components were comprised of multiple material types, and physical separation could not be accomplished. When these circumstances were encountered, the ratio of material types based on weight was estimated. The part number, description and weight of each part was recorded in an Excel spreadsheet. The total weight for each material type for that component group was then determined.

Once the material identification and measurements were completed, each integrated circuit chip (IC) found in the motherboard, as seen in Figure 1, was identified and cataloged. Each chip was given a unique identifier determined by a marking on the board, or other information that would help to identify its location. The top of the chip packaging was then ground using a small die grinder to expose the semiconductor wafer inside. Figures 2 and 3 show the actual grinding of a motherboard's IC and the exposed silicon wafer, respectively. Measurements of each outer chip package and inner wafer were taken using a small machinist's scale. The relative area of the wafer in relation to the total chip area was then calculated using the sum of all areas for that component group. In additions, the pins that connect the IC were counted.

After all parts were identified, measured and recorded, they were labeled and stored in plastic bags. All bags from a particular component group were then placed in one "master" bag for the group.

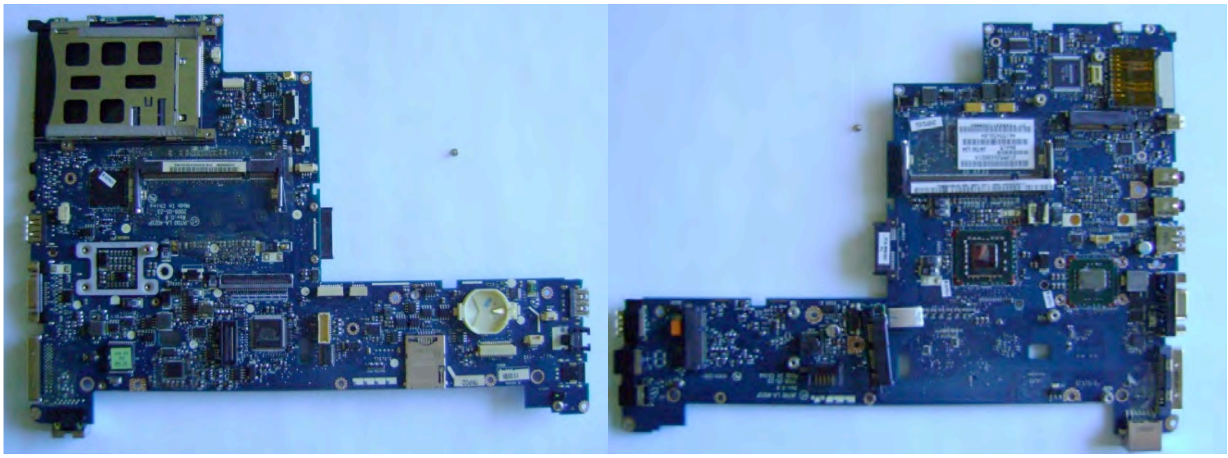

Figure 1: Motherboard for a OEM2 12" 2008 laptop (a) Side 1 (b) Side 2

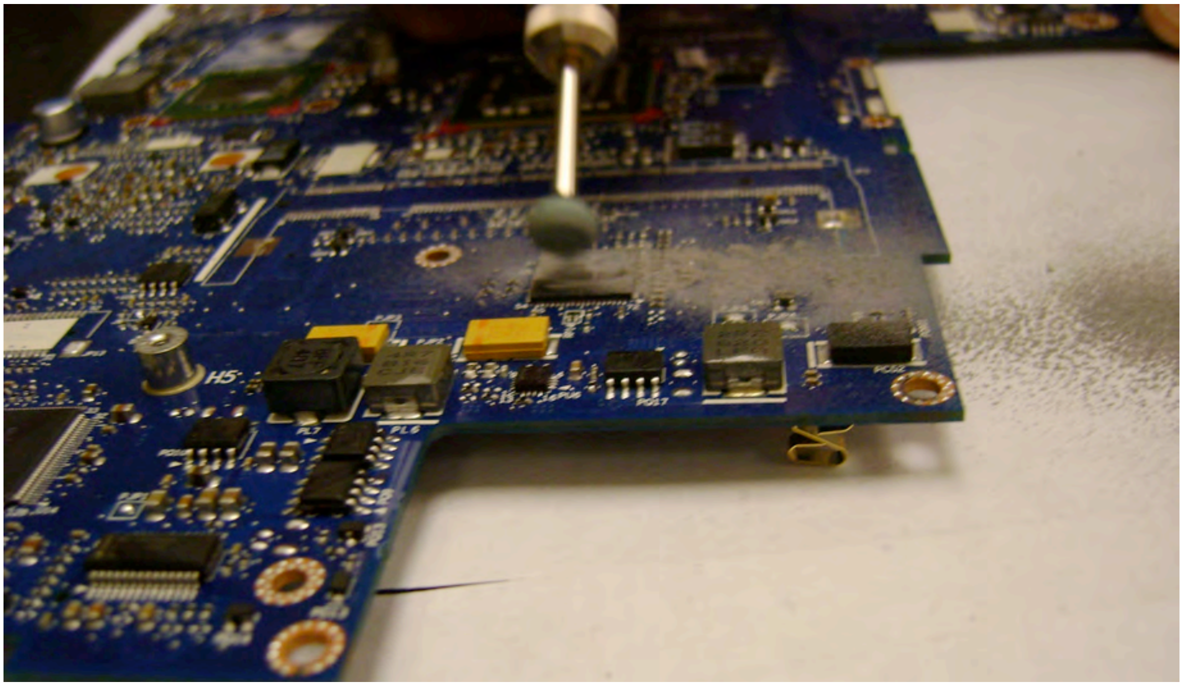

Figure 2: Grinding off integrated circuit packaging to reveal contained silicon area

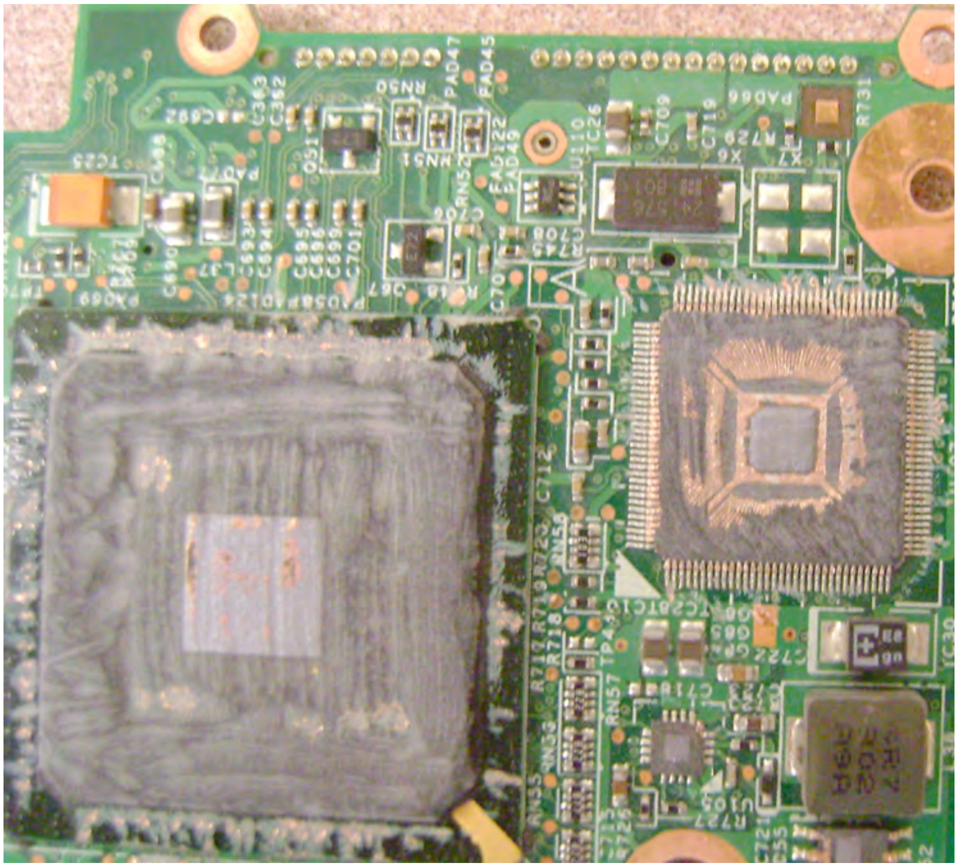

Figure 3: Exposed silicon wafer area from motherboard's integrated circuits. The small grey rectangle within the larger black rectangle is silicon wafer.

## *Mass and materials in laptop computers*

The next task is to explore trends in material content of laptop computers, hopefully identify patterns relevant for finding carbon footprints. Using the data collected for each part, all the materials used in the component group assembly and the total weight of each material was determined. This value was then checked against the weight measurement recorded prior to disassembly for quality control purposes. Once all of the materials and weights for all of the component group assemblies was complete, all common materials were summed to determine the material make up of the entire laptop unit. Again, the sum of all the parts was checked against the weight of the entire laptop prior to disassembly for quality control purposes. The difference in between summed and aggregate weights ranged between 0.02% and 0.17 % for all laptops. The material and sub-system inventory for the complete laptops is presented in Table 3 and Table 4. Figures 4 and 5 presents the material ratios (mass material /total mass) and sub-system ratio (mass sub-system/total mass) for each laptops.

Table 3: Bill of materials for complete laptops (grams)

| | **OEM1 2001 15"** | **OEM1 2008 15"** | **OEM2 2008 12"** | **OEM2 2008 14"** | **OEM2 2008 17"** |
|---|---|---|---|---|---|
| Aluminum | 447 | 227 | 219 | 425 | 580 |
| Battery Cell | 204 | 275 | 277 | 278 | 377 |
| Copper | 84 | 24 | 39 | 35 | 74 |
| Magnesium | 0 | 0 | 214 | 326 | 494 |
| Plastic | 963 | 1,128 | 398 | 603 | 782 |
| PWB Material | 413 | 268 | 229 | 268 | 406 |
| Iron and Steel | 835 | 516 | 266 | 265 | 396 |
| Others | 451 | 249 | 101 | 207 | 346 |
| **Total** | **3,397** | **2,686** | **1,742** | **2,407** | **3,453** |

Table 4: Bill of sub-systems for complete laptops (grams)

| | **OEM1 2001 15"** | **OEM1 2008 15"** | **OEM2 2008 12"** | **OEM2 2008 14"** | **OEM2 2008 17"** |
|---|---|---|---|---|---|
| Battery | 369 | 324 | 324 | 317 | 430 |
| Chassis bottom | 266 | 387 | 173 | 269 | 370 |
| Chassis Top | 294 | 244 | 152 | 205 | 400 |
| Display Assembly | 944 | 676 | 321 | 574 | 845 |
| Optical Drive | 172 | 174 | 145 | 180 | 174 |
| Fan | 12 | 36 | 12 | 33 | 27 |
| Floppy Disk | 256 | 0 | 0 | 0 | 0 |
| Hard Drive | 147 | 106 | 63 | 109 | 109 |
| Heat Sink | 45 | 39 | 26 | 39 | 161 |
| Keyboard | 161 | 153 | 92 | 133 | 181 |
| Motherboard | 396 | 211 | 215 | 213 | 348 |
| Speaker | 37 | 7 | 5 | 18 | 37 |
| Others | 299 | 332 | 214 | 318 | 370 |
| **Total** | **3,397** | **2,687** | **1,742** | **2,407** | **3,453** |

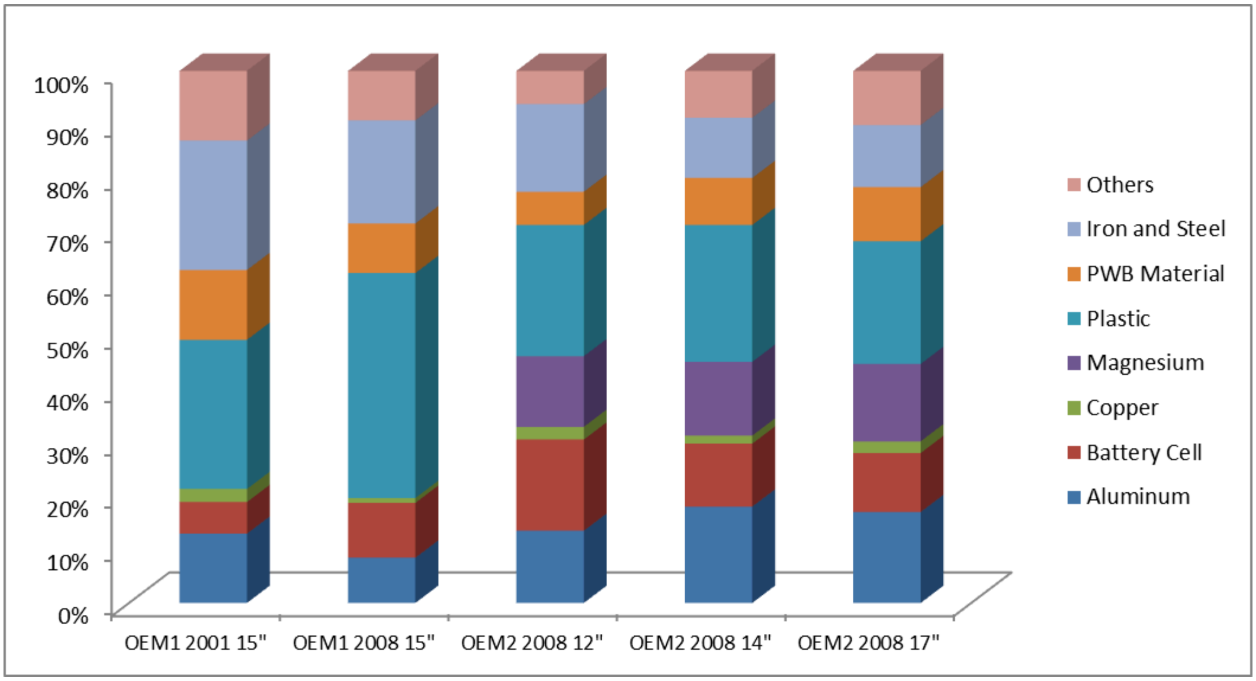

Figure 4: Material ratios (mass material/total mass) for complete laptops

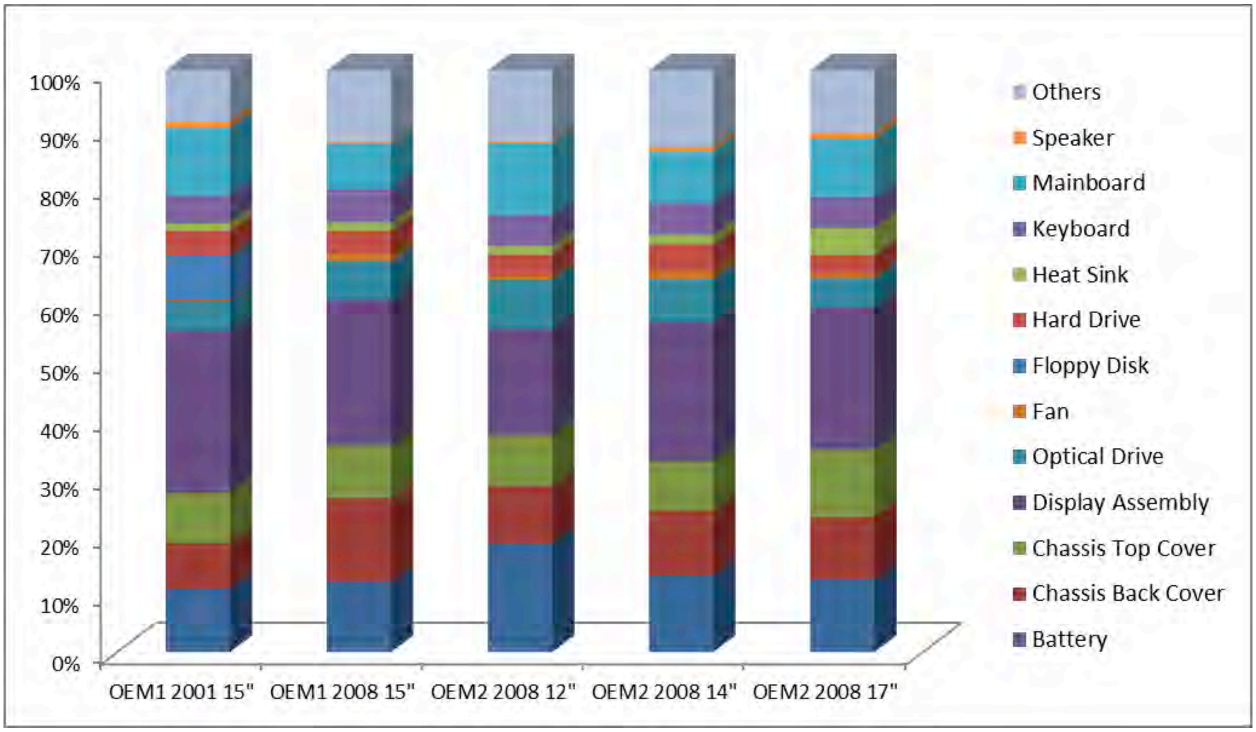

Figure 5: Sub-system ratio (mass sub-system/total mass) for complete laptops

The most notable trend is that with a few exceptions the materials and sub-system rations are similar for all the laptops studied. First comparing 2008 OEM2 laptops of different sizes (12", 14" and

17”), both the material and sub-system ratios are nearly constant regardless of screen size. For example, the content of magnesium alloys ranges from 12 to 14 % and printed wiring boards (PWB) account for 11 to 13% of the total weight. At the sub-system level, the chassis or enclosure component accounts for 19 to 23% and the motherboard for 9 to 12% of the total weight.

Comparing the 2001 and 2008 OEM1 Laptops shows larger differences in materials and sub-system rations, not surprising considering technological progress. One important difference between the models is the exclusion of the floppy disc drive in the 2008 model. Also, in can be seen in the material ratio a trend to use less ferrous (e.g. steel) and non-ferrous (e.g. aluminum) materials and more plastics materials (e.g. ABS and PC). Even so the ratios of major materials used, plastic, aluminum and steel, are very similar for the 2001 and 2008 models.

Finally, is important to mention that as power adapters have not been included in the disassembly process and PWB have been reported as a “material” with no further disaggregation, the copper content in the BOM for all laptops (copper content is high in power adapters and PWB) appears to be low.

## *Chassis or enclosure materials for laptops*

Given that the chassis/enclosure materials used is a major source of variability in the bill of materials, this section explores trends in materials used. Manufacturers have used different types of materials for the laptop chassis or enclosure. The materials that have been used are: Acrylonitrile butadiene styrene or ABS, Aluminum, Carbon-fiber Plastic, Glass-fiber Plastic, Magnesium, Polycarbonate or PC, Steel, and Titanium. Selection of the materials is a function of material technology, mechanical properties, density, durability, manufacture, and overall cost, computer functionality, consumer profile, equipment cost, and others. For example, a more durable and lighter material will be the preferred option for a business consumer profile, the one that travels more often. The blend of ABS and PC (ABS/PC), including percentages of recycled material, is probably the most common type of material currently used for laptop chassis. The use of ABS/PC is mostly seen in low-end and medium-end products. Also, there is an increasing trend to use higher percentages of recyclable ABS/PC materials. The mechanical properties and density of magnesium and aluminum, makes them a preferred material for light, durable and high-end products, trend that will probably continue in the future. In addition, manufacturers are anticipating the use of bio-plastics for laptop chassis in the future and depending on its mechanical properties, bio-plastics can be used combined with other materials, such as aluminum and magnesium.

In order to better understand trends in the materials used in enclosures data was collected for 92 IBM/Lenovo laptop models manufactured from 2000 to 2010 (Lenovo Personal Systems Reference 2010). Figure 6 shows this trend; for example, the continuous use of ABS as an enclosure material from 2001 and 2010, the use of ABS/PC starting 2003 through 2010, with interruptions in 2005 and 2006 and the use of PC from 2007 to 2010. Also, titanium and magnesium composites were used from 2000 to

2005 and 2003 to 2006, respectively. In addition, carbon-fiber plastics and glass-fiber plastics have been also used by IBM/Lenovo for the laptop chassis, starting 2000 and 2001, respectively. Recently, in 2009 and 2010, Lenovo's chassis used the following materials: Magnesium-Aluminum, Magnesium alloy, carbon-fiber plastics, PC, glass-fiber plastic, Aluminum, ABS/PC and ABS.

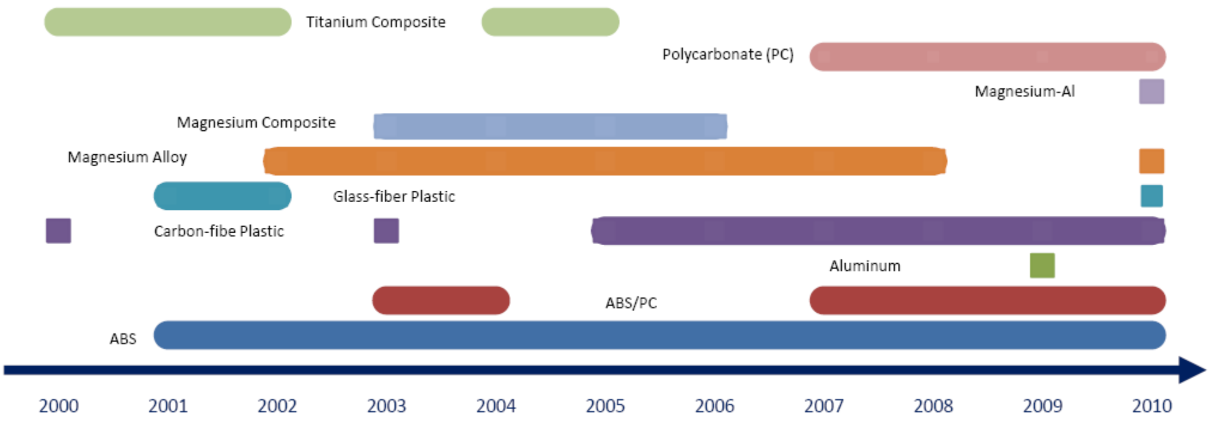

Figure 6: Chassis or enclosure materials used by selected IBM/Lenovo laptops during 2000-2010 (n=92)

The five laptops dismantled for this project used the following major materials: magnesium alloy, aluminum, steel and ABS/PC. Is important to note that the disassembled OEM2 laptops are aimed at a business "road-warrior" consumer, where durability and lightness are key characteristics. In contrast the OEM1 laptops dismantled in this project were oriented for a residential consumer, where equipment cost is considered a main driver. Figure 7 plots the enclosure/chassis materials for the five dismantled laptops. The main materials used for the three OEM2 laptops (12", 14" and 17") were magnesium and aluminum; where the bottom enclosure used magnesium alloy and the display enclosure or top cover used a combination of magnesium (inner sheet with a honeycomb pattern) and aluminum (outer sheet). The OEM1 laptops (2001 and 2005 15") used a blend of ABS and PC for the display enclosure and ABS/PC and Steel for the base or bottom enclosure.

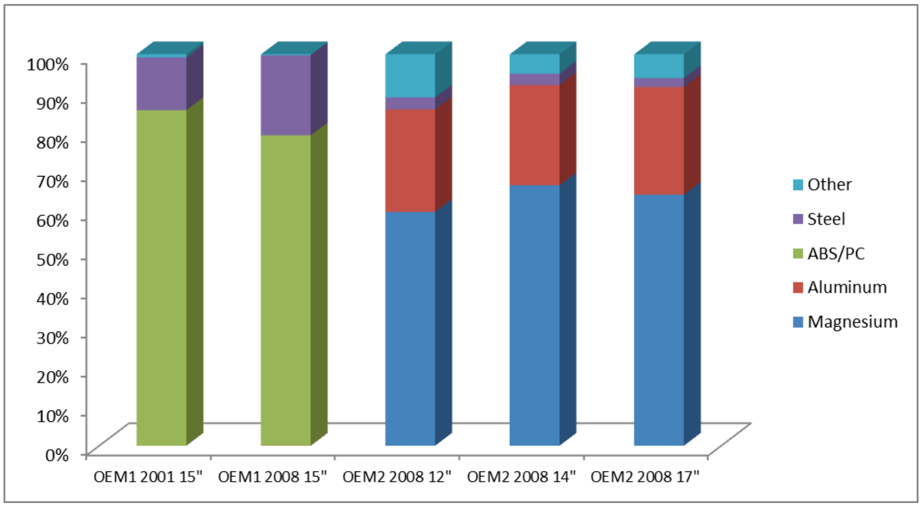

Figure 7: Chassis or enclosure materials for the dismantled laptops

## *Semiconductor attributes: silicon wafer content of motherboard*

Another objective of this study is to examine trends in key component attributes for different models of laptop computers. Given the importance of microchip manufacture in the footprint of computers and the prevalence of using silicon wafer area as a parameterization for life cycle inventory estimation and the importance of, total silicon wafer area was measured for all five laptops. After dismantling each laptop completely, all the Integrated Circuit (IC) Chips on the motherboard were ground to reveal the silicon wafer. This data was analyzed to study scaling trends (by year and by screen size) of the ICs on the motherboard. Figure 8 below shows the total silicon area on the motherboard for all the five dismantled laptops. Each bar represents the sum of the silicon area of all the chips on the motherboard for a given laptop.

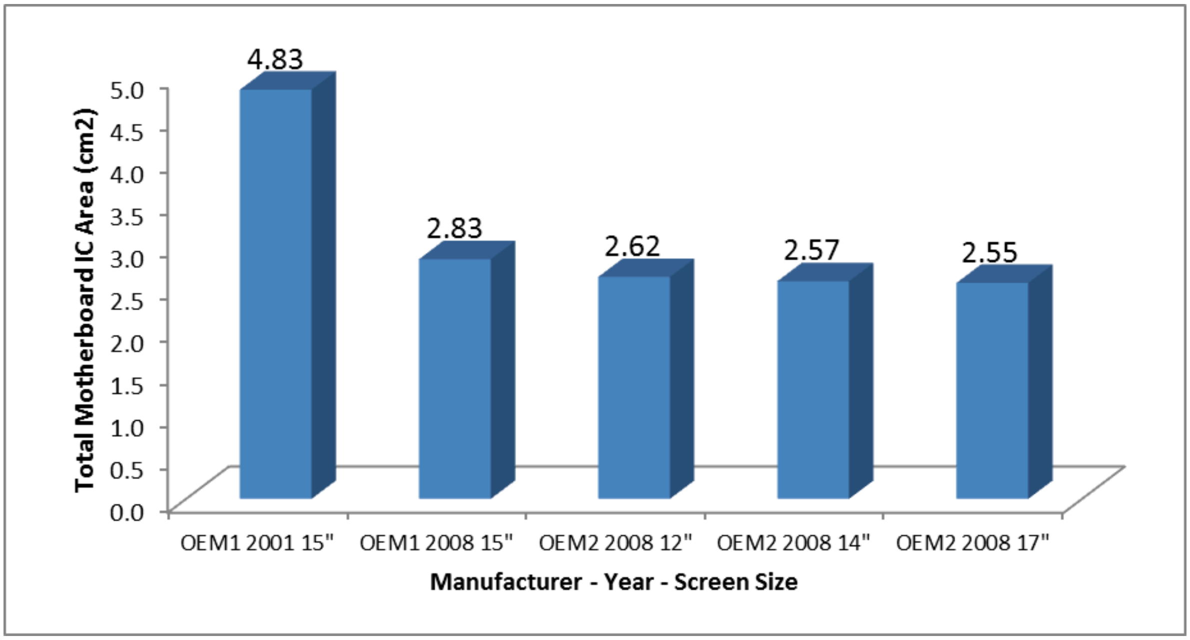

Figure 8: Total silicon area on the motherboard for dismantled laptops

The results in Figure 8 have important implications for the carbon footprinting of electronics. The 2001 OEM1 laptop had a total silicon area of 4.83 $cm^2$ and clearly the total silicon area has drastically decreased (by about 50%) since 2001. Combined with results that the energy use in semiconductor manufacturing continues to evolve (Boyd et al 2009b, Deng and Williams 2010), it is clear that carbon footprinting of semiconductors must account for technological change in both BOM and process energy use.

For laptops manufactured in a given year (2008), the total silicon area is very similar irrespective of screen size: a total silicon area ranging between 2.55$cm^2$ and 2.83 $cm^2$, around a 10% variation within a given year the variability in silicon wafer content of different laptops models appears small or of similar order to the variability caused by parameterizing semiconductor manufacturing based on aggregated wafer area (Deng and Williams 2010). If this is indeed the case, *currently available data for* *does not show a statistically significant difference in the carbon footprint of microchips in different laptop models*. Further disaggregation of semiconductor manufacturing (e.g. by type of chip, number of layers, process steps) may reveal differences in the carbon footprint. Whether this difference would be large enough to justify the significant data collection involved is not yet clear.

## *Semiconductor attributes: silicon wafer and packaging area*

Given the labor intensity associated with either grinding chip packaging or advanced imaging to determine silicon area, it is worth exploring whether external characteristics of a chip might be a reasonable indicated of contained silicon wafer. The area of packaging and number of pins can be determined by inspection and data more readily in chip spec documents, thus in the next two sections the possible relationship between silicon wafer area, packaging area and the number of pins is explored.

The first analysis compares to the ration of silicon wafer area to packaging area for individual chips on the motherboard. Scaling was studied with respect to manufacture year and laptop screen size. Figures 9 and 10 show results for each motherboard chip for silicon area to package ratio. The chips (ICs) are ordered in increasing value of ratio. Figure 9 shows this relationship between the two comparable OEM1 laptops manufactured in different years (2001 and 2008). The 46 shown on the x-axis for the 15" OEM1 in 2008 indicates that 46 distinct integrated circuits were identified on the motherboard. Figure 10 shows the same for the different OEM2 laptops all manufactured in 2008. Each color represents a different laptop and each bar on the figure represents a single IC's silicon area to package area ratio.

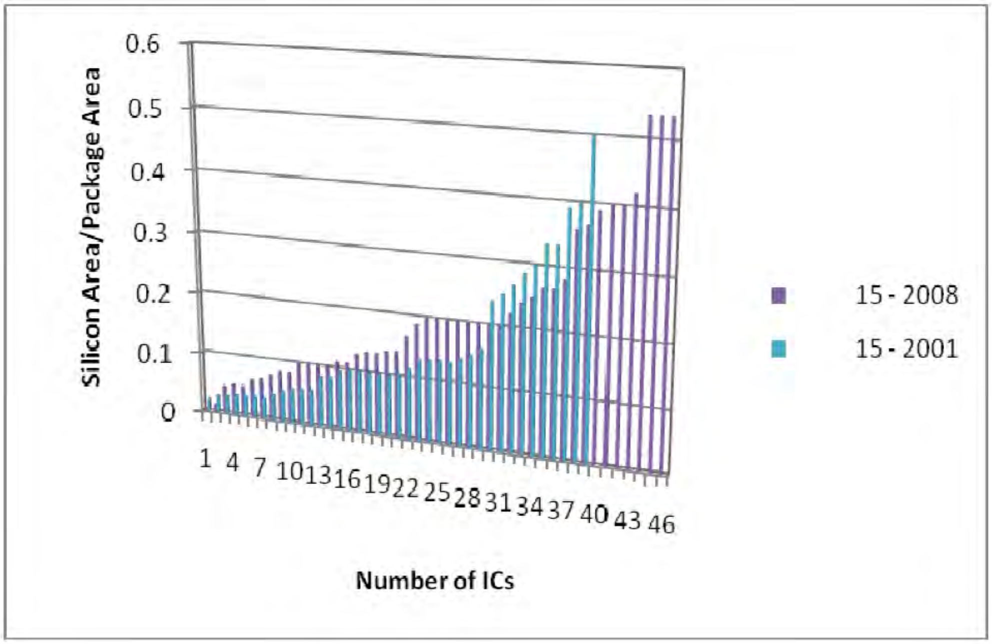

Figure 9: Ratio of silicon area to package area for similar size OEM1 laptops manufactured in 2001 and 2008

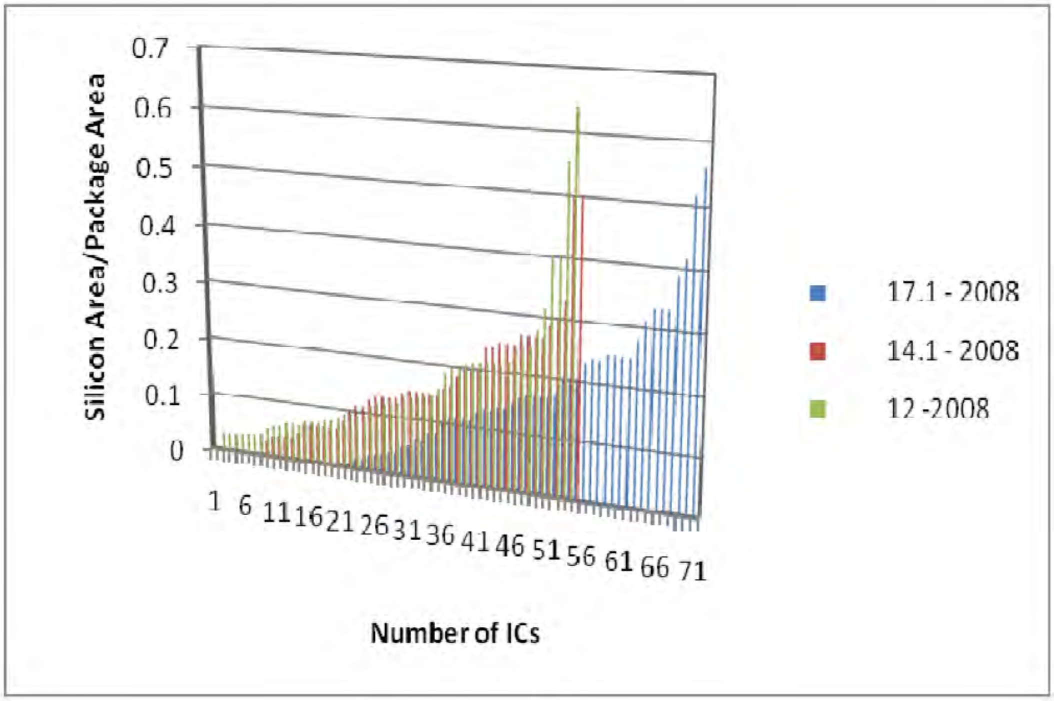

Figure 10: Ratio of silicon area to package area for various OEM2 laptops manufactured in 2008

The main result of Figures 9 and 10 is that the ratio of wafer to packaging is far from constant, varying from .0125 to .64 depending on the chip, a factor of 51 difference. Packaging area is thus an extremely poor indicator of contained wafer. It is likely that additional information on the type of chip (e.g. CPU, DRAM, etc) would lower variability, but it is not clear at this point whether such a disaggregated model would reduce variability to an acceptable level.

Figure 9 shows that the OEM1 laptop manufactured in 2008 had more ICs than the OEM1 manufactured in 2001. Although the number of chips has gone up the distribution for 2001 is comparable to 2008. From figure 8 it is evident that the OEM1 2001 has the largest total silicon area though it has less number of chips when compared to the OEM1 2008. Therefore we can safely conclude that the average chip size has decreased from 2001 to 2008.

There are about 70 ICs on the 17.1 inch OEM2 and around 55 in the 14.1 and 12 inch OEM2's manufactured in the same year (from Figure 9). Although the numbers show that the number of chips increase with the increase in screen size there is no clear correlation.

While the ratios wafer to packaging area at the chip level are highly variable, it is possible that aggregated packaging area over the whole motherboard could be a reasonable measure of wafer area. Figure 11 below shows the total packaging area of the ICs on the motherboard for all the five laptops. Each bar represents the sum of the packaging area of all the chips on the motherboard for a given laptop. Comparing with Figure 8 showing the total silicon wafer area for the same laptops it is clear that there is poor correlation between packaging and wafer area even at the aggregate level.

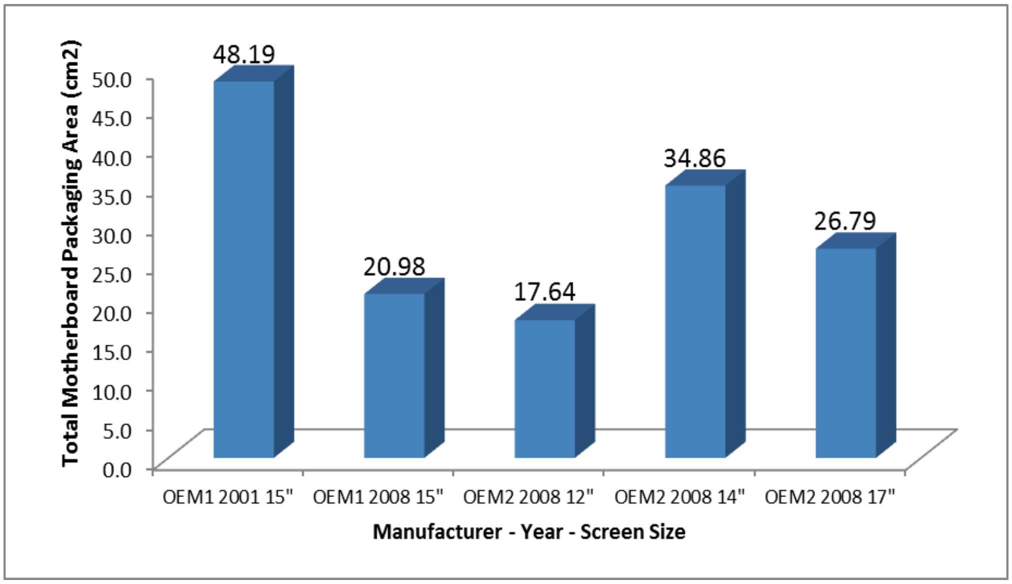

Figure 11: Laptop versus total packaging area on the motherboard

## *Semiconductor attributes: silicon wafer and number of pins*

A second hypothesis is that the number of pins per IC might correlate with wafer area. To check this hypothesis the silicon area per IC and the number of pins per IC is analyzed the 15” OEM1 manufactured in 2008, the 14” OEM2 manufactured in 2008 and the 17’ OEM2 manufactured in 2008. Figures 12-14 present the results of this analysis. Each point on the figure represents an IC on the motherboard. From the results in Figures 12-14 it is clear that there is no significant correlation between total number of pins and the wafer area. The number of pins is thus not clearly related to known environmental characteristics and at this point not a good candidate for parameterization in BOA. It is possible that a more disaggregated model including additional information on the type of chip (e.g. CPU, DRAM) may lead to a better correlation.

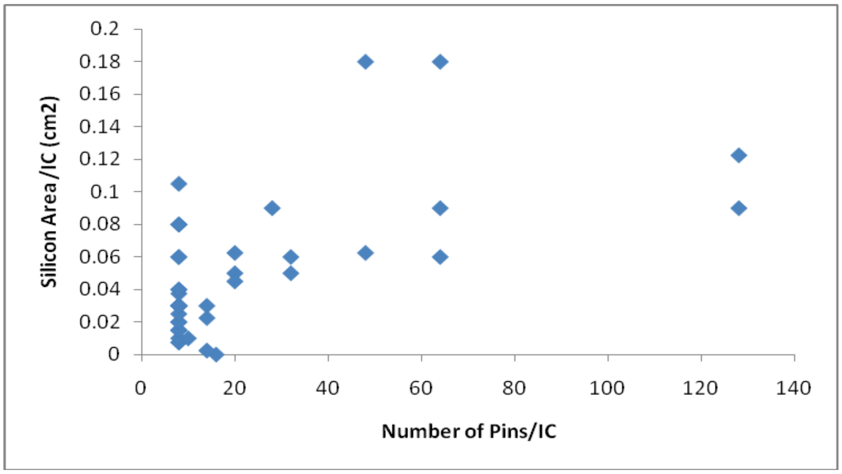

Figure 12: Number of pins versus silicon area for the 15” OEM1 manufactured in 2008

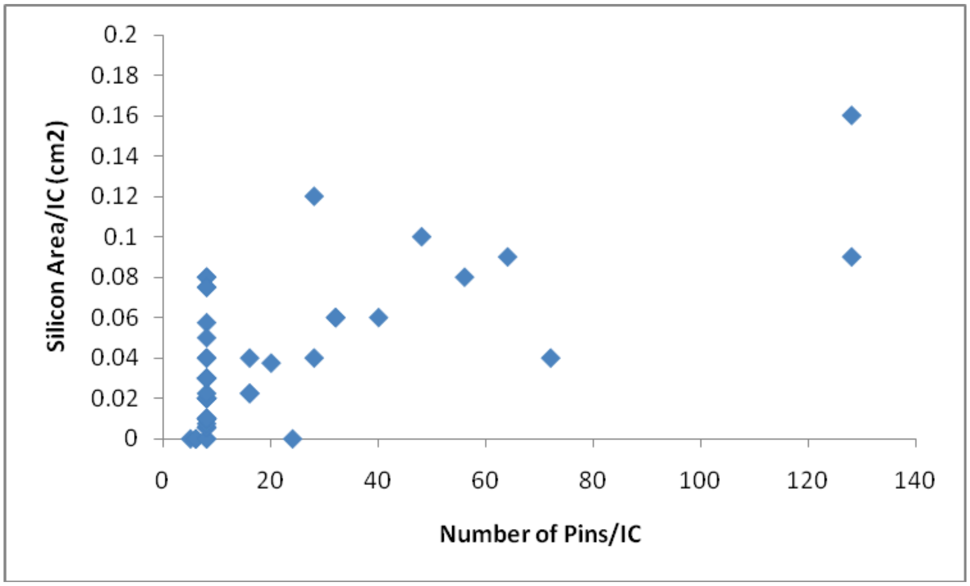

Figure 13: Number of pins versus silicon area for the 14" OEM2 manufactured in 2008

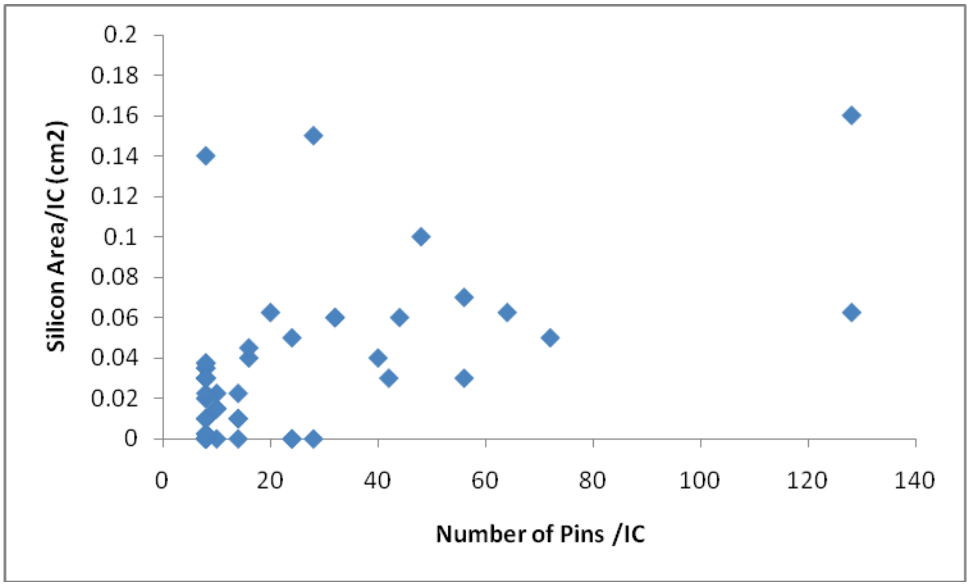

Figure 14: Number of pins versus silicon area for the 17" OEM2 manufactured in 2008

## *Conclusions*

Recapping results drawn from the disassembly modeling and attempting to draw general conclusions:

- The mass fractions of bulk materials are relatively constant over different years and screen sizes. This suggests that the carbon emissions from producing bulk materials might be reasonably approximated by a parametric model scaled by the total mass of the laptop.

- The total silicon wafer area in a laptop motherboard is nearly constant for different screen sizes, but differs substantially according to the year of manufacture. Assuming silicon wafer area is indeed a sufficiently accurate parameterization to describe carbon emissions of chip-making (still an unproven assumption), then the carbon contribution from semiconductor manufacturing might be reasonably approximated by a model driven by time trends in BOA and carbon emissions per wafer processed.
- The area of chip packaging does not correlate with contained silicon wafer. Any model relating the package and wafer area would need to encode additional information such as the type of chip.
- The number of pins does not correlate with contained silicon wafer. Any model relating the number of pins and wafer area would need to encode additional information such as the type of chip.

At the risk of over-generalizing, these results suggest that the carbon footprint of a laptop may be relatively insensitive to detailed disaggregation of the BOA. If a Product Characterization Rule (PCR) aims to distinguish laptops based on product attributes rather than distinguishing supply chains, it may be possible to describe "baseline" carbon emissions via a simple model depending on mass, with adjustments made for qualitative technology differences such as casing material choice or LED versus fluorescent bulbs.

Clearly there are a number of caveats to these conclusions. One type of caveat is the limited scope of the study, e.g. small sample size, the consideration of only motherboards. A second type of caveat relates to the modeling assumptions. As yet there is not sufficiently disaggregated process data available to properly test the carbon implications of different parameterizations of BOA.

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