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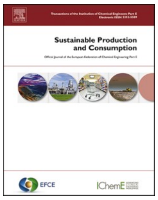

Circular strategy assessment for digital services: The CADiS framework

Raphael Ricardo Zepon Tarpani [a], Joan Manuel F. Mendoza [b,c], Laura Piedra-Muñoz [d], Alejandro Gallego-Schmid [a,*]

[a] Tyndall Centre for Climate Change Research, Department of Mechanical, Aerospace and Civil Engineering, University of Manchester, Floor 5, Core 1W, Engineering Building A, Booth Street E, Manchester M13 9PL, UK
[b] Mondragon Unibertsitatea, Faculty of Engineering, Mechanics and Industrial Production, Loramendi 4, Mondragon 20500, Gipuzkoa, Spain
[c] IKERBASQUE, Basque Foundation for Science, Plaza Euskadi 5, 48009 Bilbao, Spain
[d] Department of Economics and Business, Mediterranean Research Center on Economics and Sustainable Development, CIMEDES, Agrifood Campus of International Excellence, ceiA3, University of Almería, Almería, Spain

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ABSTRACT

The incorporation of digital technologies (DTs) and digital services into our daily lives is expected to grow in the years ahead. Whereas these technologies and services are recognised as important enablers of sustainable development, their resource footprint and environmental impacts are often underestimated or overlooked. One of the key proposals expected to mitigate the negative consequences of DTs and digital services is the development circular economy (CE) strategies. In an attempt to synthesise these important concepts while contributing to environmental sustainability, this paper introduces the Circular strategy Assessment for Digital Services (CADiS) framework. Its main goal is to support a simultaneous holistic understanding of the environmental impacts of digital services and the role of CE strategies in ameliorating them. Its open structure and granularity in terms of system coverage (nano/micro, meso and macro levels) and flow analysis (materials, energy and the role of data management) allow pinpointing the most suited interventions for achieving greater circularity and environmental sustainability. For this, the CADiS framework considers circularity (C) indicators and life cycle impact assessment (LCIA), which could be considered independently or merged, to promptly evaluate many scenarios at once. To demonstrate its practical application, a case study of an eHealth service deployed in three distinct elderly living schemes is presented. The evaluated digital health and well-being service integrates six types of electronic devices for urgent notifications, audio, and video communication, and is interconnected using Power over Ethernet (PoE) infrastructure. The results identified the scenario that incorporates regenerative/cleaner energy sources and closing material loops as the best-performing one. Given the ever-expanding importance of digitalization in our society, the CADiS framework is timely to facilitate environmental assessment reporting and increase the circularity of digital services to achieve sustainable development.

1. Introduction

In light of the urgent challenges posed by climate change, resource depletion, and many other environmental, human health and social issues, it is crucial to reconsider our current mode of production and consumption of goods, and provision and use of services. This includes a shift towards practices that are aligned with sustainability principles (Broman and Robèrt, 2017) and fit within the planetary boundaries (Pope et al., 2017; Richardson et al., 2023). In this regard, digitalization is seen as one of the most promising transversal solutions to contribute to these objectives, including fulfilling the Agenda 2030 (Ghobakhloo, 2020; Mondejar et al., 2021). Digitalization is often depicted through terms such as Industry 4.0, information and communication technology (ICT) or smart technologies. To provide digital solutions, digital technologies (DTs) such as digital twins, cyber-physical systems (CPS), Internet of Things (IoT), and artificial intelligence (AI), are essential for tasks such as assessment, control, storage, communication, and task execution (Autio et al., 2021; Verhoef et al., 2021). Digitalization, therefore, paves the way for the provision of digital services (e.g., e-services, online services, virtualization, digital servitization), which are experiences, interactions, functionalities or solutions provided through

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* Corresponding author.
E-mail address: alejandro.gallegoschmid@manchester.ac.uk (A. Gallego-Schmid).

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Nomenclature

A/C	Air conditioning
AI	Artificial intelligence
C	Circularity
CADiS	Circular strategy Assessment for Digital Services
CE	Circular economy
CPS	Cyber-physical systems
DTs	Digital technologies
EECs	Electric and electronic components
EEE	Electrical and electronic equipment
ELECTRE	Elimination Et Choice Translating Reality
ELS	Elderly living scheme
EoL	End-of-Life
EU	European Union
GIS	Geographical information system
GPS	Global position system
HVAC	Heating, ventilation, and air conditioning
ICT	Information and communications technology
IoT	Internet of Things
IT	Information technology
kWh	Kilowatt-hour
LAN	Local area networks
LCA	Life cycle assessment
LCIA	Life cycle impact assessment
NHS	National health service
MCDA	Multi-criteria decision analysis
PCB	Printed circuit board
PoE	Power over Ethernet
PSS	Product- service systems
SDGs	Sustainable development goals
SSCM	Sustainable supply chain management
TOPSIS	Technique for order of preference by similarity to ideal solution
WEEE	Waste electrical and electronic equipment
UK	United Kingdom

DTs, typically accessible to humans through screens and gadgets (e.g., virtual reality headsets, laptops, tablets and smartphones) (Münch et al., 2022; Struwe and Slepniov, 2023; Tóth et al., 2022).

DTs and digital services are thus capable of providing "smarter" and more sustainable solutions by improving, enhancing, and dematerializing supply, production, consumption, maintenance and recycling value chains (Ghobakhloo, 2020; Martínez et al., 2022). There are, however, many environmental concerns associated with widespread digitalization (Istrate et al., 2024). For instance, the swift progression of ICT, combined with the growing use, rapid obsolescence rate and shorter replacement intervals (plus limited and high-cost repair and/or low reuse interest) of electrical and electronic equipment (EEE), can potentially intensify resource consumption, whether through direct or indirect means (Galvin, 2015; Sengupta et al., 2022; Shittu et al., 2021). This is also leading to a growing increase in the generation of electronic waste (e-waste), as 60 % to 80 % of electronic devices end up in landfills or incineration facilities. Global e-waste generation in 2019 reached 53.6 Mt, and only 17 % were formally recycled, representing a loss of valuable materials for the industry, worth around US$57 billion (Forti et al., 2020; Sengupta et al., 2022). Furthermore, there are social consequences from precarious labour conditions and concerns about job security (Foroohar, 2019; Kunkel and Tyfield, 2021) to human health effects (due to toxic metal content, such as lead and mercury, and chemical substances, such as polybrominated biphenyls and halogenated flame retardants) ranging from decreased cognitive functions to posture-related injuries (Sharma et al., 2021; Small et al., 2020; Susilowati et al., 2022). Importantly, studies suggest that around 65 %% of the e-waste shipments leaving the European Union (EU) enter the African continent, where the recycling activities are performed by home-based recyclers using low-tech methods (e.g., manual dismantling, cleaning with hazardous solvents, open burning and acid leaching) to recover valuable components/materials, exposing themselves and the environment to toxic substances (Ádám et al., 2021).

Consequently, the greater reliance on critical and strategic metals embedded in EEE (e.g., gold, silver, copper, lithium, neodymium), the increased electricity consumption for EEE and digital infrastructure operation (e.g., internet), and the corresponding e-waste generation can heighten global environmental impacts (Ha et al., 2022; Lange et al., 2020; Piscicelli, 2023). Research suggests that, in some cases, the adoption of DTs or digital services could lead to environmental impacts that are equal to or surpass those of traditional counterparts, raising concerns about their actual contributions to sustainable development (Abdelkafi et al., 2022; Bull and Kozak, 2014; Verdecchia et al., 2022).

Circular economy (CE) depicts a set of principles and strategies aimed at mitigating the adverse environmental consequences associated with the prevailing linear "take-make-consume-dispose" economic model. The main purpose of CE is to foster sustainable development by narrowing (use less), slowing (use for longer), closing (use again) and regenerating (use renewables) resource flows (Leipold et al., 2023; Schöggl et al., 2020; Velenturf and Purnell, 2021). Naturally, the integration of digitalization and CE is currently seen as synergetic and transversal drivers for sustainable development. This is because DTs and digital services are capable of providing solutions that, if coupled with CE strategies, can improve resource efficiency and decrease environmental impacts compared to traditional counterparts (Chauhan et al., 2022; Dantas et al., 2021; Mendoza and Pigosso, 2023). Nonetheless, concerns remain over its potential to increase consumption levels and environmental impacts due to rebound effects and burden shifts (Castro et al., 2022; Mendoza et al., 2017; Zink and Geyer, 2017). Therefore, while DTs can facilitate transitions towards CE, it is crucial to acknowledge that relationships between digitalization, CE and sustainability are, at best, intricate (Lange and Santarius, 2020; Santarius et al., 2023a, 2023b). Currently, as demonstrated in this article, there is a lack of information on the actual environmental benefits CE strategies can bring to DTs and digital services.

Accordingly, the primary novelty of this paper lies in the development of a practical framework designed to guide actions towards reducing the life cycle resource consumption and environmental impacts of digital services by implementing CE strategies. First, a literature review on the topic is discussed in Section 2. After, the framework called Circular strategy Assessment for Digital Services (CADiS) is presented in Section 3, whose goal is to provide backbone information to aid structure and integrate the topics mentioned above (CE, life cycle environmental impacts, and digitalization), and how they can be operationalized in practice to inform academia, stakeholders, and public policies towards the environmental sustainability of digital services. The CADiS framework has been applied to evaluate three elderly living schemes (ELSs) in the United Kingdom (UK) that provide a digital health and well-being service, and the results are reported based on a previous study by the authors (Section 4). This is followed by a brief discussion about the potential application of the CADiS framework in different fields and its future developments (Section 5). Finally, the significance of the CADiS framework for sustainable development is highlighted in the conclusion of the study, particularly emphasizing its role in incorporating and quantifying the benefits of CE within digital services (Section 6).

2. Literature review

One of the first works to appraise the links between digitalization and CE was Okorie et al. (2018), who stated that research at the time was predominantly centred around engineering and computer sciences, with less emphasis on environmental, business, and material sciences. Later, Alcayaga et al. (2019) explored the relationships between CE, IoT, and Product-Service Systems (PSS), and concluded that coverage at the time was limited, mostly due to the complexity inherent to these concepts. The authors discussed the role of IoT in tracking product lifecycles, business opportunities from DTs for industries, and the benefits of data-enabled product upgradability in PSS. In the same year, Ingemarsdotter et al. (2019) developed a framework categorizing CE strategies by IoT-enabled tracking, monitoring, control, optimization, and design. The authors analyzed case studies to determine the current distribution of IoT-enabled CE strategies in the industry, and the findings indicated that most were related to efficiency improvement and product lifetime extension.

Demestichas and Daskalakis (2020) reviewed the literature concerning ICT solutions that facilitate a transition towards CE and found that research was predominantly focused on the reduction CE strategy. Most of the significant challenges hindering the adoption of ICT solutions for CE are consumer and business attitudes, economic costs, and potential environmental repercussions. Kristoffersen et al. (2020) introduced a framework for a smart CE aimed at manufacturing companies, seeking to align DTs with CE strategies to achieve sustainable consumption and production. It provides a structured way to understand how DTs can enhance resource efficiency and reduce waste in manufacturing besides highlighting the importance of effectively using data from DTs to achieve more resource-efficient CE. Çetin et al. (2021) explored the role of DTs in enabling the CE within the built environment. The authors developed a circular digital built environment framework, pinpointing ten key DTs that facilitate circular practices including additive/robotic manufacturing, AI, big data analytics, blockchain, building information modelling, digital twins, geographical information system (GIS), material passports, and IoT. In the same year, Magrini et al. (2021) discussed the application of DTs (more specifically IoT and blockchain), in the context of a CE for professional EEE. They highlight the importance of tracing, tracking, and storing information to enhance resource efficiency by preventing waste EEE (WEEE) loss. The authors present the outcomes of interviews conducted with companies, discussing potential improvements in WEEE management and proposing the use of a combination of IoT and blockchain to enable producers to maintain control over products until their end of life (EoL).

Rusch et al. (2022) emphasized that DTs should not be viewed in isolation but rather as complementary tools to enhance data collection, management, and processing. The authors discussed that despite their potential, DTs for sustainable product management are not yet fully integrated into CE strategies, and bridging the gap between theory and practice in the field is crucial to sustainable development. Liu et al. (2022) delve into the application of DTs in the context of CE to provide a comprehensive understanding from the operational perspective. The authors identified several critical digital functions of DTs (i.e., automation, digital analysis, and data collection and integration) and introduced a framework outlining seven mechanisms through which they can boost CE. The framework pinpointed five areas for further exploration besides offering a structured approach to identify the most suitable digital functions to foment CE. Bressanelli et al. (2022) explored synergies between digitalization and CE to create sustainable business models. The authors created a conceptual framework for the smart circular economy where DTs are integrated throughout product life cycles to implement CE strategies. The study suggested that research should focus on expanding from individual organizations to entire digital ecosystems.

Schöggl et al. (2023) investigated digitalization trends in manufacturing companies, focusing on both CE and sustainability aspects. The findings revealed that companies often possess appropriate technical systems, but the implementation of DTs (such as predictive maintenance enabled by AI and demand forecasting through big data analytics) remains low. Company-wide adoption of DTs is currently limited to pilot projects, indicating a lack of established strategies, and there is a need for scalable best practices, industry-specific approaches, and synergy between information technology (IT) and CE/sustainability departments. Trevisan et al. (2023) reviewed multiple papers and case studies seeking to explore barriers to employing DTs for CE. Their research challenges the notion that companies alone are responsible for overcoming these barriers, emphasizing the need for synchronized efforts at various levels, and the key contribution of the work lies in a framework categorizing these barriers into eight dimensions.

Liu et al. (2023) conducted a literature review on emerging DTs utilized in sustainable supply chain management (SSCM) and how they contribute to CE. The authors identified key DTs that have significant roles in enhancing data management, information transmission, and decision-making. The work introduced a framework designed to bridge gaps between traditional SSCM frameworks and efforts on the integration of DTs to ensure circular SSCM. The authors highlighted the need for more precise evaluations that consider adaptable algorithms for dynamic contexts, upgradable systems, and policy research to foster innovation in digitalization and SSCM. Finally, Cagno et al. (2023) contributed with an integrated and scalable framework that offers practical guidance for theoretical discussions on sustainability, CE, and information systems. Their work serves as a tool for identifying synergies and enabling decision-making in businesses and industries using indicators to monitor DTs in terms of their performance. The authors suggest future research should further explore theoretical and empirical synergies among these aspects and gather empirical evidence to measure environmental performance.

From the above, it can be observed that research up to the moment examines how digitalization benefits CE strategies, with little to no mention of the reciprocal relationship. Moreover, there is an even more noticeable gap: a structured and unified framework that comprehensively evaluates both circularity and the life cycle environmental impacts of digital services or DTs in tandem. Furthermore, accurately accounting for the resource intensity of data management required by digital services is crucial for effectively estimating and communicating their true environmental performances. By addressing these shortcomings, it is possible to bridge the divide between theoretical principles and the implementation of sustainable digital services - this is the primary aim of the CADiS framework.

3. Methods: The CADiS framework

The CADiS framework is designed to guide organizations and professionals implement CE strategies in digital services. It offers a structured approach to identifying the most effective ones by exploring environmental impacts from various levels and their origins. The framework operates across multiple system levels and consider from initial planning to EoL management, providing a clear action plan to help organizations define the scope of actions needed to achieve circularity and sustainability goals in digital services (ISO, 2024a, 2024b). The Fig. 1 outlines the steps of the framework, and Table 1 the main terms used during its description in the next sections. Step 1 involves evaluating the materials and energy required for data management at nano/micro, meso, and macro levels. Step 2 creates different scenarios through changes in the inventory created in Step 1 based on CE strategies. In Step 3, quantitative evaluations and comparisons are made among the obtained results, which are then interpreted in Step 4 to generate recommendations for improving the environmental sustainability of the digital service.

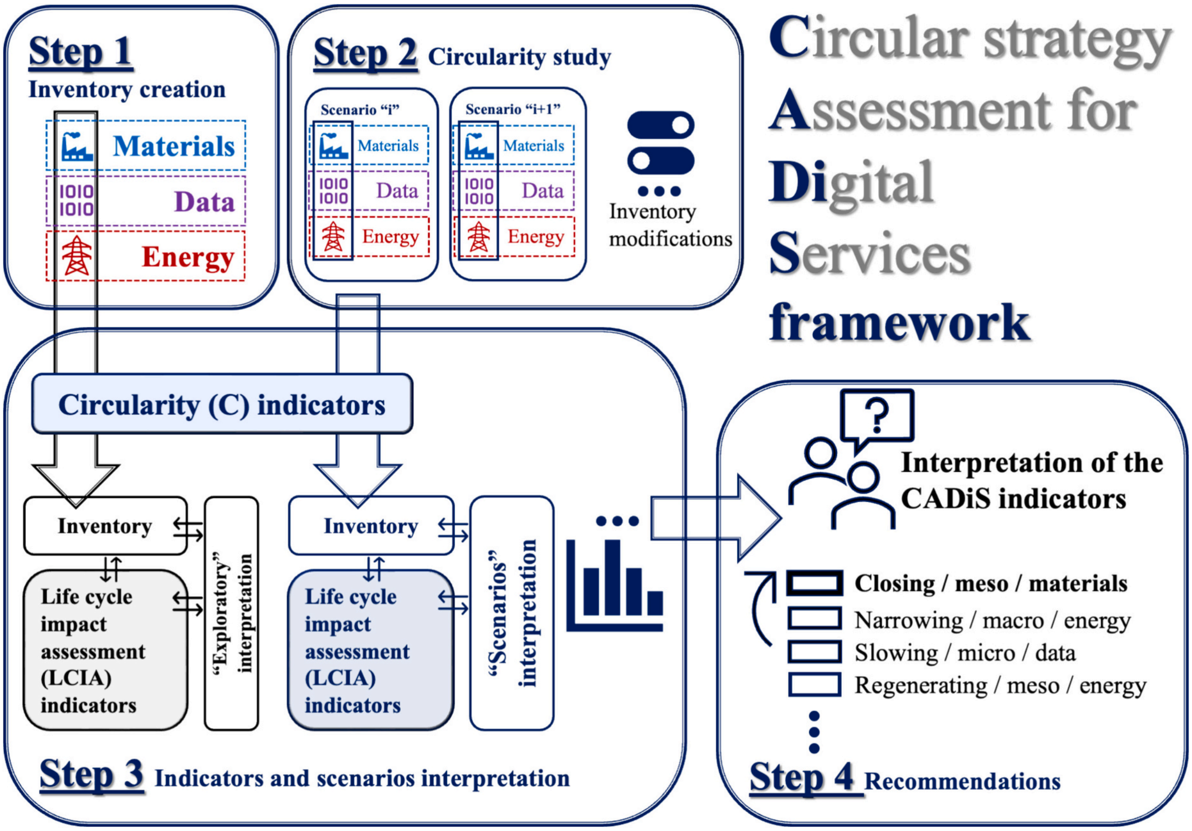


Fig. 1. Flowchart representation of CADiS (Circular strategy Assessment for Digital Services) framework.

3.1. Step 1: Inventory creation

The CADiS framework starts in Step 1 by creating the quantitative inventories of materials and energy necessary for the deployment and operation (including maintenance) of the digital service (i.e., baseline), taking into consideration data management requirements. This is both an exploratory and preparatory step for the circularity study in Step 2. To begin, an initial perspective for the digital system under study is required in terms of its geographical coverage. This means that there is a starting point that must be expanded to other levels (for more information in this regard, please see SI section SI-1.1 and SI-1.2). Note that building a complete and comprehensive quantitative inventory for the digital service requires a thorough investigation across all system levels where the service demands materials (e.g., EEE, batteries, other parts) and energy (e.g., for lighting, EEE operation, HVAC) for data management. This process can be time-consuming and involves gathering information from various sources including technical manuals, IT industry experts, dismantling of EEE, relevant literature, and other investigative approaches. This and other aspects of the framework are shown in Fig. 2, and the key considerations for users when creating the inventory in Step 1 are outlined in the following sections.

3.1.1. Data management considerations

Digital services collect, process, transfer, and store sensitive data to and from the environment and technosphere. Therefore, data management plays an important role in the provision of any digital service (Kouhizadeh et al., 2021; Tóth et al., 2022). Data collection and retrieval are essential for synchronizing, monitoring, controlling, and functioning of DTs and digital services. It takes place from nano/micro (sensors, gadgets, electronic devices), meso (regional data centres, phone towers, internet backbone), to macro (internet, large data centres, satellites) levels. Data transfer encompasses the movement of data between EEE located in different physical locations. As for data collection and retrieving, it can take place at different levels between sensors and electronic devices (nano/micro level), electronic devices to phone towers (nano to meso level), and across global digital platforms, large data centres and satellites (macro level) (Coroama et al., 2013; Pothitou et al., 2017; Ruiz et al., 2022) – enabling data sharing between sensors and electronic devices on a global scale, e.g., internet or IoT (nano to macro level). Therefore, it is crucial to recognize that material elements and energy consumption of digital services more than frequently extend beyond their access points (e.g., the smartphone owned by the user of the digital service).

Our increasing dependence on digital services requires an ever-expanding infrastructure for data storage (it is estimated that from 2020 to 2025 the global data storage capacity will increase from 6.7 to 16 zettabytes) (Pansera et al., 2024). Data processing and predictive tools include digital platforms, streaming services, AI, machine learning, and big data analytics. These often necessitate robust computational infrastructure, specialized protocols/algorithms, and dedicated facilities (e.g., supercomputer environments and cloud services) (Kaack et al., 2022; Meulemeester and Martens, 2023). This results in a continual rise in power consumption to meet the computational output demand (Bauer et al., 2021; NVIDIA, 2023; Tang et al., 2022). For secure data transfer protocols, data encryption (such as blockchain technology) is crucial to safeguard data from cyberattacks and privacy concerns, ensuring it is not intercepted or tampered with (Kwon et al., 2023). This is especially important for sensitive data like electronic health records and nuclear power plant interfaces (Busquim e Silva et al., 2021; Markopoulou and Papakonstantinou, 2021). Recent estimates suggest Bitcoin mining consumes 110–140 TWh per year (equivalent to the annual consumption of countries like Sweden, Malaysia or Ukraine), and each Bitcoin transaction is comparable to the monthly electricity consumption of an average U.S. household (about 850 kWh) (Amenta et al., 2021; Digiconomist, 2023; Qin et al., 2023).

Given the data management needs described above, it can be inferred

Table. 1
Description and examples of the main terms used during the CADiS (Circular strategy Assessment for Digital Services) framework (see also SI-1.1).

		Examples		
Term	Description	Nano/micro level	Meso level	Macro level
Digital service	Digital services offer a wide range of functions and experiences to users, industries, corporations, and governments. Among the key objectives are enhancing functionality, greater convenience, efficient access to information, facilitating communication, supporting transactions, and enabling remote task execution. Additionally, they often provide scalability and customization, adapting to diverse needs and user demands.	Social media platforms, e-commerce platforms, content sharing platforms, service-orientated platforms	VPNs, regional digital platforms, edge computing, autonomous vehicles, smart grids, smart cities, e-government platforms	“Big Tech”, “FinTech”, “cloud” services, global telecommunication networks
System levels	It aims to depict the physical location and role of the EEE/environmental repercussions of providing the digital service.	Electronic devices and gadgets/ Emission of hazardous substances from EEE dismantling	EEE is used in servers, internet backbone, regional databases, smart cities/Emissions from recycling facilities, habitat fragmentation, direct water consumption in data centres	EEE used in submarine cables and satellites, “Big Tech” databases/ Global warming, fossil fuel resource depletion, metal depletion (e.g., life cycle impacts)
Electrical and electronic equipment (EEE)	Electrical equipment are devices powered by electricity for performing various tasks, such as generating light, producing heat, or driving mechanical systems. Electronic equipment comprises devices that use electronic components to process, store, or transmit information.	Hard disk drives, displays, screens and electronic devices like gadgets such as smartphones, laptops, tablets, drones, routers, servers, kitchen appliances, electric vehicles and automated machines	Infrastructure for street lighting systems, smart grids, national telecommunication networks, internet backbone networks, and regional data centres	Infrastructure for global telecommunication networks (e.g., satellites, submarine cables) and global data centres
Battery (also EEE)	An electrochemical device that stores chemical energy and converts it into electrical energy through controlled chemical reactions. When discharged, it releases electrical energy to power EECs and EEE. An external electrical current reverses these chemical reactions during charging, replenishing the battery’s stored energy.	Lithium-ion batteries in smartphones, Nickel-metal hydride batteries in digital cameras, alkaline batteries in remote controls	Lithium-ion batteries for backup power applications in server rooms, Lead-acid batteries in uninterruptable power supplies	Lithium Iron Phosphate and Vanadium redox flow batteries in global data centres, Lithium-ion batteries in solar and wind farms powering internet infrastructure
Electrical and electronic components (EECs)	Electrical components are used to manage, regulate, or utilize electrical energy within circuits. Electronic components serve specific functions in electronic circuits such as signal processing, amplification, modulation, and control. They range from small sensors and gadgets to mechanical parts of robots and vehicles, all the way up to the global telecommunications infrastructure.	Sensors, electric motors, integrated circuits, printed circuit boards, resistors, capacitors, signal repeaters, diodes, etc.		
Other parts	Aside from EECs and batteries, EEE consists of various other parts depending on their functions and design.	Casings, frames, enclosures, heat sinks, wires, cables, bezels, screws, lenses, fasteners, etc.		
Data collection & retrieval	It involves collecting, fetching and retrieving information from a variety of sources. This includes physical inputs from sensors or digital data from a wide range of sources, spanning from gadgets to global databases and communication networks.	Smartphone apps, computer software, environmental monitoring stations, soil moisture sensors, smart home sensors	Environmental monitoring networks, regional smart grids, regional supply chain management systems	Internet, GPS, IoT, global databases, global financial networks
Data transfer	Encompasses the movement of digital information between EECs, EEE or systems. It involves transmitting data between sensors, devices, networks, and globally across the internet.	Bluetooth, Wi-Fi, NFC, LANs, PoE	5G technology, phone towers network, internet backbone networks	Internet, radio networks, satellite communication networks
Data storage	Refers to the structured retention of digital information, which is essential for preserving and accessing data for digital services. The selection of storage technology depends on factors like data volume, desired performance, scalability, security concerns, and budget constraints.	Flash drives, hard disk drives, solid state drives	LANs, local and regional data centres, data warehousing solutions	Global data centres

(*continued on next page*)

Table. 1 (*continued*)

		Examples		
Term	Description	Nano/micro level	Meso level	Macro level
Data process & encryption	Processing data involves organizing, analysing, or transforming collected and retrieved data into useful information. This process often requires computing large datasets using software and algorithms (machine learning or AI). Encrypting data entails converting it into a secure, encoded format using cryptographic techniques (like blockchains) to enhance security and protect sensitive information.	Smartphone apps, computer software/Device-level encryption, card payment encryption, messaging app encryption	Smart grid management, internet access points, content management systems, supercomputer tasks, edge computing/Database encryption, SSH, TLS, VPNs, P2P networks	Digital platforms and cloud services (IaaS, PaaS, SaaS, FaaS)/Global secure communication networks, global encryption key management platforms, blockchain technology, HTTPS, SSH, TLS
Heating, ventilation, & air conditioning (HVAC)	These can range from simple to complex EEE systems that regulate temperature, humidity, and air quality to maintain optimal operating conditions for server rooms and global data centres, while also ensuring comfort, health, and safety in enclosed spaces.	Ventilation fans, ductless mini-split air conditioners	Central air conditioning systems, packaged air conditioning units	Hybrid air conditioning systems, precision air conditioning, chilled water systems, in-row cooling units
Operating periods & modes	The operating periods of EEE are determined by their specific design and intended purposes. Electrical devices generally function through on/off cycles, drawing power only during active periods. Electronic devices often utilize modes such as sleep, standby, idle, and hibernation to conserve energy while awaiting tasks. Thus operational periods and modes are influenced by user behaviour and commands, and they significantly impact the service life and energy consumption of EEE.	Power consumption of electric motors operation, power consumption during standby periods of kitchen appliances, idle mode power consumption of laptops	Power consumption of air conditioning operation in server rooms, idle mode power consumption of air conditioning in server rooms, idle mode power consumption of servers in local data centres	Power consumption of servers in global data centres; power consumption for data transmission over submarine cables, power consumption for satellite communication

5G: fifth-generation technology in cellular networks. FaaS: Function as a Service. GPS: Global Positioning System. HTTPS: Hypertext Transfer Protocol Secure. IaaS: Infrastructure as a Service. IoT: Internet of Things. LAN: Local Area Network. NFC: Near-Field Communication. P2P: Peer-to-Peer. PaaS: Platform as a Service. PoE: Power over Ethernet. SaaS: Software as a Service. SSH: Secure Shell Protocol. VPN: Virtual Private Network. TLS: Transport Layer Security. Wi-Fi: Wireless Fidelity. "Big Tech": Refers to the largest and most influential technology companies, often dominating their respective markets. "FinTech": Companies that leverage technology to offer innovative services in sectors such as finance, including banking, payments, lending, investments, insurance, and wealth management. Hibernation Mode: A power-saving mode that saves the current state of EEE to memory, allowing it to power down completely while preserving the current state. Idle Mode: A state that minimizes power consumption during periods of non-use of the EEE. Sleep Mode: A low-power state that allows EEE to quickly resume full functionality when prompted. Standby Mode: A state that prioritizes quick activation of the EEE, typically consuming more power than sleep mode but less than when fully operational.

that these tasks are often both material and energy-intensive in digital services. Consequently, it can have a significant influence on the initial estimation of materials and energy necessary for training, deploy, setup and operating them. To sum up, the seemingly abstract realm of data management in digital services has tangible consequences on material usage and energy consumption, and these should be carefully evaluated case-by-case, especially considering their immense computational load and data generation, and growing deployment on a global scale. Next can be found comments highlighting key aspects to help the user create material and energy inventories and operationalize the CADiS framework.

3.1.2. *Materials and energy inventory*

Metals are crucial for deploying DTs from nano/micro to macro levels as they are essential for wires, cables, integrated circuits, electric motors, and batteries - which form the key infrastructure components of any digital service. Consider, for example, the case of printed circuit boards (PCBs), a crucial electrical and electronic component (EEC) in most EEE (see Table 1), where copper is commonly used for crafting circuits along with gold due to their remarkable conductivity and superior oxidation resistance. The soldering process involves the use of silver and tin for component connections, in addition to preventing oxidation and corrosion (Alcaraz Ochoa et al., 2019; Canal Marques et al., 2013; Dong et al., 2018). Furthermore, the manufacturing of integrated circuits also requires large amounts of resources (Intel, 2023; Nagapurkar and Das, 2022; TSMC, 2022). Rare-earth elements, such as neodymium are vital for high-performance magnets used in EEE, like magnetic resonance imaging machines (van Nielen et al., 2023). It is important to note that even though these metals are present in relatively small amounts in electronic devices, their collective environmental impacts are considerable due to their sheer numbers (Bookhagen et al., 2020; Hu and Yan, 2023; Kumar et al., 2017; Tran et al., 2018). Other materials in EEE may include plastics, silicones, rubbers, and glasses (Tarpani and Gallego-Schmid, 2024).

Batteries are essential for many digital services from nano/micro to macro levels as they allow DTs to operate remotely and/or during blackouts. Lithium-ion batteries are indispensable for powering EEE such as smartphones, drones, and electric vehicles, while lead-acid batteries are often considered for stationary applications (e.g., uninterruptable power supplies) (Frith et al., 2023; Hiremath et al., 2015; Picatoste et al., 2022). Information about the materials needed to build the inventory at the nano/micro level can be obtained by dismantling the EEE used in the digital service (Ferreira et al., 2021; Tarpani and Gallego-Schmid, 2024). More specifically, on the meso and macro levels, direct water consumption (considered in the CADiS framework within the material inputs category) for cooling large data centres has been suggested to be a significant source of concern, especially for water-stressed regions. Estimates for the direct and indirect water usage of data centres place it within the spectrum of 1 to 205 l per gigabyte transmitted (Mytton, 2021; Ristic et al., 2015).

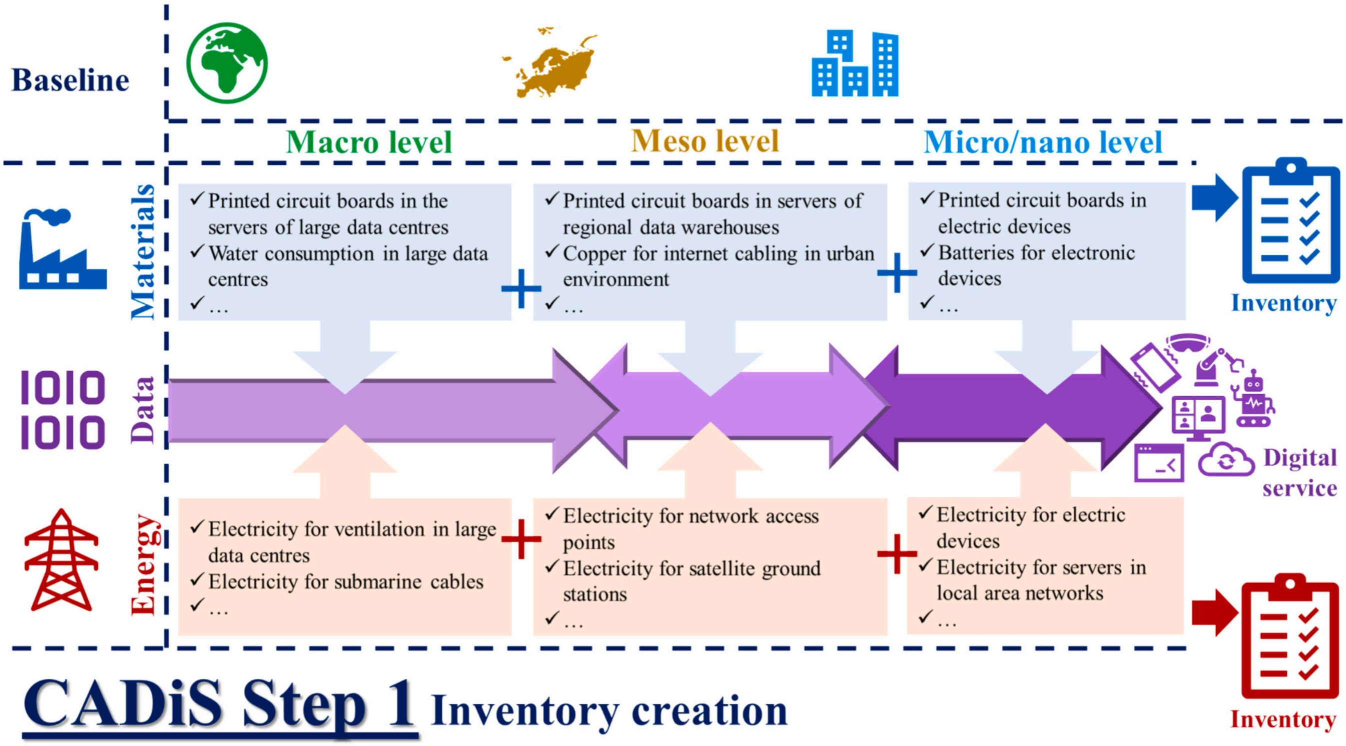


Fig. 2. First step of the CADiS framework: quantitative inventory of materials and energy used in the digital service. For more information see Fig. 1 and SI-1.1.

A steady electricity supply is crucial as our reliance on DTs and ICT continues to escalate worldwide (Gasser et al., 2020; Morley et al., 2018). The ubiquitous and constant use of sensors and electronic devices at the nano/micro level adds to the contribution of electricity consumption by digital services (Rault et al., 2014; Ruiz et al., 2022; Schien et al., 2013; Shi et al., 2023). Hence, their collective global impact in terms of energy consumption is certainly not negligible (Cheng et al., 2022; Pothitou et al., 2017; Ruiz et al., 2022), especially considering idle, sleep and standby periods (Baliga et al., 2011; Tuomela et al., 2021). At the meso level, private server rooms, phone towers and internet backbone networking demand substantial power to operate (Jin et al., 2020; Motlagh et al., 2020). Another aspect to considered at this system level is the energy consumption in workplaces for lighting and heating (Shi et al., 2023).

At the macro level, large data centres, where vast amounts of data are stored and processed, are remarkably energy-intensive facilities due to continuous server operation, energy conversion losses, and the requirement of heating, ventilation and air conditioning (Ham et al., 2015; Long et al., 2022; Whitehead et al., 2015; Zhang et al., 2023). Estimates on the energy consumption of data transmission over the internet current range at 0.02–0.08 kWh per gigabyte (Aslan et al., 2018; Coroama et al., 2013; Malmodin et al., 2014).

3.2. Step 2: Circularity study

Embracing CE principles for digital services could potentially reduce their environmental impacts in addition to fostering sustainable innovations by encouraging, for instance, the development of eco-friendly technologies, new business models, conscious service operation, and efficient recycling activities. Accordingly, Step 2 of the CADiS framework aims to understand these changes in the environmental impacts of adopting one or more CE strategies in the provision of digital services (i.e., CE solutions). As life cycle thinking is at the core of the framework (see SI-1.2), the information found next should be interpreted as literature material for performing the necessary modifications to the inventory created during Step 1. Step 2 can be repeated as many times as needed to create different scenarios, which are then evaluated in Step 3 (see Section 3.3). This iterative process offers a structured approach for assessing the environmental impacts of digital services while identifying opportunities and synergies through the application of one or more CE strategies.

An important consideration to keep in mind during this step are “domino” and “cascade” effects among the different system levels that CE strategies can have on the inventory established in Step 1. As illustrated in Fig. 3, when modifying the inventory created in Step 1 according to the CE strategies defined here in Step 2, there are both direct and indirect effects on materials and energy consumption at different system levels. For example, reducing data storage at the macro level leads to fewer servers required in large data centres. Similarly, taking PCBs found in electronic devices (nano level) to recycling (meso level) can yield benefits from avoiding virgin metals consumption (macro level). This is an important aspect of the CADiS framework and more details in this regard can be found in the work of Ravikumar et al. (2024) and SI-1.2.

3.2.1. Circular economy strategies

The next sections show literature studies covering CE strategies according to the CADiS framework flows (i.e., materials, energy, and data management) that could work as a starting point to modify and/or expand the inventory from Step 1. These were categorised as narrowing (refuse, rethink, reduce), slowing (reuse, repair, refurbish, remanufacture, repurpose), closing (recycle, recover), and regenerating (shift to low toxicity and renewable sources) (Konietzko et al., 2020; Morseletto, 2020). The user is responsible for identifying which CE strategies, individually or in combination, should be implemented to reduce environmental impacts and improve the circularity of the digital service, based on identified hotspots and relevant literature - for more studies tackling CE strategies for digital services discussed below please check SI-2.1.

3.2.1.1. Narrowing (refuse, rethink, reduce). Eco-design is often regarded as the initial step in the CE strategy narrowing since it is aimed at

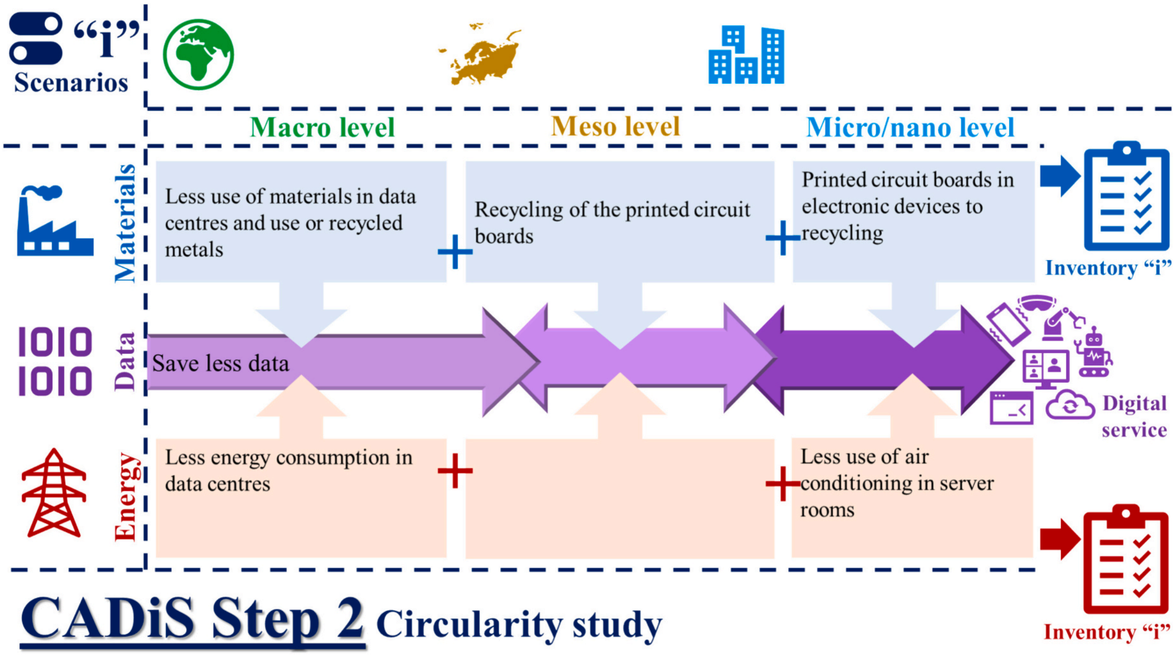


Fig. 3. Second step of the CADiS framework: study of circular modifications to the materials and energy inventory for the digital service developed in Step 1. For more details, refer to Fig. 1 and SI-1.2.

streamlining material flows. This process entails evaluating the redundancy, upgradeability, scalability, and adaptability of EECs, batteries and other parts to meet evolving technological demands and needs of EEE used in digital services (Dahmani et al., 2021; Desing et al., 2021). Based on previous research (see Section 3.1.2), the initial focus should be on reducing the consumption of critical and strategic metals in PCBs and batteries (Canal Marques et al., 2013; Liu et al., 2014). This would not only mitigate various environmental and social impacts associated with mining but also minimize the risk of supply disruptions and manufacturing bottlenecks (Gaustad et al., 2018; Hu and Yan, 2023). Besides decreasing energy use during the manufacturing of EEE, narrowing energy consumption in digital services can happen through measures that optimize their operating periods (i.e., on, idle, sleep, standby, hibernation and off) (Pothitou et al., 2017; Varjovi and Babaie, 2020). Another important action is to find ways to reduce HVAC in server rooms and data centres (Jin et al., 2020; Moazamigoodarzi et al., 2020). Lastly, digital service providers can use more energy-efficient EEE in data centres, which are designed to perform the same computational tasks using less electricity (Long et al., 2022; Zhang et al., 2023).

Regarding data, efforts to reduce data transfer (e.g., maintain minimal internet bandwidth requirements) and storage, and implement more efficient algorithms undoubtedly contribute to a more streamlined digital infrastructure. For instance, refusing to collect and process unnecessary data encourages innovative approaches to data management (Rault et al., 2014; Rong et al., 2016) without compromising the quality of the resulting insights (Todman et al., 2023). Furthermore, adhering to responsible data management practices, such as minimizing data needs, employing low-code development, and promoting green software initiatives, is in harmony with privacy principles (Green Software Foundation, 2024; Lange and Santarius, 2020; Varjovi and Babaie, 2020). Virtualization technologies allow multiple virtual servers to run on a single physical server, thus reducing the number of physical servers (Kouhizadeh et al., 2021).

3.2.1.2. Slowing (reuse, repair, refurbish, remanufacture, repurpose). Slowing the use of materials in digital services involves promoting technology design for durability (long-lived products), responsible (re) use and facilitating repair practices to extend the lifespan of EEE/batteries and its EECs. Additionally, creating a market and policies development for reused, refurbished and/or remanufactured components are also an important aspect to consider (Boniface et al., 2024; Parajuly and Wenzel, 2017). Repurposing EECs, batteries and other parts of EEE can also help achieve material circularity while contributing to reducing the demand for raw materials, thus minimizing environmental impacts (Diener et al., 2019; Pérez-Martínez et al., 2021). Encouraging these solutions decreases WEEE build-up and losses in urban centres (Guzzo et al., 2021; Rocha and Penteado, 2021). Nonetheless, preparing WEEE for reuse also causes environmental impacts and these should be taken into consideration (Kouloumpis et al., 2023). Another approach to slowing is reconfigurable hardware design initiatives, increasing the lifespan of the EECs (Bossuet, 2014; Sudheshwar et al., 2023).

Linked to the above but in the realm of energy, the manufacturing of some EECs and batteries requires substantial energy inputs (cumulative energy demand), particularly for processing raw materials and manufacturing procedures. This is especially true for semiconductors and integrated circuits due to their increasing complexity and miniaturization (Kuo et al., 2022; Nagapurkar and Das, 2022). Therefore, a parallel can be made that slowing the use of EEE indirectly reflects in slowing energy use for digital services as a whole. While advancements in energy efficiency have led to reductions in per-unit energy consumption, the widespread of EEE, faster technological obsolescence, and the expansion of digital infrastructure are barriers in terms of slowing energy use by digital services.

Slowing data use entails fostering data literacy, ethics, and awareness to cultivate a culture of responsible data stewardship (Green Software Foundation, 2024), including the reuse of existing data among digital services. For instance, user preferences and behaviour data collected by one digital service can be reused to personalize user experiences in another (Alataş, 2021; Kwon et al., 2023). Furthermore, repurposing data for alternative uses within ethical and privacy boundaries may slow down data-gathering needs elsewhere (e.g., for data analysis or product development) (Jensen et al., 2023; Lange and Santarius, 2020). Lastly, Kern et al. (2018) proposes a hierarchical framework for assessing software sustainability that aligns with slow software utilization. It aims to establish a standardized eco-labelling system for software design, applicable across various architectures and usage patterns. The objective is to promote the development of more sustainable software solutions that not only reduce resource consumption but also enhance compatibility, portability, and interoperability.

3.2.1.3. *Closing (recycle, recover).*

Closing resource use on the materials found in EEE is dependent on the creation of an active business environment, available infrastructure, eco-design, and policy creation, among other aspects capable of correctly dealing with this task (Andersen and Jæger, 2021; Guzzo et al., 2021). Among the important targets during the recycling of WEEE is the sustainable recovery of metallic resources found in EECs and batteries. However, these face difficulties such as high input of chemicals and energy besides toxic residue generation (Bookhagen et al., 2020; Dutta et al., 2018; Jin et al., 2022). Additionally, some aspects of WEEE recycling necessitate careful evaluation such as transportation distances, sorting and dismantling procedures (Greer et al., 2021; He et al., 2024; Nelen et al., 2014), and consideration of future recycling routes and scenarios (Šimaitis et al., 2023). For energy, as happened for the slowing CE strategy, closing resource loops could focus on such possibilities during the manufacturing of EECs and batteries, which are known to be energy-intensive. Moreover, data centres and server rooms generate a significant amount of heat which could be recovered for other uses (Luo et al., 2019).

The concept of recycling and recovery can be extended to the data in digital services. For example, information such as user preferences collected by one service can be analysed and adjusted (via big data analytics, machine learning, and AI) to personalize user experiences or services on another related or unrelated digital platform or industry (Armando Barron-Lugo et al., 2021; Zhang et al., 2020). By examining historical data to understand customer behaviours, product life cycles, and market trends, digital service providers can build useful datasets for several other digital services, encouraging an open-source approach to sharing data across multiple platforms (Bag et al., 2020; Jensen et al., 2023).

3.2.1.4. *Regenerating.*

The regeneration principle for materials is in its infancy. Still, it currently involves revitalizing EECs through self-healing capabilities (e.g., some graphene-based electronic components) and biodegradable materials (e.g., natural polysaccharides in transistors) (Konwar and Tiwari, 2024; Li et al., 2019). Akin to slowing, targeted software updates for specific EEC functions could facilitate the revitalization of some WEEE for diverse sets of applications (Bossuet, 2014; Sudheshwar et al., 2023). For energy, the regeneration principle usually focuses on the use of renewable energy sources like solar or wind power. Current cloud service providers and Big Tech companies are increasingly investing in renewable energy projects to offset their carbon footprint (Alphabet Inc., 2023; Apple Inc., 2023; NVIDIA, 2023). In the realm of data, one approach of the regeneration principle may utilize evolutionary algorithms (or machine learning and AI) to fulfil gaps in existing datasets, thereby circumventing the necessity of collecting new data (Al-Obaidy and Ayesh, 2015; de Carvalho and da Silva, 2021).

3.2.2. *Circularity indicators for the CADiS framework*

Based on the CE strategies and solutions discussed in Section 3.2.1, the CADiS framework encourages users to select the most relevant circularity (C) indicators for conducting the quantitative evaluation of the digital service. This evaluation should initially focus on EEE with larger/heavier PCBs and batteries, and higher power consumption (see Step 1) in the system levels considered (or with sufficient information) for the study as these are expected to contribute more significantly to environmental impacts. By first concentrating on these key components, CE strategies can be more effective in decreasing the environmental impacts of the digital service. Nonetheless, Step 3 helps to more easily identify which are the EEE that contribute most to the overall environmental impact of the digital system under evaluation.

Over the past few years, especially from 2015 onwards when the EU Circular Economy Action Plan was officially launched (European Commission, 2015), a variety of multiple micro, meso and macro level C-indicators have been proposed by academics (e.g., Pauliuk (2018) and Harris et al. (2021)), industry (e.g., OECD (2021) and WBCSB (2023)), and standardisation bodies or policymakers (e.g., ISO (2024c), European Commission (2023)) to measure and monitor C-performance. However, limited access to information and the use of narrowed or inadequate indicators can lead to misleading results (Kurucz et al., 2017). For this reason, it is important to choose appropriate indicators about the digital service under assessment according to the scale and goals of the study. To simplify this process, Table 2 provides an overview of C indicators applicable to EEE (as a vector for the delivery of digital services) (see more information in SI-2.2).

As shown in Table 2, different types of indicators could be used to measure C performance. However, as research on the topic is still emergent, there are no indicators available that address all CE strategies and aspects (e.g., CE solutions, resource flows, and life cycle stages) in a single formula. This is especially relevant for the CE principle of resource flow regeneration where, to the author's knowledge, there are no specific C indicators focused on exploring this particular topic beyond the consideration of low-toxicity content, and renewable energy and material ratios in substitution of virgin inputs. For the case of data management in the realm of digital service provision, only two C indicators were identified in the literature. Thus, while it is expected that future research addresses these issues, users of the CADiS framework are required to select and analyse the more pertinent C indicators related to the digital service to explore CE strategies based on the goals of the study and identified hotspots.

3.3. *Step 3: Indicators calculation and scenario interpretation*

This step of the CADiS framework integrates and evaluates the information gathered during Step 1 and Step 2 using the life cycle assessment (LCA) methodology (ISO, 2006a, 2006b) (Fig. 4). LCA is an established, systematic, and comprehensive methodology to evaluate the environmental impacts throughout entire life cycles (i.e., cradle-to-grave approach), meaning it considers all stages from resource extraction, manufacturing, transportation, use, and EoL (Hauschild et al., 2018; Hellweg et al., 2023). This, in turn, facilitates improved and robust decision-making on environmental issues (Pryshlakivsky and Searcy, 2021). It is important to mention that different approaches to the LCA methodology (e.g., attributional, prospective, hybrid, and consequential - see SI-2.3.1) could be considered during Step 3. For instance, prospective LCAs of emerging technologies could be more suitable for some DTs as they strive to account for variabilities in technological maturity levels (Moni et al., 2020; Pizzol et al., 2021).

3.3.1. *CADiS indicators*

The CADiS indicators consist of circularity (C) and life cycle impact assessment (LCIA) indicators - these can be considered separately, combined, or merged. As can be seen in Fig. 4, C indicators should ideally be merged during the LCIA of the digital service. Although recommended, this is currently not always possible due to methodological issues as currently LCA has as a reference a linear economy (Brändström and Saidani, 2022; Luthin et al., 2024). Therefore, C and LCIA indicators often fail to fully capture each other's scope (Harris et al., 2021; Picatoste et al., 2022). The CADiS framework addresses this by providing a structured approach to assess the environmental impacts of DTs and digital services holistically, helping designers align design choices with both circularity and sustainability. Importantly, when considering C and LCIA indicators measuring environmental impacts separately or combined, it becomes necessary to avoid double-counting of life cycle stage (s) and/or temporal scope - for more information please consult SI-2.3.

Table. 2
Descriptions of available quantitative indicators/metrics for assessing the circularity performance of digital services using the CADiS framework.

Circular economy strategies		Flow	Index/ indicator	Description	Reference
Narrowing	Refuse Rethink Reduce	Materials	REAPro	The "Resource Efficiency Assessment of Products" (REAPro) is designed to assess resource efficiency, focusing on identifying key areas of concern at the EoL of EEE. It provides quantitative indicators for reusability, recyclability, and recoverability (in both mass and environmental impact terms); and a qualitative assessment of the use of hazardous substances to inform eco-design measures. It includes a case study about LCD televisions.	(Ardente and Mathieux, 2014a)
			L & C	Sustainable resource use requires increasing both longevity (L) and circularity (C). Drawing from existing measures, the article develops and refines quantitative indicators for L and C based on refurbishment, recycling, and recovery considerations. A method using a matrix to integrate both indicators to bolster their effectiveness in resource sustainability during the eco-design phase of EEE is provided.	(Figge et al., 2018)
			Resource Pressure	The "Resource Pressure" proposes decision support focused on resource utilization using key CE parameters for guidance and an ex-ante assessment. The final quantitative indicator is based on six parameters (mass, product lifetime, manufacturing losses, primary material content, recyclability and cascadability) which can be estimated during the eco-design process of EEE.	(Desing et al., 2021)
			EoL index	Bridging the knowledge gaps between the EoL and design stage is crucial for integrating considerations into product development. This paper introduces the "EoL index", which analyses knowledge during this stage of EEE to assist designers in making informed decisions. Its application is illustrated through a case study on a power tool.	(Lee et al., 2014)
			WUE	The article evaluates the intricate realm of water usage within data centres, scrutinizing the current methods employed for measuring its consumption, including "Water Usage Effectiveness" (WUE). Furthermore, it explores ongoing initiatives and strategies aimed at curbing and optimizing water consumption in data centres.	(Mytton, 2021)
			MCI	The "Material Circularity Index" (MCI) for a product measures the extent to which linear flows have been minimised and restorative flows maximised for its component materials, and how long and intensively it is used compared to a similar industry-average product. It is essentially constructed from a combination of three product characteristics: the mass of virgin raw material used in manufacture, the mass of unrecoverable waste that is attributed to the product, and a utility factor that accounts for the length and intensity of the product's use.	(Ellen Macarthur Foundation, 2015)
			PCI	The "Product Circularity Index" (PCI) considers the life cycle of a product (including manufacturing efficiencies, longevity, second life and recycling) to provide a single circularity metric. In practice, it represents an improvement over the MCI by considering separate manufacturing steps to explore how the different restorative flows can re-enter the production chain at the appropriate stage. It is illustrated through a case study on washing machines.	(Bracquené et al., 2019)
		Energy	–	Increased durability in EEE does not necessarily guarantee improved environmental performance due to potential declines in energy efficiency over time and technological obsolescence. This article introduces a method for evaluating the environmental impact of EEE durability to ascertain whether extending its lifespan could yield substantial benefits across its life cycle. A case study involving washing machines is presented.	(Ardente and Mathieux, 2014b)
			PUE	This paper reviews existing approaches for evaluation metrics and methodologies to address the soaring energy consumption of data centres. It highlights the benefits and limitations of widely used metrics like "Power Usage Effectiveness" (PUE) and suggests a multi-metric evaluation approach to provide a more comprehensive understanding of data centre energy efficiency.	(Long et al., 2022)
			–	Traditional data centre HVAC frequently lacks efficiency because of inadequate control and awareness over airflow and temperature. Moreover, current optimization methods necessitate extensive prior simulations or experiments. This article introduces a mathematical model capable of accurately predicting temperatures in enclosed small data centres, offering a metric for potential improvement measures in terms of energy consumption of data centres.	(Moazamigoodarzi et al., 2020)
		Data	–	The exclusive focus on deep learning accuracy neglects economic and environmental considerations. To address this, this paper proposes recognition and training efficiency as universal metrics for assessing deep learning sustainability, considering factors like energy consumption and model complexity. These metrics enable standardized measurement and classification of models, libraries, and platforms, similar to ratings for EEE data narrowing.	(Lenherr et al., 2021)
Slowing	Reuse Repair Refurbish Remanufacture Repurpose	Materials	eDiM	Introduces the "Ease of Disassembly Metric" (eDiM) for estimating disassembly time using the Maynard Operation Sequence Technique (MOST). It considers a simple calculation sheet with six inputs that together with a database determine disassembly time, incorporating action sequences and essential product data. The article aims to ensure verifiability, making it suitable for inclusion in policy measures. It is illustrated using the case of an LCD monitor.	(Vanegas et al., 2018)
			LI	Unlike current approaches that evaluate resource usage based on value; the "Longevity Indicator" (LI) focuses on how long resources stay in use in EEE. It consists of three key components: initial lifetime, earned refurbished lifetime, and	(Franklin-Johnson et al., 2016)

(continued on next page)

Table. 2 (*continued*)

Circular economy strategies		Flow	Index/ indicator	Description	Reference
				earned recycled lifetime. This is illustrated through the example of precious metals in smartphones.	
			MDI	The “Material Durability Indicator” (MDI) integrates three primary factors: chemical durability, mechanical durability and environmental performance. Each factor encompasses a subset of engineering parameters or properties that are well studied and documented in the open literature. The MDI can be interpreted as a trade-off between chemical and mechanical durability, and environmental impacts associated with material generation, processing and recycling.	(Mesa et al., 2020)
			UOR-FRS	These two indicators, “in-Use Occupation Ratio” (UOR) and “Final Retention in Society” (FRS), focus on measuring the circularity of materials by quantifying their in-use occupation, which refers to the maintenance of materials in a useful state in products for as long as possible by avoiding dissipation or hibernation. They are illustrated through the assessment of a laptop.	(Moraga et al., 2021)
		Energy	–	–	–
		Data	–	The article explores the environmental sustainability of software products and introduces a causal model linking software use to its environmental impacts, with a focus on the entire software life cycle. It evaluates indicators based on criteria such as resource efficiency, hardware lifespan, and user autonomy in managing software resources.	(Kern et al., 2018)
Closing	Recover Recycle	Materials	ReSICLED	The “Recovery Systems modelling & Indicators Calculation Leading to End-of-Life-conscious Design” (ReSICLED) integrates recovery aspects into the EoL EEE design. It enables recovery-conscious designs in products by analysing existing methods and proposing the right improvements. The article provides simulation in real industrial practice to demonstrate significant gains in product recoverability.	(Mathieux et al., 2008)
			–	Eco-design for disassembly aims to lower the expenses involved during this stage, thus facilitating increased recovery and recycling of EEE and EECs. It provides eleven quantitative indicators (reusable parts; recyclable materials; reversible joints; same material joints; parts with labels; tools for disassembling; time for disassembly; intelligent materials; time for battery changing; laminated or compound materials; painted, stained, or pigmented surfaces) to improve eco-design measures. A case study about water source heat pumps is shown.	(Cerdan et al., 2009)
			–	The paper suggests expanding existing quantitative indicators for evaluating the performance of collection and recovery of WEEE based on their composition. The approach relies on three key parameters: monitoring WEEE flow, its composition, and assessing of recycling efficiency. A case study is shown about CRT screens and FDP displays in France.	(Horta Arduin et al., 2020)
			MMF	There is a need to identify and prioritize EECs with the highest potential value at the EoL of EEE considering both economic and environmental factors. To aid manufacturers in making optimal decisions at this stage, the paper introduces the “Multicriteria Matrix Framework” (MMF) to evaluate EECs based on residual value, environmental burden, weight, quantity, and ease of disassembly. It aims to minimize landfill waste by promoting reuse or recycling of components. A case study is shown involving a network terminal.	(Iakovou et al., 2009)
			RBR & CPI	These studies examine the “Recyclability Benefit Rate” (RBR) and “Circular Performance Indicator” (CPI) to quantify the environmental savings from recycling compared to virgin production and disposal. Applied to plastic waste recycling cases in Flanders, these studies analyse and evaluate closed-loop and open-loop recycling scenarios against incineration and landfilling routes.	(Huysman et al., 2015a, 2015b, 2017)
			MFA-WEE	The escalation of e-waste presents a significant challenge, and comprehensive data about its quantity and distribution are essential for effective management and environmental protection. This paper employs Material Flow Analysis (MFA) to systematically examine WEEE disposal patterns. The paper presents a case study of obsolete TVs originating from urban households in Vietnam.	(Tran et al., 2018)
			RDI	The “Recycling Desirability Index” (RDI) captures and quantifies four significant factors in product recycling: the simplicity of taking products apart, the material security index, the maturity of recycling technologies and the monetary value of materials. It is illustrated in the paper through its application to several EEE.	(Mohamed Sultan et al., 2017)
		Energy	CI	The “Circularity Index” (CI) is a simple ratio describing the combined effects of stock dynamics and dissipative losses. It can be used to quantify the energy required for material recovery relative to the energy required for primary material production from virgin ore. Accordingly, CI allows the analysis product circularity by considering quantity and quality losses when reprocessing materials.	(Cullen, 2017)
			Qc	Considering the quality of recycled products, functionality of substances, and mass balance, the “Circularity of Material Quality” (Qc) considers the net energy savings due to recycling primary material compared to the embodied energy of primary materials to identify the best strategies for life cycle management. The article contains an example of stainless steel recycling.	(Steinmann et al., 2019)
		Data	–	–	–
Regenerating		Materials	MEM	Existing metrics do not highlight the interplay between nano/micro (product), meso (industrial and urban symbiosis), and macro (continental to global) level circularity. Moreover, existing metrics do not capture all material loops and do not adopt a value chain perspective on material flows. To improve the connection between circularity metrics and environmental performance, the “Material Efficiency Metric” (MEM) is aimed at converting mechanisms of closing, narrowing and slowing material loops into a single-point value. As this metric covers these three CE	(Brändström and Eriksson, 2022)

(*continued on next page*)

Table. 2 (*continued*)

Circular economy strategies	Flow	Index/ indicator	Description	Reference
			strategies is it considered that it can facilitate (directly or indirectly) the regeneration of resource flows, it is included here.	
	Energy	–	–	–
	Data	–	–	–

CE: circular economy. CRT: cathode-ray tube. EEC: electric and electronic component. EEE: electric and electronic equipment. EoL: end of life. FDP: flat panel display. LCD: liquid crystal display. HVAC: heating, ventilation and air conditioning. WEEE: waste electric and electronic equipment.

3.3.1.1. *Circularity (C) indicators.*

The user of the CADiS framework can select the most suitable circularity metrics for the study from the available (or future) studies (see examples in Table 2, Section 3.2.2). Ideally, as mentioned earlier, the indicators should be assessed using the LCA methodology. However, they can also be assessed separately and later added to the LCIA indicators. Nonetheless, attempts are available in the literature to combine both approaches (Brändström and Saidani, 2022; Cilleruelo Palomero et al., 2024; Desing et al., 2021; Diez-Cañamero and Mendoza, 2023; Hatzfeld et al., 2022; Huysman et al., 2015b, 2017; Jerome et al., 2022; Luthin et al., 2024; Niero and Kalbar, 2019; Rigamonti and Mancini, 2021; van Stijn et al., 2021). The methodological findings from these studies can undoubtedly improve the identification of opportunities to mitigate environmental hotspots through technological and business model innovations fomented by CE strategies (ISO, 2024b; Mendoza and Pigosso, 2023; Ravikumar et al., 2024).

3.3.1.2. *Life cycle impact assessment (LCIA) indicators.*

The LCA methodology is divided into four main steps: i) goal and scope definition; ii) inventory creation; iii) impact assessment; and iv) interpretation (ISO, 2006a, 2006b). The goal and scope of the CADiS framework are defined according to each study. In this step, the functional unit is defined - a standardized measure used in LCA to compare the environmental impacts of products or services by focusing on the specific function they provide. It should be defined from the inventories in Step 1 and Step 2 and include all quantitative data on materials and energy consumption across the different system levels (e.g., nano/micro, meso, macro) and must align with the intended purpose of the digital service (see more info in SI-2.3.2). Regarding LCIA, the latest methodologies, such as ReCiPe 2016, provide up to 18 midpoint and three endpoint impact categories (Bueno et al., 2016; Huijbregts et al., 2017). Currently, efforts are being undertaken to incorporate planetary boundaries and more environmental impact categories (Bjørn et al., 2020; Guinée et al., 2022; Hellweg et al., 2023). Moreover, uncertainty analysis is an optional but recommended step in LCA for assessing the reliability of the LCIA results, ultimately enhancing its robustness and credibility (Igos et al., 2019). For instance, Clément et al. (2020) and Alcaraz et al. (2018) analyse the intricate interplay of materials, energy sources, production

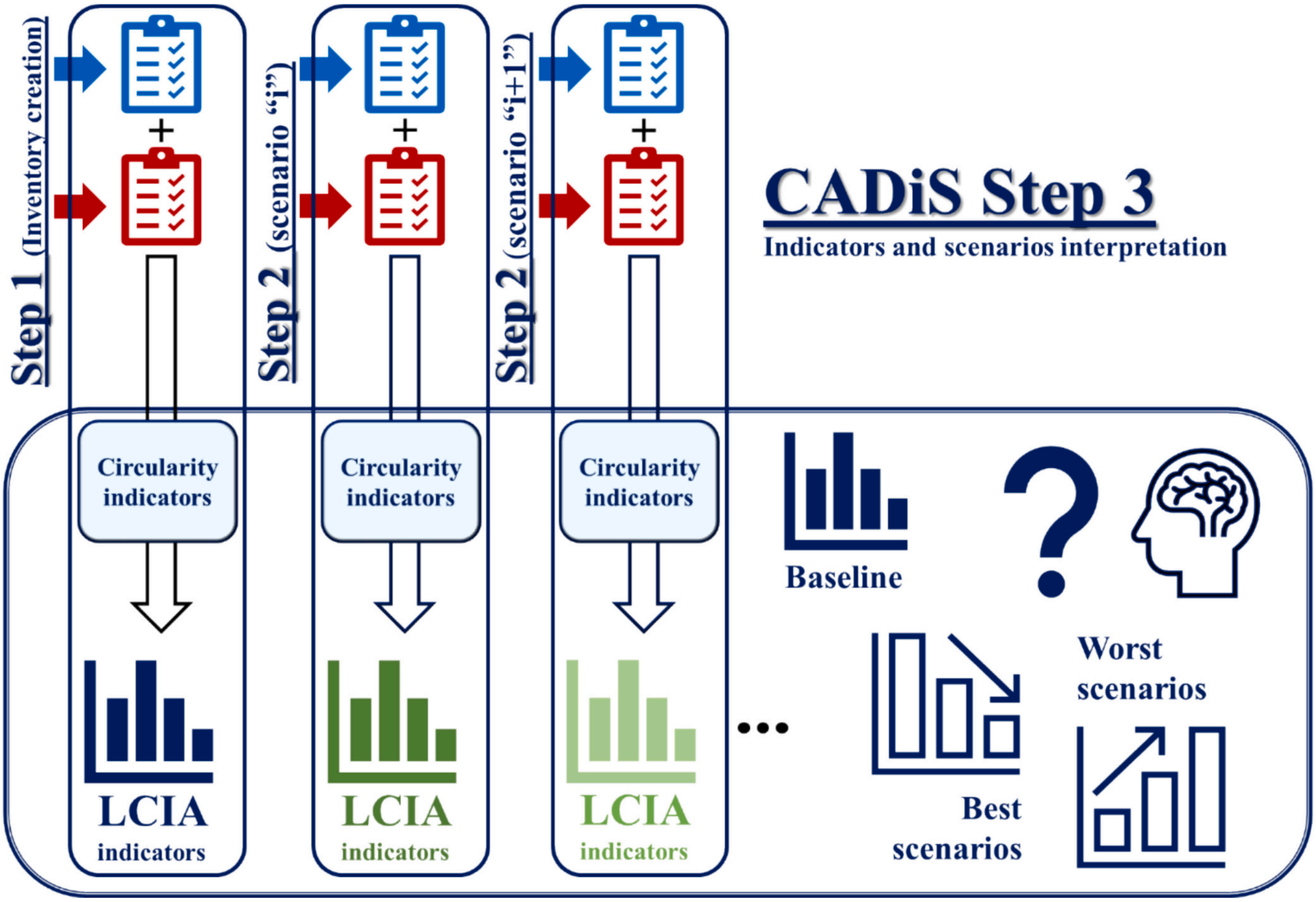


Fig. 4. Third step of the CADiS framework: calculation of indicators and interpretation of scenarios for circular strategies in digital services. For more details, refer to Fig. 1 and SI-2.3.

processes, and data quality in determining the outcome uncertainty of the life cycle environmental impacts of smartphones and tablets. For available life cycle impact categories and methodological considerations regarding the LCA of digital services, please refer to SI-2.3.2.

3.3.2. Scenarios interpretation

Interpreting the results of a LCA is an interactive process that involves all steps of the methodology. Typically, the main topics of interest include verifying data quality and assumptions (e.g., value choices, system boundaries, inventory completeness), identifying environmental hotspots, and comparing and analysing trade-offs among impact categories (EC-JRC, 2011; Zampori et al., 2016). In Step 3, users should also strive to understand the most effective and synergistic combinations of CE strategies to identify the best solutions for the digital service. This involves determining the most influential CE strategies and system levels, as well as identifying the environmental impacts stemming from materials, energy, and data management – to be reported in Step 4. Therefore, Step 3 focuses on identifying opportunities for C improvement by comparing the scenarios created in Step 2.

To identify the best scenario(s) and opportunities for circularity within the CADiS framework, users should engage in a process of eliminating the worst-performing scenarios based on the C and/or LCIA indicators mentioned earlier. In Step 2, the framework encourages users to make the most relevant circular modifications to the baseline inventory (Step 1), drawing on literature reviews, technical information, and expert input. In Step 3, a quantitative analysis is conducted to evaluate the scenarios by assessing their LCIA indicators (using end-point or mid-point categories, with the option to apply normalization and weighting) and considering or not circularity metrics. This process allows users to eliminate the scenarios that perform poorly in reducing environmental impacts, ultimately identifying the scenario(s) and circular opportunities that most effectively contribute to environmental sustainability.

3.4. Step 4: Recommendations

To promote environmental sustainability and integrate CE criteria into current and future digital services, along with associated sustainability policies, Step 4 of the CADiS framework can potentially offer valuable insights. In this step, interpretations originated from Step 3 are consolidated and organized to establish a systematic approach to unveil elements that can improve the environmental sustainability of the digital service after discussions with stakeholders (as outlined in Fig. 5).

Techniques such as multi-criteria decision analysis (MCDA) can provide weighting and screening of the best scenarios (and, therefore, the most efficient CE solutions) for the digital service, besides providing the integration of C and LCIA indicators (Luthin et al., 2024; Saidani et al., 2022; Saidani and Kim, 2022). In this regard, can be cited the work of Niero and Kalbar (2019) that considered the compensatory method Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) to couple C and lifecycle-based indicators to address the complexities of assessing beer packaging in the United Kingdom (UK) and Indian markets. Later, dos Santos Gonçalves and Campos (2022) provided a systematic literature review that highlights the role of multi-criteria methods in the evaluation of CE. The authors emphasize that these methods are essential for tackling the inherent complexity of circular systems, providing decision-makers with a structured approach to manage diverse criteria and stakeholder interests and preferences. More recently, Barrak et al. (2024) considered the non-compensatory method Elimination Et Choice Translating Reality (ELECTRE) to combine C and LCA, this time evaluating a novel building block.

Therefore, Step 4 serves as synthesis wherein recommendations are organized and reported according to the outlined below:

- Ranking of CE strategies: the results from Step 3 are methodically compared and ranked among themselves. This help in the alignment and prioritization of CE strategies, and thus enabling of synergies for advancing the environmental sustainability of the digital service. This might involve specifying the best overall scenario(s) according

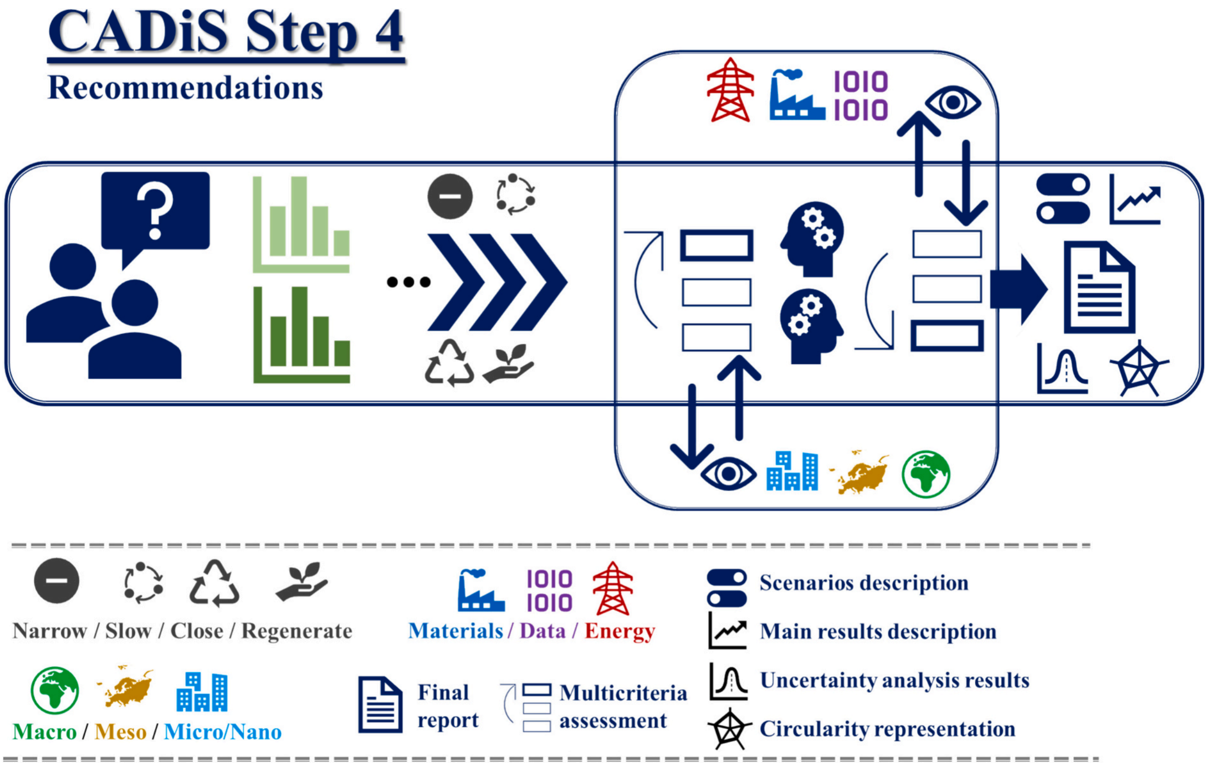


Fig. 5. Fourth step of the CADiS framework: recommendations for reducing the environmental impacts of digital services through the application of circular economy (CE) strategies. For more details, refer to Fig. 1.

to the most effective combinations of CE strategies or chosen MCDA method.

- Materials, energy, and data management considerations: understanding the environmental consequences of applying CE strategies to materials, energy, and data separately provides valuable insights for enhancing the circularity and environmental management of digital services. This detailed analysis offers a more nuanced perspective on environmental impacts and enables stakeholders to identify the most effective CE interventions for areas where the digital service has the greatest environmental footprint.
- System level considerations: the delivery of digital services can have infrastructure and environmental impacts that span from local to global scale. Recommendations should enable stakeholders to consider the full range of interactions and environmental impacts associated with different physical locations related to the provision of digital services. This underscores the need for a global perspective in sustainable development goals, particularly in the context of Global North-Global South relationships. By doing so, the recommendations can effectively address the extensive environmental and social implications of digital services while identifying potential pathways for value creation through the application of CE strategies.

3.5. Case study

To illustrate the steps of the CADiS framework, a case study is presented in Section 4 showcasing its application to a digital health and well-being service implemented in elderly living schemes (ELSs) in the UK. The eHealth service uses six types of electronic devices that enable residents to make video and audio calls, send and receive well-being notifications, and interact with other residents, visitors, staff, and offsite monitoring. These devices are interconnected and powered via Power over Ethernet (PoE) technology and linked to offsite monitoring through an internet router in the server room. The study included disassembling these devices to collect data on the EEE, supplemented by site visits and product manuals. To evaluate CE strategies, eight simple scenarios were developed aimed at improving the environmental sustainability of the digital service. Four scenarios focused on combining various circular strategies using a life cycle approach, while the other four specifically targeted eco-design measures to assess the circularity of the six electronic devices used in the service. The digital service and the infrastructure necessary to run it is described in Fig. 6.

4. Results for the case study

4.1. Step 1: Inventory creation

Step 1 started by disassembling the six electronic devices used for the digital service in the ELSs (LivingHub, Video deskphone, Door entry, Pendant, Handset, Base unit) to obtain information about their EECs, batteries, and other parts (Fig. 7). Additional information needed to complete the initial inventory of materials and energy for the digital service was gathered from site visits to three ELSs and manuals provided by the manufacturers of the remaining EEE (like those found in the server rooms - see scheme in Fig. 6). The final results of this step indicate that 285–375 g of EEE and 66.1–185.7 kWh are consumed annually to provide the digital service to an average resident. It is important to note that data management from internet use for this specific digital service was found to be negligible.

4.2. Step 2: Circularity study

Based on a literature review on the circularity of EEE, their energy use, and WEEE management (see Section 3.2.1), a total of eight hypothetical scenarios were created to test the best-performing one, and are described in Table 3. The scenarios in Step 2 cover different combinations of CE strategies using LCIA and C indicators at the nano/micro, meso, and macro levels - thus providing different perspectives on how to improve the environmental sustainability of the digital health and well-being service. Note that as the EU has increased recycling targets (European Commission, 2015; Shittu et al., 2021), the four scenarios evaluating LCIA indicators using CE strategies include the recycling of metals, PCBs and batteries (closing WEEE) (illustrated in Fig. 8). To evaluate the CE strategy of closing the material cycle for the six electronic devices, four C indicators related to eco-design measures were

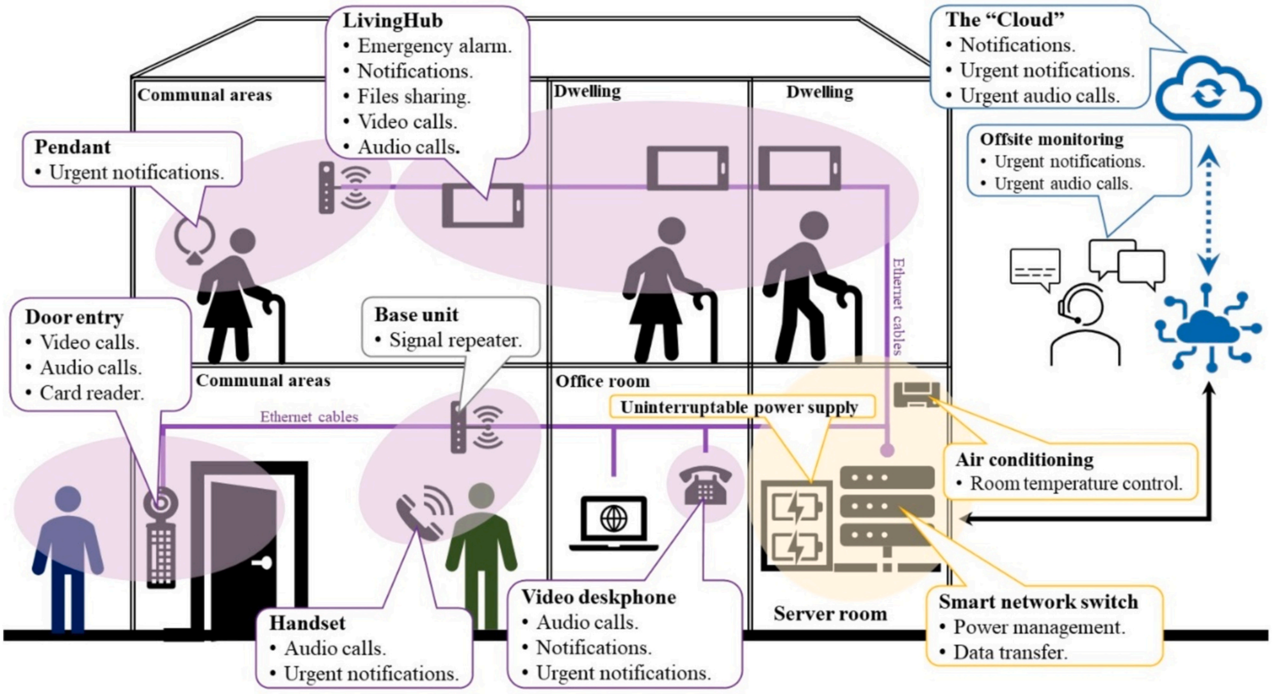
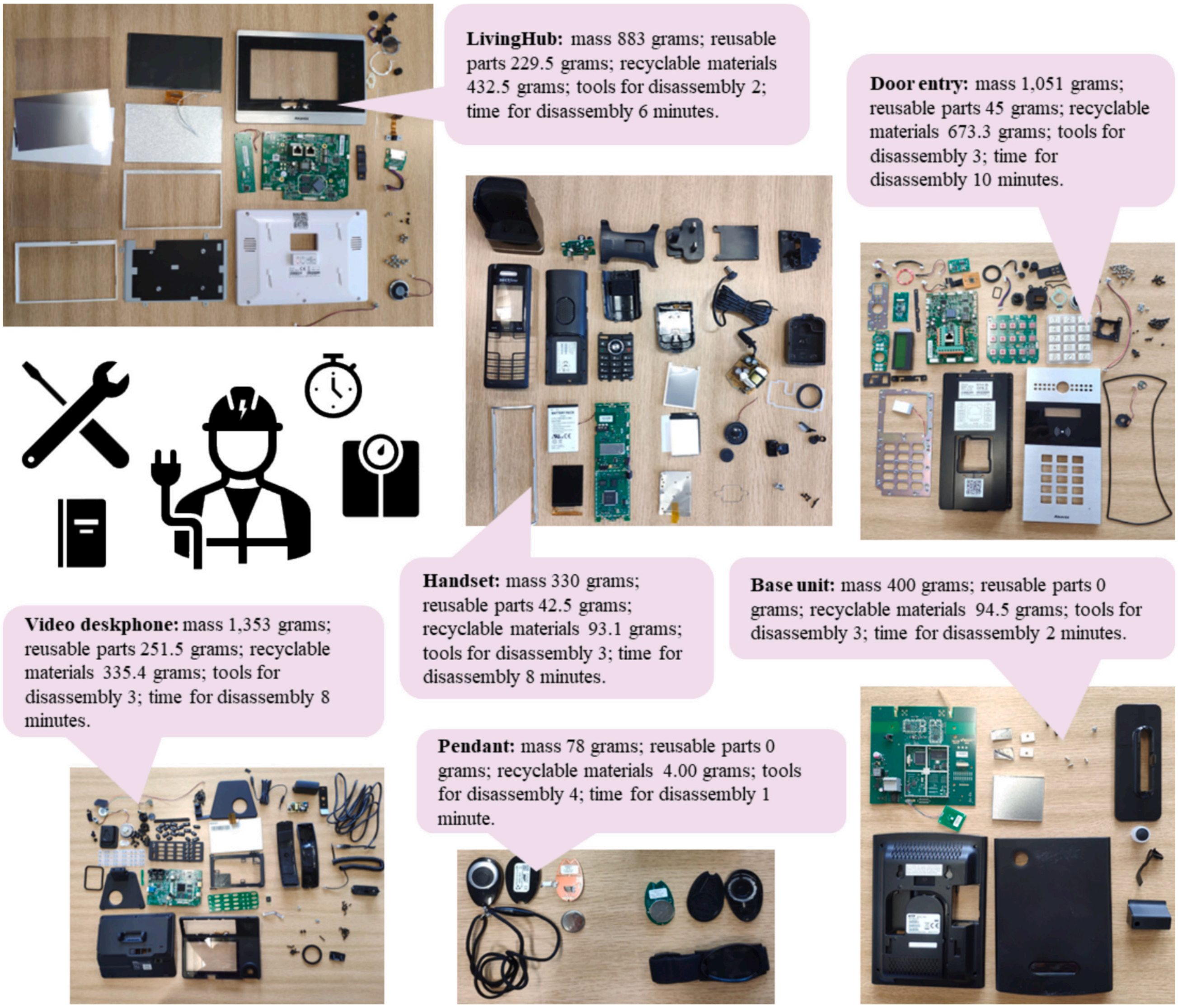


Fig. 6. Illustration of the digital health and well-being service in the elderly living schemes (ELSs) and the functions of the electronic devices (see details in Tarpani and Gallego-Schmid (2024)).



LivingHub: mass 883 grams; reusable parts 229.5 grams; recyclable materials 432.5 grams; tools for disassembly 2; time for disassembly 6 minutes.

Door entry: mass 1,051 grams; reusable parts 45 grams; recyclable materials 673.3 grams; tools for disassembly 3; time for disassembly 10 minutes.

Handset: mass 330 grams; reusable parts 42.5 grams; recyclable materials 93.1 grams; tools for disassembly 3; time for disassembly 8 minutes.

Base unit: mass 400 grams; reusable parts 0 grams; recyclable materials 94.5 grams; tools for disassembly 3; time for disassembly 2 minutes.

Video deskphone: mass 1,353 grams; reusable parts 251.5 grams; recyclable materials 335.4 grams; tools for disassembly 3; time for disassembly 8 minutes.

Pendant: mass 78 grams; reusable parts 0 grams; recyclable materials 4.00 grams; tools for disassembly 4; time for disassembly 1 minute.

Fig. 7. Main information gathered during the dismantling of the six types of electronic devices. For the complete initial materials and energy inventories of the digital service see Tarpani and Gallego-Schmid (2024).

chosen (these are considered separate from the LCIA indicators).

4.3. Step 3: CADiS indicators and interpretation

4.3.1. Calculation of the indicators

To assess both the baseline and the four scenarios with LCIA indicators, the functional unit is to “provide the digital service to an average resident for 20 years”, and the creation of the complete foreground inventory for the digital service can be consulted in Tarpani and Gallego-Schmid (2024). The ecoinvent v3.8 was used as the life cycle background database (Wernet et al., 2016) and the ReCiPe 2016 v1.06 methodology and its 18 mid-point categories (Huijbregts et al., 2017) considered as LCIA indicators. For the eco-design of the electronic devices, four C indicators were selected from Cerdan et al. (2009) (see Table 2 and calculations in SI-3.2). Both LCIA and C indicators are considered separately - note that modifications to the baseline inventory (Step 1) differ as C indicators are based on the proportion of total mass of reusable/recyclable materials, and tools and time for disassembly; while LCIA indicators are calculated through modifications to the baseline inventory in Step 2.

4.3.2. Results and scenarios interpretation

The average results from the three ELSs have been considered for the sake of simplicity, but the same procedure is valid to assess each one separately - for the granular interpretation of results and hotspots from the LCA of the digital health and well-being service see Tarpani and Gallego-Schmid (2024). Regarding LCIA indicators, the global warming potential for the baseline is 999 kg CO_2 eq. per resident. All scenarios showed improvements, ranging from slight (Sc3-close: 989 kg CO_2 eq. per resident) to significant reductions (Sc4-regenerate: 483 kg CO_2 eq. per resident) (see results for all 18 impact categories in Table S5). Overall, the LCA revealed that the primary contributors to the LCIA indicators are materials in PCBs (largely from impacts of global gold and silver production) and electricity consumption in server rooms (mainly for air conditioning, with most of the impact from natural gas and nuclear power plants). For C indicators, the results show that, on average, about 20 % of the mass of electronic devices is reusable, 43 % is recyclable, and it takes approximately 591 min to fully dismantle all electronic devices from a typical ELS (see the detailed results for LCIA and C indicators in section SI-3.2).

To readily identify which are the best scenarios among the LCIA and C indicators, a representation of the normalized results (higher results more preferable/circular – see SI-3.2) can be seen in Fig. 9. On the left,

Table. 3
Baseline and scenarios (and their respective circular economy strategies and system levels) considered for the CADiS framework assessment of the digital health and well-being service.

		CE strategies, system levels	Description
Assessed with LCIA indicators	Step 1 Baseline	Inventory creation	The baseline explores the materials, energy and data for the deployment and operation of the digital service. It does not encompass any CE strategy.
	Step 2 Sc1-narrow	Narrowing A/C use, micro Closing WEEE cycle, nano-meso	This scenario evaluates the life cycle environmental impacts of combining narrowing at the micro level (decrease the operation period of A/C units by 28 % in server rooms) and closing at the meso level (recycling all metals, printed circuit boards and batteries).
	Step 2 Sc2-slow	Slowing EEE use, micro Closing WEEE cycle, nano-meso	This scenario evaluates the life cycle environmental impacts of combining slowing at the micro level (increasing the lifespan of EEE by 20 %) and closing at the meso level (recycling all metals, printed circuit boards and batteries).
	Step 2 Sc3-close	Closing WEEE cycle, nano-meso	This scenario evaluates the life cycle environmental impacts of closing at meso level (recycling all metals, printed circuit boards and batteries).
	Step 2 Sc4-regenerate	Cleaner energy for EEE, macro Closing WEEE cycle, nano-meso	This scenario evaluates the life cycle environmental impacts of combining regeneration at the macro level (using cleaner electricity to power the EEE, i.e., the French grid) and closing at the meso-level (recycling all metals, printed circuit boards and batteries).
Assessed with C indicators	Step 2 Eco-1	Eco-design measures, nano	Eco-design measures for the electronic devices were assumed to result on average in a 5 % increase in reusable parts and recyclable materials, one less tool required for disassembly, and a 5 % decrease in disassembly time.
	Step 2 Eco-2	Eco-design measures, nano	Eco-design measures for the electronic devices were assumed to result on average in a 15 % increase in reusable parts and recyclable materials, one less tool required for disassembly, and a 15 % decrease in disassembly time.
	Step 2 Eco-3	Eco-design measures, nano	Eco-design measures for the electronic devices were assumed to result on average in a 25 % increase in reusable parts and recyclable materials, one less tool required for disassembly, and a 5 % decrease in disassembly time.
	Step 2 Eco-4	Eco-design measures, nano	Eco-design measures for the electronic devices were assumed to result on average in a 15 % increase in reusable parts and recyclable materials, one less tool required for disassembly, and a 15 % decrease in disassembly time.

A/C: air conditioning. CE: circular economy. EEE: electric and electronic equipment. EoL: end of life.

the normalized LCIA indicators for the baseline and four scenarios are compared using box plots. Sc1-narrow shows considerable improvement, with higher values and moderate variability. Sc2-slow demonstrates further improvement over Sc1-narrow, with a broader range but a higher median, indicating better life cycle outcomes for the digital service. Sc3-close exhibits less variability but significantly worse results compared to the other three scenarios, implying that closing the WEEE cycle alone presents notable disadvantages when compared to the other CE strategies. Sc4-regenerate has the second-widest range of values but the highest mean results, showing that regenerative approaches can significantly reduce the life cycle impacts of the digital service compared to baseline and the other three scenarios. The graph on the right is a bar chart showing the sum of normalized C indicators for four eco-design measures. Eco-1 has the lowest sum of normalized C indicators, meaning it performs the worst. In contrast, Eco-2 and Eco-3 have the highest values, indicating they provide the best performance in terms of the selected C indicators, with similar results for both. Eco-4 also performs well but is slightly below Eco-2 and Eco-3. This suggests that Eco-2 and Eco-3 could be more effective at improving eco-design of the electronic devices.

4.4. Step 4: Recommendations for the digital service

After verifying data quality, reporting environmental hotspots, and analysing significant trade-offs among the scenarios, Step 4 aims to communicate the main findings of the study to stakeholders and provide actionable recommendations for ensuring circularity, value creation and sustainability (see ISO (2024b) and ISO (2024c)). We do not present the MCDA in this step due to the simplicity of the case study; instead, we focus on presenting the main results and interpretations from Step 3 according to the commented in Step 4 (Section 3.4). Consequently, the recommendations for the digital health and well-being service are outlined as follows:

- Ranking of CE strategies: the results for Sc4-regenerate (cleaner energy for EEE at the macro level; closing WEEE at the meso level) is the most attractive CE strategy combination for the digital service. This is followed by Sc2-slow (slowing EEE use at the micro level, closing WEEE at the meso level). The combination of Sc1-narrow and Sc2-slow could be analysed to check if it would result in LCIA indicators comparable to Sc4-regenerate. For the C indicators, Eco-2 and Eco-3 have similar results.
- Materials, energy, and data considerations: the environmental impacts steamed from the materials in the EEE of the digital service are over 95 % from PCBs. Efforts should focus on reducing the amount of PCBs, extending their lifespan, and replacing them with greener alternatives (see Table S1). Further development of C indicators for the six electronic devices using LCA methodology could guide actions to identify which PCBs should be prioritized for recovery or recycling - see Cerdan et al. (2009), Vanegas et al. (2018), Desing et al. (2021) and van Stijn et al. (2021). The majority of the impacts from energy use stem from the air conditioning operation in the server rooms, and reducing their operating periods or moving the servers to locations requiring less HVAC (e.g., basements of the ELS) are potential options for decreasing the environmental impacts. Data management does not influence the results.
- System levels considerations: the digital service is provided at the nano/micro level to users in ELSs in the UK, with most of the environmental impacts coming from the materials used in PCBs and the energy required for air conditioning in the server rooms of the ELSs. However, its life cycle environmental impacts have macro consequences as the supply chain spans globally. In addition to impacts such as global warming and resource depletion potentials, several regions worldwide face consequences from local impacts originating from mining, beneficiation, and refining activities - primarily of gold,

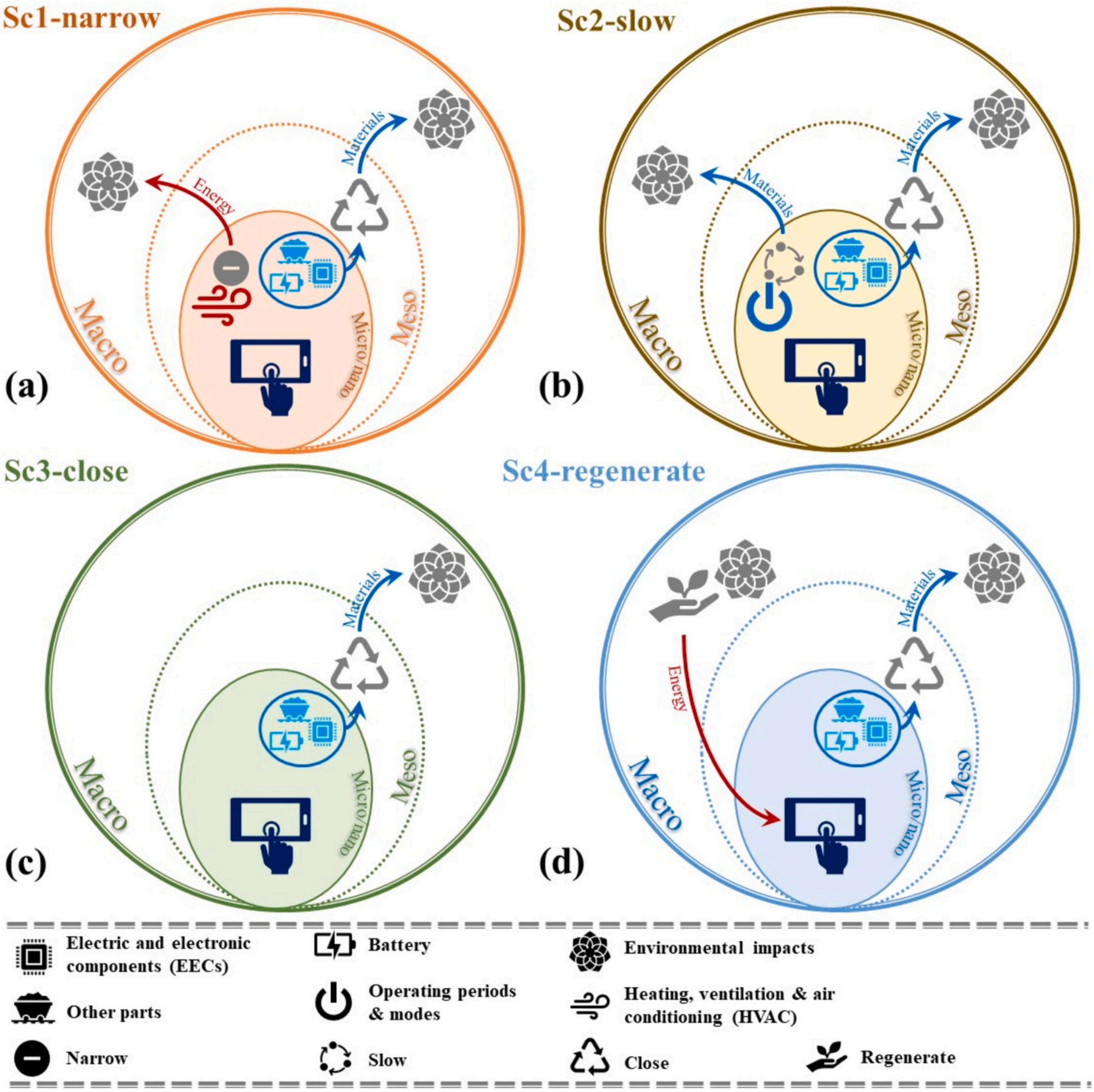


Fig. 8. Representation of the four scenarios for the assessment of CE strategies using LCIA indicators with the CADiS framework.

silver, copper and hard coal - in countries like Australia, Brazil, Canada, Chile, China, Mexico, Peru, Russia, and the United States.

5. Discussion

The CADiS framework developed in this paper aims to promote sustainability in the digital services sector. It provides insights, guidance, and a systematic approach to assessing and improving the environmental performance of digital services through CE criteria. This is because, even though digitalization can promote "smart" solutions (Mondejar et al., 2021), it is crucial to evaluate them from a global and life cycle perspective due to the environmental impacts stemming from the growing number of EEE (e-waste generation is predicted to exceed 74 Mt. by 2030) and the intensity of energy consumption required for internet provision (about 10 % of global electricity consumption and growing) (Forti et al., 2020; Sovacool et al., 2022). In the UK, the National Health Service (NHS) has been working since 2008 to achieve its climate change reduction goals, and digitalization is expected to play a major role in this regard (Bloomfield et al., 2021; Gray, 2022; Tennison et al., 2021). This include eHealth services aimed at the growing ageing population due to high costs, shortage of professionals, and other concerns such as cultural barriers and regulatory challenges (Awad et al., 2021; Oderanti et al., 2021). The results obtained from applying the CADiS framework to evaluate a digital health and well-being service in the UK demonstrate its role in guiding the eHealth sector towards sustainability and circularity.

Digitalization is also expected to play a crucial role in raising public awareness of environmental issues and promoting pro-environmental behaviours and policies, particularly when interventions are adapted to regional socioeconomic contexts. However, its ability to support the CE and reduce overall environmental impact remains uncertain (Zhang and Gong, 2023). In this regard Santarius et al. (2023a, 2023b) propose an approach that moves beyond mere efficiency and consistency, introducing the concept of "digital sufficiency," which aims to reduce resource and energy demand while maintaining the benefits of digitalization. The concept revolves around four interconnected dimensions: hardware sufficiency (sustainable production and usage of hardware); software sufficiency (optimize software to minimize energy consumption); user sufficiency (responsible and conscious user behaviour); and economic sufficiency (addressing the underlying economic structures

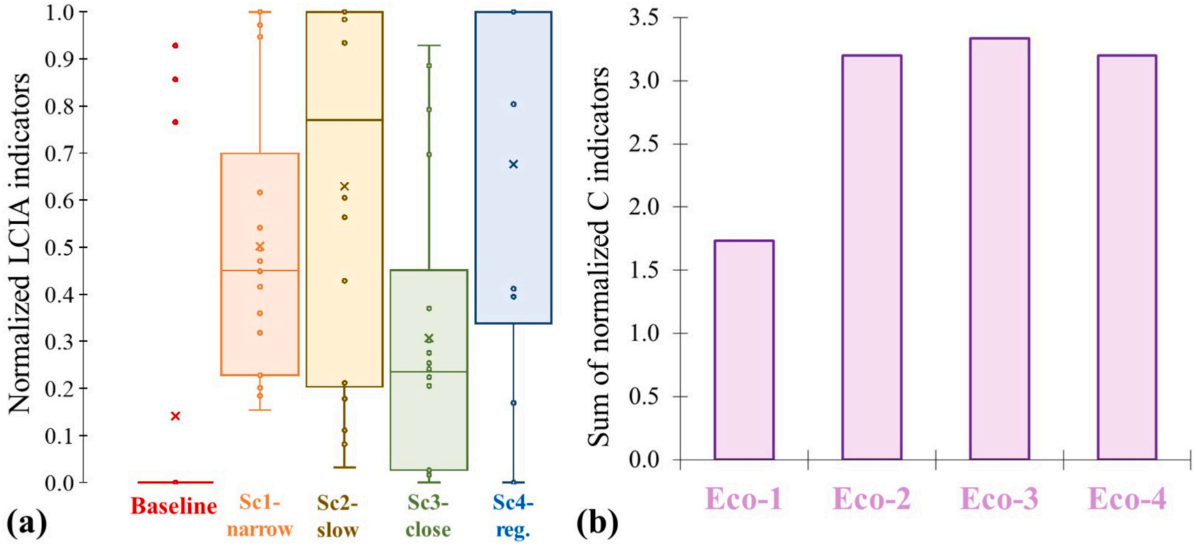


Fig. 9. Examples of visual representations of the CADiS framework results. (a) Box plots of the normalized results for LCIA indicators for baseline and the four scenarios. (b) Sum of the normalized C indicators results for eco-design measures in the six electronic devices. See the description of the scenarios in Table 3.

that drive ICT use). Therefore, the CADiS framework surely can provide valuable guidance on how to realize digital sufficiency.

Future advancements in the CADiS framework can be summarized in four main topics. The first one is the development of a comprehensive set of C indicators related to digital services, addressing the current limitations in assessing the circularity of energy use and data management (see Table 2 in Section 3.2.2). The second is to incorporate research on the merging of C and LCIA indicators to better assess digital services. This would greatly enhance the understanding of the environmental benefits, burdens and trade-offs associated with implementing CE strategies aimed at slowing and closing material loops considering different time and spatial dimensions (Section 3.3.1). The third recommendation involves establishing robust, structured, and regularly updated life cycle background databases that cover a wider range of processes tailored for or associated with digital services. This might include unit processes to address the manufacturing, operation, and EoL stages of more EEE and EECs; the energy consumption and infrastructure related to the internet (such as submarine cables, phone towers, and global data centres); or possibly adding processes related to data management (e.g., storage, encryption, cloud computing). Lastly, it is crucial to consider rebound and push effects in the development of the CADiS framework. Understanding and addressing these effects are essential for the long-term sustainability of circular initiatives within digital services given their disruptive nature and global socioeconomic implications. More details on these topics can be found in SI-4.

6. Conclusions

As digital technologies (DTs) and digital services become deeply integrated into our daily lives, their potential to contribute to sustainable development is increasingly being acknowledged. However, the environmental impacts (e.g., global warming potential, resource consumption, habitat destruction) associated with these technological advancements are often underestimated or overlooked, hindering the ability to assess their sustainability accurately. To address these challenges, adopting circular economy (CE) strategies presents a promising solution to mitigate their negative environmental consequences. This paper introduces the Circular strategy Assessment for Digital Services (CADiS) framework to illuminate the role of CE principles in reducing the environmental impacts of digital services throughout their lifecycle. It offers users and stakeholders a structured yet flexible approach to evaluating simultaneously environmental impacts and circularity by considering several circularity (C) and life cycle impact assessment (LCIA) indicators, which can be considered separated, combined, or merged. The CADiS framework, therefore, facilitates informed decision-making by pinpointing areas for enhancing digital services across nano/micro, meso, and macro levels and can promptly identify the most effective scenarios and CE strategies. In doing so, stakeholders can navigate the complexities inherent to digital services while aligning them with sustainable development goals.

As digitalization exerts its various facets in different regions of the world, the importance of the CADiS framework becomes increasingly evident, emerging as a timely framework for conducting thorough environmental assessments of the circularity of digital services. Through a case study on eHealth service provision in elderly living schemes in the United Kingdom, we demonstrated the applicability of the CADiS framework and its significance for the healthcare sector. Our findings emphasize the importance of incorporating regenerative and cleaner energy sources and implementing material loops to enhance circularity and reduce environmental footprints. Moreover, it is important to acknowledge the global ramifications of the life cycle impacts of the digital service, particularly concerning energy consumption for server rooms and production of gold, silver, and copper used to manufacture the printed circuit boards.

CRediT authorship contribution statement

Raphael Ricardo Zepon Tarpani: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Joan Manuel F. Mendoza:** Writing – review & editing, Writing – original draft. **Laura Piedra-Muñoz:** Investigation, Writing – review & editing. **Alejandro Gallego-Schmid:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization.

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.

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Appendix A. Supplementary data

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