Semantic Web and its Role in Facilitating ICT Data Sharing for the Circular Economy: An Ontology Survey

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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 and analysis of existing ontologies for ICT, materials and the CE, their limitations and applications, which can help guide CE's further implementation by focusing on facilitating FAIR data.

Keywords: Ontology, ICT, Materials, Circular Economy, Data Sharing, FAIR Data, 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 [2], recycling [3], remanufacturing [4], and repurposing [5]. 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 over the use phase of a product. This phase occurs simultaneously with the use cycle and has a direct impact

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[1] https://ellenmacarthurfoundation.org/circular-economy-diagram
[2] https://ellenmacarthurfoundation.org

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.

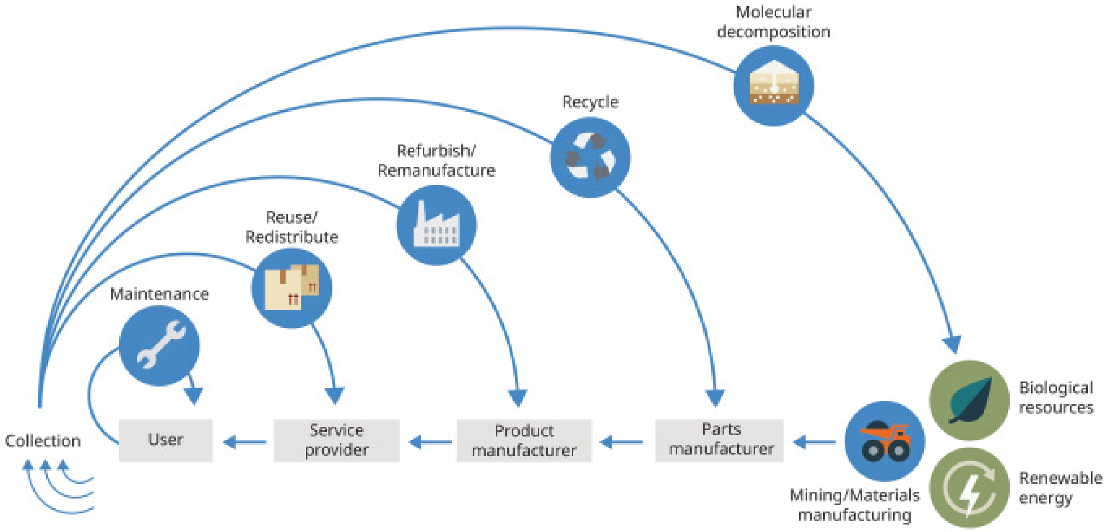

Fig. 1. Circular Strategies for Products and Materials [6]

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 [7][8]. 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 3-4 years [9], while research shows that they should last 7 years before they are replaced [10]. 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 [11]. 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 [12]. 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 through its life-cycle impacting the health and safety of mining communities and their surrounding

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

environments, intense energy consumption (see [13]) 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.

Based on the findings in a report[4] [9] by the Amsterdam Economic Board[5], the adoption of the CE in the ICT sector (in the Netherlands) is currently limited. Examples of barriers to this are siloed knowledge about the CE and ICT within and between organisations and the lack of transparency and traceability of ICT procurement (i.e. the process of obtaining goods or service for a business) [9]. In organisations many departments (e.g. sales, IT, finance, delivery) are involved in the decision making-process for the implementation of information technology (IT) infrastructures. ICT experts provide technical assistance, while CE experts develop sustainability strategies that procurers can follow. However, the explanations for each decision (and the data for it) often remain within specific expert groups. Knowledge exchange should be better facilitated in an understandable for all expert groups manner so that both technical requirements and sustainability factors are considered during ICT procurement and maintenance. Data findability, acessibility and interpretation are also common barriers when data sharing needs to be facilitated between companies, suppliers and manufacturers. For example, the production of an iPhone involves more than 200 component suppliers, spread over 43 countries and 6 continents [14]. Each supplier has specialised knowledge about their products such as their material composition, design and hardware-software dependencies. Such information is rarely available to end users and decision makers (procurers). Inaccurate, incomplete and unavailable data about ICT itself can lead to misleading and incorrect sustainability recommendations during processes such as life cycle assessment (LCA) [15]. Several studies, namely [16][17][18] confirm that data's availability, format standardisation and quality are some of the key challenges for LCAs. Motivated by the lack of data availability, studies such as [7] [19] have made progress in publishing online ICT's (laptops, tablets) material data in the form of a bill of materials (BoMs). The datasets are limited (only several brand and models which can be considered outdated), present material data for a specific component or for the device as a whole and do not follow a standard format that can easily facilitate their federation and interpretation. This can also be seen as a result of the CE standardisation still being under development. There is yet no single CE standard to be used as a main reference point across the European Union (EU) thus there is a lack of a unified terminology for CE's processes and guidelines/best practices for implementing the CE across different sectors.

Having such standard(s) could also help to derive clear requirements for what specific ICT data should be made available, to whom under what circumstances. ICT devices such as a laptops comprise of multiple components (e.g. display screen, keyboard, base panel, top panel, cooling fan, random-access memory (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[6] and/or personalised based on the model and manufacturer of the product and the needs of the end-users. In both cases, unprecedented amount of heterogeneous data about both the device itself, its performance over time and the testing performed on it are generated, which is expensive with regards to the computational power and additional support that might be needed to generate, process, store and maintain data.

These are also factors that need to be considered when developing technology that aims to support ICT decision making in cases such as predictive maintenance and sustainable procurement 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 [20]). As discussed in [21], 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 [22] process (see Table 1). Through

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[4] https://amsterdameconomicboard.com/en/news/circular-ict-procurement-is-to-drastically-reduce-waste/

[5] https://amsterdameconomicboard.com/en/

[6] 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.

the years, research such as [23][24] has shown ontologies' ability to not only organise and interconnect knowledge within organisations but to also make it accessible and interoperable across machines. Due to their ability to represent dynamic contexts in a machine-readable format ([25][26]), ontologies have been widely utilised as knowledge organisation schemas in diverse domains such as cultural heritage as discussed in [27][28]. Further, reseach has shown that ontologies can successfully assist and even improve machines' decision making in scenarios such as recommendations [29][30][31], legal compliance [32][33][34][35], predictive maintenance [36][37][38][39], tourism [40], chemical safety and drug design [41] and intelligent surveillance [42]. 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. Technology-wise, when it comes to facilitating ICT data sharing for the CE, more and more experts have been utilising Semantic Web technologies. 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 [43][44][45]). *"Linked Data can function as an exchange medium for the CE driving the "push and pull" between diverse industry resources."* [46]. However, there is a lack of systematic semantic analysis (i.e. discussion on the mechanisms used for building the model, the 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 existing semantic models for ICT devices and materials in the CE. 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, sub-classes, object and data properties) for reuse or extension, when building semantic technology-based tools for the CE. Further, we present 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 can help both CE experts and ontology engineers as it provides an overview of existing domain ontologies, information on how they were built, their limitations (Section 4), and how they can be reused (Section 5). Further, we provide examples of research work (Section 4.4) that showcases the successful utilisation of ontologies within CE software tools.

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 followed by a discussion in Section 6 and the conclusions in Section 7.

2. Methodology

To compile this paper, guided by our previous survey in the Semantic Web domain (see [47]), we undertook several steps which are presented on Figure 2. We began with background research into the CE to better understand its scope, goals and current level of implementation (Step 1). Next, based on the authors' diverse expertise (computer science, CE, industrial design and sustainability) and the collaboration with refurbishment, ICT and CE domain experts, we reviewed some of the current challenges/barriers that limit the further adoption of the CE (Step 1.1). The collaboration has been done in the scope of the Circular Resource Planning for IT (RePlanIT)[7] project, which aims to utilise ontologies to build digital product passports (DPPs) of ICT that can assist predictive maintenance and sustainable ICT procurement. During Step 1.2 we explored the technology needs of tools that support FAIR data implementations for the CE. Next, during Step 1.3, we mapped the existing CE challenges to each FAIR principle (Table 1). During Step 1.4, we extended Table 1 so that it clearly states how ontologies can be used to help solve each CE challenge to support the corresponding FAIR principle. To have a clear scope in the broad ICT domain, laptops (some of the most used and disposed of ICT devices nowadays) were selected as our main ICT use case (Step 2). During Step 3, we investigated the life-cycle of ICT devices and their components in the CE and designed an abstract model as presented on Fig. 3. Following this and focusing on laptops, we derived a set of competency questions (Step 3.2, Table 8 in the Appendix) that can be used as requirements for types of data needed to describe an ICT device, its components and materials in the CE. Next in Step 4, based on this we begin our survey of existing semantic models for the following three domains: ICT (with a focus on laptops), materials and the CE. During our investigation, we encountered several studies that do not directly present ontologies but rather show their utilisation in the CE in practice. These studies have been briefly reviewed as well in Section 4.4. After the survey and summary of the related work, we evaluated (in Step 5) each one of the publicly available ontologies with the set of competency questions introduced in Step 3.2. This helped understand to what extent each ontology can model the domain and what specific concepts from it can be reused (to support best practices in ontology engineering). The analysis highlighted several discussion points, which we reflected on in Step 6 (see Section 6). Finally, all findings were concluded in Step 7 (Section 7).

The main sources for this survey were peer-reviewed scientific publications in the CE, ICT and Semantic Web domains, which we identified via Google Scholar[8], ACM Digital Library[9], IEE Xplore[10], Scopus[11] and DBLP[12]. A search for resources was also performed on the websites of standardisation bodies such as the British Standards Institution (BIS)[13], the EU Commision[14], the International Electrotechnical Commission (IEC)[15] and the International Organisation for Standardisation (ISO)[16]. The main keywords used were *CE, CE strategies, CE data sharing, CE privacy, CE data model, CE ontology, CE taxonomy, CE standards, CE legislation, CE sustainability, linear economy, CE tools, sustainable ICT, circular ICT, ICT data model, ICT ontology, ICT taxonomy, ICT data sharing, laptops, ICT environmental impact, ICT manufacturing, materials, critical materials, raw materials, materials*

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[7] https://www.ams-institute.org/urban-challenges/circularity-urban-regions/circular-resource-planning-for-it-replanit/

[8] https://scholar.google.com

[9] https://dl.acm.org

[10] https://ieeexplore.ieee.org/Xplore/home.jsp

[11] https://www.scopus.com

[12] https://dblp.org

[13] https://www.bsigroup.com/en\protect\discretionary{\char\hyphenchar\font}{}{}GB/

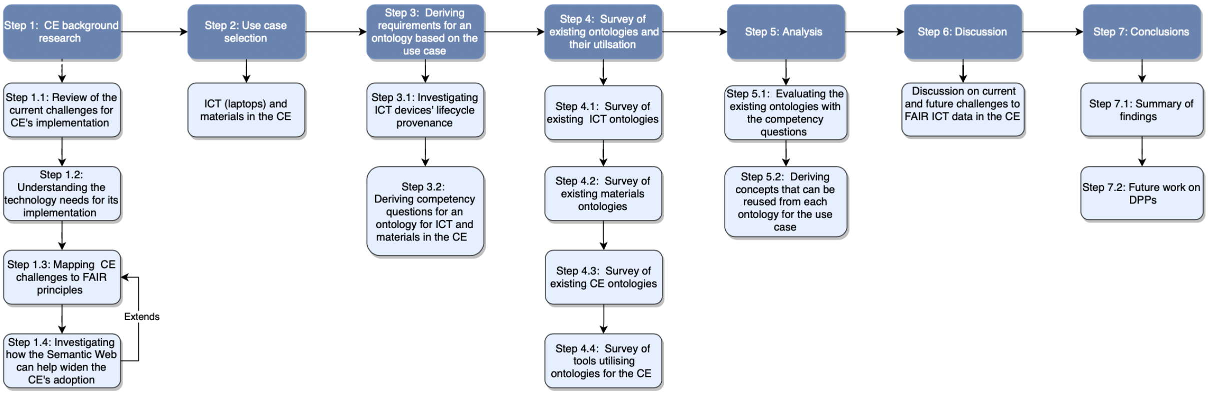
[14] https://digital-strategy.ec.europa.eu/en/policies/

[15] https://www.iec.ch/news-resources/reference-material#codes

[16] https://www.iso.org/home.html

data model, materials ontology, materials taxonomy, FAIR principles, FAIR data sharing. Insights have also been gathered from the authors' current involvement in RePlanIT and part participation in the CampaNeo[17] smashHit[18], KI-NET[19] projects, which focused on IoT data sharing, digital twins and predictive maintenance enabled by ontologies and knowledge graphs.

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 its life-cycle provenance. An ICT device (e.g. a laptop) can be represented in terms of the components that it is comprised of. Each component has provenance information, 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 lifecycle assessment [48][49], establishing responsibility along the supply chain and for implementing CE strategies such as predictive maintenance.

Based on this and on our collaboration with the refurbishment, sustainability and CE experts during the RePlanIT[7] project, we present a set of competency questions (see Table 8 in the Appendix) that can be used as a starting point (or a guideline) when building an ontology for ICT's and its materials' lifecycle management in the CE. We have also used the competency questions to evaluate the relevance of each existing ontology (Section 5) with regards to our use case. The evaluation results can help to better understand which semantic model and which specific concepts from it can be reused to build a common shared vocabulary for ICT in the CE. Table 8 presents the competency questions organised in six categories: (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 example, the first category (ICT devices) comprises of questions such as *"What is the type of the ICT device?, What is the brand of the device?, When was the device assembled?, What are the components of a device? etc."* which assist in building a general semantic representation of a device. The next categories (e.g. ICT device component) focus on lower-level

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[17] https://projekte.ffg.at/projekt/3314668
[18] https://smashhit.eu
[19] https://ki-net.eu

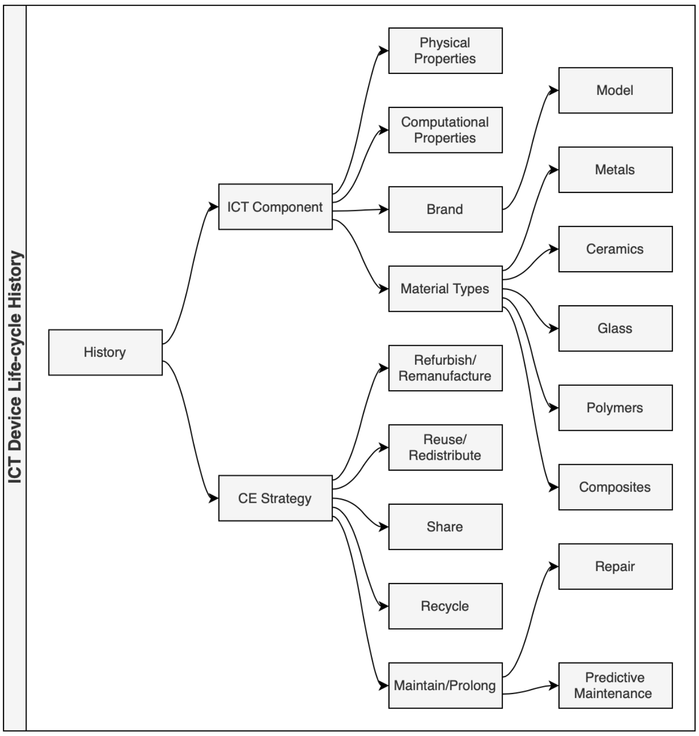

Fig. 3. Conceptual Model for an ICT Device Life-Cycle

questions (e.g. *"What is the serial number of the component?, What is the status of the device's component? Has it been reused, remanufactured, or refurbished before?, What is the brand of the component?"*) and help define a more granular laptop representation (one can answer the questions for each component of a laptop). To further support the ontology engineering process, we have derived the key concepts that an ontology should represent to answer each question (see Table 8 in the Appendix).

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. 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. [50]

Daouadji et al. [50] present an ICT resource management ontology for the energy efficiency domain. The ontology, which was built with the Resource Description Framework (RDF)[20], models three of the most common types

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[20] https://www.w3.org/RDF/

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 an 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 [50]. The ontology 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 [51] [52].

4.1.2. *ICT Governance and Policy Taxonomy by Lampathaki et al. [53]*

Motivated by the technological advancements of government-supporting tools and the increasing need for data governance, Lampathaki et al. [53] propose a taxonomy that helps categorise ICT research. Being developed in the context of the CROSSROAD[21] 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, 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 [54]*

The lack of standardisation in terminology in the ICT domain has also inspired Gower and Andrich [54], 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)[22] 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 [54] 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 [55]*

Dhingra and Bhatia [55] 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[23] 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 [55] follows the ontology engineering methodology from [56] 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,

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[21] https://cordis.europa.eu/project/id/248484

[22] https://cordis.europa.eu/project/id/270746/en

[23] https://protege.stanford.edu

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 [57]

By following the International Patent Classification (IPC)[24] [58] system, the ICT patents presented in it and by building upon the Japan Patent Office (JPO)[25] classification system [59], Inaba and Squicciarini [57] 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 [57] 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 [57] 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.

4.1.6. oneM2M Base Ontology [60]

The ontology is the main semantic model used by the oneM2M[26] 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 also be extended with specific concepts such as sensors and switches from the DogOnt ontology to achieve higher expressivity. As discussed in [61], mapping of other ontologies such as the SmartAppliances REFerence (SAREF)[62], to oneM2M is possible and guidelines are provided in [63].

4.1.7. DogOnt Ontology for IntelligentDomotic Environments by Bonino and Russis [61]

One of the earliest and most expressive Web Ontology Language (OWL)[27] ontologies that focuses on smart device modelling is the DogOnt by Bonino and Russis [61]. 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) [64], Dublin Core[28], Creative Commons [29], Measurement Units Ontology(MUO)[30] and Unified Code for Units of Measure (UCUM)[31] have been reused. Further, as shown in [61], 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[32], 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).

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[24] https://www.wipo.int/classifications/ipc/en/
[25] https://www.jpo.go.jp/e/
[26] https://www.onem2m.org
[27] https://www.w3.org/TR/owl-ref/
[28] https://www.dublincore.org/specifications/dublin-core/dcmi-terms/
[29] https://creativecommons.org/ns
[30] https://databus.dbpedia.org/ontologies/elite.polito.it/ontologies--muo-vocab--owl
[31] https://databus.dbpedia.org/ontologies/elite.polito.it/ontologies--ucum-instances--owl
[32] http://iot-ontologies.github.io/dogont/documentation/index-en.html

4.1.8. Laptop Ontology by Ayundhita et al. [65]

Similarly to [55], 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 [66], 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. [67]

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. [67] 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 and the Simple Knowledge Organisation System (SKOS) [68] have been reused. The ontology is openly available online[33] 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[34] [67].

4.1.10. Hardware and DevOps Ontology by Corcho et al. [69]

In addition to the work in [67], Corcho et al. have built an ontology [69] 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 [67], concepts from Dublin Core, SKOS, DevOps [67] have been reused. Both the ontology and its documentation are available online[35], 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

Table 2 presents a summary of the overviewed ICT semantic models based on the criteria that was specified in the beginning of Section 4. For each model, the table provides information on its type (taxonomy, schema, ontology), scope and year of last update. We have also reviewed each model's conformace to best practices for ontology engineering in terms of the followed Semantic Web standard, the model's availability and the level of reuse of existing ontologies (also noted in the table). Known limitations, current and possible applications for each model are presented as well. The information has been derived from each models' online documentation and scientific publication and by using the OOPS! [70] pitfall scanner (for the public ontologies). A "-" symbol is used when no information has been found in the resources.

10 semantic models (3 taxonomies, 1 RDF schema and 6 ontologies) have been identified as revelant to the ICT domain. The literature review has shown that the available semantic models vary in expressivity (refers to the granularity level of the represented knowledge). Some taxonomies such as [54] and [57] are highly expressive

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[33] https://oeg-upm.github.io/devops-infra/index.html

[34] https://www.huawei.com/en/?ic_medium=direct&ic_source=surlent

[35] https://oeg-upm.github.io/devops-infra/ontology/hardware/index-en.html

Table 2

Overview of ICT Semantic Models

Study	Type	Year of Latest Update	Semantic Web Standard	Scope	Reuse of Existing Ontologies	Availability	Limitations	Applications
Daouadji et al. [50]	Schema	2010	RDF	Energy efficiency; low carbon grid networks.	-	Private	No public URIs, unclear if competency questions were used and if existing ontologies were reused.	Used within a framework, which assists users in identifying the best resources that can be used for a specific task in terms of carbon footprint and energy consumption.
Lampathaki et al. [53]	Taxonomy	2010	-	ICT governance and policy management.	-	Private	Upper level (general) taxonomy for the ICT domain. No specific ICT devices and components are modelled.	Assisting ICT governance.
Gower and Andrich [54]	Taxonomy	2014	-	ICT for AT.	-	Private	Focus mainly on ICT features and clusters in the AT domain.	Used to support AT information interoperability within the ETNA framework.
Dhingra and Bhatia [55]	Ontology	2015	OWL	ICT; laptops (specification, review, selling).	-	Private	Focus on laptops for the e-commerce domain. Specific URIs, namespaces and object properties were not mentioned.	Used for modelling laptop information needed for the online selling.
Inaba and Squicciarini [57]	Taxonomy	2017	-	ICT technology based on IPC and JPO standards.	-	Public	Remains a taxonomy. Focus mainly on ICT software, ICT services and areas of applications and not on ICT types and their hardware.	Represents specific electrical components in ICT and can be used to classify ICT based on its applications.
oneM2M Consortium [63]	Ontology	2019	OWL	IoT and oneM2M device ecosystem	-	Public	Generic ICT device representation with focus on operations, services, functions and their inputs and outputs. Missing class annotations and object property characteristics, inconsistent labelling.	Can be used to extend SAREF [62] ontology with more context for ICT use. Guidelines have been provided as well.
Bonino and Russis [61]	Ontology	2019	OWL	Smart devices and IEs.	SSN, Dublin Core, Creative Commons, MUO, UCUM	Public	Focus primarily on home and office appliances and sensors in them. Properties missing domain and range, unconnected concepts, inconsistent reuse and naming of concepts.	Used to assist in auto-completion mechanisms, which based on reasoning can help model dynamic house modelling processes.
Ayundhita et al. [65]	Ontology	2019	OWL	Laptops and laptop CRS.	-	Private	Focus only on laptops and information that can help improve online retail recommendations (e.g. functional specifications). Not available online and not documented.	Used for improving laptop retail recommendations based.
Corcho et al. [69]	Ontology	2021	OWL	Hardware and DevOps.	Dublin Core, SKOS	Public	High-level ICT representations. A complex ontology network that although built in a modular manner has many interdependencies.	Used as a basis for a knowledge graph that assists question answering by a chatbot.
Corcho et al. [67]	Ontology	2021	OWL	ICT infrastructures and configuration management systems.	Dublin Core, DevOps	Public	As part of the ontology network in [67] it is dependent on other modules in it. Labelling inconsistencies and unconnected concepts within the ontology.	Used to extent [] with specific hardware concepts such as disks, switches, networks cards. These concepts can also be reused when modelling ICT devices such as laptops and their components.

(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 the hardware and DevOps ontology [69], DogOnt [61] represent less concepts but are already encoded as ontologies, are openly availabe and ready for reuse. Ontologies such as [67], [50] [53] focus on representing ICT infrastructures and their management as a whole, while others (see [69][61]) represent specific ICT hardware components and their capabilities. Only 4 of the ontologies ([63][61][69][67]) 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 or 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"* [71] 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 existing ontologies, which is currently at a low level, should be encouraged (e.g. making ontologies and taxonomies public).

4.2. Semantic Models for Materials

This subsection presents an overview of semantic models for materials motivated by the the existing work that was reviewed in [72]. The importance of ICT and materials in the CE is discussed in Section 1.

4.2.1. MaTOnto by Cheung et al. [73]

Motivated by the increased availability of material data and the lack of its standartisation, Cheung et al. [73] 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 [74] 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 [75], W3C's Time[36], ABC Metadata [76] and the EXPO [77] ontologies. In addition to making the MatOnto openly availabe, the authors include specific namespaces in its specification in [73] 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 [44]

Data heterogeneity is also a challenge in the materials domain. In [44], 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) lack consistency. 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 [44] supports their reuse and extension. However, the ontologies are private and no specific namespaces are presented in [44]. 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. [78]

As part of the eNanoMapper[37] project, Hasting et al. focus on the semantic representation of nanomaterials and propose the eNanoMapper[38] ontology. The ontology, built with OWL, provides a detailed schema of nanoparticles based on their properties, constituency and shape [78]. 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[39] and ChEBI [79] have been reused. Further, the authors have implemented an ontology "slimming" library [40] that supports the reuse by selecting only concepts

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

[37] www.enanomapper.net

[38] http://enanomapper.github.io/ontologies/enanomapper.owl

[39] https://basic-formal-ontology.org

[40] athttp://github.com/enanomapper/slimmer/

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. [80]

To built the MMOY ontology, Zhang et al. [80] undertake a slightly different approach for ontology engeneering to the existing traditional (manual) ones. The authors utilise the String Matching on Ordered Alphabets (SMOA) [81] algorithm, which extracts existing metalic material related concepts from the Yago[41] knowledge base. This is done with the help of keywords and synonyms generated with WordNet[42]. 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 [80] 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. [80] 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) [82]

Developed as part of several European projects (e.g. SimDOME [43], OntoCommons[44]) 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)[45], the ontology for the Battery Value Chain (BVC) [46] and the Mappings ontology[47]. 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, due to its abstract nature and domain complexity, reusing or extending EMMO might require iterative collaboration between domain and ontology experts.

4.2.6. The BIM-based holistic tools for Energy-driven existing Residences (BIMMER) Ontology [83]

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[48], Smart Appliances REFerence (SAREF)[62], SKOS, Time [49]). 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 [83] and have transformed the OWL serialisation to JSON-LD format.

4.2.7. Materials Graph Ontology by Voigt and Kalidindi [84]

The work of Voigt and Kalidindi [84] 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 [85] 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

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[41] https://yago-knowledge.org

[42] https://wordnet.princeton.edu

[43] https://simdome.eu

[44] https://ontocommons.eu

[45] https://github.com/BIG-MAP/BattINFO

[46] https://github.com/Battery-Value-Chain-Ontology/ontology

[47] https://github.com/emmo-repo/domain-mappings

[48] http://www.w3.org/2003/01/geo/wgs84/_pos#

[49] https://www.w3.org/2006/time#

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 [86]. 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 [50].

4.2.8. *Materials Design Ontology (MDO) by Lambrix et al. [87]*

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) [88] community. The main goal of OPTIMADE is to make materials databases interoperable by setting a standardised REST APIs [88]. By following the NeOn [89] methodology for ontology engineering and using OWL2 DL [90], Lambrix et al. have built the MDO ontology in a modular way. MDO models knowledge in the materials domain, 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[51] [91] ontology). Quantities, Units, Dimensions and Data Types Ontologies (QUADT) [92] ontology has been reused as well. 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[52] of the ontology.

4.2.9. *Dislocation Ontology by Ihsan et al. [93]*

Ihsan et al. [93] 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"* [93]) 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 has been published online [53]. Several concepts (e.g. lattice, occupancy) from existing ontologies such as the Materials Design Ontology (MDO)[54] [87] have been reused. The study in [93] 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 and Molecules Basic Ontology (MAMBO) by Piane et al. [94]*

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[55] and can already be used as a guideline for future work in the domain.

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. In the past few years, several material ontologies have been built as shown in Table 3. Apart from, the MMOY [80] ontology, which was built automatically, all other ontologies were built manually with domain experts in Protégé (some with WebProtégé). This relates to the need for

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[50] https://www.sciencedirect.com/science/article/pii/S0167577X21005322?via%3Dihub#m0005
[51] https://www.w3.org/TR/prov-o/#Agent
[52] https://github.com/LiUSemWeb/Materials-Design-Ontology
[53] https://materials-data-science-and-informatics.github.io/Dislocation-Ontology-Suite/DISO/index.html
[54] https://liusemweb.github.io/mdo/full/1.1/index.html
[55] https://github.com/daimoners/MAMBO

Table 3

Overview of Materials Semantic Models

Study	Type	Year of Latest Update	Semantic Web Standard	Scope	Reuse of Existing Ontologies	Availability	Limitations	Applications
Cheung et al. [73]	Ontology	2008	OWL	Materials and material discovery.	Standards Units and Dimensions, Time, ABC Metadata, EXPO	Public	Represents materials from a chemistry and physics perspectives. Reuse in generic cases such as materials in ICT will require the support of a material scientist. Several classes miss domain and range, definition of wrong equivalent classes, missing annotations.	Semantically represent the process of material discovery.
Ashino et al. [44]	Ontology	2010	OWL	Material's composition and properties.	-	Private	Unavailability of the ontology. Inconsistent naming of classes and properties in the different modules of the ontology.	Used to synchronise material data exchange between databases.
Hastings et al. [78]	Ontology	2015	OWL	Nanomaterials and nanosafity.	BFO, ChEBI	Public	Limited use cases it can be reused in due to its focus mainly on a specific type of materials - nanomaterials.	Used for evaluating nanomaterisls' safety.
Zhang et al. [80]	Ontology	2016	RDF	Metals and metalic properties.	-	Private	Focuses only on metals and their chemical properties, which limits its reuse. Class and object property URIs are not available. Limited semantics. Generated automatically from Yago data at a specific time and is subject to structural change everytime the data source is updated.	Used to validate an approach for automatic ontology generation.
EMMO Consortium [82]	Ontology	2021	OWL	4D objects, materials, material types, physics and chemistry.	Dublin Core	Public	Abstract representation of objects from analytical philosophy and physics perspectives. Limited details about ICT and materials are modelled. Its wider reuse for more generic use cases can be a challenge.	Reused by the BattNFO, BVC and the Mappings ontology etc. as an upper level ontology. Can be used to represent different perspectives of the world at different complexity levels.
BIM-MER Project [83]	Ontology	2021	OWL	Buildings, building materials and weather.	GEO, SAREF, SKOS, Time	Public	Limited scope on building materials (e.g. building boards) and not on material's composition itself. Several modules of the ontology need to be reused to represent concrete material use.	Used to model renovation processes in buildings.
Voigt et al. [84]	Ontology	2021	OWL	Material's processes, performance, properties and structure.	-	Public	No specific materials have been represented. Lack of annotations and object property characteristics.	Can be used as an upper level ontology for modelling generic material discovery.
Ihsan et al. [93]	Ontology	2021	OWL	Crystaline materials and crystaline dislocations.	MDO	Private	The ontology is in the initial stages of its development and is focused on only one material and one of its properties.	Used as a vocabulary for crystalline dislocations.
Piane et al. [94]	Ontology	2022	OWL2	Materials and nanomaterials.	-	Public	Initial stage of developments.	Used as a vocabulary and in assisting the integration of data for molecular materials, nanomaterials and calculations with them.
Lambrix et al. [87]	Ontology	2022	OWL2 DL	Materials, solid state physics and condensed matter theory.	PROV-O, QUDT	Public	Structural changes possible due to it being in early stages of development with envisioned iterations.	To support data harmonisation and federation between several materials databases.

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 [94] and MDO [87] follow OWL2 and OWL2 DL Semantic Web standards, which support better expressivity [71]. Regarding the scope of the ontologies, some such as [78] and [94] model materials at nanoscale, while [73] focuses on modelling materials in a generic way. The EMMO [82] ontology, on the other hand, look at materials from a philosophical perspective, while [80] and [93] focus on specific materials and their properties (metals and crystalline materials). As shown in Table 3, 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.

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. [95]

As a result of an in depth analysis of the CE, Chiaroni et al. [95] 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 levels 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 [46]

Motivated by the potential benefits of utilising Linked Data for data sharing in the CE, Sauter and Witjes present a taxonomy and ontology in [46] for the CE to help standardise product passport data exchange. The developed taxonomy focuses on a retail use case in the CE and on the combination of Linked Data and QR codes. It 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 [96] 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)[45]

Following their previous work in [46], Sauter et al. [45] extend the existing CEO ontology and propose the CAMO ontology. Similarly to [87], 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 [45]. The Place Reference Theory (PRT) has been reused and extended by CEO to model in detail agent and their CE actions. After RDF serialisation, both CEO and CAMO have been used to annotate a small dataset from the Madaster[56] as a proof of concept. The evaluation of the ontologies have concluded that Linked Data can successfully support data exchange and data traceability in the CE. However, validation on a wider scale with larger dataset is needed as suggested by the authors. Both ontologies are openly available and currently under development.

4.3.4. CE Indicators Taxonomy by Saidani et al. [97]

Led by the lack of standardisation for the adoption 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 lifecycle (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 implementation . Several groups of indicators have been defined as well-descriptive, performance, efficiency, policy effectiveness and total well-fare. The proposed indicators have

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[56] https://madaster.com

Table 4

Overview of CE Semantic Models

Study	Type	Year of Latest Update	Semantic Web Standard	Scope	Reuse of Existing Ontologies	Availability	Limitations	Applications
Chiaroni et al. [95]	Taxonomy	2016	-	CE, its adoption and evaluation.	-	Private	Focused on e-commerce business models and processes and not on products. Validated with limited number of explorative studies. Implementing the taxonomy into an ontology or its combination with technology has not been discussed.	Used as a framework to evaluate CE's adoption and specify different modes of CE's adoption.
Sauter and Witjes [46]	Taxonomy	2017	-	CE in the retail sector.	-	Private	Limited focus on textiles as a product in the CE. Early stage proof of concept taxonomy build based on one of CE's activities (recycling) as a main use case.	To represent the life-cycle of textiles in the CE. Sets the foundation for a DPPs ontology for textiles in retail.
Sauter et al. [45]	Ontology	2019	OWL	CE and CE processes for construction sector.	PTR	Public[59]	Proof of concept ontology specification. Wide scale validation with data and real-world use cases is needed.	Aligning of product descriptions for the construction sector. Proposed to be used as a standard model for publishing CE data for buildings in decentralised settings.
Saidani et al. [97]	Taxonomy	2019	-	CE and CE indicators.	-	Private	Products in the CE have not been considered as the main focus is on defining CE indicators.	Utilised as a database within the C-Indicators Advisor[58] tool to guide users' selection of indicators.

been selected by following specific, measurable, achievable, relevant and time-Bound (SMART) [98] and clear, relevant, economic, adequate, monitorable (CREAM) mnemonics and have been utilised in a macro-based Microsoft Excel[57] tool (the The Circularity Indicators Advisor (CIA) Tool [58] that is open access. However, no efforts have been made yet to translate the taxonomy into a machine-readable format (e.g. RDF).

4.3.5. Summary

Similarly to the analysis in Section 4.1.11, in this section we summarise the findings from the literature review of existing CE semantic models (see Table 4). Our survey 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 [95] and [97] can be used to define an initial set of competency questions for ontology engineers. We were able to identify only 1 ontology (see [45]), which also follows Semantic Web standards. The work in [45], 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 [61][69][67] and material ontologies such as [84][80][44] 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 DPPs and supporting decision making in the IoT and recommender systems.

4.4.1. Laptop Recommender System by Ayundhita [65]

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 [66][99][100]), Ayundhita[65] 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

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

[58] https://www.circulareconomyindicators.com/advisor.php

[59] Online resources (http://ld-ce.com/vocab/CAMO and http://ld-ce.com/vocab/CEO) from [45] not accessible on May 11th 2023

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 [65].

4.4.2. SmartTags IoT Product Passport for CE by Gligoric et al. [101]

To support the transition from linear to CE, Glicoric et al. propose a method for building DPPs 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 [101] focus primarily on the development of the tags with thermochromic and photochromic ink and on the description of the ontologies. From a technology perspective, it is 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. [102]

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. [102]. 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"* [102] have been defined with the ROWL [103] 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"* [101].

5. Analysis

Ontology reuse is one of the recommended practices in ontology engineering that many follow. Our overview of the related work has shown that currently there is no unified consistent model that can represent the life-cycle of ICT and its materials in the CE. In order to build such (interdisciplinary) ontology, reuse can be a key strategy. To support this, we have evaluated each one of the open-access ontologies from Section 4 against the competency questions from Table 8. Each ontology was investigated in terms of its ability to represent information (i.e. the key concepts) needed to answer each competency question. When a key concept was found it was listed as defined by the ontology to ease its future reuse. If key concepts were not found, we have viewed the ontology as unable to answer the question. As expected, the ICT ontologies can answer most of the questions focused on ICT devices and their components, while the materials ontologies can answer the questions about materials. There is a clear domain knowledge separation. This might not be an issue for domain-specific research, but is a barrier for cross-domain collaboration (e.g. circular ICT). Table 5, 6 and 7 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.

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

Table 5

ICT Ontology Evaluation with the Competency Questions

Ontology	**Which competency questions can be answered?**	**Relevant Concepts and Object Properties**
oneM2M Base Ontology[63]	Q1, Q10	base_ontology:Device, base_ontology:InterworkedDevice, base_ontology:consistsOf, base_ontology:isPartOf
DogOnt by Bonino and Rusiss [61]	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. [69] and Corcho et al. [67]	Q1, Q8, Q12	devops-infra:hardwareType, devopsnet:HardwareItem, devopsnet:HardwareBatch, devopsnet:F5Hardware, devopsnet:Disk, devopsnet:unitPrice, devopsnet:serialNumber, devopsnet:highAvailabilityStatus, devopsprod:PhysicalServer, devopsprod:Server

Table 6

Materials Ontology Evaluation with the Competency Questions

Ontology	**Competency Questions**	**Concepts**
Cheung et al. [73]	Q50	matonto:Material, matonto:Ceramics, matonto:Polymers, matonto:Glasses, matonto:Composites, matonto:Metals, matonto:Structure, matonto:ChemicalQuality, matonto:formula
Hastings et al. [78]	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 [82]	Q51, Q59	emmo_material:NanoMaterial, emmo_material:NaturalMaterial, emmo_material:EngineeredMaterial, emmo_manufacturing:ContinuumManufacturing, emmo_manufacturing:DiscreteManufacturing
BIMMER [83]	Q49, Q50, Q51,	mat:Material, mat:MaterialProfile, mat:MaterialConstituent, mat:MaterialConstituentSet, mat:Measurement, mat:MaterialLayer, mat:hasMaterial
Voigt et al. [60] [84]	Q49, Q50	ex:Material, ex:Process, ex:composed_of, ex:next_in_process, ex:used_in
Piane et al. [94]	Q49, Q50	mambo:Material, mambo:atom, mambo_is_partOf, mambo:hasStructure, mambo:formula, mambo:is_part_of, mambo:formula
Lambrix et al. [87]	Q49, Q50	base: relatesToMaterial, base: relatesToStructure, structure:Composition, structure:hasElement, structure:hasComposition, structure:ElementRatio

Table 7

CE Ontology Evaluation with the Competency Questions

Ontology	**Competency Questions**	**Concepts**
Sauter et al. [45]	Q49, Q50, Q55, Q57	camo:biological, camo:technological, camo:alloy, camo:metal, ceo:Activity, ceo:Creation, ceo:PostUse, ceo: ReverseLogistics

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 built to support specific software functionalities and no ontological evaluation in terms of quality (with HermiT [104], OOPS! [70]) was performed within the associated scientific publications. Discussion and guidelines for reuse for other use cases are, usually, not provided. The ontologies were evaluated through their successful software utilisation and use case-specific expressivity (the granularity of the represented knowledge). The common pitfalls that we encountered when analysing them with OOPS! include: missing annotations of classes and properties, missing inverse properties, inconsistent naming conventions, no specification of object property's characteristics (e.g. if the property is functional, symmetric, asymmetric, transitive), unconnected classes, missing domain and range of classes. In addition, most of the publicly available ontologies have not been documented using standard tools such as WIDOCO[61] [105], which is good practice for ontology publishing.

The ICT ontologies in Table 5 can answer several of the competency questions regarding hardware, sensors and processing in a generic manner. For example, DogOnt [61] 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 [69] and [67] 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 6), although varying in expressivity, are generic enough to be reused or extended for our use case. The ontologies in [73][83][84][94] represent the concept of a material, while [82] [78] and [87] 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 [46] has been built and is currently publicly available. The work of Sauter et al. [45] has a limited expressivity in terms of the modelled ontological concepts (see Table 7). 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 5.

6. Discussion

Following the ontology analysis, this section presents several discussion points on ontology engineering, availability and on data accessibility, privacy and security. During our survey, these were highlighted as important factors for the successful implementation of the CE with semantics.

6.1. Ontology Reuse and Alignment

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 [106][107]. 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 granularity 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 [108], using the competency questions (Table 8) and analysis (Table 5, 6, 7) as guidelines, paves the way towards an ontology that can harmonise the domains.

6.2. Ontology Availability

Current challenge to the reuse of the existing ontologies is the lack of online documentation and public availability. Many of the publications that present ontologies outline their structure in a generic way that does not support reuse. Including specific namespaces and URIs of classes, their object and data properties in the publications that outline the ontologies can be a minimum viable solution. If an ontology cannot be made public due to institutional ownership rights or legal concerns, it should be clearly stated in its scientific publication. Specific creative commons (CC)[62] licences (e.g. CC-BY, CC-BY-SA, CC BY-NC) can also be applied to ontologies to protect their ownership

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[61] https://dgarijo.github.io/Widoco/doc/tutorial/#:~:text=WIDOCO%3A%20A%20WIzard%20for%20DOCumenting,and%20all%20of%20its%20functionalities.

[62] https://creativecommons.org

and to specify in what cases and how they can be shared, reused and adapted. Another possibility in such cases is that access to the ontology itself can be granted upon request as well. Finally, ontology's availability should be considered as an important criteria when reviewing scientific publications that present ontologies as their main contributions. The unavailability of some of the reviewed in this survey ontologies also restricts us from verifying that they can indeed be upgraded from OWL to OWL2 (the current version) without any issue. The issues that can arise are also unclear due to this.

6.3. Data Accessibility

Despite the benefits of having FAIR data in the CE, data accessibility for external to an organisation entities (e.g. researchers, third-party party service providers) remains an obstacle. Many companies are reluctant to freely share their data due to various reasons such as market competition and security. The accessibility to data is also affected by the organisation's internal digital IT infrastructure and the types of database used (e.g relational or graph). Data is spread between different departments and databases. The access to it requires specific access rights even within organisation. Even when such access is granted, federating data from different relational databases can be a cumbersome time-consuming task. Linked data and semantics can help in this regard as discussed in the introduction (Section 1). Data licensing and contract-based subscriptions to it can be a solution that facilitates external access to it. An example of a technology solution that supports this is the Data Licenses Clearance Center (DALICC)[63] [109]. Last but not least, legislation itself can have a significant impact on organisations's motivation to make such data available for reuse and analysis especially for data sharing and processing that support sustainability.

6.4. Data Privacy and Security

ICT data sharing for the CE also raises privacy concerns as any data that can be related back to an individual (e.g laptop's usage behaviour and performance over time) is considered personal under the General Data Protection Regulation (GDPR) [110] (Art. 4(1)). Such data should be protected and processed in a GDPR-compliant manner. Establishing privacy preserving mechanisms through the implementation of specific privacy enhancing technologies (PETs) [111] can be a solution that enables (sensitive) data to be shared when building DPPs in both business to business (B2B) and business to consumer (B2C) use cases. In the case that ICT DPPs have been implemented and are actively used, ontologies can be used to defining specific agreed upon data access and usage rights (e.g. policies) as discussed in [32] [112]. This will enable different levels of DPP data transparency and accessibility to support the growth of the CE.

7. Conclusions

This paper presented a survey of existing semantic models in the ICT, materials and CE domains. While there is a variety of such models, they have been built for use cases within their domain and rarely connect to knowledge from other domains. Many of the existing models remain taxonomies thus their full potential, from a semantic and technological perspective, has not been realised yet. The surveyed ICT ontologies model specific hardware and rarely reach hardware's material composition level, while the materials ontologies focus on the materials themselves (their discoverability, chemical properties, compatibility, reactions). There is a clear partition of the two domains, which are, however, significantly interrelated within the CE domain.

We believe that this survey can be useful to both sustainability domain experts (e.g. industrial ecologists) 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. For instance, Gjose et al. [113] present an upper level ontology that models data needed for LCAs. Insights form our survey can be used in the future to extended the work in [113] with specific ICT, materials and CE concepts. Doing so will allow one to semantically representing detailed ICT data for LCAs, which can potentially result in more

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[63] https://www.dalicc.net

precise and insightful results. 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. The digitization of CE processes such as maintenance (or predictive maintenance) that support service optimisation at scale is highly dependent on data's availability and interoperability. Reusing and further sharing insights from such processes in a consistent machine-readable format can help optimise production and manufacturing supply chains.

Current standardisation efforts are leading to the development of DPPs, which aim to bring more transparency of products' lifetime provenance in terms of its manufacturing, materials and their sources, use etc. DPPs, which as we discuss in [114] can be represented with Semantic Web technology (e.g. ontologies and knowledge graphs) to store diverse data about ICT such as functional specifications, manufacturing and materials details and more dynamic data such as performance (e.g. energy consumption) over time. Knowledge graph-based DPPs as a technology solution can help establish better transparency and traceability into ICT supply chains by making data about material mining, ICT device manufacturing and its use accessible, reusable and interoperable. Building such digital infrastructures that support FAIR principles can boost the transition to a CE and can help cultivate a more sustainable digital economy driven by data reuse.

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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] E. Williams, R. Kahhat, B. Allenby, E. Kavazanjian, J. Kim and M. Xu, Environmental, social, and economic implications of global reuse and recycling of personal computers, *Environmental science & technology* **42**(17) (2008), 6446–6454.

[3] J.M. Allwood, Squaring the circular economy: the role of recycling within a hierarchy of material management strategies, in: *Handbook of recycling*, Elsevier, 2014, pp. 445–477.

[4] G.I. Zlamparet, W. Ijomah, Y. Miao, A.K. Awasthi, X. Zeng and J. Li, Remanufacturing strategies: A solution for WEEE problem, *Journal of Cleaner Production* **149** (2017), 126–136.

[5] E. Long, S. Kokke, D. Lundie, N. Shaw, W. Ijomah and C.-c. Kao, Technical solutions to improve global sustainable management of waste electrical and electronic equipment (WEEE) in the EU and China, *Journal of Remanufacturing* **6** (2016), 1–27.

[6] 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.

[7] 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.

[8] 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.

[9] 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.

[10] 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.

[11] 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.

[12] 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.

[13] 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.

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

[15] K. Troullaki, S. Rozakis and V. Kostakis, Bridging barriers in sustainability research: A review from sustainability science to life cycle sustainability assessment, *Ecological Economics* **184** (2021), 107007.

[16] 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.

[17] J. Reap, F. Roman, S. Duncan and B. Bras, A survey of unresolved problems in life cycle assessment: Part 2: Impact assessment and interpretation, *The International Journal of Life Cycle Assessment* **13** (2008), 374–388.

[18] L.L. Kjaer, A. Pagoropoulos, J.H. Schmidt and T.C. McAloone, Challenges when evaluating product/service-systems through life cycle assessment, *Journal of Cleaner Production* **120** (2016), 95–104.

[19] 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.

[20] 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.

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

[22] 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.

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

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

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

[26] 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.

[27] 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.

[28] M. Doerr, Ontologies for cultural heritage, in: *Handbook on ontologies*, Springer, (2009), pp. 463–486.

[29] 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.

[30] 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.

[31] 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.

[32] 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).

[33] 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).

[34] 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.

[35] 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.

[36] 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.

[37] 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.

[38] 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.

[39] 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.

[40] 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.

[41] 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.

[42] 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.

[43] 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.

[44] 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.

[45] 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.

[46] 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).

[47] 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* (2021), 1–27. doi:10.3233/SW-210438.

[48] 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.

[49] 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.

[50] 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.

[51] A.-G. Olabi, Circular economy and renewable energy, Vol. 181, Elsevier, (2019), pp. 450–454.

[52] 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.

[53] 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.

[54] 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.

[55] V. Dhingra and K.K. Bhatia, Development of ontology in laptop domain for knowledge representation, *Procedia Computer Science* **46** (2015), 249–256.

[56] 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).

[57] 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.

[58] World Intellectual Property Organization (WIPO), International Patent Classification (IPC), (2022), Available at https://tind.wipo.int/record/44834.

[59] 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.

[60] 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.

[61] D. Bonino and F. Corno, Dogont-ontology modeling for intelligent domotic environments, in: *International Semantic Web Conference*, Springer, 2008, pp. 790–803.

[62] 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.

[63] 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.

[64] 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.

[65] 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.

[66] 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.

[67] 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.

[68] A. Miles and J.R. Pérez-Agüera, Skos: Simple knowledge organisation for the web, *Cataloging & Classification Quarterly* **43**(3–4) (2007), 69–83.

[69] 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.

[70] M. Poveda-Villalón, A. Gómez-Pérez and M.C. Suárez-Figueroa, Oops!(ontology pitfall scanner!): An on-line tool for ontology evaluation, *International Journal on Semantic Web and Information Systems (IJSWIS)* **10**(2) (2014), 7–34.

[71] 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/.

[72] 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).

[73] 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.

[74] 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.

[75] 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.

[76] C. Lagoze and J. Hunter, The ABC ontology and model, *Journal of Digital Information* **2**(2) (2002).

[77] 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.

[78] 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.

[79] 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.

[80] 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.

[81] 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.

[82] E. Consortium, Elementary Multiperspective Material Ontology (EMMO), 2021, Available at https://github.com/emmo-repo/EMMO.

[83] 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.

[84] S.P. Voigt and S.R. Kalidindi, Materials graph ontology, *Materials Letters* **295** (2021), 129836.

[85] W.D. Callister and D. Rethwisch Jr, Materials science and engineering, John Wiley and Sons, SBN, (2010).

[86] 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.

[87] P. Lambrix, R. Armiento, H. Li, O. Hartig, M.A.N. Pour and Y. Li, The Materials Design Ontology, *Transport* **8**(10), 24.

[88] 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.

[89] 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$_2$.

[90] 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.

[91] 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).

[92] R. Hodgson, P.J. Keller, J. Hodges and J. Spivak, Qudt-quantities, units, dimensions and data types ontologies, *USA Available http://qudt.org March* **156** (2014).

[93] A.Z. Ihsan, D. Dessì, M. Alam, H. Sack 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).

[94] F.L. Piane, M. Baldoni, M. Gaspari and F. Mercuri, Introducing MAMBO: Materials and molecules basic ontology, *arXiv preprint arXiv:2111.02482* (2021).

[95] D. Chiaroni and A. Urbinati, in: *The 27th edition of the Annual Scientific Meeting of the Italian Association of Management Engineering (AiIG), Higher Education and Socio-Economic Development*, (2016).

[96] M. Hepp, Goodrelations: An ontology for describing products and services offers on the web, in: *Knowledge Engineering: Practice and Patterns: 16th International Conference, EKAW 2008, Acitrezza, Italy, (2008)*, Springer, pp. 329–346.

[97] 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.

[98] B. Marr, *Big Data: Using SMART big data, analytics and metrics to make better decisions and improve performance*, John Wiley & Sons, (2015).

[99] 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.

[100] 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.

[101] 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.

[102] 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.

[103] F. Gandon, M. Sheshagiri and N.M. Sadeh, ROWL: Rule language in OWL and translation engine for JESS, *Mobile Commerce Laboratory* (2004).

[104] B. Glimm, I. Horrocks, B. Motik, G. Stoilos and Z. Wang, HermiT: an OWL 2 reasoner, *Journal of Automated Reasoning* **53** (2014), 245–269.

[105] D. Garijo, WIDOCO: a wizard for documenting ontologies, in: *The Semantic Web–ISWC 2017: 16th International Semantic Web Conference, Vienna, Austria, October 21-25, 2017, Proceedings, Part II 16*, Springer, (2017), pp. 94–102.

[106] 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.

[107] 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.

[108] C. Shimizu, K. Hammar and P. Hitzler, Modular ontology modeling, *Semantic Web* (2021), 1–31.

[109] T. Pellegrini, G. Havur, S. Steyskal, O. Panasiuk, A. Fensel, V. Mireles, T. Thurner, A. Polleres, S. Kirrane and A. Schönhofer, DALICC: a license management framework for digital assets, *Proceedings of the Internationales Rechtsinformatik Symposion (IRIS)* **10** (2019).

[110] Regulation (EU) 2016/679 of the European Parliamentand of the Council of 27 April 2016 on the protectionof natural persons with regard to the processing of per-sonal data and on the free movement of such data, andrepealing Directive 95/46/EC (General Data Protection-Regulation), *Official Journal of the European Union, L119* (May 2016). https://eur-lex.europa.eu/eli/reg/2016/679/oj.

[111] I. Goldberg, D. Wagner and E. Brewer, Privacy-enhancing technologies for the internet, in: *Proceedings IEEE COMPCON 97. Digest of Papers*, IEEE, (1997), pp. 103–109.

[112] B. Esteves and V. Rodríguez-Doncel, Analysis of ontologies and policy languages to represent information flows in GDPR, *Semantic Web* (2022), 1–35.

[113] A. Ghose, M. Lissandrini, E.R. Hansen and B.P. Weidema, A core ontology for modeling life cycle sustainability assessment on the Semantic Web, *Journal of Industrial Ecology* **26**(3) (2022), 731–747. doi:https://doi.org/10.1111/jiec.13220. https://onlinelibrary.wiley.com/doi/abs/10.1111/jiec.13220.

[114] A. Kurteva, Towards FAIR ICT data sharing in the circular economy with knowledge graphs, in: *NWO ICT Open Conference, Utrecht, The Netherlands*, (2023), Available at https://www.researchgate.net/publication/370106721_Towards_FAIR_ICT_Data_Sharing_in_the_Circular_Economy_with_Knowledge_Graphs.

Appendix

A set of competency questions for building an ontology that represents ICT devices such as laptops and their materials in the CE. The questions have been organised in six categories: ICT device, its components, physical, computational and material properties and CE strategy. For each question, key concepts that an ontology should represent, have been provided.

The first category questions can help represent an ICT device and its components in generalised way. The second category presents component specific questions. The physical properties of ICT such as overall weight, component weight, warranty etc. are usually assigned by the device's manufacturer or refurbisher. The computational properties, on the other hand, are the ones that can be calculated (or computed) for each device or fleet of devices in an organisation while in use. For example, energy consumption and efficiency are dynamic values. A refurbishers' stock availability for specific ICT devices can also vary on a daily basis. The material properties questions are aimed at an ICT device and its components' material composition. We present material questions at a component level. However, when such information for an ICT device is available for all of its components, the overall material composition of the device can be derived as well. The final category questions help represent CE processes for a specific device and/or its component(s).

Table 8: Competency Questions for an ICT, Materials and CE Domains Ontology

No	Question	Key Concepts
1. ICT Device		
Q1	What is the type of the ICT device?	Device, laptop
Q2	What is the brand of the device?	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? (Refers to the agent that has ownership rights over the device.)	Device owner, organisation, person
Q7	Who provides the hardware? (Refers to the agent that provides hardware components needed for repair, refurbishment etc.)	Device provider, organisation, person
Q8	What is the current status of the device? (Has it been reused, remanufactured, refurbished, recycled or is it new?)	Device, status, reused, remanufactured, refurbished, recycled, new
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
2. ICT Device Components		
Q12	What is the serial number of the component?	Device 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, location, 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 ports are used?	Port, type, USB-A, USB-C
Q32	What type of camera is used?	Camera, type, brand, model
Q33	What types of sensors are used?	Sensors, sensor types
3. 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)
4. 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
5. 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
6. 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