Materials Today: Proceedings xxx (xxxx) xxx

Contents lists available at ScienceDirect

Materials Today: Proceedings

journal homepage: www.elsevier.com/locate/matpr

The significance of product design in the circular economy: A sustainable approach to the design of data centre equipment as demonstrated via the CEDaCI design case study

Kristina Kerwin [a,*], Deborah Andrews [a], Beth Whitehead [b], Naeem Adibi [c], Silvio Lavandeira [a]

[a] London South Bank University, 103 Borough Road, London SE1 0AA, UK
[b] Operational Intelligence, South Bank Technopark, 90 London Rd, London SE1 6LN, UK
[c] WeLOOP, 254 Rue du Bourg, Lambersart 59130, France

ARTICLE INFO

Article history:
Available online xxxx

Keywords:
Product design
Circular economy
Data centres

ABSTRACT

Society depends on fast, uninterrupted 24/7 data transfer in almost every aspect of our lives. Data centres (DC) across the globe process billions of gigabytes of data every day. There are currently about 7 million data centres globally and the sector is expected to grow fivefold by 2030, inevitably increasing already high demand for millions of tonnes of resources, including critical raw materials (CRM). The infrastructure for recycling sectoral waste is lacking, wasting millions of tonnes of materials. Many virgin materials are located in conflict zones, which jeopardises the supply chain that the sector heavily relies on, consequently posing a danger of severe material shortages in the future. Present design thinking does not balance optimisation of the performance and operational energy requirements and designing for circularity. To date, server design has mainly been focused on energy efficiency. However, a Circular Economy (CE) entails consideration of a complete life cycle of the product, including embodied impacts. Because sectoral data processing and energy requirements continue to grow, sustainable design and innovation in line with the 2020 EU Circular Economy Action Plan are crucial in promoting best practices and managing the sector's energy demand in the future. This paper describes a proposed sustainable server design developed as part of the CEDaCI (a Circular Economy for the Data Centre Industry) project and based on the design requirements outlined by the EU Circular Economy Action Plan 2020 together with other directives. It presents recommendations for good practice methods, futureproofing data centre equipment design for a Circular Economy and building a critical foundation for sustainable hardware design that can be developed in the future.

1. The significance of product design in the Circular Economy

The man-made world functions within the domain of the Linear Economy. We extract Earth's natural resources to make objects that we use for a brief period before they break, then we dispose of those products giving little thought about what happens to the waste afterwards. Most products are designed for single use within a limited period of time. The duration of time the product is used before it breaks is calculated during its design stages. This approach is called *planned obsolescence*. The concept was introduced around the 1930 s with its further, broader adaptation in the 1950 s. Planned obsolescence had become a staple in the realm of product design because of its fundamental capacity to drive sales and bring in profits and had been the driving wheel behind the linear economy.

There are different approaches used by designers to facilitate planned obsolescence [1] such as (though not exhaustive): frequent feature changes in core components to prevent remanufacture and upgrades; use of lower grade materials to shorten the life span of the products; use of adhesives or non-standardised fastenings to prevent repairs; removal of key features and presenting those as separate add-on products. There are billions of different products on the market designed with no consideration for end-of-life (EoL) and material reclamation, and impossible to repair. However, recent global efforts to curb the detrimental

* Corresponding author.
E-mail address: kerwink2@lsbu.ac.uk (K. Kerwin).

https://doi.org/10.1016/j.matpr.2022.04.105
2214-7853/

Please cite this article as: K. Kerwin, D. Andrews, B. Whitehead et al., The significance of product design in the circular economy: A sustainable approach to the design of data centre equipment as demonstrated via the CEDaCI design case study, Materials Today: Proceedings, https://doi.org/10.1016/j.matpr.2022.04.105

environmental impacts from human activity and excessive manufacturing – that leads to natural resource depletion, air pollution, rising greenhouse gas emissions and piling-up waste – have prompted a shift in the rethinking of The Governments' policies towards a more sustainable approach to manufacturing and product design. To date, various policy efforts that had been put in place to improve the environmental footprint of goods seem to primarily concentrate on the reduction of greenhouse gas emissions. Hence, many electrical and electronic appliances are designed with an emphasis on product energy efficiency as the use stage is considered to be the major contributor to the generation of CO_2. Although this is a positive step towards a Circular Economy there are still issues with the current legislation.

While reducing product use stage energy impact remains a prerogative there are other environmental implications stemming from excessive manufacturing and consumerism, therefore a much broader approach would be appropriate – the most viable system that can fully address global environmental issues is a Circular Economy (CE). The model implies a whole-systems approach to product design which includes each stage of the product life cycle: from manufacturing, to use and EoL with consideration of all the stakeholders along a complete value chain right from the first design concept.

Recently, there have been a number of encouraging developments in policymaking, for example in 2020, the EU Circular Economy Action Plan was released [2]. It is a future-oriented agenda that outlines overall EU eco-design requirements and recommendations for sustainable design in key product value chains: from packaging and textiles to electronics, vehicles, and construction - in order to drive the global shift towards a Circular Economy. This is the first major effort by policymakers to go beyond a single focus on energy efficiency and start considering whole value chains of products or in other words putting product life cycle assessment (LCA) at the centre of product design.

One such product value chain with excessive manufacturing, high waste ratio, lack of recycling and material reclamation infrastructure and activity is electronic and electrical equipment (EEE). The existing emphasis in data centre equipment design is primarily on energy efficiency due to the industry's strong adherence to Moore's law. However, global waste electronic and electrical equipment (WEEE) in 2019 was 53.6 million metric tonnes (Mt). The Global E-waste Monitor 2020 estimates that by 2030 the amount of WEEE worldwide will exceed 74 Mt [3]. IT equipment used by the data centre industry (DCI) is particularly high in precious metals (PM) and critical raw materials (CRM).

2. The data centre industry and its challenges

Data centres (DC) underpin every aspect of our infrastructure and make the world go round because almost everything in this digital age depends on fast, uninterrupted data transfer. DCs are clusters of sophisticated state-of-the-art computer hardware called servers and other technologies that support DC function. The size of a data centre would depend on the type of its business model and can house thousands or just a few servers.

Currently, there are around 7 million data centres worldwide, and although, this figure had decreased by just over 15% since 2015 [4], the growth in reliance on data centre services is ongoing as our infrastructure becomes more and more digitalised [5]. The prediction is that the service provision will increase fivefold by 2030 [6].

When it comes to the design of the equipment, most of the focus so far has been on the performance and power efficiency of the servers. According to the report published by Supermicro, at present, the industry accounts for approximately 3% of the global energy consumption [7]. This figure tends to change depending on the source. For example, according to IEA, the share is 1% [8]. While the increased performance helped to curtail the energy demand by the sector, sectoral data processing will continue to grow subsequently increasing its energy requirements. In addition to the rising energy demand, there is a growing demand for raw materials including CRM for the manufacture of the new equipment, as refresh rates can vary between 1 and 5 years [9].

However, the recycling and materials reclamation infrastructure for WEEE is severely underdeveloped – in addition to widely-used metals such as iron, copper, and aluminium only precious metals (PM) and a small number of CRM are being recovered. The procedure is chemically burdensome as the equipment at its EoL (end-of-life) undergoes numerous mechanical and chemical separation processes. Due to the use of hazardous chemicals for material recovery, the process itself has a negative impact on the environment together with the loss of large volumes of material. According to The Global E-waste Monitor 2020 out of all WEEE generated globally, only 17.4% was officially recycled in 2019 and millions of tonnes of materials are either lost to landfill, incinerated or are unaccounted for at the EoL [3], as well as the supply chain that DCI heavily relies on, is at risk because many virgin materials are situated in geopolitically sensitive locations.

There is no doubt that energy efficiency has a considerable effect on curbing sectoral greenhouse gas emissions, and it is important to factor this into equipment design. However, the industry's transition to the Circular Economy will not be workable unless the design approach is altered to consider every stage of the equipment life cycle. The manufacturing stage consists of the extraction of raw materials, their transformation into components and assembly of the final product. Each phase from production to logistics draws on energy and resources. Every stage within the supply chain during the manufacturing process has a significant detrimental environmental impact on the ecosystem starting from carbon emissions and pollution and leading to socio-economic impacts.

For example, in 2020, provisional results from a screening LCA on a hypothetical liquid-cooled vs existing standard latest generation air-cooled server indicated that when taking into account the embodied impacts, the balance between performance optimisation, reducing the requirements for operational energy and designing for circularity is lacking. Different refresh rate scenarios of the servers were compared, and although the operational energy impacts increased during longer refresh periods, the accumulative environmental impact from the manufacturing of the new equipment was significantly higher at shorter refresh rates (See Fig. 1) [10].

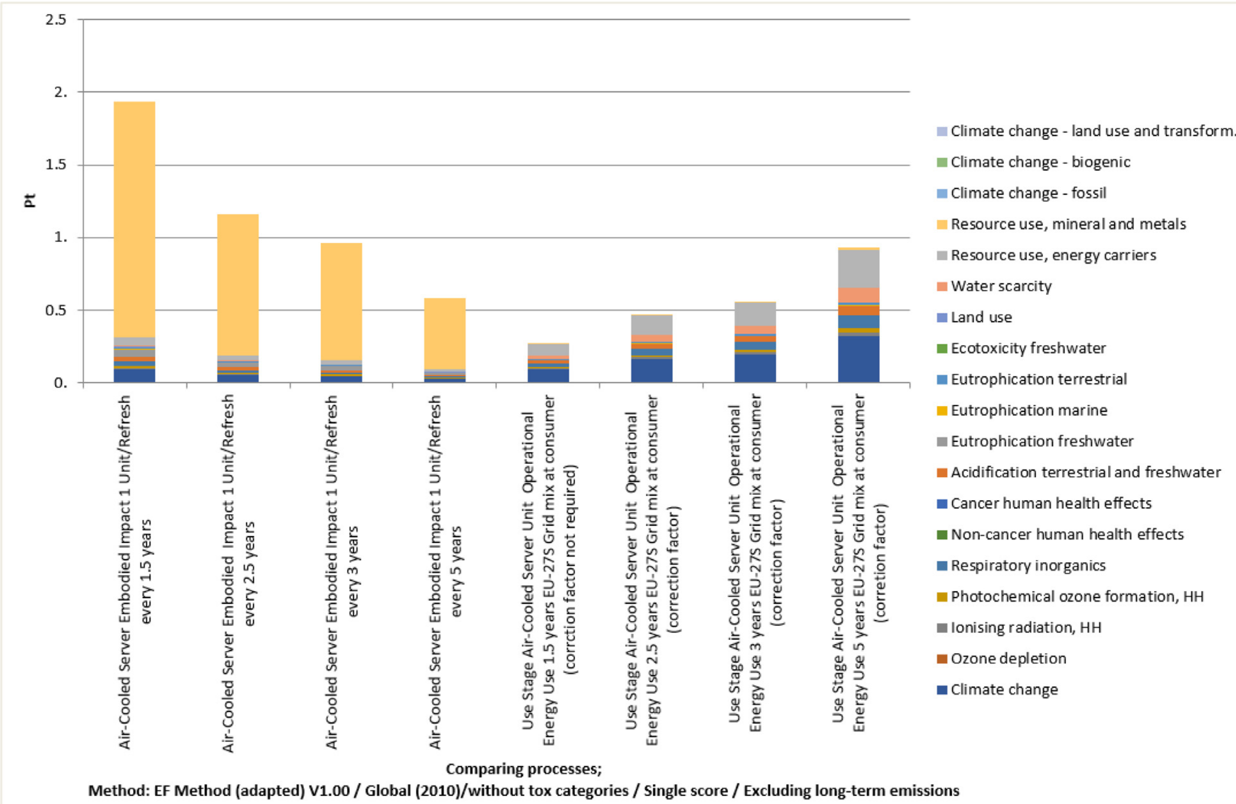

Fig. 1. Air-cooled server Embodied vs Use stage Environmental Impact Scores at different refresh rates.

This is because during a 5-year period for every server that is refreshed every 1.5 years 3.33 new servers would have to be manufactured depleting the Earth's resources, virgin materials, and CRM. Moreover, during that period the same amount of equipment will be going to waste, processing of which is also energy and environmentally demanding. This simple exercise shows the importance of considering every stage of the equipment lifecycle and incorporating sustainable design thinking and a holistic design approach at the initial R&D stage rather than simply focusing on a single issue of energy efficiency.

Considering the growing demand paired with shorter refresh rates and significant sectoral contribution to e-waste production (which is already a growing problem), it is imperative to advocate sustainable design and innovation as best practice in line with the 2020 EU Circular Economy Action Plan [2] in order to control DCI's energy and resource demand in the future.

To date, there are several EU eco-design policies and recommendations that support DCI transition towards a Circular Economy. In essence, the current eco-design policy stipulates that server manufacturers make sure the product meets specific energy requirements and other provisions outlined in DIRECTIVE 2009/125/EC (or Lot 9) [11]. Although the manufacturers must provide a range of product specific information such as energy efficiency, data security, instruction manuals, limited information on CRM content, compliance with RoHS [12] and declare the presence of persistent organic pollutants (POP) as well as make instruction and repair manuals easily available and consider the right to repair ensuring that product fastening techniques do not obstruct the disassembly, repair or reuse of main components – there are no policies regarding standardisation of server design.

3. Problems associated with server design - CEDaCI findings

A disassembly analysis of 16 different server models across different server generations was carried out (See Fig. 2) as part of CEDaCI – a Circular Economy for the Data Centre Industry – a unique 5-year Interreg-funded project that runs across 7 countries in North-Western Europe (NWE): UK, France, Netherlands, Germany, Belgium, Luxembourg, and Ireland. The project is led by London South Bank University (LSBU) in The UK and was specifically initiated in support of the data centre industry transitioning to circularity.

The research revealed that modern enterprise servers are designed with a degree of modularity aimed at general repair and fast remanufacturing as a small number of parts can be replaced and repaired. Unfortunately, there is no standardisation in the overall design, which differs considerably between models and generations, meaning the majority of parts cannot be interchanged between the models and generations. This lack of design consistency does not allow for maximum reuse of the equipment and encourages excessive manufacturing which is hampering sectoral efforts in its transition to circularity. The life cycle inventory data collected by CEDaCI indicates that on average, server mechanical components such as the chassis contain 3–4 different steel alloys and around 3 different polymers as well as textiles, paper, aluminium, zinc, and copper. On top of the basic mechanical design, there are numerous chemicals used in the electronics including CRM, PM and PGM (platinum group metals) which makes an overall materials list used in serves extensive.

Parts that are usually designed to be easily removed are hard drives, fans, power supplies, processors and heatsinks, memory,

Fig. 2. Top view of different server models and generations analysed by CEDaCI.

expansion card/graphic cards and the motherboard; however, these parts contain a number of subassemblies and are not necessarily designed for repair. Fans, for example, are standard parts that are encapsulated in a casing designed to only fit one particular fan cage within a specific server model and generation (See Fig. 3). The fan casing is made of fire-retardant plastic (PC-ABS-FR that is not widely recycled at present) and is difficult to remove without breaking. Fans also have different end connectors that differ with each model and generation which means the components cannot be used in a different server. Likewise, such design elements apply to hard disks and power supplies, although those components may be interchanged between adjacent generations, they cannot be used in different server brands.

Other feature inconsistencies that are present not only between models and brands but also between generations include small changes in chassis design. For example, lids are often designed with the same or similar locking mechanism, which is placed at a different location on the top plane depending on the server generation, meaning the lid can only fit a specific machine (See Fig. 4). Yet, such design alteration does not play any role in the server performance.

The same design principle is used for the whole chassis and rail assemblies where component constraint points are often moved, or the design is changed completely to stop parts from being interchanged between generations or models. Thus, for every model and generation a different set of chassis, fan cages, hard disk caddies, power supply units and cooling assemblies is created, which promotes unnecessarily excessive manufacturing. Servers can also use either of the two sizes of hard drives: 3.5 and 2.5 in., or LFF and SFF (large and small form factor) respectively. One server model usually has two design options: either the chassis is designed to fit LFF disks, or the chassis is designed to fit SFF disks – the front panel is slightly different depending on the disk type. In addition, there is a common use of different plastics and other materials specifically for the design aesthetics to differentiate newer products from older products. Such irrelevant design changes do not improve the performance of the servers in any way, yet a number of new components are manufactured every time a new server upgrade is issued. There is also no need for the perpetual enhancement of the aesthetics of the design as servers are machines designed for function and performance and are placed in racks hidden away in DC rooms with no feature display purpose.

4. CEDaCI design case study

4.1. CEDaCI server design considerations

Considering current eco-design policy requirements outlined in the EU Circular Economy Action Plan 2020 [2] in conjunction with the results from different server model assessments, and the consistent design pinch points outlined by CEDaCI, the project team proposes that future server design should emphasise standardisation of the chassis features by creating a set of universal server enclosures for most commonly used server form factors (sizes), that can be used as stand-alone units or within a rack. The enclosures will be able to accommodate parts from any server manufacturer, model, or generation in its given product range in the future. The design of parts' enclosures on all other levels of assembly must be standardised as much as is physically possible. For example, redesigning fan and hard disk enclosures and creating a standard fit-all power supply module. The parts must be universal and simplified. Any design feature that prevents repair or disassembly for recycling must be eradicated. This can be achieved by removing the unnecessary fastenings. Overengineering of parts must be avoided to reduce material use, however, parts must remain durable enough to reduce the need for the manufacturing of new components. By eliminating non-recyclable non-durable plastics and reducing CRM content in non-electronic components – the range of materials used within the product can be reduced. Allowing

Fig. 3. Server fan assemblies from different server models and generations.

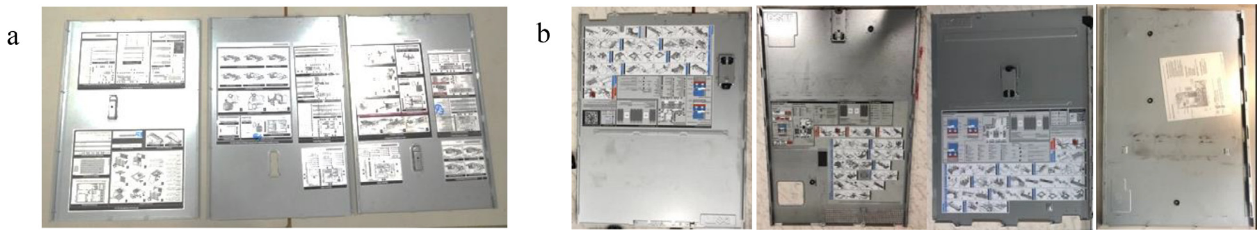

Fig. 4. The differences in server lid design across generations and models: HPE (a) and Dell PowerEdge (b).

open-source firmware will aid cross model parts use. The development of modular PCBs using biodegradable substrate must be considered in the future together with other cooling options such as liquid cooling. Aluminium is commonly used in server design, however, since 2020 bauxite has been considered a CRM. It is important to keep Al content to a minimum and to expand the use of recycled sources. Locally sourced, recovered materials should be used in manufacturing as much as possible which will depend on the location of intended server use. Local businesses should be considered for product assembly, remanufacture and transportation. For example, if the server intended use location is Europe, then manufacturing and assembly must be allocated to Europe.

Using these design parameters outlined for an ideal sustainable machine, the CEDaCI design team created a benchmark design for a universal, reusable server chassis that can hold 2U-3U form factor (FF) compatible components for a standard rack-mounted server (See Fig. 5). For the purpose of design feasibility demonstration, a 2U FF was chosen as a base model. The design is mainly concentrated on the mechanical parts of the server with a degree of PCB modularity that is physically possible to achieve at present. The reasoning behind the design being focused on the chassis is the fact that server uniqueness and hardware upgrades, in terms of performance and capacity, occur at the electronics (PCB, IC) level regardless of how those electronic components are fixed to the box they are placed in. Therefore, it is imperative to standardise, simplify and make the chassis reusable by creating common component constraint points and by removing any unnecessary fastenings to reduce the manufacturing impact and the number of components to a minimum.

The model is currently in CAD format and is intended to be used as a standardised benchmark design in future server generations. For example, the server has a unique hard drive caddy designed to hold either 2.5 or 3.5-inch storage drives without the need to manufacture chassis with a different front installation for each disk size. Another feature is a universal fan enclosure designed without the need for the specialist casing to hold the fans in place.

The server was designed using minimum types of materials with sheet steel being the base material. Stainless steel was allocated for the ejector clips and stand-offs. Polymer use was reduced to a minimum and there is only one plastic part which is the riser for the fan connector. The complexity of the injection moulded fan riser plastic part is minimal, and the material is intended to be from a recycled source. Each manufacturing process was considered implementing the simplest mode of steel production. Due to the lack of standardisation of power supply units (PSU) across the board, CEDaCI had chosen HPE Flexible Slot Power Supply as a benchmark because the manufacturer had introduced a standardised PSU unit that is interchangeable across their server models [13].

Server manufacturing and assembly site must also be considered and would depend on the intended use location, as this would reduce the environmental impact from the transportation of the parts and the product itself. Furthermore, the analysis of the

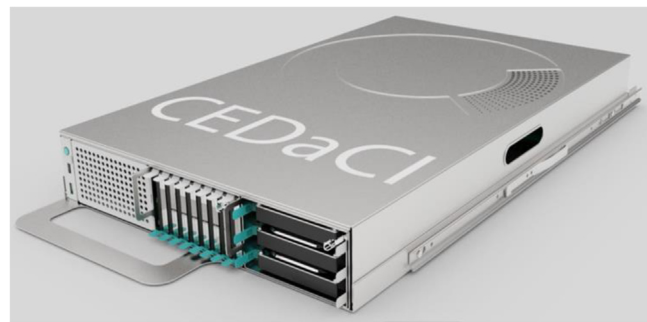

Fig. 5. CEDaCI Server.

electricity generation from the renewable sources at the possible manufacturing locations should be carried out. Countries with a greater share in renewable energy should be considered as preferred settings, to lessen the environmental impact from the manufacturing stage.

4.2. Comparing CEDaCI server circularity against the current standard server models

Analysis of the CEDaCI server against the current models of standard 2U servers confirms the noticeable design improvements. The mass of the CEDaCI server chassis against the latest current generation 2U server model (excluding hard disks and memory) is 14 kg vs. 22 kg, with a total of 65 vs 117 main assembly components and fastenings, and plastics 85.69 g vs 889.45 g respectively.

Finally, the CEDaCI server model was evaluated using CDCC (Circular Data Centre Compass) evaluator. CDCC is an online decision-making tool, based on a unique CEDaCI multi-step life cycle assessment method in conjunction with current eco-design policy and regulations. The model was compared against similar products – two current, but not the latest, server models 1U and 2U FF. The following categories were assessed: power specifications, security, software & firmware updates, availability of product specific-information, availability of instruction manuals, ease of product disassembly, the complexity of the design & manufacture, chemical content & recycling, resource tracking and tracing, and CE & environmental considerations. An informed assumption was made on a number of outputs as not all information was readily available. However, the hypothesis was based on expert opinion related to currently available data. The details are presented in Fig. 6.

So far, the availability of software, firmware and security updates is only required for 8 years, CEDaCI proposes making such functionality available for longer, considering there are instances when servers are kept operational for over a decade. CEDaCI also proposes making an allowance for the use of open-source firmware and software for the updates and upgrades of the obsolete hardware and making product specific information available in digital

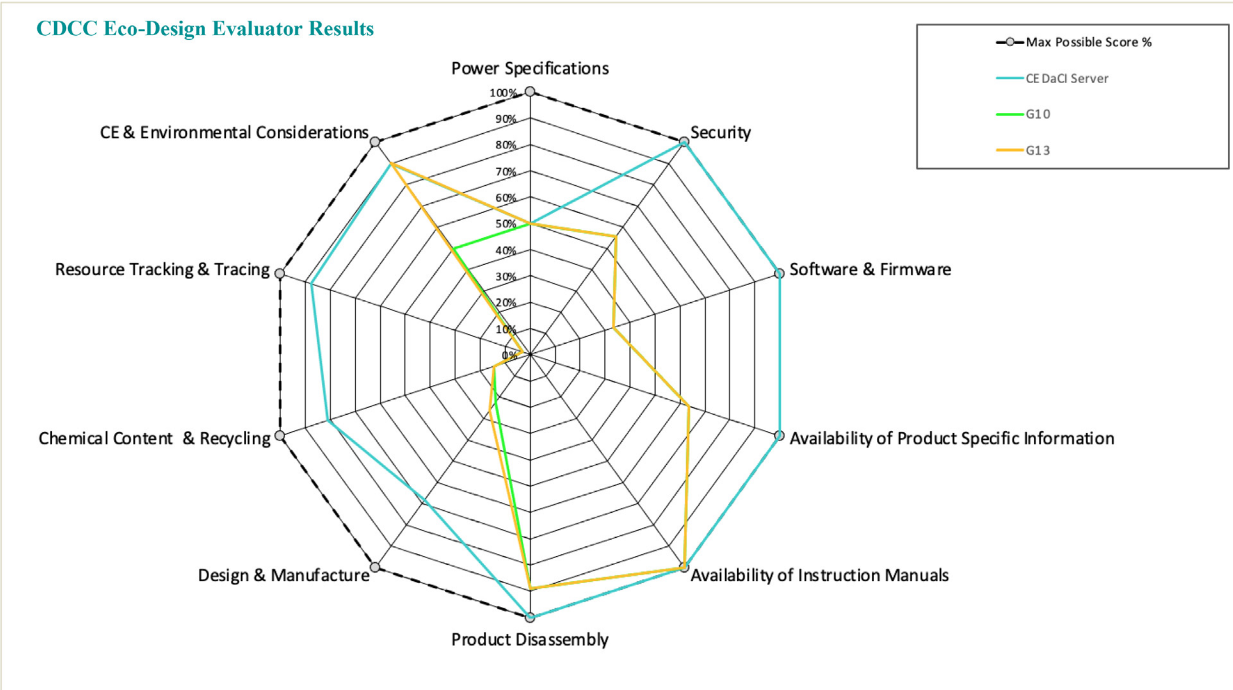

Fig. 6. CDCC Eco-Design Evaluation of CEDaCI server vs current 1U and 2U server models.

format for longer than the required 8-year period. Hence, in these categories CEDaCI server scored a higher percentage than the current server models. Similarly, in such categories as ease of product disassembly, the complexity of the design & manufacture, chemical content & recycling, resource tracking & tracing – the CEDaCI server scored higher than the conventional machines because of the design and LCA considerations that were taken into account and outlined earlier in Sections 4.1 and 4.2. The current generation of conventional machines also scored fairly highly in categories related to ease of product disassembly, availability of instruction manuals and CE & environmental considerations, which indicates that the manufacturers have already implemented a number of obligatory and voluntary changes.

On the other hand, since it is the electronic components that make up the server and because the electronics of the server will be determined by the manufacturers, the CEDaCI server score was equal to that of current server generations in the power specification category, as well as in the category related to the availability of the instruction manuals which is a legal requirement.

5. Conclusion and future work

This 'Circular Server' design is a real-life demonstration of how a sustainable product can be created by applying sustainable design thinking and life cycle assessment methods, together with a holistic design approach and the integration of the eco-design policy requirements outlined by the EU Circular Economy Action Plan 2020 [2], and other directives. By designing a standardised sustainable server, the CEDaCI project has futureproofed data centre equipment design for Circular Economy and built a critical foundation for a sustainable hardware design that can be expanded to achieve an ultimate goal of complete circularity in the future. This practice also established a broader change by offering good practice design methods and recommendations that can be adopted by product designers throughout the design industry leading to the crucial shift in design thinking in the future.

CEDaCI is continuing research into server design and the team is currently working on a comprehensive LCA model that will compare to the LCA of a number of server models and generations as well as some of the most circular models on the market including liquid-cooled machines. The future work will also involve testing the performance and recyclability of the latest electronic component designs using novel, environmentally friendly substrate materials such as biodegradable, soluble, or compostable printed circuit boards against conventional substrates.

CRediT authorship contribution statement

Kristina Kerwin: Conceptualization, Writing – original draft. **Deborah Andrews:** Supervision. **Beth Whitehead:** Supervision. **Naeem Adibi:** Supervision. **Silvio Lavandeira:** Technical support.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

CEDaCI project is co-financed by Interreg NWE programme. The project runs across 7 countries in North-Western Europe and is led by London South Bank University. CEDaCI Team would like to thank and acknowledge the assistance of Peter Adams from the LSBU Technical Support team for providing invaluable practical expertise in the development of the electronic components for the CEDaCI server. We would also like to express our gratitude to iNet, Cistor, Techbuyer, and ITRenew who kindly donated their server equipment to make this research possible.

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