Semantic Web and its Role in Facilitating ICT Data Sharing for the Circular Economy: State of the Art Survey

Anelia Kurteva *, Kathleen McMahon, Alessandro Bozzon and Ruud Balkenende
Industrial Design Engineering Faculty, Delft University of Technology, The Netherlands
E-mails: a.kurteva@tudelft.nl, k.s.mcmahon@tudelft.nl, a.bozzon@tudelft.nl, a.r.balkenende@tudelft.nl

Abstract. The exponentially growing digitisation of services that drive the transition from industry 4.0 to industry 5.0 has resulted in a rising materials demand for ICT hardware manufacturing. The environmental pressure, CO_2 emissions (including embodied energy) and delivery risks of our digital infrastructures are increasing. A solution is to transition from a linear to a circular economy (CE), through which materials that were previously disposed of as waste are re-entered back into product life-cycles through processes such as reuse, recycling, remanufacturing, repurposing. However, the adoption of the CE in the ICT sector is currently limited due to the lack of tools that support knowledge exchange between sustainability, ICT and technology experts in a standardised manner and the limited data availability, accessibility and interoperability needed to build such tools. Further, the already existing knowledge of the domain is fragmented into silos and the lack of a common terminology restricts its interoperability and usability. These also lead to transparency and responsibility issues along the supply chain. For many years now, the Semantic Web has been known to provide solutions to such issues in the form of ontologies and knowledge graphs. Several semantic models for the ICT, materials and CE domains have been build and successfully applied to solve complex problems such as predictive maintenance. However, there is a lack of a systematic analysis of the existing semantic models in these domains. Motivated by this, we present a literature survey of existing ontologies for ICT, materials and the CE, their possible applications, limitations and current CE standardisation efforts that can help guide its further implementation.

Keywords: Ontology, ICT, Materials, Circular Economy, Data Sharing, Sustainability

1. Introduction

Facing global issues surrounding resource scarcity, energy consumption and carbon emissions, and ever growing waste streams, there is an increase in societal and governmental focus on solutions that rethink the current linear economic structure. One such solution that has seen legislative progress over the last decade in particular is the idea of a circular economy (CE) [1], commonly understood to be a model through which materials that were previously disposed of as waste are re-entered back into product life cycles through operations (or strategies) such as reuse, recycling, remanufacturing, and repurposing. Figure 1, which is an adaptation of the CE Butterfly[1] diagram by the Ellen MacArthur Foundation[2], visualises the possible circular strategies that can be used for products and materials. The maintenance phase includes all monitoring, software upkeep, cleaning, and minor repairs necessary

*Corresponding author. E-mail: a.kurteva@tudelft.nl.
[1]https://ellenmacarthurfoundation.org/circular-economy-diagram
[2]https://ellenmacarthurfoundation.org

1570-0844/$35.00 © 0 – IOS Press. All rights reserved.

over the use phase of a product. This phase occurs simultaneously with the use cycle and has a direct impact on its lifetime by allowing the maintainer to proactively catch and prevent major failures. Reuse and redistribution occur when the product owner has decided that the product has reached its end of first use, but the product is in (or can be returned to) good working condition. The product owner can, for instance, choose to redistribute the device to another internal department or otherwise sell or donate the device for reuse elsewhere. Organisations such as the Toronto Tool Library[3] provide a centralised subscription-based access to an inventory of various tools. Refurbishment and remanufacturing also occur at the end of first use. However, the product is usually relinquished back to the producer, supplier, or an ICT asset disposition company where it will undergo functionality and safety testing and may undergo data wiping, repairs or parts replacement, upgrades, and cosmetic touch ups. The product is generally returned to a *"like new"* condition for resale. Recycling occurs when the product owner decides the product has reached its end of life, where the product will no longer be used and becomes waste. The decision of when a product has reached end of life is made by the product owner and does not necessarily denote the end of the product's functional usability. The recycling process involves the dismantling of a product, through mechanical or chemical means, down to its smallest possible constituent parts with the intention to reuse these recycled materials. Current recycling processes are often technologically limited in how efficiently they can recover pure, undegraded materials. Finally, the molecular decomposition phase occurs where biodegradable materials, such as bio-based plastics, are broken down to a molecular level.

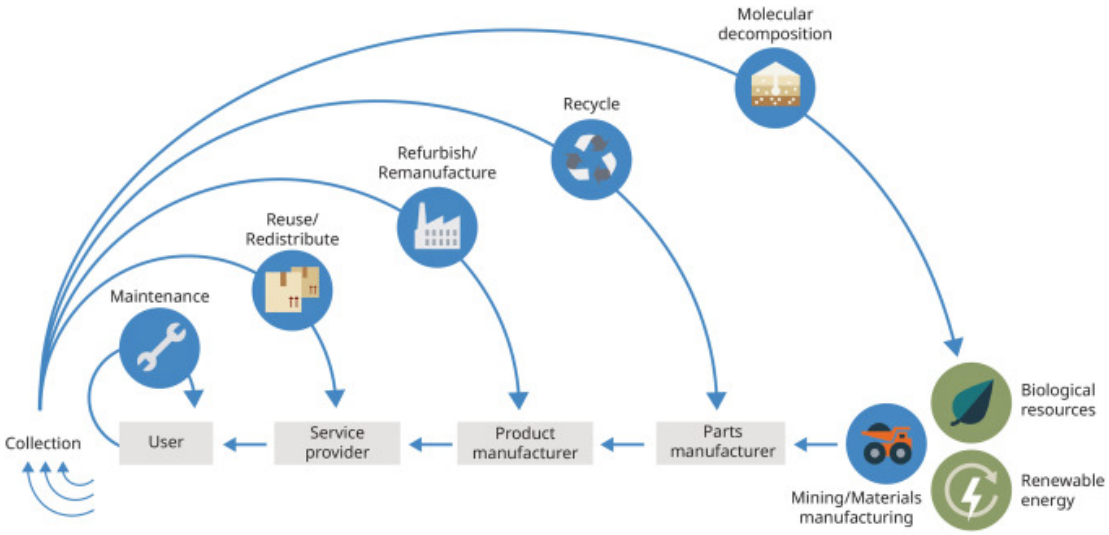

Fig. 1. Circular Strategies for Products and Materials [2]

Information and communications technology (ICT) (e.g. laptops, smartphones, data servers), is a major stream of focus in the CE due to its increasing impact on the environment, society, and the economy [3][4]. The increasing digitisation and unprecedented amount of data that is generated on a daily basis has resulted in ICT hardware such as laptops, smartphones and data servers are being used on average for 3 and 4-5 years [5] respectively, while research shows that they should last 7 years before they are replaced [6]. Based on this, at its current state, the ICT sector is not sustainable as there is a discrepancy between the economic lifetime and technical lifetime of ICT hardware. The results is short lifetime replacement cycles that increase the carbon footprint. Further, it is responsible for 2.1%–3.9% of the global greenhouse gas emissions [7]. The composition of ICT hardware alone, made up of varying combinations of critical raw materials, makes an interesting and important case for the growing CE [8]. Access to these materials is often fraught with complications relating to limited natural supplies, difficult geographic deposit locations, and precarious political agreements. The issues surrounding ICT hardware continues to follow the product

[3]https://www.torontotoollibrary.com

through its life-cycle impacting the health and safety of mining communities and their surrounding environments, intense energy consumption (see [9]) and CO_2 emissions during manufacturing, further impacting environmental and human health at end of life as a hazardous waste, and resulting in the loss of financially and otherwise valuable materials through disposal and inefficient recycling technologies. The CE seeks to address these issues through both product lifetime extension, i.e., keeping the materials in their original product longer, closing resource loops, and through the reuse or re-purposing of products, product components, and materials.

However, the adoption of the CE in the ICT sector is currently limited. An ICT device such as a laptop comprises of multiple components (e.g. display screen, keyboard, base panel, top panel, cooling fan, RAM, hard disk, palm rest assembly, battery, hinges, speaker, optical drive, antenna). Each component has sub-components such as sensors and specific material composition. When a product needs to be refurbished, repaired, remanufactured it has to go through multiple processes (e.g. hardware and software testing). Testing can be standardised via tools such as Aiken[4] and/or personalised based on the model and manufacturer of the product and the needs of the end-users. In such cases, unprecedented amount of heterogeneous data about both the product itself and the testing performed on it are being generated, which is expensive with regards to the computational power needed to generate, process, store and maintain data.

Another barrier is the lack of information and knowledge about circular solutions among ICT decision-makers within industry and academia. In organisations many departments (e.g. sales, IT, finance, delivery) are involved in the decision making-process for the implementation of ICT environments, which results in misleading, inaccurate, or incomplete data and information on how to interpret the data (also discussed in [10]). For example, the production of an iPhone involves more than 200 component suppliers, spread over 43 countries and 6 continents [11]. Each supplier has specialised knowledge about their products such as their material composition, design and the used technology. Such information is rarely available to end users and decision makers. This additional concerns due to the lack of transparency and traceability along the resulting fragmented data value chain. Although, several studies such as [3] [12], have made ICT products' material information public in the form of a bill of materials (BoM), it is challenging for a non-expert in the domain to interpret it and make truly informed and impactful sustainability decisions. These are also obstacles that affect the development of technology that aims to support ICT decision making in cases such as predictive maintenance and sustainable procurement (i.e. the process of obtaining goods or service for a business) recommendations. Further, with the transition from industry 4.0 to 5.0, having meaningful data is essential as it can not only drive the automation but also the optimisation of services (in terms of computational costs and even energy consumption [13]). As discussed in [14], to gather and process such data, collaboration between different domain experts from the ICT, materials and sustainability domains is needed.

The Semantic Web can provide a findable, accessible, interoperable, reusable (FAIR) solution to these challenges in the form of ontologies that can technologically drive the data FAIRification [15] process (see Table 1). Through the years, research has shown the benefits of ontologies for solving the issues of data heterogeneity, interoperability, misinterpretation and lack of contextual meaning has been the main aim [16][17][18][19][20][21]. Further, ontologies can successfully assist machines in various decision making scenarios such as recommendations [22][23][24], legal compliance [25][26][27] [28], predictive maintenance [29][30][31][32], tourism [33], chemical safety and drug design [34] and intelligent surveillance [35]. This is due to ontologies' ability to enrich data with context and provide information in a machine-readable format. Further, both organisations and individuals can benefit significantly from the utilisation of ontologies, which help establish common understanding (i.e. unified vocabulary of real world concepts and their meaning) of a domain. From technology perspective, to be able to deal with the unprecedented amount of heterogeneous data when developing CE sustainability assisting tools, especially for ICT data sharing, more and more experts have been utilising the Semantic Web. As a start, the focus has been on building simpler knowledge organisational systems such as taxonomies. However, there has been a rise in building and utilising more complex linked data models such as ontologies and knowledge graphs (see [36][37][38]). *"Linked Data can function as an exchange medium for the CE driving the "push and pull" between diverse industry resources."* [39]. However, there is a lack of systematic semantic analysis (i.e. discussion on the mechanisms used for building the model, the

[4]https://aikensoftware.com

Table 1
FAIR Principles, ICT Challenges and the Semantic Web

FAIR Principle	Current ICT and CE Challenges	Semantic Web Solution
Findable	Lack of available information and knowledge about circular solutions among ICT decision-makers.	Ontologies, as a technology, can be used to support the discovery of new and traceability of existing information in the ICT and CE domains via the interpretation of the URIs defined for each concept.
Accessible	Many departments (e.g. sales, IT, finance, delivery) are involved in the decision making process for the implementation of an ICT environment, which results in knowledge silos. Only authorised individuals can access specific data.	Ontologies help integrate disparate silos of data by defining a unified terminology of a domain, which represents all of the involved entities (people, organisations, software) their specific roles, access rights etc.
Interoperable	It is challenging for a non-expert in the domain to interpret materials and ICT data and make truly informed and impactful sustainability decisions.	Ontologies transform data into information through the use of RDF triples and URIs and represent it in a machine interpretable format. This can help build more intelligent tools (with artificial intelligence) to support informed human-decision making in the CE.
Reusable	Lack of standardisation and documentation that is publicly available. Data from one silo/department has to be translated and interpreted when used for other purposes by another department. For example, data on existing laptop types in use by an IT department of some organisation might be made available for the purpose of adopting CE strategies by the procurement department. However it first needs to be accessed, interpreted and translated for the purpose of circular decision making.	An ontology can be used as a standard unified data model within an organisation to showcase (in one place) what data is used and is needed for specific processing (e.g predictive-maintenance). As a recommendation, an ontology should be documented and can be publicly available to support its reusability (a recommended principle for ontology engineering) and extension.

followed linked data principles, the scope and guidelines towards their reuse) of the existing ontologies for ICT data and materials and their relation to the CE domain.

This paper presents a systematic analysis of ontologies for the CE domain with specific focus on ICT and materials modelling. The main use case that motivated our work is the increasing use and manufacturing of ICT devices such as laptops and the associated ecological footprint. The paper is aimed at motivating and assisting ontology engineers in selecting ontologies (e.g. classes and sub-classes) for reuse or extension, when building semantic technology-based tools for the CE. Our work also presents an overview of tools in the domain that utilise semantic technologies. By analysing the state-of-the-art, we provide guidelines for building and utilising ontologies for advancing the implementation of the CE. We believe that our work is also helpful for non-experts knowledge engineers as it presents the successful utilisation of the Semantic Web for ICT and material data sharing in the CE. Finally, we present a discussion on existing CE standards and their possible future effect on technology.

The rest of the paper is structured as follows. Section 2 outlines the followed methodology, while Section 3 presents a set of requirements used for the selection and analysis of relevant existing semantic models. Section 4 presents an overview of existing semantic models in the ICT, materials and CE domains. The section also presents CE tools that utilise Semantic Web technologies. The analysis of the related work is presented in Section 5. Section 6 discusses current CE standardisation efforts followed by the conclusions in Section 7.

2. Methodology

To compile this paper, guided by our previous survey in the Semantic Web domain (see [40]), we followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) [41] methodology, which focuses on transparent reporting of systematic reviews and meta-analyses. We undertook several steps which are presented on Figure 2. We begin with a research of the CE, understating its objectives and the current technological and non-technological barriers to its wider implementation. Next, in Step 2, we looked into the benefits of the Semantic Web for the CE and derived a set of requirements (for an ICT ontology for the CE) in the form of competency questions. Step 3 and 4 focused on collecting and analysing relevant existing work. Next, in Step 4, we present the current

state of CE standards that could help drive the future implemetation of the CE with ontologies furter. The final step focuses on summarising the findings and leading the future work discussions.

The main sources of information were peer-reviewed scientific publications in the CE, ICT and Semantic Web domains, which we identified via Google Scholar[5], ACM Digital Library[6], IEE Xplore[7], Scopus[8] and DBLP[9]. A search for resources was also performed on the websites of standardisation bodies such as the British Standards Institution (BIS)[10], the EU Commision[11], the International Electrotechnical Commission (IEC)[12] and the International Organisation for Standardisation (ISO)[13]. Some of the main keywords used were *CE, CE ontology, ICT ontology, ICT data sharing, critical materials, materials ontology, CE standards and CE tools*. Inputs have also been gathered from the authors' involvement in CE projects such as RePlanIT [14] and data-driven project such as CampaNeo[15], smashHit[16], KI-NET[17].

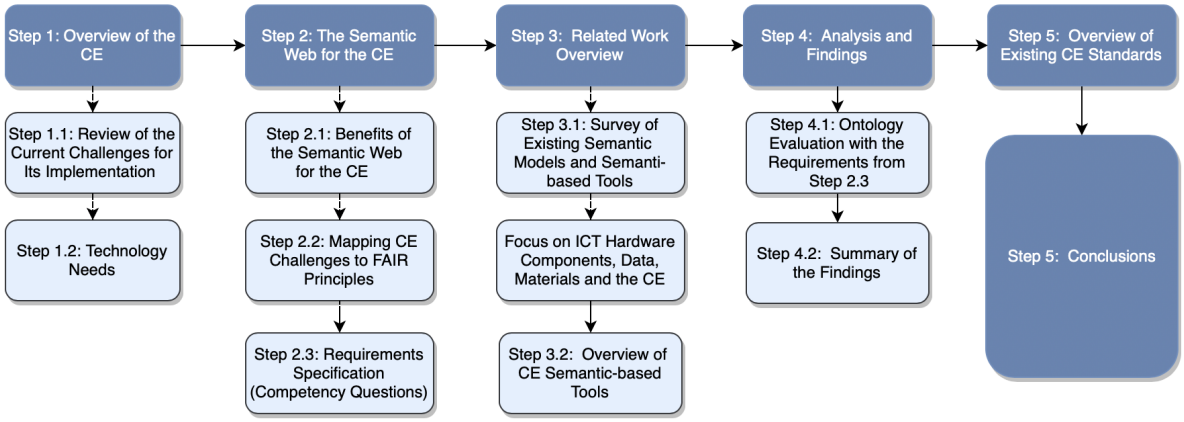

Fig. 2. Survey Methodology

3. Requirements for an ICT Ontology for the CE

To illustrate the complexity of interlinking the ICT, materials and CE domains we present a graphical representation on Figure 3 of and ICT device's life-cycle in terms of the recorded history. An ICT device (e.g. a laptop) can be represented in terms of the components that it is comprised of. Each component has history, which is a record of its material, computational and physical properties and changes in them that have occurred as a result of an implemented CE strategy. ICT and materials provenance and lineage is vital for supporting product life-cycle assessment [42][43]), establishing responsibility along the supply chain and for implementing CE strategies such as predictive maintenance.

[5]https://scholar.google.com
[6]https://dl.acm.org
[7]https://ieeexplore.ieee.org/Xplore/home.jsp
[8]https://www.scopus.com
[9]https://dblp.org
[10]https://www.bsigroup.com/en\protect\discretionary{\char\hyphenchar\font}{}{}GB/
[11]https://digital-strategy.ec.europa.eu/en/policies/
[12]https://www.iec.ch/news-resources/reference-material#codes
[13]https://www.iso.org/home.html
[14]https://www.ams-institute.org/urban-challenges/circularity-urban-regions/circular-resource-planning-for-it-replanit/
[15]https://projekte.ffg.at/projekt/3314668
[16]https://smashhit.eu
[17]https://ki-net.eu

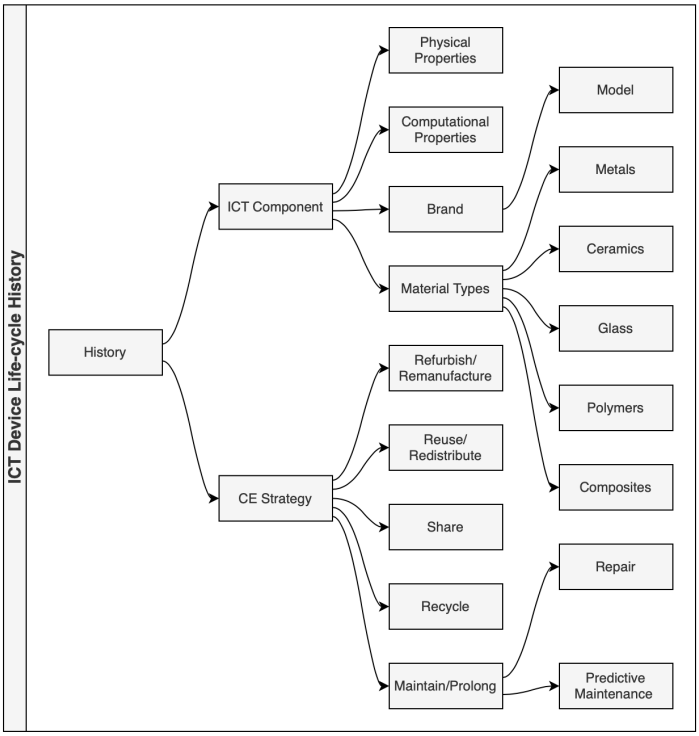

Fig. 3. Conceptual Model for an ICT Device Life-Cycle

Based on this and on our collaboration with the refurbishment industry, we present a set of competency questions (Table 2), which will be used for the evaluation of the existing ontologies outlined in Section 4. The main use case that the competency questions address is ICT devices (i.e. laptops) data sharing for the CE. Table 2 presents a competency questions for (i) ICT devices (e.g. laptops), (ii) ICT device's components (common in various ICT devices such as laptops), (iii) physical properties of ICT devices and their components such as weight, age, warranty duration, usually (specified by a manufacturer but can be updated after a CE strategy such as refurbishment is used) (iv) computational ICT properties that are the result of a process and/or analysis (e.g. energy consumption, CO_2 emissions), (v) material properties of ICT devices and (vi) CE strategies that can be adopted. For each question, we have derived the key concepts that an ontology should represent to answer it.

Table 2: Competency Questions for an ICT, Materials and CE Domains Ontology

No	Question	Key Concepts
ICT Device		
Q1	What is the type of the ICT device?	Laptop, data server, router, switch
Q2	What is the brand of the device?	Brand
Q3	What is the brand model of the device?	Device, Brand, model
Q4	Where was the device assembled?	Device, Location, country, state, region, city
Q5	When was the device assembled?	Device, assembly date, year, date, time
Q6	Who owns the device?	Device owner, organisation, person
Q7	Who provides the hardware?	Device provider, organisation, person

Q8	What is the status of the device? Has it been reused, remanufactured, or refurbished before?	Device, status, refurbished, remanufactured, repaired, reused
Q9	What is the device's grade after refurbishment, repair, remanufacturing?	Grade, pristine, damaged, damage level, damage type
Q10	What are the components of a device?	Device, components, hardware, software
Q11	What is the device's operating system?	Device, operating system
ICT Device Components		
Q12	What is the serial number of the component?	Component serial number
Q13	What is the brand of the component?	Component, brand
Q14	What is the brand model of the component?	Component, brand, model
Q15	What is the type of the component in terms of its location within a device?	Device, component, peripheral (i.e. external), integrated
Q16	What is the status of the device's component? Has it been reused, remanufactured, or refurbished before?	Component status, refurbished, remanufactured, repaired, reused
Q17	Why was the component reused, remanufactured, repaired or refurbished before?	Component, circular strategy, repair, remanufacture, refurbishment, reason
Q18	What is the current age of the component?	Component age, year, month, day
Q19	What type of network card is used?	Network card, type, brand, model
Q20	What type of chipset is used?	Chipset, type, brand, model
Q21	What type of expansion slots are used?	Expansion slot, type, brand, model
Q22	What type of storage is used?	Storage, type, brand, model
Q23	What is the display type?	Display, type
Q24	What is the display's resolution?	Display, resolution
Q25	What is the device's screen-to-body ratio?	Device, screen-to-body ratio
Q26	What type of sound card is used?	Audio, sound card, type
Q27	What type of keyboard is used?	Keyboard, type
Q28	What type of pointing device is used?	Pointing device, type
Q29	What type of wireless technology is used?	Wifi technology
Q30	What type of battery is used?	Battery, type, alkaline, NiCad, Li-Ion
Q31	What types of USB ports are used?	USB port(s), type

Q32	What type of camera is used?	Camera, type, brand, model
Q33	What types of sensors are used?	Sensors, sensor types
ICT Physical Properties		
Q34	What is the weight of a device?	Device, weight
Q35	What is the weight of a device's component?	Component, weight
Q36	What is the current age of a device?	Device, age, year, month, day
Q37	What is the current age of a device's component?	Component, age, year, month, day
Q38	What is the duration of the device's warranty?	Device, warranty, type, duration
Q39	What type of damage does the device's warranty cover?	Warranty, coverage, damage type
Q40	What is the duration of the device component's warranty?	Device, component, warranty, type, duration
Q41	What is the memory capacity of the device?	Memory capacity (e.g. in Megabytes, Gygabytes)
ICT Computational Properties		
Q42	What is the energy consumption of the device?	Device, energy consumption in Watthour (Wh), kilo watthour (kWh)
Q43	What is the device's energy efficiency?	Device, Energy efficiency grade/rating (A-G)
Q44	What is the device's carbon dioxide (CO_2) footprint? (During the production and/or use phase)	Device, carbon dioxide (CO_2) footprint in kg per year
Q45	What is the cost of the device before and after a CE strategy is used?	Device, manufacturer's cost, cost after repair, refurbishment, remanufacturing
Q46	What is the cost of the component before and after a CE strategy is used?	Component, manufacturer's cost, cost after repair, refurbishment, remanufacturing
Q47	What is the stock availability of the device?	Number of devices in stock, purchase availability
Q48	What is the stock availability of the component?	Number of device components in stock, purchase availability
ICT Material Properties		
Q49	What material is used?	Material, name, chemical formula
Q50	What is the type of the used material?	Material, type (e.g. metal, composite, polymer, ceramics)
Q51	How much material (in grams) is present in the component?	Material, component, availability, weight
Q51	What is the criticality of the material?	Material, status, critical, criticality level
Q53	What is the cost of the material? E.g., 1g of gold is around 54.346 Euro	Material, material cost, weight
CE Strategy		

Q54	What CE strategy is recommended for the specific device?	Device, CE strategy, recommendation
Q55	What CE strategy is recommended for the specific device's component?	Device component, CE strategy, recommendation
Q56	Why is the specific CE strategy recommended?	Recommended CE strategy, reason
Q57	What CE strategy is selected?	CE strategy, refurbish, remanufacture, repair, share, reuse, recycle
Q58	Why is the specific CE strategy used?	Selected CE strategy, reason
Q59	How many times has as a CE strategy been performed?	Device, component, CE strategy, number of times performed

4. State of the Art

Based on the main use case of ICT hardware's life-cycle in the CE (including materials), this section presents an overview of existing semantic models in the ICT, materials and CE domains. An overview of the existing CE tools that utilise semantics is presented as well. Further, we have used the work in [44] and [45] as a baseline for our survey and ontological analysis. For each ontology, we presents its (i) purpose and scope, (ii) modelling language, (iii) conformace to best practices for ontology engineering, (iv) level of reuse of existing ontologies, (v) availability (open-access or private), (vi) limitations and (vii) possible applications.

4.1. Semantic Models for ICT

This section presents an analysis of the existing semantic models in the ICT domain ranging from single device-focused ontologies to more generic semantic models such as top level-ontologies.

4.1.1. ICT Energy Resource Management Ontology by Daouadji et al. [46]

Daouadji et al. [46] present an ICT resource management ontology for the energy efficiency domain. The ontology, which was built with the Resource Description Framework (RDF)[18], models three of the most common types of ICT - Networking, Computing and Storage and generic resources related to them such as CPU and bandwith. The connection with the energy efficiency domain is set by the *used-by* object property, which relates and ICT resource to either *Green* or *Dirty* energy types. The ontology is not open access, which limits the analysis that can be performed on it. Competency questions, if used, are also not presented. Although, one could gain an idea of the data model at a taxonomy level, no specific URIs are presented in the paper. This limits the ontology's reuse and application for other use cases. The reuse of existing ontologies has not been discussed as well. The ontology has been utilised for implementing a scalable framework, which assists users in identifying the best resources that can be used for a specific task in terms of cleanliness [46]. The ontology itself, based on the information in [46], can be used as a starting point for building more complex semantic models for ICT use in the CE, where energy efficiency and use of renewable energy can be viewed as a sustainability indicator [47] [48].

4.1.2. ICT Governance and Policy Taxonomy by Lampathaki et al. [49]

Motivated by the technological advancements of government-supporting tools and the increasing need for data governance, Lampathaki et al. [49] propose a taxonomy that helps categorise ICT research. Being developed in the context of the CROSSROAD[19] project, the taxonomy's domain is defined as ICT for governance and policy modelling. The authors focus on building a generic unified model for the different applications and research areas (e.g. social networking, linked data, IoT, cloud computing) for ICT. Five research areas have been defined in total,

[18] https://www.w3.org/RDF/
[19] https://cordis.europa.eu/project/id/248484

each with several sub-areas to provide a detailed specification of ICT applications. No details of ICT devices or components are presented as the taxonomy focuses on upper level knowledge representation. Although the data model is not openly available and is at a taxonomy level, it can be used as a guideline for an ontology or for extending existing ontologies with the possible applications of ICT, especially when security and privacy are the key focus.

4.1.3. ICT Assistive Technology Taxonomy by Gower and Andrich [50]

The lack of standardisation in terminology in the ICT domain has also inspired Gower and Andrich [50], who propose a taxonomy for ICT devices' features in the assistive technology (AT) domain. The taxonomy comprises of two main categories - features and clusters. Features represent different measures (e.g. weight, length) and attributes (boolean values) of ICT devices, while clusters are a combination of several features. Some of the modelled clusters, which help represent knowledge about an ICT device in detail, include browsers, licenses, price, visualisation and energy type. The taxonomy has been successfully adopted by the European Thematic Network on Assistive Information and Communication Technologies (ETNA)[20] framework, which aims to provide access to the different ICT products available on the market based on the needs of the end-users. The ISO 9999, ISO 24751 and ISO division 22.39.12 standards were taken into consideration when building the taxonomy. The taxonomy is not openly available, however, the presented hierarchy in [50] can be already reused for defining an ontological model of an ICT device, its functionalities, capacity, input and output. Further, the authors provide a discussion about the maintenance of the taxonomy, which is an often overlooked discussion in such papers.

4.1.4. Laptop Ontology by Dhingra and Bhatia [51]

Dhingra and Bhatia [51] discuss the different requirements and tools that are available for building ontologies and propose a three ontologies in the laptop domain, which represent laptop reviews, specifications and sellers. Each ontology was built with the Protégé[21] ontology development environment. In the laptop review ontology, a laptop can be associated with specific advisors in the form of customer feedback, rating and reviews, which were collected from different media sources (i.e. newspapers and magazines). The laptop specification ontology models laptop specifications such as audio devices (microphone, stereo speakers), brand, camera, dimensions, display size. The laptop seller ontology, on the other hand, focuses on the selling process itself (from purchase to delivery). Different payment methods are modelled as well. Although the work in [51] follows the ontology engineering methodology from [52] it is not openly available, there is no mention of the specific object properties between the classes, how all three ontologies connect and if any existing ontologies were reused. Namespaces are not presented as well, which limits the reuse of the work. The evaluation of the ontology with a set of competency questions, which were translated into Description Logic (DL) queries, showed that it is expressive enough to be used in use cases such as buying of laptops.

4.1.5. ICT Taxonomy by Inaba and Squicciarini [53]

By following the International Patent Classification (IPC)[22] [54] system, the ICT patents presented in it and building upon the Japan Paatent Office (JPO)[23] classification system [55], Inaba and Squicciarini [53] propose the J tag ICT taxonomy. The taxonomy categorises ICT products based on the technology area of their application. 13 such areas have been defined in [53] amongst which are mobile communication, security, sensor and device network, Each technology area is also divided into several subareas and is associated with specific IPC classes from the IPC classification system. For example, the ICT device area has as a subarea an electronic circuit, which is associated with IPC codes H03B (direct generation of oscillations), H03C (modulation) etc. The presented taxonomy in [53] is one of the most detailed that was encountered during our survey. The authors have analysed different standards and have provided a detailed specification of the whole taxonomy. Although, no ontology has been built, the J tag taxonomy documentation can be used as guidelines for any ICT practitioner and ontology engineer working in the domain.

[20] https://cordis.europa.eu/project/id/270746/en
[21] https://protege.stanford.edu
[22] https://www.wipo.int/classifications/ipc/en/
[23] https://www.jpo.go.jp/e/

4.1.6. oneM2M Base Ontology [56]

The ontology is the main semantic model used by the oneM2M[24] initiative, which is a collaboration between 8 leading IoT standardisation organisations. The base ontology, built with OWL, models the concept of a device as a thing that has to achieve a specific task and which can also be a collection of several devices (with unique identifiers). Each device has a service and operation with input and output data associated with it. Services have specific functions (e.g. controlling and measuring). To achieve its task, a device needs to complete a specific function. Although an ontology is metadata by itself, the concept has been defined as a separate class to represents the values and measures of things. Based on the predefined namespaces, existing ontologies have not been reused. The oneM2M ontology by itself can be reused as an upper level ontology when building a more detailed semantic model of ICT devices. It can be also be extended with specific concepts such as sensors and switches from the DogOnt ontology to achieve higher expressivity. As discussed in [57], mapping of other ontologies such as the SmartAppliances REFerence (SAREF)[58], to oneM2M is possible and guidelines are provided in [59].

4.1.7. DogOnt Ontology for IntelligentDomotic Environments by Bonino and Russis [57]

One of the earliest and most expressive Web Ontology Language (OWL)[25] ontologies that focuses on smart device modelling is the DogOnt by Bonino and Russis [57]. The ontology, which was built for the domotic domain, represents smart devices, their location, capabilities and technology-specific features and states. With this level of detail, DogOnt can assist ontology engineers in modelling complex Intelligent Enviroments (IEs) and devices such as home and office appliances that comprise them. However, ICT is not the main focus of the work, specific switches (e.g. on off, rocket and level control) and sensors (e.g. temperature, CO_2, humidity and light detection) are modelled as well. Several ontologies such as the Semantic Sensor Network (SSN) [60], Dublin Core[26] and Creative Commons [27] have been reused. Further, as shown in [57], the authors provide reasoning mechanisms based on DogOnt (e.g. model instantiation), which show its successful utilisation. Detailed specification of the ontology is available online[28], which supports its future reuse and extension - one of the core principles of the Semantic Web. On the other hand, DogOnt's high level of expressivity raises the challenge of its reuse as well (how and what to reuse).

4.1.8. Laptop Ontology by Ayundhita et al. [61]

Similarly to [51], Ayundhita et al. propose an ontology for the laptop domain aimed at assisting a conversational recommender system (CRS) in making better product recommendations. The developed ontology, which builds upon the work in [62], models three main laptop-related concepts - functional requirements, the product itself and the products' specification (gathered from its manufacturer). Several types of products such as notebooks and ultrabooks have been modelled. The instances of these classes can be categorised as high, mid and low-end products based on product specifications such as RAM memory. The ontology is not open access and it is not clear if the authors followed Semantic Web standards such as OWL and RDF when building it. However, the authors have shown its successful utilisation and improvement of the accuracy of CRS's recommendations.

4.1.9. High-Level Ontology Network for ICT Infrastructures by Corcho et al. [63]

To solve some of the challenges within ICT services such as lack of common understanding, heterogeneous data and the presence of knowledge silos, Corcho et al. [63] propose a network of 9 interconnected ontologies that model different entities (organisations, data centers), hardware and software components and network security. These ontologies fall under a top-level ontology which has the specific goal to present a high-level model of ICT component configurations, resources and the relationships that hold between in a machine readable format that supports ICT service management. The ontology was built by following the Linked Open Terms (LOT) methodology with OWL and Protégé. Dublin Core, VANN [64] and the Simple Knowledge Organisation System (SKOS) [65] have been

[24] https://www.onem2m.org
[25] https://www.w3.org/TR/owl-ref/
[26] https://www.dublincore.org/specifications/dublin-core/dcmi-terms/
[27] https://creativecommons.org/ns
[28] http://iot-ontologies.github.io/dogont/documentation/index-en.html

reused. The ontology is openly available online[29] which eases its reuse. The modular design that was adopted supports the reuse of the ontology network at different levels (each one of the 9 ontologies can be reused). Further, the ontologies were used as a schema for a knowledge graph which has also been used for question answering by a chatbot deployed at Huawei[30] [63].

4.1.10. Hardware and DevOps Ontology by Corcho et al. [66]

In addition to the work in [63], Corcho et al. have built an ontology [66] that focuses on representing hardware items related to software development and IT operations (DevOps) infrastructures. The ontology, built with OWL, represents several types of hardware items (e.g. disk, frame, network card, server hardware), server hardware types such as firewalls and switches and characteristics such as bandwith, port, power, disk size that can be used to describe the items in detail. Similarly to [63], concepts from Dublin Core, VANN and SKOS have been reused. Both the ontology and its documentation are available online[31], which promotes its reuse within the Semantic Web community. Currently, several inconsistencies in the labeling are evident. Further, due to the limited documentation online, it is not clear if the ontology has been evaluated with competency questions and if it has already been utilised in specific use cases. Several of the defined concepts such as disk, switch and network card and their object properties can be reused to improve the level of expressiveness in top-level ontologies or when following a bottom-up methodology for ontology engineering.

4.1.11. Summary

When analysing the existing semantic models we focus on three factors: type of semantic model (taxonomy or ontology), level of expressivity and availability. The first factor relates to the actual realisation of the semantic model. Some of the overviewed models are only taxonomies, which while useful for individuals and companies to establish a common understanding about a system, do not provide a machine-understandable information as they have not been implemented into ontologies yet. The second factor relates to the level of detail of each semantic model (if the model focuses on specific hardware or is more generic and can be used as a top level ontology). The third factor (availability) focuses on how easy it is to access and reuse the existing ontologies. Ontology reuse is a well known principle of the Semantic Web, however, to be able to reuse concepts one needs to have an access to the specific URIs of classes and object properties and their interdependencies (the domain, range and characteristics). This is not possible when an ontology is private. Table 3 presents the overviewed ICT semantic models, how they were build (manually or automatically), the followed Semantic Web standard, the specific domain they have been built for and their availability. The information has been derived from each models' online documentation and scientific publication. A "-" symbol is used when no information has been found in the resources.

10 semantic models (3 taxonomies and 7 ontologies) have been identified as revelant to the ICT domain. The literature review has shown that the available semantic models vary in expressivity. Some taxonomies such as [50] and [53] are highly expressive (represent numerous ICT-related concepts) and even follow specific ICT standards. However, they have not been implemented into ontologies yet thus their true benefit for machines (e.g. utilisation for decision making) is unexplored. Other models such as [66], [57] represent less concepts but are already encoded as ontologies, are openly availabe and ready for reuse. Ontologies such as [63], [46] [49] focus on representing ICT infrastructures and their management as a whole, while others (see [66][57]) represent specific ICT hardware components and their capabilities. Only 4 of the ontologies ([59][57][66][63]) are openly available, which allows one to reuse specific namespaces and URIs. Although the rest of the semantic models (taxonomies and ontologies) have been documented in the form of public reports and scientific publications, namespaces and URIs, to support their reuse, are rarely available online. Furter, OWL was the most used Semantic Web standard. OWL2, which has *"increased expressive power for properties, extended support for datatypes, simple metamodeling capabilities, extended annotation capabilities, and keys"* [67] has not been used (or atleast discussed) in the studies. In conclusion, the analysis has shown that modelling the ICT domain is a complex use case dependent task. The reuse of the exiting ontologies, which is currently at a low level, should be encouraged (e.g. making ontologies and taxonomies public).

[29] https://oeg-upm.github.io/devops-infra/index.html
[30] https://www.huawei.com/en/?ic_medium=direct&ic_source=surlent
[31] https://oeg-upm.github.io/devops-infra/ontology/hardware/index-en.html

Table 3
Overview of ICT Semantic Models

Study	Semantic Model Type	Year of Latest Update	Engineering Method	Semantic Web Standard	Scope	Availability
Daouadji et al. [46]	Ontology	2010	Manual	RDF	Energy Efficiency, Low Carbon Grid Networks	Private
Lampathaki et al. [49]	Taxonomy	2010	Manual	-	ICT Governance and Policy Management	Private
Gower and Andrich [50]	Taxonomy	2014	Manual	-	ICT for AT	Private
Dhingra and Bhatia [51]	Ontology	2015	Manual (Protégé)	OWL	ICT; Laptops (Specification, Review and Selling)	Private
Inaba and Squicciarini [53]	Taxonomy	2017	Manual	-	ICT Technology Based on IPC, JPO	Public
oneM2M Consortium [59]	Ontology	2019	Manual	OWL	IoT and oneM2M Devices Ecosystem	Public
Bonino and Russis [57]	Ontology	2019	Manual (Protégé)	OWL	Smart Devices and IEs	Public
Ayundhita et al. [61]	Ontology	2019	-	-	Laptops and Laptop CRS	Private
Corcho et al. [66]	Ontology	2021	Manual	OWL	Hardware; DevOps	Public
Corcho et al. [63]	Ontology	2021	Manual (Protégé)	OWL	ICT Infrastructures; Configuration Management Systems	Public

4.2. Semantic Models for Materials

This subsection presents an overview of semantic models for materials based on the work in [44]. The importance of ICT and materials in the CE is discussed in Section 1.

4.2.1. MaTOnto by Cheung et al. [68]

Motivated by the increased availability of material data and the lack of its standartisation, Cheung et al. [68] present the MatOnto ontology, which aims to ease data-driven material discovery. The ontology follows the OWL Semantic Web standard and is based on the DOLCE [69] upper level ontology. MatOnto models several categories (ceramic, glass, polymer, metal) of materials, their properies (magnetic, chemical, mechanical, biological) and data measured during the materials' modelling and evaluation. To model specific scientific activities and experiments related to material discovery several other ontologies have been reused as well. These include the Ontolingua's Standard Units and Dimensions [70], W3C's Time[32], ABC Metadata [71] and the EXPO [72] ontologies. In addition to making the MatOnto openly availabe, the authors include specific namespaces in its specification in [68] as well. Such information eases ontology engineers when reusing existing work and saves time as one can directly see if the concept that is describes in the study has been reused or not. MatOnto can be used to semantically describe the whole process of discovering new materials, their characteristics and possible interactions and entities such as projects and organisations involved in the process..

4.2.2. Materials Ontology by Ashino [37]

Data heterogeneity is also a challenge in the materials domain. In [37], Ashino sees this as an opportunity to create an infrastructure that supports material knowledge exchange. The author presents a materials ontology, built with OWL, that comprises of 7 sub-ontologies related to materials and their properties. The ontologies are organised in three groups - core ontologies, material information and peripheral ontologies. The core ontologies model various materials, processes, properties and the environment. The substances ontology, for example, can represented different substances as either pure or mixture. Each material can be associated with its relevant chemical, thermal and mechanical properties, which are modelled by the property ontology. From an ontology engineering perspective, the naming (or labels) of some sub-ontologies (e.g. core ontologies and peripehrial ontologies) the can be seen

[32]https://www.w3.org/TR/owl-time/

as problematic. Although several existing ontologies have been discussed, it is not clear if they have been reused and the level of their reuse. The modularity of the ontologies in [37] supports their reuse and extension. However, the ontologies are private and no specific namespaces are presented in [37]. The ontology has been successfully utilised as a way to synchronise material data exchange amongst three different databases and can be informative with regards to the types of properties that can be modelled.

4.2.3. eNanoMapper by Hastings et al. [73]

As part of the eNanoMapper[33] project, Hasting et al. focus on the semantic representation of nanomaterials and propose the eNanoMapper[34] ontology. The ontology, built with OWL, provides a detailed schema of nanoparticles based on their properties, constituency and shape [73]. It also models physicochemical and biological characteristics of engineered nanomaterials, which is useful for building nanomaterials for specific purposes such as drug delivery. eNanoMapper was built based on ontology reuse. Specifically, BFO[35] and ChEBI [74] have been reused. Further, the authors have implemented an ontology "slimming" library [36] that supports the reuse by selecting only concepts and relationships that meet a predefined set or requirements. The library and the ontology are both openly available which is a step towards their reuse in the nanomaterial safety domain.

4.2.4. Metallic Materials Ontology (MMOY) by Zhang et al. [75]

To built the MMOY ontology, Zhang et al. [75] undertake a slightly different approach for ontology engeneering to the existing traditional (manual) ones. The authors utilise the String Matching on Ordered Alphabets (SMOA) [76] algorithm, which extracts existing metalic material related concepts from the Yago[37] knowledge base. This is done with the help of keywords and synonyms generated with WordNet[38]. The process is also supported by logic rules, which model the specific requirements that need to be met when extracting both hierarchical and non-hierarchical structures. The resulting ontology was evaluate with regards to precision, recall, F1 measure and time performance. The results showed the feasibility and correctness of the approach. However, although MMOY represents diverse metallic materials (e.g. alloy, iron), it lacks concept descriptions [75] and consistent utilisation of RDF and URIs as data was extracted from various Yago files. Further, MMOY is private, which restricts its analysis from an ontology engineering perspective. Finally, to show the successful application of the ontology, Zhang et al. [75] have built a prototype visualisation system based on it, which helps individuals explore specific metals and their properties.

4.2.5. Elemental Multi-Perspective Material Ontology (EMMO) [77]

Developed as part of several European projects (e.g. SimDOME [39], OntoCommons[40]) that focus on material science standartisation, EMMO was built to represent even the smallest 4D world object that exists from different perspectives. The ontology comprises of several top and middle layer ontologies. The top level EMMO ontologies model quantum, physical and void items and collection of items, while the middle level ontologies focus on supporting the application of EMMO to specific domains. By being built with OWL, EMMO also supports the semantic representation of materials and is already reused by ontologies such as the Battery Interface Ontology (BattINFO)[41], the ontology for the Battery Value Chain (BVC) [42] and the Mappings ontology[43]. On its own, EMMO reuses Dublin Core and is openly available, which supports its further extension and reuse for modelling of materials at physical and chemistry levels. However, a certain level of philosophical expertise is needed to do so due to the complexity of the defined concepts and relationships.

---

[33] www.enanomapper.net
[34] http://enanomapper.github.io/ontologies/enanomapper.owl
[35] https://basic-formal-ontology.org
[36] athttp://github.com/enanomapper/slimmer/
[37] https://yago-knowledge.org
[38] https://wordnet.princeton.edu
[39] https://simdome.eu
[40] https://ontocommons.eu
[41] https://github.com/BIG-MAP/BattINFO
[42] https://github.com/Battery-Value-Chain-Ontology/ontology
[43] https://github.com/emmo-repo/domain-mappings

4.2.6. The BIM-based holistic tools for Energy-driven existing Residences (BIMMER) Ontology [78]

The BIMMER ontology, built with OWL, is a modular ontology that focuses on representing several domains such as the building, material, energy consumption and weather in order to assist the integration of multiple external data sources for building model generations. Sensor data (e.g. occupancy measurements) has been modelled as well, which is an extension of existing such ontologies. Several ontologies have been reused (e.g. GEO[44], Smart Appliances REFerence (SAREF)[58], SKOS, Time [45]). The ontology represents both high- and low-level concepts in the domains mentioned above and is openly available. To ease its reuse even further, within the BIMMER project, the authors have provided a detailed documentation in [78] and have transformed the OWL version into a JSON-LD data model.

4.2.7. Materials Graph Ontology by Voigt and Kalidindi [79]

The work of Voigt and Kalidindi [79] presents a materials graph and an ontology based on it that aim to support the fomalisation and merge of knwoledge in the domain. The authors follow the suggested material definition in [80] based on which four components (i.e. processing, structure, properties, performance) define a material. Provenance of the material's process history and process hierarchies can be modelled as well. This is helpful when determining the sequence of process execution (e.g. heat treat, soak, ramp) for each material. The ontology presents the minimum set of concepts needed to model existing and new materials and their dependencies (i.e. relationships that hold between the materials). The ontology has been sucessfully used to generate a materials graph by utilising the dataset from [81]. Although several standards and ontologies have been discussed, it is not clear if the authors have reused any of them. Supplementary materials, including the ontology itself are also available online [46].

4.2.8. Materials and Molecules Basic Ontology (MAMBO) by Piane et al. [82]

Piane et al. present the MAMBO ontology that semantically represents materials at molecular level to support community's' material development efforts at nanoscale level. In contrast to most of the overviewed ontologies by far, MAMBO is built with OWL2, which provides better expressivity when modelling ontologies. In MAMBO, a material has a structure, which can comprise of different molecular units. Each such unit can be modelled down to particle and atomic level. Materials can also be related to measurements and calculations. Existing ontologies have not been reused. Due to its modularity, MAMBO can be easily extended and reused for other domains such as molecular materials, nanomaterials, supramolecular and bio-organic systems as suggested by the authors. More specifically, MAMBO can be integrated with already existing ontologies such as EMMO and MDO. Although the ontology is still in its initial development stages, it is openly available[47] and can already be used as a guideline for future work in the domain.

4.2.9. Dislocation Ontology by Ihsan et al. [83]

Ihsan et al. [83] narrow the focus of their work down to specific class of materials called crystalline and the commonly encountered disclocations (i.e. *"a line-like defect"* [83]) in their structure. The main goal of the ontology is to formalise the existing knowledge on crystallines based on their crystallography and to encourage future research in the domain. The proposed ontology is not openly available. However, from the available information in [83] it becomes clear that it follows RDF serialisation. Several concepts (e.g. lattice, occupancy) from existing ontologies such as the Materials Design Ontology (MDO) have been reused. The study in [83] presents initial steps for the development of such ontology thus deeper exploration of the domain is needed to build a more mature ontology.

4.2.10. Materials Design Ontology (MDO) by Lambrix et al. [84]

One of the latest ontologies in the domain is the MDO ontology, which was built to help integrate heterogeneous databases and extend the existing efforts of the Databases Integration for Materials Design (OPTIMADE) [85] community. The main goal of OPTIMADE is to make materials databases interoperable by setting a standardised REST APIs [85]. By following the NeOn [86] methodology for ontology engineering and using OWL2 DL [87], Lambrix et al. have built the MDO ontology in a modular way. MDO models knowledge in the materials domain,

[44] http://www.w3.org/2003/01/geo/wgs84/_pos#
[45] https://www.w3.org/2006/time#
[46] https://www.sciencedirect.com/science/article/pii/S0167577X21005322?via%3Dihub#m0005
[47] https://github.com/daimoners/MAMBO

Table 4
Overview of Material Semantic Models

Study	Semantic Model Type	Year of Latest Update	Engineering Method	Semantic Web Standard	Scope	Availability
Cheung et al. [68]	Ontology	2008	Manual	OWL	Materials; Material Discovery	Public
Ashino et al. [37]	Ontology	2010	Manual (Protégé)	OWL	Materials Composition; Materials Properties	Private
Hastings et al. [73]	Ontology	2015	Manual	OWL	Nanomaterials; Nanosafity	Public
Zhang et al. [75]	Ontology	2016	Automatic (SMOA Algorithm; Logic Rules)	RDF	Metals; Metallic Properties	Private
EMMO consortium [77]	Ontology	2021	Manual (Protege)	OWL	4D Objects; Materials; Material Types; Physics; Chemistry	Public
BIMMER Project [78]	Ontology	2021	Manual	OWL	Buildings; Building Materials; Weather	Public
Voigt et al. [79]	Ontology; Graph	2021	Manual	OWL	Materials; Material Processes; Material Performance; Material Properies; Material Structure	Public
Ihsan et al. [83]	Ontology	2021	Manual	RDF	Crystaline Materials; Crystaline Dislocsations	Private
Piane et al. [82]	Ontology	2022	Manual (WebProtége)	OWL2	Materials; Nanomaterials	Public
Lambrix et al. [84]	Ontology	2022	Manual	OW2 DL	Materials; Solid State Physics, Condensed Matter Theory	Public

specifically solid state physics, condensed matter theory and various material calculations. The ontology comprises of a *Core* module representing top-level concepts, *Structure* module representing structural material information (e.g. composition, lattice, occupancy) and a *calculation* module categorising the different computational methods used for creating the materials. Materials' provenance information such as the agent associated with it and the date and time it was published can be represented with the *Provenance* module (reused from the PROV-O[48] [88] ontology). Further, the authors have proposed several extensions of MDO. However, the work is still in progress and has not been included in the openly available version[49] of the ontology.

4.2.11. Summary

By following the same criteria as presented in Section 4.1.11, in this section we present a summary of all findings regarding the state of the art of materials' semantic models. To begin with, we have found that mostly ontologies for materials have been built. In addition, there are catalogues such as the European Waste Catalogue (EWC) [50], which is a collection of waste categories that help classify different types of waste based on their material composition. The EWC is also available online[51].

In the past few years, several material ontologies have been built (see Table 4). Apart from, the MMOY [75] ontology, which was built automatically, all other ontologies we built manually with domain experts in Protégé (some with WebProtégé). This relates to the need for human involvement in the ontology engineering process. Although with automatic methods ontologies can be built faster, they usually lack the human knowledge of the domain, the iterative collaboration between several domain experts and URIs. Newer ontologies such as MAMBO [82] and MDO [84] follow OWL2 and OWL2 DL Semantic Web standards, which support better expressivity [67]. Regarding the scope of the ontologies, some such as [73] and [82] model materials at nanoscale, while [68] focuses on modelling materials in a generic way. The EMMO [77] ontology, on the other hand, look at materials from a philosophical perspective, while [75] and [83] focus on specific materials and their properties (metals and crystalline materials). As shown in Table 4, most of the ontologies are openly available, which is a good Semantic Web practice for knowledge exchange. Finally, the reuse of these ontologies is also supported by their modular design.

[48] https://www.w3.org/TR/prov-o/#Agent
[49] https://github.com/LiUSemWeb/Materials-Design-Ontology
[50] https://www.sustainabilityexchange.ac.uk/the_european_waste_catalogue_ewc
[51] http://www.environment-agency.gov.uk/business/topics/waste/31873.aspx

4.3. Semantic Models for the CE

This section presents an overview of the existing semantic models that represent the CE domain.

4.3.1. CE Business Models (CEBMs) by Chiaroni et al. [89]

As a result of an in depth analysis of the CE, Chiaroni et al. [89] present a taxonomony for it. The main goal of the taxonomy is to help determine the degree of adoption of the CE based on two factors - customer value proposition and the value network. Product or service price and promotion, features related to them and the degree of circularity have been defined as the most important criteria for business categorisation based on customer value proposition. For the value network, the following variable types have been defined - Design for Recycling (DfR), Design for Remanufacturing and Reuse (DfRe), Design for Disassembly (DfD) and Design for Environment (DfE). Further, three level of CE adoption have been distinguished, namely linear, upstream, downstream and full circular. Although the proposed taxonomy is used as a framework for the evaluation of the CE's adoption, it presents CE terminology and processes that can be modelled with an ontology to support machines. The proposed taxonomy is documented in detail but from a business and CE domain expert perspective. Technology utilisation has not been discussed.

4.3.2. CE Conceptual Model by Sauter and Witjes [39]

Motivated by the potential benefits of utilising Linked Data for data sharing in the CE, Sauter and Witjes present a taxonomy and ontology in [39] for the CE to help standardise product passport data exchange. The developed ontology focuses on a retail use case in the CE and on the combination of Linked Data and QR codes. The proposed taxonomy models resources and actors. Resources can be bio-based or technological, while actors can be organisations and individuals (e.g. designers, farmers, consumers). Each resource has product parts and material composition. Provenance information such as the products' creation company, certifications (e.g. Fair Trade) and use activities are modelled too. Specific CE stages such as repair, recycling and reuse are modelled as post-use activities related to reverse logistics services. Based on this taxonomy and with a set of competency questions, the authors have proposed an ontology. Discussion about the possible reuse and extension of the Good Relations ontology is present as well. Although, the ontology's implementation is set as future work, the current taxonomy presents the minimum information that is needed for modelling generic product passports. It can be used as a base ontology that can be extended for more complex use cases.

4.3.3. Circular Exchange Ontology (CEO) and the Circular Materials and Activities Ontology (CAMO)[38]

Following their previous work in [39], Sauter et al. [38] extend the existing CEO ontology and propose the CAMO ontology. Similarly to [84], the NeOn methodology is followed. The CEO ontology, which models agents, activities and referents, needed for modelling a CE processes, is loaded in Protégé and extended. The new concepts that have been defined (e.g. post-use, reverse logistics, product, resource) help specify the processes in more detail and are later used for building specific product passports. The CAMO ontology, on the other hand, is modular and focuses on classifying different materials, products and activities [38]. Both ontologies, after RDF serialisation, have been used to annotate data from the Madaster[52] platform. The evaluation of the ontologies have concluded that Linked Data can successfully be used to support data exchange and data traceability in the CE. Both ontologies are openly available and currently in development.

4.3.4. CE Indicators Taxonomy by Saidani et al. [90]

Led by the lack of standardisation for the adoptation of the CE, Saidani et al. present a set of indicators (in the form of a taxonomy) for the evaluation of its performance. The concept categories that the authors focus on are CE loops, CE implementation, performance and perspectivity of circularity. For example, the CE loop represents the life-cycle (i.e. maintain, reuse, remanufacture, recycle stages) of a product within the CE, while the CE implementation focuses on the CE level (micro, meso, macro) of its adoptation. Several groups of indicators have been defined as well- descriptive, performance, efficiency, policy effectiveness and total wellfare. The proposed indicators have been selected by following Specific, Measurable, Achievable, Relevant and Time-Bound (SMART) [91] and clear, relevant, economic, adequate, monitorable (CREAM) mnemonics and have been utilised in a macro-based Microsoft

[52] https://madaster.com

Table 5
Overview of CE Semantic Models

Study	Semantic Model Type	Year of Latest Update	Engineering Method	Semantic Web Standard	Scope	Availability
Chiaroni et al. [89]	Taxonomy	2016	Manual	-	CE; CE Adoptation; CE Evaluation	Private
Sauter and Witjes [39]	Taxonomy	2017	Manual	-	CE; Retail	Private
Sauter et al. [38]	Ontology	2019	Manual (Protégé)	RDF	CE; CE Processes	Public
Saidani et al. [90]	Taxonomy	2019	Manual	-	CE;CE Indicators	Private

Excel[53] tool that is open access. However, no efforts have been made yet to translate the knowledge into a machine-readable format (e.g. RDF).

4.3.5. Summary

Our survey into semantic models for the CE has shown that there is a limited number of studies available. Most of these present taxonomies based on specific use case analysis and standards. The provided CE terminology and process information from [89] and [90] can be used to define an initial set of competency questions for ontology engineers. We were able to identify only 1 ontology (see [38]), which also follows Semantic Web standards. The work in [38], specifically the extended CEO and proposed CAMO ontologies, provide a generic data model down to material level. However, specific types of products and materials, which can be critical have not been modelled. On the other hand, CAMO is openly available and can be reused and extended with ICT ontologies such as [57][66][63] and material ontologies such as [79][75][37] to build an ontology for the CE that focuses on ICT data sharing.

4.4. Utilisation of Semantic Web Technologies in the CE

This section presents an overview of the utilisation and integration of Semantic Web technologies, namely ontologies in the CE. Some of the most common applications include building digital product passports and supporting decision making in the IoT and recommender systems.

4.4.1. Laptop Recommender System by Ayundhita [61]

Motivated by the lack of knowledge about the technical specifications (e.g. hard drive capacity, processor types) of hardware such as laptops and based on their previous research in the field (see [62][92][93]), Ayundhita[61] propose an ontology-based conversational recomender system (CRS) that aims to support end users in buying laptops. The CRS promts users with questions about the desired random access memory (RAM), processor, camera and makes recomendations to the user. Users can also give ratings for each recommendation, which helps optimise and improve the system with regards to the quality of the recommendations. To generate the questions, the system utilises an ontology that models laptops' functional requirements and product specifications such as RAM. The system was evaluated with regards to its performance and user satisfaction. The analysis showed that the ontology-based CRSM achieved both better recomendation accuracy (84.6%) and higher user satisfaction in comparison to general e-commerce systems. Although an ontology was sucessfully utilised, it is not openly available and implementation details about it's specific use are not provided in [61].

4.4.2. SmartTags IoT Product Passport for CE by Gligoric et al. [94]

To support the transition from linear to CE, Glicoric et al. propose a method for building digital product passports based on the combination of physical components (i.e. barcodes printed with functional ink) and software. On the software side, the authors propose a modular ontology for the CE. The ontology comprises of several sub-ontologies that model virtual entities, smart tags, users, services and sensor observations made by each tag. The work in [94] focus primarily on the development of the tags with thermochromic and photochromic ink and on the description of

[53] https://www.microsoft.com/en-us/microsoft-365/excel

the ontologies. From a technology perspective, it is s unclear how exactly the ontologies were utilised and how the product passport was built. However, the proposed work is one of the few on the topic and justifies the advantages of using ontologies in the CE.

4.4.3. IoT-enabled decision support system (DSS) for CE by Mboli et al. [95]

A recent work, which has set as one of its main goals to raise awareness about the CE and assist its implementation within industry, is the ontology-driven IoT decision support system (DSS) by Mboli et al. [95]. The authors present a novel approach for supporting circularity decision making by combining the semantic representation of all CE-related processes, forward and backward logistics and rule-based reasoning. With the help of the ontology, each IoT component (also referred to as product) can be associated with different stages of the CE based on its usecycle and life-cycle. For example, the DSS uses rules such as *"if the usecycle is low and life-cycle is very high, recommendation will be direct reuse"* [95] have been defined with the ROWL [96] rule language in OWL. Implementation details regarding the DSS system and the utilisation of semantics have not been presented. However, the proposed approach has been evaluated with three scenarios focused on the status quo in linear economies, the reuse and the remanufacture CE stages. The results have justified the soundness of the proposed approach for a DSS and the use of an ontology to support data interoperability within it.

4.4.4. Summary

Although several ontologies for the CE have been built, there is limited work on their utilisation. The existing work briefly discusses their development and use but does not provide specific implementation details on exactly how the ontologies were utilised. It's unclear if they were used just as a schema and guidelines or actually integrated (and how) within the systems. Most of the work presents approaches and their prototype implementation. To conclude, our survey into the field has confirmed that *"the work on ontology for the CE is under-researched and there are only a few studies on this topic"* [94].

5. Analysis

To support ontology reuse, when building an ontology that covers all these domains, we have evaluated each one of the open-access ontologies from Section 4 against the competency questions from Table 2. Table 6, 7 and 8 present each ontology from its corresponding domain, the competency questions that it can answer and the relevant concepts and object properties that can be reused.

Table 6
ICT Ontology Evaluation with the Competency Questions

Ontology	Which competency questions can be answered?	Relevant Concepts and Object Properties
oneM2M Base Ontology[59]	Q1, Q10	base_ontology:Device, base_ontology:InterworkedDevice, base_ontology:consistsOf, base_ontology:isPartOf
DogOnt by Bonino and Rusiss [57]	Q1, Q33	dogont:Device, dogont:Appliances, dogont:WhiteGoods, dogont:BrownGoods, dogont:Computer, dogont:Sensor, dogont:Co2Sensor, dogont:HumiditySensor, dogont:TemperatureSensor, dogont:isSensorOf
Corcho et al. [66] and Corcho et al. [63]	Q1, Q8, Q12	devops-infra:hardwareType, devopsnet:HardwareItem, devopsnet:HardwareBatch, devopsnet:F5Hardware, devopsnet:Disk, devopsnet:unitPrice, devopsnet:serialNumber, devopsnet:highAvailabilityStatus, devopsprod:PhysicalServer, devopsprod:Server

When evaluating the existing ontologies with the competency questions, the main challenges we encountered were the lack of public access and standard documentation to them. The evaluation was performed by examining either the ontology's online documentation or its source file when a documentation was not available. Most of the ontologies were build in an "ad hoc" manner to support specific software functionalities and no ontological

[54]The ontology does not have a namespace. For readability purposes, we have assigned the namespace "ex".

Table 7
Materials Ontology Evaluation with the Competency Questions

Ontology	Competency Questions	Concepts
Cheung et al. [68]	Q50	matonto:Material, matonto:Ceramics, matonto:Polymers, matonto:Glasses, matonto:Composites, matonto:Metals, matonto:Structure, matonto:ChemicalQuality, matonto:formula
Hastings et al. [73]	Q10, Q49, Q50, Q51	ncitname:Name, bfo:materialEntity, chebi_ontology:chemicalsubstance, chebi_ontology:mixture, chebi_ontology:PureSubstance, envo:EnvironmentalMaterial, envo:OrganicMaterial, envo:MetallicMaterial, envo:Plastic, envo:Resin, quality:Mass, enanomapper:has_component_part, enanomapper:has_part
EMMO [77]	Q51, Q59	emmo_material:NanoMaterial, emmo_material:NaturalMaterial, emmo_material:EngineeredMaterial, emmo_manufacturing:ContinuumManufacturing, emmo_manufacturing:DiscreteManufacturing
BIMMER [78]	Q49, Q50, Q51,	mat:Material, mat:MaterialProfile, mat:MaterialConstituent, mat:MaterialConstituentSet, mat:Measurement, mat:MaterialLayer, mat:hasMaterial
Voigt et al. [54] [79]	Q49, Q50	ex:Material, ex:Process, ex:composed_of, ex:next_in_process, ex:used_in
Piane et al. [82]	Q49, Q50	mambo:Material, mambo:atom, mambo_is_partOf, mambo:hasStructure, mambo:formula, mambo:is_part_of, mambo:formula
Lambrix et al. [84]	Q49, Q50	base: relatesToMaterial, base: relatesToStructure, structure:Composition, structure:hasElement, structure:hasComposition, structure:ElementRatio

Table 8
CE Ontology Evaluation with the Competency Questions

Ontology	Competency Questions	Concepts
Sauter et al. [38]	Q49, Q50, Q55, Q57	camo:biological, camo:technological, camo:alloy, camo:metal, ceo:Activity, ceo:Creation, ceo:PostUse, ceo: ReverseLogistics

evaluation was performed within the associated scientific publications. Discussion and guidelines for reuse for other use cases are, usually, not provided. The ontologies were evaluated only through their successful software utilisation and use case-specific expressivity. Some of the common pitfalls that we encountered when analysing them include the lack of consistency in concepts' labeling, lack of ontology reuse, undefined namespaces and missing concept descriptions.

The ICT ontologies in Table 6 can answer some of the competency questions regarding hardware, sensors and processing in a generic manner. For example, DogOnt [57] represents the concept of a computer, which is relevant for our use case (i.e. laptops). Several types of sensors such as CO_2, have been represented as well. Both [66] and [63] represent ICT hardware components such as a hard disk and server, which can be reused to extend our use case.

The materials ontologies (see Table 7), although varying in expressivity, are generic enough to be reused or extended for our use case. The ontologies in [68][78][79][82] represent the concept of a material, while [77] [73] and [84] can be reused to extend them with specific types of materials (e.g. natural, engineered, organic, plastic, resin, metallic) and their composition. However, none of the ontologies provides information about the criticality of the materials, which is an economic indicator in our case.

Regarding the semantic models for the CE domain, to our knowledge, only one ontology [39] has been build and is currently publicly available. The work of Sauter et al. [38] has a limited expressivity in terms of the modelled ontological concepts (see Table 8). However, by representing several generic types of materials and CE activities, it successfully connects the materials and CE domains. The ontology can be seen as a starting point for an ICT and materials ontology for the CE and can be extended to represent different hardware by reusing concepts from the existing ICT ontologies from Table 6.

To summarise, based on our analysis, to interlink the ICT, materials and CE domains, the existing ontologies can be aligned (e.g with an upper-level ontology) or can be reused separately (e.g. reuse of specific classes, object and data properties or extension with missing concepts). Aligning the ontologies requires an expert to monitor the quality of the alignment as duplicate concepts, inconsistencies in labelling and lack of background knowledge can

occur [97][98]. The reuse of specific ontology also requires an ontology engineer working closely with domain experts to derive use case requirements and select the most suitable ontology for reuse (from each domain) as each varies in its level of expressiveness and scope. Although this survey focused on laptops (as an example of ICT), their materials and life-cycle in the CE, we believe that the use case can be a good starting point in bridging the gap between the domains. Many ICT devices such as laptops and data servers have multiple hardware components and materials in common (e.g. hard drives, central processing units (CPUs), and power supply). Following a modular ontology engineering approach such [99], using the competency questions (Table 2) and analysis (Table 6, 7, 8) as guidelines, while considering existing standards (Section 6), paves the way towards an ontology that can harmonise the domains.

6. CE Standards

Standards, which are technical documents that provide businesses and organisations a guideline of requirements and specifications for best practice for various processes, are an important driver for harmonisation of practices and terms. These aim to improve processes in terms of safety, quality, accessibility, etc. On top of maximising environmental, consumer, and worker safety, which contribute to building a CE in line with wider sustainable development goals, international standards provide a number of benefits for the implementation of the CE. Standards encourage businesses to adopt CE practices, thus, supporting government efforts to implement such practices; they promote fair competition by leveling the playing field for circular products and facilitate trade by promoting confidence in products and product flows [100][101].

However, across countries and regions the application of standards and their development can result in different practices as well as the use of differing terminology and goals [102]. Often, country specific standards will be used in neighboring countries, such as the common use of the British Standard (BS)[55] and International Organisation Standard (ISO)[56] across European countries prior to the development of EU standards (which are often harmonised from existing standards). In other cases, such as those for eco-design standards, a product might adhere to the criteria of more than one standard in order to be sold in different markets, such as a company having their laptops certified by the EPEAT[57] eco-label to sell in the US and also by the China Environmental Label (CEC)[58] for sale in China. Within the EU, there is an ongoing attempt to develop and harmonise the use of one standard for each process across all EU member states. With that in mind, the following subsections outline some of the most common standards related to the CE.

6.1. BIS 8001 [103]

BIS 8001 is a framework for implementing the principles of the CE in organisations The standard was published by BSI in 2017 based on internal and collaborative studies of existing standards relating to concepts within the circular economy such as waste prevention and the management of resources. BIS 8001 is made to be used by all sectors, sizes, and knowledge levels of organisations or businesses to improve their adoption of circular economy practices. One aim of the standard is to provide a document that standardises the use of terminology that has otherwise been interpreted and used differently by businesses, organisations, and governments.

6.2. ISO/TC 323 [104]

This technical committee, organised under ISO, is focused on standardizing the development of frameworks, guidelines, and tools to support the implementation of circular economy practices in line with the United Nation's (UN) Sustainable Development Goals (SDGs)[105]. Through this committee six standards are under development with working groups focused on CE related subjects such as terminology, practical approaches, and circularity measuring [104].

[55] https://www.bsigroup.com/en-GB/
[56] https://www.iso.org/home.html
[57] https://www.epeat.net
[58] http://en.mepcec.com

6.3. IEC TC 111 [106]

IEC TC 111 is a committee of the International Electrotechnical Commission (IEC)[59] aiming to collaborate in the development of IEC standards relating to the environmental requirements for electrical and electronic equipment. This committee is currently involved in the development of several general and product specific standards providing guidelines on areas such as eco-design, material efficiency, and waste management of electrical and electronic equipment.

6.4. Summary

This section illustrated the current status of standards for the CE as considerably under development, with no single standard yet accepted as the legal standard to be used across the European Union (EU). Development of these standards is being conducted at the international level, such as with the ISO and IEC standards above, at the regional level, such as standards for circular practices in batteries, plastics, through CENELEC[60] (see [107]) in the EU, and are also being contributed to at the national level, an example of which can be seen in the National Standards Association of Ireland's[61] NSAI/TC066 committee for facilitating the development of CE standards. The consensus of these committees will eventually provide insight on the standardisation of important aspects of the circular economy such as terminology, best practice, and measuring for the overall economy as well as for particular sectors (e.g. electrical and electronic equipment, batteries, and plastics).

7. Conclusions

This paper presented a survey of existing semantic models in the ICT, materials and CE domains and current standardisation efforts. While there is a variety of such models, they have been build for use cases within their domain and rarely connect to knowledge from other domains. The surveyed ICT ontologies model specific hardware and its components and rarely go to the hardware material composition level, while the materials ontologies focus on the materials themselves (their chemical properties, compatibility, reactions). There is a clear partition of the two domains, which are, however, significantly interrelated within the CE domain.

Ontology modularisation has been a common engineering principle that the majority of the reviewed studies follow as it eases reuse and extension. However, ontology reuse (at different levels) has not been a commonly followed practice, which is in contradiction with some of the studies' outputs. A present challenge to their reuse is the lack of online documentation and public availability. Further, many of the existing models remain taxonomies thus their full potential, from a semantic and technological perspective, has not been realised yet.

In conclusions, we believe that this survey can be useful to both sustainability domain experts and ontology engineers. For sustainability experts, our work is a source of information on how the field of the Semantic Web can provide technology such as ontologies that can be used to advance the implementation of the CE. Ontology engineers, on the other hand, can benefit from the systematic analysis of existing work in the domain, which aims to support and ease ontology reuse and the implementation of FAIR ICT data sharing for the CE.

Acknowledgments

This work is supported by the Circular Resource Planning for IT (RePlanIT) project, which is funded by a Topsector Energy subsidy from the Ministry of Economic Affairs and Climate Policy in the Netherlands. We would like to express our gratitude to the whole project consortium (Aliter Networks, Ideal&Co, WCooliT, Amsterdam Institute for Advanced Metropolitan Solutions (AMS), KPN, GreenIT Amsterdam Foundation, Amsterdam Economic Board Foundation, Municipality of Amsterdam and Rijkswaterstaat) that helped shape and motivate our work. Further, we thank Ingrid de Pauw and Joppe van Driel for the constructive feedback.

[59] https://www.iec.ch/homepage
[60] https://www.cencenelec.eu
[61] https://www.nsai.ie/standards/sectors/circular-economy-standards/

References

[1] J. Kirchherr, D. Reike and M. Hekkert, Conceptualizing the circular economy: An analysis of 114 definitions, *Resources, conservation and recycling* **127** (2017), 221–232. doi:10.1016/j.resconrec.2017.09.005.

[2] C. Bakker and R. Balkenende, Chapter 7 - A renewed recognition of the materiality of design in a circular economy: the case of bio-based plastics, in: *Materials Experience 2*, O. Pedgley, V. Rognoli and E. Karana, eds, Butterworth-Heinemann, 2021, pp. 193–206. ISBN 978-0-12-819244-3. doi:10.1016/B978-0-12-819244-3.00020-X.

[3] C.W. Babbitt, H. Madaka, S. Althaf, B. Kasulaitis and E.G. Ryen, Disassembly-based bill of materials data for consumer electronic products, *Scientific Data* **7**(1) (2020), 1–8. doi:10.1038/s41597-020-0573-9.

[4] L. Deng, C.W. Babbitt and E.D. Williams, Economic-balance hybrid LCA extended with uncertainty analysis: case study of a laptop computer, *Journal of Cleaner Production* **19**(11) (2011), 1198–1206. doi:10.1016/j.jclepro.2011.03.004.

[5] J. van Driel, Naar een circulaire keten voor ICT-hardware [Towards a circular chain for ICT hardware], 2020, Available at https://usi.nl/wp-content/uploads/2021/02/Eindrapport-Naar-een-circulaire-keten-voor-ICT-def.pdf.

[6] C. Bakker, F. Wang, J. Huisman and M. Den Hollander, Products that go round: exploring product life extension through design, *Journal of Cleaner Production* **69** (2014), 10–16. doi:10.1016/j.jclepro.2014.01.028.

[7] C. Freitag, M. Berners-Lee, K. Widdicks, B. Knowles, G.S. Blair and A. Friday, The real climate and transformative impact of ICT: A critique of estimates, trends, and regulations, *Patterns* **2**(9) (2021), 100340. doi:10.1016/j.patter.2021.100340.

[8] P.A. Wäger, R. Hischier and R. Widmer, The material basis of ICT, in: *ICT innovations for Sustainability*, Springer, 2015, pp. 209–221. doi:10.1007/978-3-319-09228-7_12.

[9] R. Hischier, V.C. Coroama, D. Schien and M. Ahmadi Achachlouei, Grey energy and environmental impacts of ICT hardware, in: *ICT Innovations for Sustainability*, Springer, 2015, pp. 171–189. doi:10.1007/978-3-319-09228-7_10.

[10] B. Sprecher, R. Kleijn and G.J. Kramer, Recycling potential of neodymium: the case of computer hard disk drives, *Environmental science & technology* **48**(16) (2014), 9506–9513. doi:10.1021/es501572z.

[11] Apple Inc., Supplier List, 2022, Available at https://www.apple.com/supplier-responsibility/pdf/Apple-FY21-Supplier-List.pdf.

[12] B.V. Kasulaitis, C.W. Babbitt, R. Kahhat, E. Williams and E.G. Ryen, Evolving materials, attributes, and functionality in consumer electronics: Case study of laptop computers, *Resources, conservation and recycling* **100** (2015), 1–10.

[13] M. Uddin and A.A. Rahman, Energy efficiency and low carbon enabler green IT framework for data centers considering green metrics, *Renewable and Sustainable Energy Reviews* **16**(6) (2012), 4078–4094.

[14] G. Kamiya, Data centres and data transmission networks, 2022, Available at https://www.iea.org/reports/data-centres-and-data-transmission-networks.

[15] A. Jacobsen, R. Kaliyaperumal, L.O.B. da Silva Santos, B. Mons, E. Schultes, M. Roos and M. Thompson, A generic workflow for the data FAIRification process, *Data Intelligence* **2**(1–2) (2020), 56–65.

[16] R. Benjamins, D. Fensel and A. Gómez-Pérez, Knowledge management through ontologies, CEUR Workshop Proceedings (CEUR-WS.org), 1998.

[17] D. Fensel, Ontology-based knowledge management, *Computer* **35**(11) (2002), 56–59. doi:10.1109/MC.2002.1046975.

[18] N. Freire and S.d. Valk, Automated interpretability of linked data ontologies: : an evaluation within the cultural heritage domain, in: *2019 IEEE International Conference on Big Data (Big Data)*, 2019, pp. 3072–3079. doi:10.1109/BigData47090.2019.9005491.

[19] P. Hitzler, A review of the Semantic Web field, *Communications of the ACM* **64**(2) (2021), 76–83. doi:10.1145/3397512.

[20] T. Berners-Lee, J. Hendler and O. Lassila, The Semantic Web, *Scientific american* **284**(5) (2001), 34–43.

[21] I. Horrocks, Semantic Web: The story so far, in: *Proceedings of the 2007 International Cross-Disciplinary Conference on Web Accessibility (W4A)*, W4A '07, Association for Computing Machinery, New York, NY, USA, 2007, pp. 120–125–. ISBN 1595935908. doi:10.1145/1243441.1243469.

[22] A. Breitfuss, K. Errou, A. Kurteva and A. Fensel, Representing emotions with knowledge graphs for movie recommendations, *Future Generation Computer Systems* **125** (2021), 715–725. doi:https://doi.org/10.1016/j.future.2021.06.001.

[23] L.O. Colombo-Mendoza, R. Valencia-García, A. Rodríguez-González, G. Alor-Hernández and J.J. Samper-Zapater, RecomMetz: A context-aware knowledge-based mobile recommender system for movie showtimes, *Expert Systems with Applications* **42**(3) (2015), 1202–1222. doi:10.1016/j.eswa.2014.09.016.

[24] S. Zhou, X. Dai, H. Chen, W. Zhang, K. Ren, R. Tang, X. He and Y. Yu, Interactive recommender system via knowledge graph-enhanced reinforcement learning, in: *Proceedings of the 43rd international ACM SIGIR conference on research and development in information retrieval*, 2020, pp. 179–188.

[25] S. Kirrane, J.D. Fernández, P. Bonatti, U. Milosevic, A. Polleres and R. Wenning, The SPECIAL-K personal data processing transparency and compliance platform, *arXiv preprint arXiv:2001.09461* (2020).

[26] K. Fatema, E. Hadziselimovic, H.J. Pandit, C. Debruyne, D. Lewis and D. O'Sullivan, Compliance through informed consent: semantic based consent permission and data management model, *Privacy and the Semantic Web - policy and technology workshop (PrivOn 2017), Co-located with ISWC 2017* (2017).

[27] T.R. Chhetri, A. Kurteva, R.J. DeLong, R. Hilscher, K. Korte and A. Fensel, Data protection by design tool for automated GDPR compliance verification based on semantically modeled informed consent, *Sensors* **22**(7) (2022). doi:10.3390/s22072763.

[28] A. Tauqeer, A. Kurteva, T.R. Chhetri, A. Ahmeti and A. Fensel, Automated GDPR contract compliance verification using knowledge graphs, *Information* **13**(10) (2022), 447. doi:10.3390/info13100447.

[29] T.R. Chhetri, A. Kurteva, J.G. Adigun and A. Fensel, Knowledge graph based hard drive failure prediction, *Sensors* **22**(3) (2022), 985. doi:https://doi.org/10.3390/s22030985.
[30] T.R. Chhetri, S. Aghaei, A. Fensel, U. Göhner, S. Gül-Ficici and J. Martinez-Gil, Optimising Manufacturing Process with Bayesian Structure Learning and Knowledge Graphs, in: *Computer Aided Systems Theory – EUROCAST 2022*, R. Moreno-Díaz, F. Pichler and A. Quesada-Arencibia, eds, Springer Nature Switzerland, Cham, 2022, pp. 594–602. ISBN 978-3-031-25312-6.
[31] O.V. Mamoutova, M.B. Uspenskiy, A.V. Sochnev, S.V. Smirnov and M.V. Bolsunovskaya, Knowledge based diagnostic approach for enterprise storage systems, in: *2019 IEEE 17th International Symposium on Intelligent Systems and Informatics (SISY)*, 2019, pp. 207–212. doi:10.1109/SISY47553.2019.9111617.
[32] O. Mamoutova, M. Uspenskiy, S. Smirnov and M. Bolsunovskaya, Ontological approach to automated analysis of enterprise data storage systems log files, *Acta Polytechnica Hungarica* **18**(9) (2021), 27–47.
[33] E. Kärle, U. Şimşek, O. Panasiuk and D. Fensel, Building an ecosystem for the tyrolean tourism knowledge graph, in: *International Conference on Web Engineering*, Springer, 2018, pp. 260–267.
[34] A. Pavel, L.A. Saarimäki, L. Möbus, A. Federico, A. Serra and D. Greco, The potential of a data centred approach knowledge graph data representation in chemical safety and drug design, *Computational and Structural Biotechnology Journal* **20** (2022), 4837–4849. doi:10.1016/j.csbj.2022.08.061.
[35] E. Della Valle, S. Schlobach, M. Krötzsch, A. Bozzon, S. Ceri and I. Horrocks, Order matters! Harnessing a world of orderings for reasoning over massive data, *Semantic Web* **4**(2) (2013), 219–231. doi:10.5555/2590215.2590219.
[36] H. Li, R. Armiento and P. Lambrix, An ontology for the materials design domain, in: *International Semantic Web Conference*, Springer, 2020, pp. 212–227. doi:10.1007/978-3-030-62466-8_14.
[37] T. Ashino, Materials ontology: An infrastructure for exchanging materials information and knowledge, *Data Science Journal* **9** (2010), 54–61. doi:http://doi.org/10.2481/dsj.008-041.
[38] E. Sauter, R. Lemmens and P. Pauwels, CEO and CAMO ontologies: a circulation medium for materials in the construction industry, in: *6th International Symposium on Life-Cycle Civil Engineering (IALCCE)*, CRC Press, 2019, pp. 1645–1652.
[39] E. Sauter and M. Witjes, Linked Spatial Data for a Circular Economy: Exploring its potential through a Textile Use Case., in: *SEMANTICS Posters&Demos*, 2017.
[40] A. Kurteva, T.R. Chhetri, H.J. Pandit and A. Fensel, Consent through the lens of semantics: State of the art survey and best practices, *Semantic Web*, 1–27. doi:10.3233/SW-210438.
[41] D. Moher, A. Liberati, J. Tetzlaff, D.G. Altman and T.P. Group, Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement, *PLOS Medicine* **6**(7) (2009), 1–6. doi:10.1371/journal.pmed.1000097.
[42] H. Jin, K. Frost, I. Sousa, H. Ghaderi, A. Bevan, M. Zakotnik and C. Handwerker, Life cycle assessment of emerging technologies on value recovery from hard disk drives, *Resources, Conservation and Recycling* **157** (2020), 104781. doi:10.1016/j.resconrec.2020.104781. https://www.sciencedirect.com/science/article/pii/S0921344920301026.
[43] G. Bailey, P.J. Joyce, D. Schrijvers, R. Schulze, A.M. Sylvestre, B. Sprecher, E. Vahidi, W. Dewulf and K. Van Acker, Review and new life cycle assessment for rare earth production from bastnäsite, ion adsorption clays and lateritic monazite, *Resources, Conservation and Recycling* **155** (2020), 104675. doi:10.1016/j.resconrec.2019.104675.
[44] R. Sileryte, A. Wandl and A. van Timmeren, A bottom-up ontology-based approach to monitor circular economy: Aligning user expectations, tools, data and theory (2021).
[45] V. Mikić, N. Gligorić and M. Ilić, A survey on interoperability semantic data ontologies for the circular economy, *The 8th Conference with International Participation Knowledge Management and Informatics*.
[46] A. Daouadji, K.-K. Nguyen, M. Lemay and M. Cheriet, Ontology-based resource description and discovery framework for low carbon grid networks, in: *2010 First IEEE International Conference on Smart Grid Communications*, IEEE, 2010, pp. 477–482.
[47] A.-G. Olabi, Circular economy and renewable energy, Vol. 181, Elsevier, 2019, pp. 450–454.
[48] S.S. Karakutuk, S. Akpinar and M.A. Ornek, An application of a circular economy approach to design an energy-efficient heat recovery system, *Journal of Cleaner Production* **320** (2021), 128851. doi:10.1016/j.jclepro.2021.128851.
[49] F. Lampathaki, Y. Charalabidis, S. Passas, D. Osimo, M. Bicking, M.A. Wimmer and D. Askounis, Defining a taxonomy for research areas on ICT for governance and policy modelling, in: *International Conference on Electronic Government*, Springer, 2010, pp. 61–72. doi:https://doi.org/10.1007/978-3-642-14799-9_6.
[50] V. Gower and R. Andrich, A taxonomy for ICT assistive technology products, *Technology and Disability* **26**(2–3) (2014), 127–136. doi:10.3233/TAD-140409.
[51] V. Dhingra and K.K. Bhatia, Development of ontology in laptop domain for knowledge representation, *Procedia Computer Science* **46** (2015), 249–256.
[52] N.F. Noy, D.L. McGuinness et al., Ontology development 101: A guide to creating your first ontology, Stanford knowledge systems laboratory technical report KSL-01-05, 2001.
[53] T. Inaba and M. Squicciarini, ICT: A new taxonomy based on the international patent classification, *OECD Science, Technology and Industry Working Papers* (2017). doi:10.1787/ab16c396-en.
[54] World Intellectual Property Organization (WIPO), International Patent Classification (IPC), 2022, Available at https://tind.wipo.int/record/44834.
[55] Japan Patent Office, Outline of Japanese patent classification systems, 2013, Available at https://www.wipo.int/edocs/mdocs/aspac/en/wipo_reg_ip_tyo_13/wipo_reg_ip_tyo_13_t18.pdf.
[56] J. Swetina, G. Lu, P. Jacobs, F. Ennesser and J. Song, Toward a standardized common M2M service layer platform: Introduction to oneM2M, *IEEE Wireless Communications* **21**(3) (2014), 20–26.

[57] D. Bonino and F. Corno, Dogont-ontology modeling for intelligent domotic environments, in: *International Semantic Web Conference*, Springer, 2008, pp. 790–803.
[58] L. Daniele, F.d. Hartog and J. Roes, Created in close interaction with the industry: the smart appliances reference (SAREF) ontology, in: *International Workshop Formal Ontologies Meet Industries*, Springer, 2015, pp. 100–112.
[59] The oneM2M Consortium, oneM2M Base Ontology Specification V3.7.3, 2019, Available at https://www.onem2m.org/images/pdf/TS-0012-Base_Ontology-V3_7_3.pdf.
[60] M. Compton, P. Barnaghi, L. Bermudez, R. Garcia-Castro, O. Corcho, S. Cox, J. Graybeal, M. Hauswirth, C. Henson and A. Herzog, The SSN ontology of the W3C semantic sensor network incubator group, *Journal of Web Semantics* **17** (2012), 25–32.
[61] M. Ayundhita, Z. Baizal and Y. Sibaroni, Ontology-based conversational recommender system for recommending laptop, in: *Journal of Physics: Conference Series*, Vol. 1192, IOP Publishing, 2019, p. 012020.
[62] Z.A. Baizal, D.H. Widyantoro and N.U. Maulidevi, Design of knowledge for conversational recommender system based on product functional requirements, in: *2016 international conference on data and software engineering (ICoDSE)*, IEEE, 2016, pp. 1–6.
[63] O. Corcho, D. Chaves-Fraga, J. Toledo, J. Arenas-Guerrero, C. Badenes-Olmedo, M. Wang, H. Peng, N. Burrett, J. Mora and P. Zhang, A High-Level Ontology Network for ICT Infrastructures, in: *The Semantic Web – ISWC 2021*, A. Hotho, E. Blomqvist, S. Dietze, A. Fokoue, Y. Ding, P. Barnaghi, A. Haller, M. Dragoni and H. Alani, eds, Springer International Publishing, Cham, 2021, pp. 446–462. ISBN 978-3-030-88361-4.
[64] I. Davis, VANN: A vocabulary for annotating vocabulary descriptions, 2005, Available at https://vocab.org/vann/.
[65] A. Miles and J.R. Pérez-Agüera, Skos: Simple knowledge organisation for the web, *Cataloging & Classification Quarterly* **43**(3–4) (2007), 69–83.
[66] O. Corcho, R. Alcazar, D.C.-F.J. Toledo, J. Arenas, M. Wang, H. Peng, N. Burrett, J. Mora and P. Zhang, Ontology for the representation of the hardware items related to a DevOps infrastructure, 2021, Available at http://w3id.org/devops-infra/hardware.
[67] World Wide Web Consortium (W3C), OWL2 Web Ontology Language: New features and rationale (second edition), 2012, Available at https://www.w3.org/TR/owl-new-features/.
[68] K. Cheung, J. Drennan and J. Hunter, Towards an ontology for data-driven discovery of new materials, in: *AAAI Spring Symposium: Semantic Scientific Knowledge Integration*, 2008, pp. 9–14.
[69] A. Gangemi, N. Guarino, C. Masolo, A. Oltramari and L. Schneider, Sweetening ontologies with DOLCE, in: *International conference on knowledge engineering and knowledge management*, Springer, 2002, pp. 166–181. doi:https://doi.org/10.1007/3-540-45810-$7_1$8.
[70] T.R. Gruber and G.R. Olsen, An ontology for engineering mathematics, in: *Principles of Knowledge Representation and Reasoning*, Elsevier, 1994, pp. 258–269. doi:10.1016/B978-1-4832-1452-8.50120-2.
[71] C. Lagoze and J. Hunter, The ABC ontology and model, *Journal of Digital Information* **2**(2) (2002).
[72] L.N. Soldatova and R.D. King, An ontology of scientific experiments, *Journal of the Royal Society Interface* **3**(11) (2006), 795–803. doi:10.1098/rsif.2006.0134.
[73] J. Hastings, N. Jeliazkova, G. Owen, G. Tsiliki, C.R. Munteanu, C. Steinbeck and E. Willighagen, eNanoMapper: harnessing ontologies to enable data integration for nanomaterial risk assessment, *Journal of biomedical semantics* **6**(1) (2015), 1–15.
[74] P. de Matos, A. Dekker, M. Ennis, J. Hastings, K. Haug, S. Turner and C. Steinbeck, ChEBI: a chemistry ontology and database, *Journal of cheminformatics* **2**(1) (2010), 1–1.
[75] X. Zhang, D. Pan, C. Zhao and K. Li, MMOY: Towards deriving a metallic materials ontology from Yago, *Advanced Engineering Informatics* **30**(4) (2016), 687–702.
[76] G. Stoilos, G. Stamou and S. Kollias, A string metric for ontology alignment, in: *International Semantic Web conference*, Springer, 2005, pp. 624–637. doi:10.1007/11574620_45.
[77] E. Consortium, Elementary Multiperspective Material Ontology (EMMO), 2021, Available at https://github.com/emmo-repo/EMMO.
[78] The BIMERR Project, Material Properties Ontology, 2021, Available at https://bimerr.eu/wp-content/uploads/pdf/4.3%20BIMERR%20Ontology%20%26%20Data%20Model%202.pdf.
[79] S.P. Voigt and S.R. Kalidindi, Materials graph ontology, *Materials Letters* **295** (2021), 129836.
[80] W.D. Callister and D. Rethwisch Jr, Materials science and engineering, John Wiley and Sons, SBN, 2010.
[81] A. Khosravani, L. Morsdorf, C.C. Tasan and S.R. Kalidindi, Multiresolution mechanical characterization of hierarchical materials: Spherical nanoindentation on martensitic Fe-Ni-C steels, *Acta Materialia* **153** (2018), 257–269.
[82] F.L. Piane, M. Baldoni, M. Gaspari and F. Mercuri, Introducing MAMBO: Materials and molecules basic ontology, *arXiv preprint arXiv:2111.02482* (2021).
[83] H. Sack, M. Alam, D. Dessı, A.Z. Ihsan and S. Sandfeld, Steps towards a dislocation ontology for crystalline materials, in: *SeDiT 2021-Semantic Digital Twins 2021-Proceedings of the Second International Workshop on Semantic Digital Twins co-located with the 18th Extended Semantic Web Conference (ESWC 2021), Hersonissos, Greece, June 6, 2021. Ed.: R. García-Castro*, 2021.
[84] P. Lambrix, R. Armiento, H. Li, O. Hartig, M.A.N. Pour and Y. Li, The Materials Design Ontology, *Transport* **8**(10), 24.
[85] C.W. Andersen, R. Armiento, E. Blokhin, G.J. Conduit, S. Dwaraknath, M.L. Evans, Á. Fekete, A. Gopakumar, S. Gražulis, A. Merkys et al., OPTIMADE, an API for exchanging materials data, *Scientific data* **8**(1) (2021), 1–10.
[86] M.C. Suárez-Figueroa, A. Gómez-Pérez and M. Fernández-López, The NeOn methodology for ontology engineering, in: *Ontology engineering in a networked world*, Springer, 2012, pp. 9–34. doi:10.1007/978-3-642-24794-1_2.
[87] P. Hitzler, M. Krötzsch, B. Parsia, P.F. Patel-Schneider, S. Rudolph et al., OWL 2 web ontology language primer, *W3C recommendation* **27**(1) (2009), 123.

[88] T. Lebo, S. Sahoo, D. McGuinness, K. Belhajjame, J. Cheney, D. Corsar, D. Garijo, S. Soiland-Reyes, S. Zednik and J. Zhao, *PROV-O: The PROV Ontology*, W3C Recommendation, World Wide Web Consortium, United States, 2013.
[89] D. Chiaroni and A. Urbinati, Circular Economy Business Models: towards a new taxonomy of the degree of circularity, 2016.
[90] M. Saidani, B. Yannou, Y. Leroy, F. Cluzel and A. Kendall, A taxonomy of circular economy indicators, *Journal of Cleaner Production* **207** (2019), 542–559. doi:https://doi.org/10.1016/j.jclepro.2018.10.014.
[91] B. Marr, *Big Data: Using SMART big data, analytics and metrics to make better decisions and improve performance*, John Wiley & Sons, 2015.
[92] Z. Baizal, A. Iskandar and E. Nasution, Ontology-based recommendation involving consumer product reviews, in: *2016 4th International Conference on Information and Communication Technology (ICoICT)*, IEEE, 2016, pp. 1–6. doi:10.1109/ICoICT.2016.7571890.
[93] Z.A. Baizal, Y.R. Murti et al., Evaluating functional requirements-based compound critiquing on conversational recommender system, in: *2017 5th International Conference on Information and Communication Technology (ICoIC7)*, IEEE, 2017, pp. 1–6. doi:10.1109/ICoICT.2017.8074656.
[94] N. Gligoric, S. Krco, L. Hakola, K. Vehmas, S. De, K. Moessner, K. Jansson, I. Polenz and R. Van Kranenburg, Smarttags: IoT product passport for circular economy based on printed sensors and unique item-level identifiers, *Sensors* **19**(3) (2019), 586.
[95] J.S. Mboli, D. Thakker and J.L. Mishra, An Internet of Things-enabled decision support system for circular economy business model, *Software: Practice and Experience* **52**(3) (2022), 772–787.
[96] F. Gandon, M. Sheshagiri and N.M. Sadeh, ROWL: Rule language in OWL and translation engine for JESS, *Mobile Commerce Laboratory* (2004).
[97] P. Shvaiko and J. Euzenat, Ten challenges for ontology matching, in: *On the Move to Meaningful Internet Systems: OTM 2008: OTM 2008 Confederated International Conferences, CoopIS, DOA, GADA, IS, and ODBASE 2008, Monterrey, Mexico, November 9-14, 2008, Proceedings, Part II*, Springer, 2008, pp. 1164–1182.
[98] L. Hollink, M. Van Assem, S. Wang, A. Isaac and G. Schreiber, Two variations on ontology alignment evaluation: Methodological issues, in: *ESWC*, 2008, pp. 388–401.
[99] C. Shimizu, K. Hammar and P. Hitzler, Modular ontology modeling, *Semantic Web* (2021), 1–31.
[100] K. Hartley, R. van Santen and J. Kirchherr, Policies for transitioning towards a circular economy: Expectations from the European Union (EU), *Resources, Conservation and Recycling* **155** (2020), 104634.
[101] S. Yamaguchi, International trade and circular economy-Policy alignment (2021).
[102] A. Flynn and N. Hacking, Setting standards for a circular economy: a challenge too far for neoliberal environmental governance?, *Journal of Cleaner Production* **212** (2019), 1256–1267. doi:10.1016/j.jclepro.2018.11.257.
[103] The British Standards Institution, BIS 8001: Framework for implementing the principles of the circular economy in organizations. Guide, 2017, Available at https://knowledge.bsigroup.com/products/framework-for-implementing-the-principles-of-the-circular-economy-in-organizations-guide/standard.
[104] International Standards Organisation (ISO), ISO/TC 323, 2018, Available at https://www.iso.org/committee/7203984.html.
[105] United Nations, The 17 Sustainable Development Goals, 2015, Available at https://sdgs.un.org/goals.
[106] International Electrotechnical Commission (IEC), TC 111: Environmental standardization for electrical and electronic products and systems, Available at https://www.iec.ch/dyn/www/f?p=103:7:614967619346446:::FSP_ORG_ID,FSP_LANG_ID:1314,25.
[107] European Committee for Electrotechnical Standardization, Standardization in a circular economy – closing the loop, 2020, Available at https://www.cencenelec.eu/media/CEN-CENELEC/News/Publications/standardization_circular_economy_closing_the_loop.pdf.