Product Design Strategies for Decarbonization and Resource Efficiency

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The environmental impact of products is highly dependent on decisions made during product design. Like other performance attributes, design for environment requires balancing tensions related to resource efficiency, reliability, repairability and other factors. The importance of quantitatively evaluating these tensions has grown, in order to guide design decisions toward optimizing for minimum environmental impact over the full lifecycle.

This paper presents how lifecycle assessment can be leveraged to evaluate these tensions. Two case studies are presented. The first focuses on optimizing the design of laptop computer displays to balance resource efficiency with repairability. The second focuses on selecting the optimal computer memory architecture to balance resource efficiency with repairability and upgradability. Both case studies demonstrate that it is simplistic to assume, in isolation, that designing for repairability and upgradability always lead to lower environmental impacts. Nuanced, quantitative assessments are required to optimize for environmental impacts over the full lifecycle of a product.

Keywords — Ecodesign, Trade-off, repairability, reliability, upgradeability

I. INTRODUCTION

Voluntary environmental initiatives and regulatory requirements are collectively driving actions to address many of today's most significant environmental challenges. Apple set a goal of becoming carbon neutral for its entire product footprint by 2030 by reducing its emissions by 75% compared with its 2015 baseline and investing in high-quality carbon removal solutions for the remaining emissions. Apple aims to make durable, long-lasting products using only recycled or renewable materials, as well as enhance material recovery.

Product longevity is a key priority both for decarbonization and resource efficiency. This is particularly important for consumer electronics, as their environmental impacts are dominated by the manufacturing phase [1]. Apple prioritizes longevity by designing durable and repairable hardware, leveraging ongoing software support to extend functionality, and providing customers with convenient access to repair services. Apple's approach is working: Apple leads the industry in longevity as demonstrated through higher value of second-hand devices relative to competitors [2], decreasing service rates, and increasing product lifespans.

However, the product design process often requires balancing competing factors that are in tension with each other, where determining which attribute to prioritize can be unclear. This can be illustrated three ways.

First, designing for longevity requires striking the right balance between durability and repairability since the technologies that increase durability can also make products harder to repair. For example, achieving high levels of liquid ingress protection on smartphones often requires the use of adhesives that make repair more challenging. Yet, Apple found that when iPhone was first designed for IPx7 liquid ingress protection, repairs for liquid damage decreased by 75%.

A second example where competing tensions can occur is in regulations that set minimum environmental standards. The Ecodesign Directive (2009/125/EC) provides consistent EU-wide rules for measuring and improving the environmental performance of energy-related products. Historically, the Ecodesign Directive focused on reducing energy consumption of products, as reducing energy consumption yielded clear environmental impact reductions and cost savings to consumers [3]. Over the last decade, Commission Regulations under the Ecodesign Directive broadened their focus to material efficiency requirements [4]. The future Ecodesign for Sustainable Products Regulation (ESPR) builds on the existing Ecodesign Directive and establishes a framework to set ecodesign requirements for product groups beyond the current scope of energy-related products. The framework will allow for a wide range of requirements on product durability, reusability, reparability, recycled content, and GHG emissions [5] which may be in tension with each other.

A third example is determining which components should be architected to be repairable. In addition, designers often have to decide on the degree of repairability, such as designing a component to be discretely replaceable (i.e. with no damage or loss to other unaffected components) or to design for an assembly to be replaceable (i.e. collection of parts). Often times, making an individual component discretely replaceable requires it to be modular, which can require additional resources such as circuit boards, connectors or fasteners — adding to the environmental impact of each and every product produced. Whether that investment of upfront resources and its associated increase in GHG emissions is worthwhile can be a function of the frequency of replacement. If the component rarely needs replacement, design for repair at the assembly level can often yield the optimal design.

These examples demonstrate that incorporating considerations on a broad range of material efficiency requirements requires managing the interconnectedness and tensions between energy efficiency, material use, durability, repairability, upgradeability, product features or performance, and other factors [6]. The challenge for product designers and policymakers alike is to reflect these tensions when designing products or setting requirements, respectively, to avoid unintended consequences. As a result, the need for quantitative tools to evaluate these tensions has grown, in order to ensure decisions are optimized to lower environmental impacts over the full product lifecycle.

This paper presents how lifecycle assessment can be leveraged to evaluate these tensions. Two case studies are presented. The first focuses on optimizing the design of laptop computer displays to balance resource efficiency with repairability. The second focuses on optimizing computer memory architectures to balance resource efficiency with repairability or upgradability.

Both case studies demonstrate the view that repairability and upgradability always lead to lower environmental impacts is simplistic. In many cases, trade-offs are introduced when optimizing solely for repairability that lead to higher GHG emissions and other impacts. Instead, nuanced, quantitative assessments are required to optimize for environmental impacts over the full lifecycle of a product.

II. Quantitative Assessment method

Lifecycle assessment can be leveraged to evaluate trade-offs between product design considerations including those related to repairability. The proposed approach first requires performing a comparative lifecycle assessment on two alternative designs to understand the difference in GHG emissions associated with manufacturing and, if applicable, product use. The net difference in GHG emissions between the two design options can then be plotted as a function of the rate a component will need replacement for repair or upgrade. This method provides a useful framework to analyse trade-offs provided reasonable projections can be made on replacement rates and product longevity.

This can be illustrated as follows:

$$\textit{Net GHG benefit} = \textit{Replacement rate} \times (\Delta\ \textit{GHG Repair}) - \Delta\ \textit{GHG manufacturing} - \Delta\ \textit{GHG use phase}$$

where:

$$\Delta\ \textit{GHG repair} = (\textit{GHG repair})_{\textit{alternative design}} - (\textit{GHG repair})_{\textit{baseline design}}$$

$$\Delta\ \textit{GHG manufacturing} = (\textit{GHG manufacturing})_{\textit{alternative design}} - (\textit{GHG manufacturing})_{\textit{baseline design}}$$

$$\Delta\ \textit{GHG use phase} = (\textit{GHG use phase})_{\textit{alternative design}} - (\textit{GHG use phase})_{\textit{baseline design}}$$

Based on this framework, the replacement rate where the net GHG benefit equals zero, which we term the breakeven point, can be calculated. If the projected replacement rate is far from the breakeven point, it provides the designer with greater certainty on which design option will yield the optimal outcome when minimizing GHG emissions is the prevailing objective.

This methodology has limitations. First, it leverages GHG emissions as the prevailing objective, without regard to other indicators such as resource consumption or waste generation. Second, the examples presented assume there is no impact on replacement rate in the two design scenarios, ignoring the impacts of replacement part costs, labour costs, or other consumer behaviours that influence whether a replacement will be undertaken. Third, the examples presented assume there is no change to product durability in the two design scenarios. These shortcomings can be overcome with more complex calculations and modelling. The analysis presented here is intended to demonstrate a framework for quantitative evaluations that can be extended to other environmental indicators or more complex scenarios.

III. Case Study 1: laptop computer display

One of the product components that most frequently needs replacement on a laptop computer is its display, predominantly as a result of accidental damage by the user. At first glance, this would appear to justify designing the display panel itself to be discretely replaceable. However, it is a useful example to employ the quantitative assessment method to interrogate design decisions on the degree of modularity and in turn, replaceability.

Most laptop display architectures can be characterized as either modular or integrated. A modular display design is made up of multiple components including a display panel with a backplate, a cosmetic enclosure, and a bezel. The backplate primarily provides the rigidity for the display panel, and the bezel bridges the gap between the display panel and the outer cosmetic enclosure which houses the assembly. Replacement of the display panel can occur without collateral loss to some other components, which is one of its primary advantages.

In contrast, an integrated display design builds the display panel into the enclosure during the manufacturing process. This eliminates the requirement for a separate backplate and enclosure, as well as the need for a bezel. This reduces the quantity of materials used and lowers GHG emissions. However, replacement of the integrated display requires replacement of the assembly that includes the enclosure.

Apple employs an integrated display architecture in recent generations of its MacBook Air and MacBook Pro laptop computers. One benefit of the integrated display architecture is it provides superior stiffness and robustness, which reduces the frequency of accidental damage. However, for the purpose of simplifying this case study, differences in durability will be ignored. Figure 1 exemplifies how modular and integrated displays are architected.

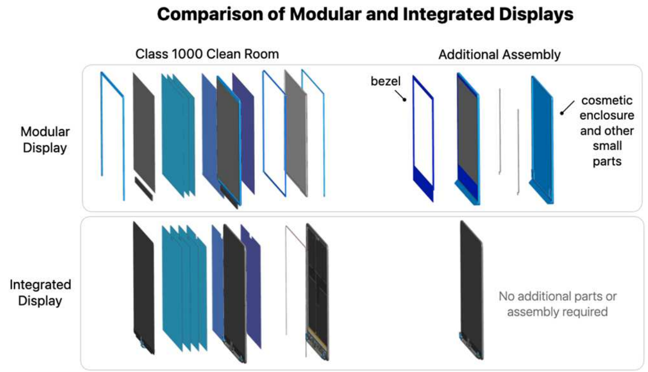

Fig. 1 Comparison of modular and integrated display architectures. Modular displays facilitate replacement of the display panel as a discrete unit, whereas integrated displays require replacement of the display panel assembly. Integrated displays tend to be more material efficient, more reliable, and have lower GHG emissions.

Modular and integrated display architectures can be modelled using lifecycle assessment. The authors chose a 13-inch laptop display to model, selecting the 13-inch MacBook Air as the baseline with its integrated display, compared against a modular display of the same screen size. If the 13-inch MacBook Air were designed with a modular display, new parts would need to be added, including a plastic ring, metal chassis, and connectors. The display cell and backlight unit would need to increase 12% in x-y dimensions as to complete a seal on the assembly, preventing particle ingress. The volume of the display housing enclosure would need to increase 30% (x +8.1mm, y +9.6mm, z +0.5mm) to fit these new parts into the system and to provide the structure needed to safely handle the assembly without risk of damage. To match the larger display housing enclosure, the lower enclosure (top case that surrounds the keyboard and trackpad, and bottom case) would need to increase 12% in x-y dimensions (x +8.1mm, y +9.6mm). Similarly, smaller housing parts like the hinge and magnets would need to increase by 30% in volume to provide the same function as in the integrated design. Finally, the redesigned device with modular display would be 3% heavier, leading to an increase in the impact of transporting the device to customers.

Both scenarios assumed the display PCB and flexes, LED and camera combo flex, and camera module would be replaced during repair, as these components are permanently attached to the display cell assembly.

	Integrated Display (baseline)		**Modular Display**	
	GHGe	Repair	GHGe change from baseline	Repair
Lower Enclosure (Top Case and Bottom Case)	11,0		+1,3	
Enclosure: Display housing, trim, hinge	6,9	●	+2,0	
Display housing lower cover	0,7	●	+0,02	●
Housing magnets	0,3	●	+0,1	
Additional parts to support modularity (P-ring, M-chassis, connectors)	-		+0,6	●
Display cell and backlight unit	15,8	●	+1,9	●
Display PCB and flexes	6,1	●	no change	●
LED/Camera combo flex	2,5	●	no change	●
Camera module	0,7	●	no change	
Module assembly	0,9	●	no change	●
Initial transport to customer	excluded	●	+0,3	
Total Manufacturing GHG Emissions	**44,8**		**51.0** △ = **+6.2**	
Total Repair GHG Emissions		**33,8**		**28.5** △ = **-5.3**

Fig. 2 GHG emissions for manufacturing and repair of an integrated and modular 13-inch laptop display expressed in kg CO2e/unit. Components with a ● indicate that replacement is required for repair.

The total manufacturing emissions associated with an integrated display was calculated to be 44.8kg CO2e per unit, compared to 51.0kg CO2e for a modular display. The higher manufacturing emissions associated with the modular display is a result of the additional components necessary to achieve modularity. In contrast, GHG emissions associated with repair are lower for the modular display, 28.5kg CO2e, compared to 33.8kg CO2e in the integrated display since the modular display requires fewer components to be replaced during the repair process.

Additionally, Apple estimated based on historical customer data that approximately 30% of display damage incidents also resulted in sufficient damage to the enclosure that would have necessitated enclosure replacement (regardless of modularity). In this scenario, modularity provides no benefit if the full display assembly, inclusive of the enclosure, requires replacement. However, this was not factored into the calculation to be conservative.

Therefore, the key question a designer should be posing is under which circumstances do the repair-related GHG emissions savings of a modular display architecture sufficiently compensate for the additional GHG emissions required to manufacture the modular display. Utilising the quantitative assessment method presented before, it was determined that the breakeven replacement rate, where the modular and integrated designs yielded the same total emissions, was 117% (i.e. 1,17 display repairs per product). If the frequency of replacement is less than 117% over the product's lifespan, integrated displays result in lower net GHG emissions. If the frequency of replacement is over 117%, modular displays result in lower net GHG emissions[1].

Projections on the frequency of replacement are required to determine the optimal design, where leveraging historical data on similar products can enable a reasonable assumption. Historical Apple data suggests that displays require service at a rate far below 117%. Even if the authors conservatively estimate that 20% of laptop displays require repair over a product's lifetime, the integrated display results in substantially less GHG emissions. Therefore, the designer is justified to select an integrated display architecture. The justification is furthermore reinforced if the calculation factored in display robustness, where integrated displays would likely require repair at a lower frequency than modular displays.

The conclusion's dependence on the replacement rate can be illustrated through Figure 3 that plots the GHG emissions of integrated and modular display architectures. This case study exemplifies that determining the appropriate degree of repairability is highly dependent on design architecture and the anticipated replacement rate. Greater modularity and higher degrees of repairability do not necessarily yield the best outcome if replacement rates are low.

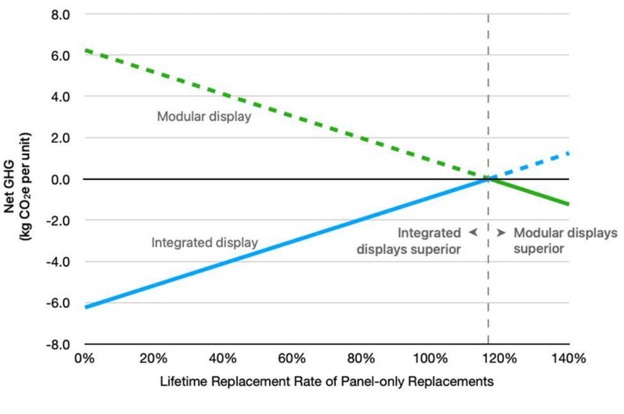

Fig. 3 GHG emissions as a function of lifetime replacement rate for displays in a 13-inch laptop computer. At replacement rates below the breakeven point of 117%, integrated displays (blue) yields a net GHG emissions savings relative to modular displays (green). At replacement rates above 117%, modular displays yield a net GHG emissions savings

IV. CASE STUDY 2: MEMORY ARCHITECTURE

The assessment method presented in the first case study can be extended to evaluate trade-offs associated with upgradability, as well as repair. To illustrate this, the following case study compares two different memory architectures used in computers: (i) unified memory integrated in a system-on-chip (SOC) package and (ii) discrete memory modules.

Computer architectures have evolved to include multiple discrete forms of memory, which over time, were integrated into the CPU, GPU or SOC package. In contrast to legacy computer architectures that required multiple discrete forms of memory in separate packages – computers with SOC architectures employ unified memory, leveraging a single pool of memory integrated into the SOC. Unified memory on the SOC package provides significant customer and environmental benefits, such as increased performance, reliability, energy efficiency [7], material efficiency and lower GHG emissions. For example, the Apple Mac Studio desktop computer was estimated to save up to 1,000 kilowatt-hours of energy per year relative to a high-end PC desktop with discrete memory modules [8] by taking advantage of Apple SoC's industry leading performance per watt. These advantages led Apple to transition to SOCs with unified memory in the early 2020s.

However, unified memory within a SOC package cannot be discretely upgraded or replaced in case of failure without a full main logic board (MLB) replacement. One advantage of computers with discrete memory modules is to enable consumers to increase the memory capacity of their computer over time. To assess the merits of each memory architecture, the quantitative assessment method was employed factoring in both upgradability and repairability.

The authors chose a 16-inch MacBook Pro laptop computer[2] using an SOC with unified memory, compared against a re-architected laptop computer with discrete memory modules. For the re-architected laptop with discrete memory, the authors modelled the use of four LPDDR[3] CAMM[4] memory modules to achieve bandwidth parity [9], as bandwidth is a key performance metric. CAMM memory modules were projected to consume significantly more energy than unified memory, requiring up to 11W additional power draw during active use, which would necessitate a larger battery to maintain equivalency in run time. In addition, CAMM memory modules would require the MLB to be redesigned, resulting in an increase of 18% in MLB component PCB usage, leading to an 8.9% increase (13.4kg CO2e) in manufacturing GHG emissions[5]. To simplify this analysis, the resulting increase in product enclosure size, packaging or transportation emissions was ignored.

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1 Calculation assumes 13-inch MacBook Air with 256GB storage and integrated display assembly, compared to a larger system with modular display enabled by additional housing components such as P-ring, M-chassis, connecters needed for discrete replacement of the display panel (adding 6.2 kg CO2e per device).

2 Calculation assumes 2022 MacBook Pro 16-inch with M2 Max / 1 TB NAND / 16 GB unified memory, compared to a system with LPDDR CAMM memory modules. In the case that memory requires service with an SOC architecture, the main logic board is replaced and refurbished.

3 Low-Power Double Data Rate (LPDDR), also known as LPDDR SDRAM, is a type of synchronous dynamic random-access memory that consumes less power and is targeted for mobile computers and devices such as mobile-phones

4 CAMM: Compression Attached Memory Module is a memory module form factor developed as a replacement for DIMM and SO-DIMM

5 As measured by layer weighted area (number of layers in a printed circuit, multiplied by the area of the printed circuit board, as a neutral representation of material usage)

The difference in material efficiency can be visualized by Figure 4, drawn to scale, that compares unified memory in an SOC (left) with LPDDR CAMM memory modules (right).

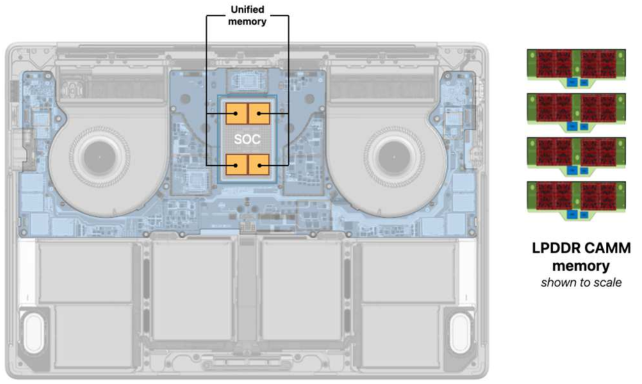

Fig. 4 Four LPDDR CAMM memory modules (right) are required to provide comparable memory performance to unified memory on Apple SOCs (highlighted in orange). To provide scale, the SOC and unified memory are shown in a 16-inch MacBook Pro, with the MLB shaded in blue.

Figure 5 compares the GHG emissions of a laptop computer with unified memory against a similarly performing product rearchitected with LPDDR CAMM memory modules. It was calculated that the total manufacturing emissions associated with an MLB with unified memory was 150.0kg CO_2e per unit, compared to 195.2kg CO_2e for a laptop with CAMM memory modules (30% increase). The bulk of the emissions increase for laptops with CAMM memory is associated with its increased power draw, conservatively assumed over a four-year lifespan. However, GHG emissions associated with replacement (either for repair or upgrade) are substantially lower for the laptop with CAMM memory, 21.9kg CO_2e, compared to 150.0kg CO_2e to replace the entire MLB[6] (85% reduction).

	SOC Unified Memory		CAMM Memory Modules	
	GHG	Replaced	GHG	Replaced
Main Logic Board (MLB)	150,0	●	133,9	
Memory modules (DRAM)	-		16,1	●
CAMM PCBs (4 total)	-		5,8	●
SoC changes to enable 4x CAMM (die & package size)	-		4,8	
Larger MLB PCB to enable CAMM interconnects	-		2,8	
Increased energy consumption during lifetime usage	-		30,6	
Battery changes	-		1,2	
Total Manufacturing GHG Emission	**150,0**		**195,2**	
Total Replacement GHG Emissions		**150,0**		**21,9**

Fig. 5 GHG emissions for manufacturing and replacement of memory in a 16-inch laptop with unified memory or CAMM memory modules expressed in kg CO_2e/unit. Components with a ● indicate that replacement is required to repair or upgrade memory. Increased energy consumption for CAMM memory modeled for four years of use to be conservative.

Therefore, the key question is under which circumstances do the replacement-related GHG emissions savings of laptops with CAMM memory modules sufficiently compensate for the additional GHG emissions required to manufacture and power the device. Utilizing the quantitative assessment method, it was determined that the memory replacement rate would need to exceed 36% (i.e. breakeven point) before the additional GHG emissions of architecting every product with discrete memory is offset by lower emissions associated with repair or upgrade, as depicted in Figure 6. If the frequency of replacement is less than 36%, a laptop with unified memory results in lower net GHG emissions.

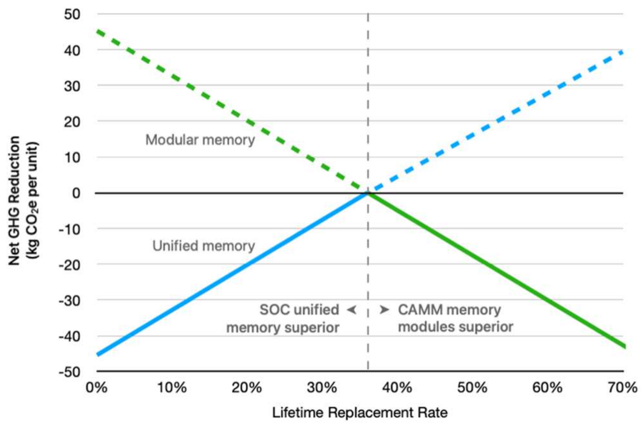

Fig. 6 GHG emissions as a function of lifetime replacement rate for memory architectures. At replacement rates below the breakeven point of 36%, unified memory yields a net GHG emissions savings relative to modular memory. At replacement rates above 36%, modular memory yield a net GHG emissions savings.

Projections on the frequency of replacement are required to determine which scenario is more favourable, using a combination of historical data and modelling for both repair and upgrades. Apple internal data on historical failure rates of memory showed that failures rarely occurred. In fact, failures rates were several orders of magnitude lower than the breakeven point and can be ignored for this analysis.

Estimates on the upgrade rate for products with unified memory were necessary since one could not assume the need for memory upgrades was equivalent to memory modules due to key differences. To estimate the upgrade rate, Apple projected the likelihood that memory upgrades would be required by evaluating the frequency that memory is oversubscribed. When memory is oversubscribed, files need to be swapped between DRAM and local storage, which degrades system performance. Apple leveraged historical anonymized field data for newer laptops with SOC-based unified memory and predecessor laptops with memory modules. For example, evaluating the 85th percentile consumer to represent a so-called power user, customers with laptops manufactured in 2018 spent more than five times the duration with oversubscribed memory, compared to laptops manufactured in 2021 with the same amount of memory in a unified memory architecture. This substantial reduction in time spent with oversubscribed memory is a result of unified

6 Reuse of replaced CAMM memory modules or MLBs is ignored to simplify the assessment on upgradability, and present a more conservative scenario.

memory's use of hardware compression, which allows better use of the existing memory. Furthermore the use of high speed solid state drives (SSD) compensates for the negative effects of oversubscribed memory and allows the user to maintain performance under heavy workloads. Therefore the need for memory upgrades when using unified memory architectures is significantly diminished — with the vast majority of customers likely to see little benefit from memory upgrades. Therefore, it was projected that the need for memory replacement in laptops with SOC-based unified memory is highly unlikely to reach the projected breakeven point.

V. Sensitivity analysis

There are several factors that can impact the presented results. Both case studies do not reflect whether suppliers are utilizing clean energy for manufacturing or the use of recycled content, both of which would change the GHG emissions of various components.

Both case studies are also sensitive to product lifespan. In the case of memory replacement, the higher power draw associated with CAMM memory modules made up the majority of the increased emissions over the baseline scenario where a conservative four year product lifespan was assumed. If the lifespan was increased to an average lifespan, the breakeven point would materially increase, making the unified memory architecture even more favourable.

Finally, the results will also be sensitive to the overall reliability of the product. In the display scenario, the lower rigidity and robustness of the modular display will likely result in a higher frequency of replacement than the integrated display.

VI. Conclusion

Product designers are faced with dozens of fundamental architectural decisions during product development where competing factors are in tension with each other. While designing for modularity, in isolation, to enable both discrete component repair or upgrade is often heralded as the most sustainable approach, this view is simplistic at best and sometimes wrong when evaluated holistically.

Lifecycle assessment can be leveraged to evaluate trade-offs between product design considerations including those related to repairability and upgradability. This approach was utilized to compare two different architectural scenarios. The first focused on a laptop computer display replacement, comparing a modular architecture to a display integrated into the enclosure. The second focused on memory architecture, comparing the use of modular memory modules to unified memory integrated in an SOC. In both cases, it was concluded that the more integrated approach yielded lower overall GHG emissions when factoring in the frequency of repair or upgrades. While two case studies were presented where the integrated design resulted in lower GHG emissions, there are instances where designing for discrete repair would result in lower emissions.

The framework demonstrates quantitative evaluations are necessary to determine optimal design architectures or regulatory policies aimed at minimizing GHG emissions. The authors consider the presented framework to be a useful tool to aide in design decisions and support regulatory policy recommendations.

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