Available online at www.sciencedirect.com

ScienceDirect

Procedia Computer Science 00 (2024) 000–000

Procedia Computer Science

www.elsevier.com/locate/procedia

The 14th International Conference on Sustainable Energy Information Technology (SEIT)
August 5-7, 2024, Marshall University, Huntington, WV, USA

Can new metrics be validated to reduce computer supply chain GHG emissions among end users?

J. Sutton-Parker [a,*] and R. Procter [a, b]

[a] University of Warwick, Computer Science Department, Coventry, CV4 7AL, United Kingdom
[b] Alan Turing Institute for Data Science and AI, London, NW1 2DB, United Kingdom

Abstract

The research objective is to create a mechanism that generates a valid 'sustainability' metric to enable prospective buyers to confidently identify low carbon footprint computers. The necessity is based upon the hypothesis that current product carbon footprint reports for computers are incomparable between brands. While the inconsistency of use-phase emissions has been addressed in prior associated research, supply chain emissions remain an issue. This is due to multiple scope 3 life cycle assessment methodologies being used by manufacturers that produce differing results even when applied to the same device. To test the theory and generate an alternative approach, the research analyses 244 notebook carbon footprint reports to show inconsistencies caused by five different methodologies. Based on the findings, an alternative approach to comparing supply chain impact is proposed that enables comparison between results. The new metric first generates an average scope 3 carbon footprint baseline value by device type (e.g. notebook). This is then reduced by specific values depending upon actions undertaken by manufacturers when calculating their original carbon footprint report. This includes deductions to the baseline value achieved by including high percentages of production and transport primary data, plus the availability and affordability of offerings that will extend device useful life spans to drive demand displacement. This includes warranty duration and cost plus ease of repair. The research finds that current methodologies create a range of inconsistency of +106% when used to calculate the carbon footprint of the same device and +142% when calculating similar device types. Therefore, the hypothesis of scope 3 emissions being incomparable is validated. Comparatively, the newly proposed mechanism shows a reduced range of inconsistency of 18% when demonstrated. As such, it is recommended that the new approach be applied to the latest version of the world's leading computer eco-label certification, TCO Certified version 10, in 2024. Doing so will enable organisations to confidently select low carbon footprint devices on a global scale and therefore meaningfully support the United Nations sustainable development goals of responsible consumption and production and ultimately climate action.

Keywords: Computer carbon footprint; supply chain greenhouse gas emissions; sustainable information technology.

* Corresponding author. Tel.: +44-(0)7976-818-530.
E-mail address: Justin.Sutton-Parker@warwick.ac.uk

© 2024 The Authors. Published by Elsevier B.V.
This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/)
Peer-review under responsibility of the Conference Program Chairs.

1. Introduction

Over 670 million personal computers and displays are manufactured each year to support demand from 4.2 billion computer users. This generates 1% of global greenhouse gas (GHG) emissions and therefore contributes to global warming [1-8]. Research shows that sustainability strategies such as selecting computers with the lowest carbon footprint will reduce these emissions by an average of 30% [9-12]. Legislation exists to support this [13-15], although current computer energy efficiency [15] and eco-certifications [16-18] helping users select such products are potentially flawed. This is because they do not include chain carbon footprint values during certification. As an example, Microsoft's Surface Laptop 3 generates 138 kgCO_2e GHG emissions [19], while Lenovo's ThinkPad P51 generates 809 kgCO_2e [20]. Both are certified as energy efficient and eco-friendly based on meeting a pre-defined electricity consumption value and because no harmful materials or processes have been used during production. However, the latter is theoretically six times more harmful to the environment due to the increased carbon footprint [11].

Leading computer eco-label TCO Certified does not include carbon footprint data within its current version 9 certification process and results. This is because research showing incomparability of use-phase GHG emissions results also hypothesises that similar inconsistency applies to computer supply chain carbon footprint values [22]. The effect of this is potentially greater because this phase includes production, distribution and end of life (EOL) processes that cause 86% of a computer's total carbon footprint [11]. If product carbon footprint values are to be introduced in future versions of eco-label certification, then supply chain carbon footprint incomparability must be examined. Additionally, it is reasonable to suggest that, as was the case with use-phase emissions, a solution must be created that enables equivalent comparison.

The prior research indicates that the issue of supply chain incomparability is caused by major computer brands using differing lifecycle assessment (LCA) methods to generate carbon footprint report [22]. It is accepted that in the short term it is not feasible that all brands will agree to use a single approach as this will require agreement between competitors and considerable change to internal processes. Consequently, to ensure a short term solution is created to enable eco-labels to introduce carbon footprint assessment into certification, the purpose of this research is twofold. Firstly, to examine and substantiate the hypothesis that current approaches are generating incomparable supply chain results. Secondly, to produce a method of assessing existing manufacturers supply chain results that produces a comparable metric to enable buyers to quickly identify low carbon footprint computers regardless of LCA method used.

2. Method

To achieve this exploratory research examines and compares supply chain results from 244 recent (2022 and 2023) notebook product carbon footprint reports [19published by brands supplying 90% of the world's personal computers. Information examined includes : 1) LCA methodology used, 2) location of production and distribution, plus GHG emissions values for 3) the supply chain total; 4) production; 5) transport; 6) end of life processes; 7) packaging; 8) display; 9) main boards; 10) power supply unit (PSU); 11) storage components; 12) chassis; 13) battery. Notebooks, rather than desktops, are selected as the product includes all elements of components found in multiple personal computer types (e.g. computer, keyboard, display). As such, the associated supply chain emissions data will potentially highlight areas with a high impact that would not come to light if a different device type is used.

Further to this, the opportunity to directly compare results produced using one LCA methodology to another is undertaken. Specifically, HP previously produced supply chain product carbon footprint reports using the Product Attribute to Impact Algorithm (PAIA) LCA [21] methodology. Recently, HP has moved to a new methodology and has re-published reports for devices using the new methodology even though the computers are no longer manufactured or available. As such, sixteen reports for legacy computers are compared to determine the difference between initial and subsequent results produced by the legacy and new methodology. The findings are then discussed in context with the exploratory research data.

Based upon the findings, an assessment criteria is created that can be applied to existing supply chain results to generate a comparable value to be used to confidently identify low carbon footprint devices. The criteria are based upon two key influencing factors of 'primary data' and 'lifespan capability'. These metrics determine the accuracy of the existing carbon footprint report and the likelihood of the device being kept for longer periods of time, therefore reducing demand and associated supply chain emissions.

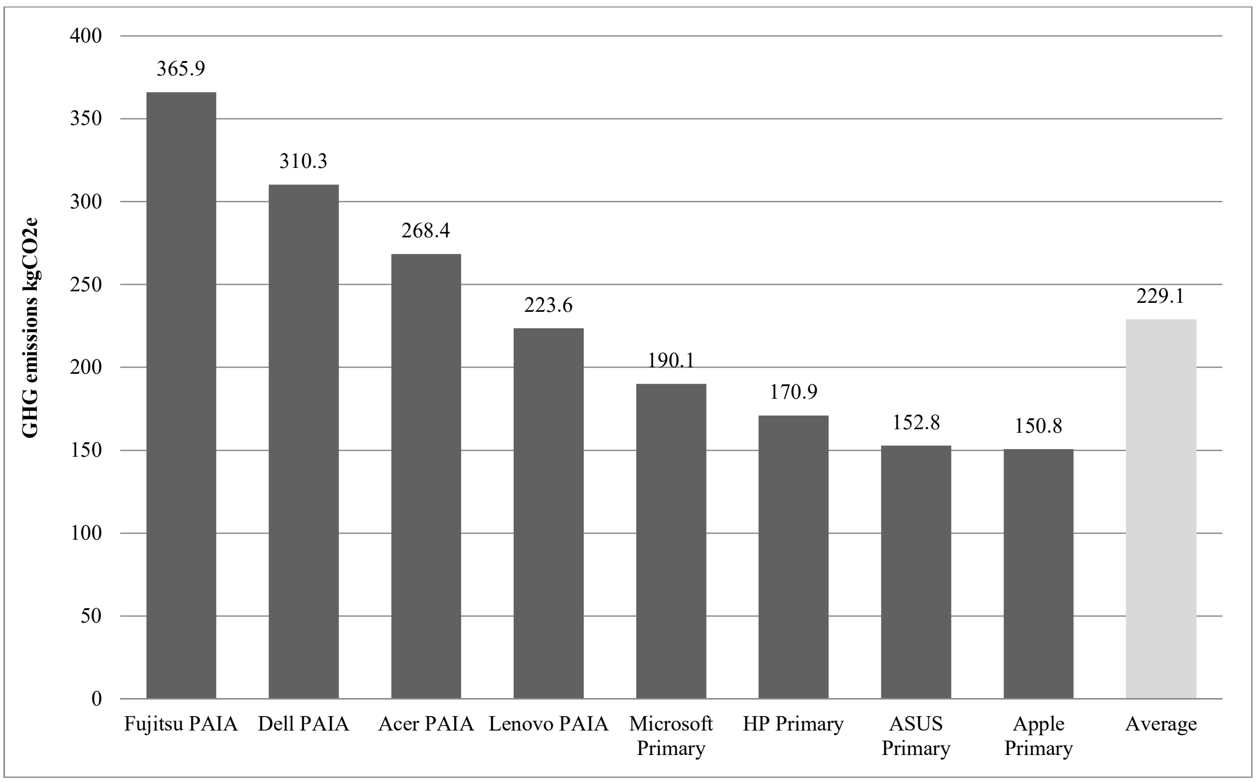
3. Results

Figure 1 shows that Acer, Dell, Fujitsu and Lenovo use the PAIA LCA [21] methodology to create product carbon footprint reports [20, 23-25]. Previously also adopted by HP, the method uses secondary data from third party lifecycle inventory (LCI) databases to generate carbon footprint averages for common computer components such as a screen, chassis, battery or storage. For each report produced a statement of inaccuracy is included and a range of plus or minus likely emissions stated. This is because the secondary data is often out of date and is not specific to the actual manufacturer, components used or transport routes and modes used to distribute the products. As such, it is unsurprising that the four manufacturers using the method are grouped together creating an average of 292 kgCO_2e supply chain emissions per notebook (Figure 1), ranging from 223 to 366 kgCO_2e [20, 23-25].

Comparatively, Apple, ASUS, HP and Microsoft use internally developed LCA methods that introduce increasing proportions of primary data used to produce results [19, 26-28]. This is achieved by directly measuring both internal assembly, packaging and transportation processes plus requiring a supply chain partners to report carbon footprint generation caused by raw material acquisition and component manufacturing. Using up to date and specific primary data produces an average supply chain emission of 166 kgCO_2e per notebook, ranging between 151 to 190 kgCO_2e [19, 26-28].

Figure 1 shows that overall, the primary data focused LCA methodologies [19, 26-28] results are 43% lower than the secondary data based PAIA methodology results on average [20, 23-25].

Figure 1. Average notebook scope 3 (supply chain) GHG emissions (kgCO_2e) results by brand

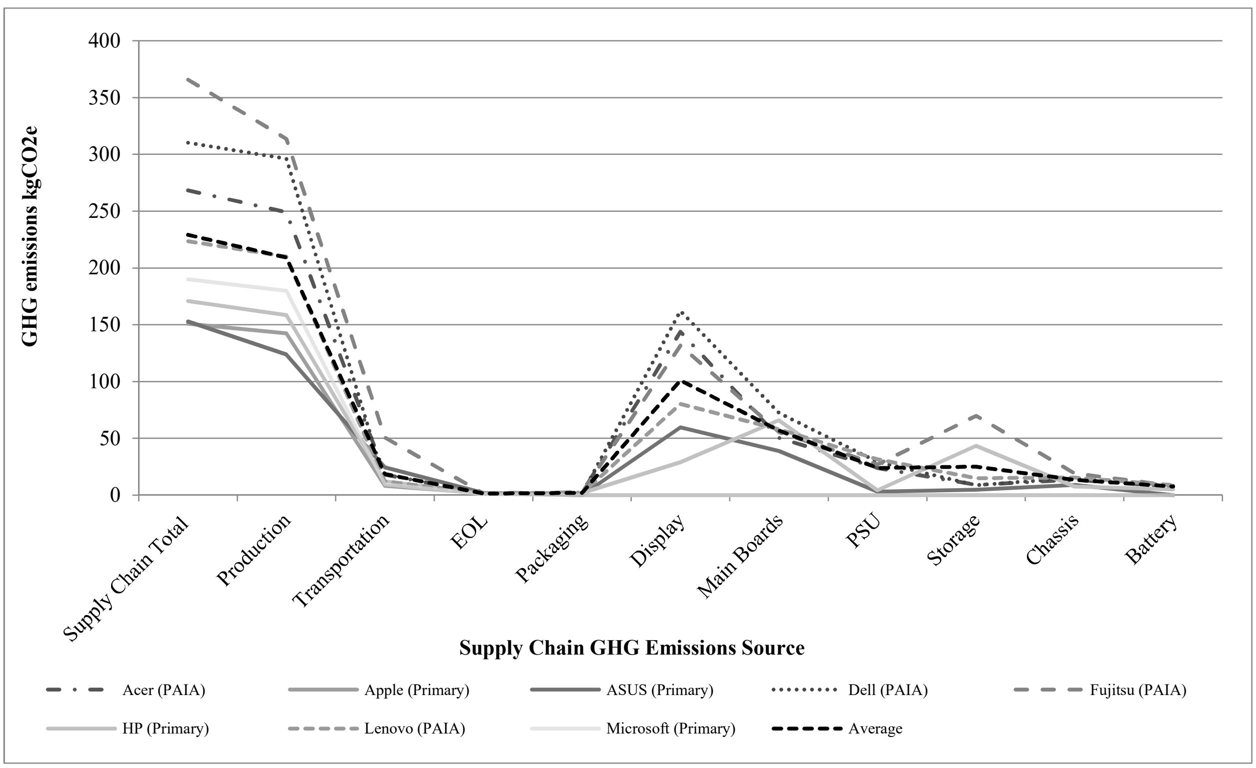


The finding suggests that the secondary data is inaccurate as it is potentially neither current nor specific. To substantiate this Table 1 shows supply chain carbon footprint results for HP notebooks that are generated using both the PAIA method and HP's new primary data based methodology [28]. On average, the new primary results are 36% lower than the legacy PAIA results (Table 1). Considering that the devices in question are no longer manufactured and therefore have not experienced change in components, processes or transportation, it is reasonable to suggest that these results combined with Figure 1 indicate secondary and primary data methodologies are incomparable.

Table 1. PAIA supply chain carbon footprint results compared to primary data LCA results

Notebook description	Report Year	LCA Methodology	Total supply chain GHG emissions ($kgCO_2e$)	Production GHG emissions ($kgCO_2e$)	Transport GHG emissions ($kgCO_2e$)	EOL GHG emissions ($kgCO_2e$)	% Reduction caused by using Primary method
HP EliteBook 830 G5 13.3"	2018	PAIA	200	166	32	2	
HP EliteBook 830 G5 13.3"	2024	Primary	146.7	135	10.8	0.9	-26.65%
HP EliteBook 830 G6 13.3"	2019	PAIA	254	220	32	2	
HP EliteBook 830 G6 13.3"	2024	Primary	150.3	138.6	10.8	0.9	-40.83%
HP EliteBook 835 G8 13.3"	2021	PAIA	285	273.34	11	0.66	
HP EliteBook 835 G8 13.3"	2024	Primary	152	140.6	9.5	1.9	-46.67%
HP EliteBook 835 G9 13.3"	2021	PAIA	204.16	183.28	9.28	11.6	
HP EliteBook 835 G9 13.3"	2024	Primary	156.75	146.3	9.5	0.95	-23.22%
HP EliteBook 840 G5 14"	2018	PAIA	236	196	38	2	
HP EliteBook 840 G5 14"	2024	Primary	178.25	163.3	13.8	1.15	-24.47%
HP EliteBook 840 G5 14"	2019	PAIA	325	262	61	2	
HP EliteBook 840 G5 14"	2024	Primary	178.2	165	11	2.2	-45.17%
HP EliteBook 840 G7 14"	2021	PAIA	261	239	20	2	
HP EliteBook 840 G7 14"	2024	Primary	151.7	140	10.8	0.9	-41.88%
HP EliteBook 840 G8 14"	2022	PAIA	281	259	20	2	
HP EliteBook 840 G8 14"	2024	Primary	165	152	12	1	-41.28%

Figure 2. Supply chain carbon footprint average results ($kgCO_2e$) by brand showing total and contributing GHG sources



Examining all product carbon footprint reports [19-20, 23-28] Figure 2 shows that on average the production phase contributes to 91.4% (209 $kgCO_2e$) of the total average supply chain carbon footprint (229 $kgCO_2e$), transportation 8% (18.4 $kgCO_2e$) and EOL 0.6% (1.4 $kgCO_2e$). Seven common components contribute to production emissions including packaging, display, main board, power supply unit (PSU), storage (e.g. solid state drive), chassis and the battery (Figure 2). Notebook displays contribute the highest to production emissions at 44% (104 $kgCO_2e$) on average (Figure 2). As the value is significant, it illustrates clearly the disparity between secondary and primary data results. Manufacturers using PAIA calculate an average production impact for a notebook display to be 124 $kgCO_2e$ whereas manufacturers using primary data produce an average 65% lower at 44 $kgCO_2e$ (Figure 2).

Due to the incomparability of results caused by using differing LCA methods, it is proposed that an average supply chain carbon footprint value is generated for end user computing device types (e.g. notebooks, desktops, tablets and displays) using all available data from all manufacturers. Using this as a baseline for all new products, the emphasis is then placed upon each manufacturer to reduce this average value via newly proposed assessment criteria (Tables 2-6). The criteria awards reduction values based upon the percentage of primary data used during the LCA process plus evidence of practices and schemes offered by the brand designed to extend device lifespans and consequently reduce new product demand.

In this scenario, as all brands will start with the same average supply chain carbon footprint value for new products, two outcomes can be expected. Firstly, manufacturers will focus on moving away from secondary data and increasing primary data inclusion during the LCA process causing acceleration in the attainment of accuracy. Secondly, the new metric will create a level playing field in the short term that will enable prospective buyers to quickly identify sustainable computers without being unintentionally misled by existing incomparable LCA results.

To create average device carbon footprint values, certain product characteristics such as screen size that influence results must be considered and sub categories created. As an example, the average supply chain emissions value for small notebooks (11-12") within the research data set is 172 $kgCO_2e$, for medium (13-15") it is 241 $kgCO_2e$ and for large (16-17") it is 284 $kgCO_2e$ [19-20, 23-28]. The same screen size approach could be applied to monitors, tablets and integrated desktops. However, for desktop computers and workstations, it is proposed that form factor sizes are used to categorise products. Fortunately, prior research already generates average computer supply chain GHG emissions known as the ‘Px3 Value’ [29], meaning that a data source exists to facilitate the process immediately.

As previously noted, the proposed criteria against which to achieve reductions to the Px3 value is divided into ‘primary data’ and ‘lifespan’ focus areas. This is to support United Nations Sustainable Development Goal 12 [30] responsible production (primary data within manufacturers) and responsible consumption (lifespan extension for end users).

The primary data criterion focuses on production and transportation as combined the two generate almost 100% of the supply chain carbon footprint (Figure 2). Based on the percentage of contribution to the total production GHG emissions shown in Figure 2, Table 2 creates a sliding scale of ‘reduction values’ achieved by increasing percentages of primary data used in during LCA calculations. Displays, main boards and storage devices contribute to 87.4% (183 $kgCO_2e$) of the production average emissions (Figure 2) and are therefore used as criteria for primary data inclusion to maximise impact. In this example, a manufacturer could reduce the ‘Px3 Value’ by as much as 70 points based upon 100% primary production data input.

Table 2. Primary data production criterion metric sliding scale

	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Displays	-4	-8	-12	-16	-20	-24	-28	-32	-36	-40
Main Boards	-2	-4	-6	-8	-10	-12	-14	-16	-18	-20
Storage	-1	-2	-3	-4	-5	-6	-7	-8	-9	-10

Table 3 follows the same approach for transportation by awarding higher reductions as the use of primary data increases. In this example, a maximum reduction of 7 points could be achieved if it is proven that 100% of LCA transportation data is primary. However, to encourage manufacturers to use low carbon transport methods such as container ships and rail freight, a sliding counter scale exists that increases the ‘Px3 Value’ if high carbon transport methods are used. As an example, if a manufacturer uses low carbon transportation for only 30% of distribution then the 7 point reduction achieved for 100% primary data will become 2 points. This is because 70% of transportation will have occurred via a combination of air freight and fossil fuel haulage creating an addition of 5 points (Table 3).

Table 3. Primary data transportation criterion metric sliding scale

	1-15%	16-30%	31-45%	46-60%	61-75%	76-90%	91-100%
Transport Primary Data	-1	-2	-3	-4	-5	-6	-7
Air freight	0.9	1.8	2.7	3.6	4.5	5.4	6.3
Fossil fuel road haulage	0.1	0.2	0.3	0.4	0.5	0.6	0.7

This research identifies that as much as 93% of an end user computing device's carbon footprint is caused by scope 3 supply chain GHG emissions. Consequently, for every year a notebook remains operational, the annualised value of scope 3 emissions decline accordingly. Setting aside scope 2 use phase emissions, this means that if a medium notebook with an average supply chain impact of 241 $kgCO_2e$ is kept for 8 years rather than the current average 4 years [ref], the entire production value of one notebook is entirely avoided during this period. This strategy is called displacement which is referring to the fact that a procurement cycle has been delayed to a later date causing demand for new devices to slow. Theoretically, if all notebooks were kept for twice the length of time global demand would be cut by 50% overnight.

To be able to extend the lifespan of a computer relies on a variety of supporting factors. Beyond operating system obsolescence which the manufacturer cannot control in many instances, this includes warranty duration and cost plus how ‘repairable’ the device is. In simple terms, if the device malfunctions and cannot be repaired with ease or at low cost, then replacement is inevitable. As such, these ‘lifespan’ influencing factors should be assessed in a similar manner as carbon footprint data in order to generate an indicator that the computer can be kept for a reasonable period of time.

Table 4 shows the actual number of warranty years offered as standard and as an extension by notebook manufacturers. All brands currently offer 1 year standard warranty. The longest extended warranty is for 5 years offered by 3 of the 8 manufacturers. This current approach indicates that if end users wish to retain a notebook for at least 5 years and have the ability for certified repair, they can only do this with 38% of brands (Table 4). To encourage 5 year warranties becoming the industry standard, the new criterion awards increasing reduction points to those brands offering such a service. In this example, a brand offering just 1 year standard warranty and 3 years extended warranty can only reduce the ‘Px3 Value’ by 4. This is because -2 points are achieved for the standard 1 year warranty and a further -1 point per additional extended warranty year. Looking ahead, the ideal warranty offering would be a 5 year standard warranty similar to those emerging in the vehicle market. In this instance, brands offering this would be able to reduce the ‘Px3 Value’ by 10.

Table 4: Lifespan manufacturer warranty criterion metric

Device Type	Brand	Standard Warranty	2 points per year for Standard Warranty	Extended Warranty	-1 point per additional year for Extended Warranty	Reduction
Notebooks	Acer	1 year	-2	5 years	-4	-6
Notebooks	Apple	1 year	-2	3 years	-2	-4
Notebooks	ASUS	1 year	-2	3 years	-2	-4
Notebooks	Dell	1 year	-2	5 years	-4	-6
Notebooks	Fujitsu	1 year	-2	5 years	-4	-6
Notebooks	HP	1 year	-2	3 years	-2	-4
Notebooks	Lenovo	1 year	-2	3 years	-2	-4
Notebooks	Microsoft	1 year	-2	4 years	-3	-5
Notebooks	Brand A	2 years	-4	5 years	-3	-7
Notebooks	Brand B	3 years	-6	2 years	-2	-8
Notebooks	Brand C	4 years	-8	5 years	-1	-9
Notebooks	Brand D	5 years	-10	0 years	0	-10

Extended warranties are a good idea if they do not become cost prohibitive. If the cost of a warranty is too high then end users will choose replacement rather than repair which in turn increases production demand. To encourage both standardisation of 5 year warranty offerings and affordability, the criterion in Table 5 is used. Only manufacturers offering 5 year warranties will have the opportunity to reduce the ‘Px3 Value’ using this metric. Again using a sliding scale, manufacturers will achieve a maximum reduction of 5 points if the cost of warranty is equal to or less than 10% of the device retail cost when new. Comparatively, if the cost of the warranty is equivalent to 18% or above then the reduction diminishes to just 1 point.

Table 5. Lifespan cost of warranty criterion metric sliding scale

	10%	12%	14%	16%	18%
Cost of 5 year Warranty as a % of device cost	-5	-4	-3	-2	-1

Table 6 is used to create a ‘lifespan’ criterion awarded based upon the device’s modularity that will influence its ease of repair. The reason for this is that if a computer cannot be repaired because components cannot be easily replaced, extended lifespan will not be achieved as it becomes more convenient and cost effective to simply replace the device. An initial definition of modular is suggested to be based upon the following criteria, although this requires agreement with manufacturers: 1) The component can be replaced as an individual item that requires no further non-faulty components to be replaced; 2) The component or a compatible equivalent must be available for the duration of the maximum extended warranty period set as a minimum expectation of 5 years; 3) The component must be available as a refurbished part; 4) The replacement procedure must be able to be conducted with standard tools and require no soldering or high level technical skills; 5) The replacement instructions must be published to the public; 6) There must be an option for organisations buying devices at scale to receive components directly for repair on site.

To create a sliding scale criterion, 8 common components are selected. The reduction value is applied based upon a balance between the contribution of the component to the production carbon footprint (Figure 2) and the perceived complexity of replacement. As an example, while storage devices create a carbon footprint 88% higher than a chassis (Figure 2), the latter will be far more complex to replace as it is part of the device’s integral structure. Consequently, should manufacturers meet the proposed modular definitions 1-6 for all components the opportunity to reduce the ‘Px3 Value’ by 10 is achieved.

Table 6. Lifespan modularity criterion metric sliding scale

	Display	Mainboard	Chassis	Keyboard	Battery	Storage	Memory	PSU
Modularity	-2	-2	-2	-1	-1	-1	-0.5	-0.5

4. Summary

The examination of existing product carbon footprint reports shows that scope 3 supply chain emissions are the greatest contributor to device carbon emissions causing as much as 93% of the overall impact [19-20, 23-28]. This pre-eminence will increase as scope 2 use-phase emissions decline because of decreasing electricity supply carbon intensity as more renewable energy is adopted globally. End user computer manufacturers responsible for over 90% of computer supply produce carbon footprint reports that potentially enable the identification of low carbon footprint products. However, the research shows that the differing methodologies used to produce reports include varying degrees of primary data that cause inaccuracies. While Apple, HP and Microsoft use primary data for both production and transport calculations, only Microsoft confirms that it has reached the use of 50% [31], leaving estimations of use in other brands to conjecture. As such, while the LCA methodologies used by all brands determine the carbon footprint of very similar products, the results range from 151-366 kgCO_2e (Figure 1) creating a maximum difference of +142% (Figure 1).

This incongruence means that prospective buyers cannot compare scope 3 carbon footprints with confidence. This is highlighted by the changes of -36% in carbon footprint for the same device when calculated by HP using firstly the legacy LCA methodology (PAIA) and the company's new approach that includes primary data (Table 1).

Consequently, the necessity to create a mechanism for eco-labels that delivers a 'sustainability' guide for buyers that is based upon the same calculation criteria is substantiated to be necessary. As discussed, the proposal is to create a numeric value that is calculated by setting a baseline average called the ‘Px3 Value’ for product types and reduced by proof of actions introduced by brands that are substantiated to reduce supply chain emissions. These include:

- Increasing use of primary data during production calculations to achieve a maximum reduction of -70
- Increasing use of primary data during transport calculations to achieve a maximum reduction of - 7
- Increasing warranty duration to 5 years as standard practice to achieve a maximum reduction of -10
- Reducing warranty cost reduction compared to unit value to achieve a maximum reduction of -5
- To increase modularity (ease of repair) to achieve a maximum reduction of -10

In total, brands that conduct the highest levels of sustainable actions during the LCA calculations and to support lifespan extension have the opportunity to achieve a maximum reduction of minus 102.

To show how such an approach will work, the process is undertaken using the medium category notebook scope 3 supply chain average of 241 as the ‘Px3 Value’. Due to a lack of evidence relating to both the percentages of primary data and transportation mix already included by the various brands [19-20, 23-28] the following theoretical assumptions are made:

- Apple 60% primary data
- Microsoft 50% primary data
- HP 40% primary data
- ASUS 30% primary
- Acer, Dell, Fujitsu and Lenovo 20% primary data
- Acer, ASUS and Fujitsu will have 40% applied for transportation mix (air and road)
- Dell and Lenovo will have 30% applied for transportation mix (air and road)
- Apple, HP and Microsoft will have 10% applied for transportation mix (air and road)
- It is assumed no components can be modularly replaced for Apple
- It is assumed PSU, memory and storage can be modularly replaced for ASUS, Fujitsu and Lenovo
- It is assumed PSU, memory, storage and keyboard can be modularly replaced for Acer, Dell and HP
- It is assumed all components can be modularly replaced for Microsoft

Applying the newly proposed approach creates harmonised results ranging from the lowest value of 188 achieved by Microsoft to the highest achieved by Lenovo at 221 (Table 7). Unlike the incongruence of +142% experienced when comparing results from differing LCA methodologies, the new approach experiences a maximum increase of 18% which considering notebooks share common parts suppliers, assembly plants and trade routes is arguably a more realistic outcome.

Table 7. Results by brand for an average notebook using the new primary data and lifespan criterion

Brand	Indicator Value	Primary Data Production	Primary Data Transport	Transport Mix	Warranty Duration	Warranty Cost	Modularity
Acer	213	-14	-2	3	-6	-5	-4
Apple	192	-42	-4	1	-4	0	0
ASUS	215	-21	-2	3	-4	0	-2
Dell	216	-14	-2	2	-6	-1	-4
Fujitsu	220	-14	-2	3	-6	0	-2
HP	203	-28	-3	1	-4	0	-4
Lenovo	221	-14	-2	2	-4	0	-2
Microsoft	188	-35	-4	1	-5	0	-10

In this example, while theoretical, a prospective buyer is now able to judge quickly whether the device emissions data is formed from consistent and accurate primary data, sustainably distributed and can be kept for at least 5 years with limited cost or complexity to reduce long term information technology carbon footprints.

Apple is displaced by Microsoft as the most sustainable device, with the latter scoring 188. While the percentage of primary data used by Microsoft (50%) is positioned in the exercise as less than Apple (60%) and the transportation mix is equivalent (10%), Apple fails to achieve comparable reductions in two areas. Firstly, Apple's 3 year warranty compared to Microsoft's 4 year offering causes the former to drop one point. While both companies fail to score on the warranty cost due to no 5 year offering being available, modularity is key to the outcome. With Apple assumed to offer no level of modularity and therefore achieving zero reduction, Microsoft is assumed to achieve the maximum score of minus 10. As such, where Microsoft was 26% higher than Apple and in 4th place based upon the LCA results (Figure 1), the brand now becomes 2% more sustainable than Apple (Table 7).

5. Conclusions

The practice of conducting LCA practices to produce product carbon footprint values is ultimately the best way to produce data that enables buyers to compare supply chain GHG emissions. However, as clearly demonstrated with at least five different methodologies being used by end user computing device manufacturers, this cannot be currently achieved with any level of confidence. Undoubtedly, this will improve in the coming decade. However, existing brands require a reason to improve and to harmonise approaches. As shown by the repositioning of ranking (Table 7), it is reasonable to suggest that this new approach and criteria could be capable of accelerating improvement to a point where the issue of incomparable carbon footprint data is fixed sooner than expected.

Consequently, it is proposed that for TCO Certification version 10, this new criterion is applied. Replacing the current LCA approach with the proposed mechanism causes all brands to be judged by the same criteria and means that the results offer a valid indication as to how each brand is responding to responsible production. By choosing devices with a low ‘Indicator Value’ (Table 7), organisations buying computers at scale can be confident that they are exercising responsible consumption and therefore driving climate action.

Limitations and recommendations

The research is limited in the fact that it focuses upon notebooks only. It is proposed that the same process be undertaken for all types of end user computing devices including desktops, all in one desktops, workstations, thin clients, tablets and discrete displays. By doing so, incongruities associated with each variation of device will emerge and specific type based metrics can be applied in a similar method as proposed here.

The most popular end user computing operating systems are Microsoft Windows (59.5%), Apple MacOS (20.4%) and Google's Chrome OS (3.2%) [32]. The necessity to replace a device is often caused by the operating system becoming unsupported by the software vendor. As an example, as many as 400 million devices will become inoperable when Microsoft ends support for Windows 10 in January 2024 [33-34]. While Microsoft offers potential support for 10 years, operating system development ceases after 5 years with only security patches being supported to the end of the total period. Additionally, depending upon when in the lifecycle of the operating system the device is purchased this period may also be reduced. This nuance also influences retention periods for devices operating variations of the Apple MacOS. The reason is that while Apple will supply security patch updates for 3 years after each new release, the software is being superseded on average every 36 months. Recently, Google has recognised the need to support longer device retention cycles to reduce device replacement and the impact of device production. As an example, Google recently announced updates for ChromeOS for 10 years [35]. The approach is designed to initially assist in the education sector where uptake for the operating system is popular. As such, 10 year life spans for Chromebooks may become a reality, significantly reducing annualised supply chain emissions. This concept has already been researched and presented to the UK Government as part of their Greening ICT national policy [36]. It is however recognised that with the exception of Apple and Microsoft, the remaining computer manufacturers do not control the software aspect of their supply chain. Therefore any immediate lifespan metric associated with operating system update and support periods will most likely be met with resistance. Contrarily, if included as a recommendation at this stage, the same brands may apply pressure on Microsoft via supplier bargaining power, threat of new entrants and substitutes. The proposed metrics would require further investigation but be based upon the concept similar to the warranty duration approach that considers period of time associated to lifespan of the device governed in part by the operating system.

References

[1] Andrae, A. S. G., and Edler, A.T., (2015). 'On global electricity usage of communication technology: trends to 2030.' Challenges 6, 117e157.

[2] Bekaroo, G., Bokhoree, C., Pattison, C. (2014), 'Power Measurement of Computers: Analysis of the Effectiveness of the Software Based Approach'. New Delhi, India: Int. J. Emerging Technol. Adv. Eng.

[3] Belkhir, L., and Elmeligi, A. (2017) 'Assessing ICT global emissions footprint: Trends to 2040 & Recommendations'. Oxford: Science Direct

[4] Global e-Sustainability Initiative. (2008), SMART 2020: Enabling the low carbon economy in the information age. Figure 3.1 The global footprint of PCs – desktops and laptops: 19. Brussels: GESI

[5] Global e-Sustainability Initiative. (2012), 'SMARTer 2020: The Role of ICT in Driving a Sustainable Future.' The ICT Industry's GHG Emissions: 22. Brussels: GESI

[6] Global e-Sustainability Initiative. (2015), '#SMARTer2030 ICT Solutions for 21st Century Challenges.' Executive Summary: ICT Solutions for 21st Century Challenges: 8. Brussels: GESI

[7] Global e-Sustainability Initiative. (2019), 'Digital with Purpose: Delivering a SMARTer2030'. Brussels: GESI

[8] Malmodin, J., Bergmark, P., Lunden, D., (2013). 'The future carbon footprint of the ICT and E&M sectors.' In: On Information and Communication Technologies

[9] Sutton-Parker, J. (2022), 'Determining the impact of information technology greenhouse gas abatement at the Royal Borough of Kingston and Sutton Council'. 1877-0509. Procedia Computer Science, Volume 203, 2022, Pages 300-309. Amsterdam, the Netherlands: Science Direct, Elsevier B.V.

[10] Sutton-Parker, J. (2022), 'Modernising and extending device lifecycles to support climate action: Nordic Choice Hotels impact case study.' California, USA: Google.

[11] Sutton-Parker, J. and Procter, R. (2023), 'Determining UK government scope 2 and 3 computer greenhouse gas emissions'. Procedia Computer Science 224C (2023) pp. 336-342. Amsterdam, the Netherlands: Science Direct, Elsevier B.V.

[12] Sutton-Parker, J. and Procter, R. (2023), 'Greenhouse gas abatement via repurposing computers'. Procedia Computer Science 224C (2023) pp. 296-305. Amsterdam, the Netherlands: Science Direct, Elsevier B.V.

[13] California Appliance Efficiency Regulations. (2021), 'Title 20 Appliance Efficiency Regulations / Section 1605. Energy Performance, Energy Design, Water Performance, and Water Design Standards: Section 1605.3. State Standards for Non-Federally-Regulated Appliances.'

[14] European Commission. (2021), 'EU green public procurement criteria for computers, monitors, tablets and smartphones'. Brussels: European Union

[15] Greening Government ICT Annual Report: <https://www.gov.uk/government/publications/greening-government-ict-annual-report-2021-to-2022 >

[16] Energy Star. (2020), 'Energy Star Program Requirements for Computers version 8.0'. Washington, USA: USEPA

[17] EPEAT. (2022), 'Electronic Product Environmental Assessment Tool (EPEAT)'. Oregon, USA: Green Electronics Council.

[18] TCO, (2023). 'TCO Certified Generation 9, for notebooks.' Stockholm, Sweden: TCO Development.

[19] Microsoft. (2022), 'Eco Profiles.' Redmond: USA

[20] Lenovo. (2023), 'ECO Declarations and Product Carbon Footprint Information Sheets'. Quarry Bang: Hong

[21] Massachusetts Institute of Technology (MIT). (2016), 'Intended Uses and Limitations of the Product Attribute to Impact Algorithm (PAIA) Model. Massachusetts: MSL

[22] Sutton-Parker, J. (2022), 'Is sufficient carbon footprint information available to make sustainability focused computer procurement strategies meaningful?' 1877-0509. Procedia Computer Science, Volume 203, 2022, Pages 280-289. Amsterdam, the Netherlands: Science Direct, Elsevier B.V.

[23] Acer (2023), 'Product Carbon Footprint: Recognizing Our Impact and Taking Action.' New Taipei City, Taiwan: Acer Inc.

[24] Dell (2023), 'Product Carbon Footprints: Minimizing our footprint, reducing emissions every step of the way.' Texas, United States: Dell Inc.

[25] Fujitsu (2023), 'Products, computing, sustainability.' Tokyo, Japan: Fujitsu

[26] Apple (2023), 'Designed with the earth in mind. Learn more about the progress of your Apple devices with our product environmental reports.' California, United States: Apple Inc.

[27] ASUS (2023), 'Carbon Footprint Report.' Taipei, Taiwan: ASUS Inc.

[28] HP (2023), 'Product Carbon Footprint.' California, United States: HP Inc.

[29] Px3 (2022), 'Applications: Estimate.' Surrey, England: Px3 Ltd.

[30] United Nations (2015), 'Department of Economic and Social Affairs Sustainable Development: 17 Goals.' New York, USA: United Nations

[23] Microsoft. (2023), '2022 Environmental Sustainability Report'. Redmond: USA

[24] Statista. (2023), 'Global market share held by operating systems for desktop PCs, from January 2013 to July 2023'. Hamburg, Germany: Statista.

[25] Canalys. (2023), 'The end of Windows 10 support could turn 240 million PCs into e-waste'.

[26] Restarters. (2023), 'End of Windows 10 support to make 400 million devices obsolete?'

[27] Google. (2023), 'Chromebooks will get 10 years of automatic updates.' California, USA: Alphabet Inc.

[28] Sutton-Parker, J. (2022), 'Determining End User Computing GHG emissions abatement within the UK Government enabled by ChromeOS.' California, USA: Google.