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Stitching Together Data: A Prototype Domain Ontology for Textile Product Lifecycle in the FEDeRATED Project

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By

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Executive Summary

Part I
The impetus for this research originates from the critical need to address the environmental impact of the textile industry, recognized as one of the most significant contributors to global waste and carbon emissions. A substantial challenge within the industry is achieving sustainability, particularly through the adoption of circular economy principles, which aim to keep resources in use for as long as possible, extract the maximum value from them while in use, and recover and regenerate products and materials at the end of each service life. The circular economy contrasts sharply with the traditional linear economy, which follows a 'take-make-dispose' model of production.
A key barrier to circularity in the textile industry is the lack of structured, accessible, and standardized data across the supply chain. Information about the composition, usage, and end-of-life options for textiles is often fragmented or unavailable, hindering effective recycling, reuse, and waste management strategies. As municipalities and organizations strive to manage their textile portfolios more proactively, they encounter significant challenges due to this information deficit. Accurate, explicit, and complete information is essential for informed decision-making regarding costs, performance, and risks—the pillars of circular economy theory. However, the data necessary to make these decisions is frequently incomplete or inaccurate, scattered across disparate sources, and not readily accessible or interpretable.

To confront this challenge, the research design employs a Design Science Research (DSR) methodology, focusing on the creation of a prototype ontology to facilitate the exchange of structured data in support of circularity. This work is guided by the overarching research question:

"How can we structure a prototype textile ontology that leverages the FEDeRATED project to maximize its contribution to providing insights into circular data?"

Seeking to help resolve this problem, the research adopts a systematic approach, starting with a literature review to grasp the current landscape and identify the gaps in ontological frameworks within the textile industry. The design progresses by intertwining the objectives of the FEDeRATED project, which aims to improve logistical transparency and efficiency through enhanced data sharing.

The envisioned prototype ontology is intended to bridge these gaps by providing a comprehensive framework that integrates seamlessly with the FEDeRATED project's broader objectives. The research meticulously charts the path from conceptualization to practical application, ensuring that the ontology not only captures the complex web of data within the textile industry but also aligns with the intricate requirements of circular economy practices. The iterative DSR approach guarantees that the ontology evolves through continuous refinement, leading to a robust and practical tool that addresses the informational shortcomings, thus enabling more sustainable management of textile resources.

Part II
Continuing from the development of a structured approach to address the data challenges in the textile industry, the subsequent stage of research delves into Problem Exploration & Definition, as outlined in Part II of the thesis. This involves an in-depth literature review examining the environmental footprint of the textile industry and the potential of circularity to reduce this impact through sustainable practices like eco-design, recycling, and the adoption of digital twins.
The study investigates the role of digitalization in enhancing the efficiency and sustainability of the textile sector, highlighting the use of digital twins for real-time insights and improved traceability. Ontologies are presented as crucial for structuring knowledge, with benefits including data integration and semantic interoperability, essential for effective communication and decision-making.
Furthermore, the Semantic Web is explored for its capacity to imbue data with meaning, facilitating machine comprehension and cooperation. This underpins the functionality of the proposed ontology within the textile industry, enabling a more intelligent and efficient digital ecosystem.
Finally, the thesis reviews the FEDeRATED project, noting its goal to improve logistics through standardized data sharing and interoperability. By aligning with the project's upper ontology, the research

aims to contribute to the development of a specialized lower-level textile ontology, fostering enhanced data exchange tailored to the textile industry's sustainability needs.

Part III
The methodology for developing the ontology involves a structured process that starts with identifying the scope and analysing stakeholders to assess their interests and needs. This understanding guides the formulation of competency questions that ultimately define the ontology's purpose and scope. A middle-out strategy is chosen for creating the class hierarchy, which balances the need for relevant details with the avoidance of superfluous abstractions. The scope of the ontology is specifically set to the textile sorters, recognizing their crucial role in the recycling process and the circular economy within the textile industry. The sorters are responsible for categorizing textiles based on type, quality, and potential for reuse or recycling. Their decisions have significant implications for waste reduction, recycling efficiency, and the overall sustainability of the industry.
The chapter culminates in a discussion on the design of the ontology that considers the functional, structural, and environmental requirements. Functional requirements ensure the ontology effectively addresses specific problems and fulfils stakeholders' needs. Structural requirements ensure coherence, sustainability, and ease of maintenance, while environmental requirements pertain to the ontology's operation within its intended context and its adaptability to changes.
The ontology aims to provide textile sorters with accurate and actionable data, enhancing the efficiency and precision of their sorting processes. By incorporating life cycle data and potentially digital twins, the ontology will give sorters insights into the environmental impact, potential reuse applications, and market value of textiles, facilitating more informed decision-making and promoting circular processes within the industry. This tailored approach underscores the importance of textile sorters and their data needs as a focal point for the research and the ontology's application.

Part IV
In Part IV of the thesis, the focus shifts to the actual construction and preliminary testing of the ontology specifically designed for textile sorters. The ontology is developed to facilitate the sorting process by providing a systematic method for categorizing textiles, thus enhancing recycling and reuse within the textile industry's circular economy framework. Designed with adaptability in mind, it is structured to evolve alongside changes in industry practices and regulatory standards.
The following part of the thesis presents the culmination of the research in the form of the evaluation and validation of the ontology designed for the textile industry. The evaluation process began with the use of the HermiT reasoner, which was continually run throughout the development of the ontology to ensure consistency and conciseness. The Ontology Pitfall Scanner (OOPS!) provided insights into errors and inconsistencies, facilitating the refinement of the ontology for a more consistent, clear, and complete structure. The validation process involved testing with mock-up data, demonstrating that the ontology can cover elements commonly found in textile products and confirming that all the competency questions had been addressed, satisfying the criteria of accuracy and completeness.
However, not all requirements were fully validated. Structural requirement 2.4, concerning the validation of definitions by industry experts, was not met due to the absence of expert endorsement. Additionally, the integration of environmental requirements 3.2 and 3.3 was beyond the scope of this research, representing a potential area for further development. Despite these limitations, the ontology's final structure is considered comprehensive for its intended scope, offering a constructive tool to promote circular practices within the textile industry. The ontology's classes, properties, and individuals are methodically documented in the appendices, marking the successful completion of the evaluation and validation phases.

Part V
The last part of the thesis concludes the study by summarizing the research conducted to create a prototype textile ontology within the context of the FEDeRATED project, which is aimed at advancing circularity in the textile industry. The findings reiterate the necessity of sustainable practices to mitigate climate change, with a particular focus on the role of textile sorters and the importance of efficient sorting for recycling and waste reduction. The research outlines significant societal contributions, such as aiding sorters in making sustainable choices, enhancing industry transparency, and improving material recovery processes. Scientifically, the thesis contributes to the field of knowledge management by developing an ontology that integrates expert opinions and research, improves data semantics, and aligns with European regulatory

standards. The ontology is designed to be adaptable to future data needs and industry practices. However, limitations are acknowledged, including the prototype nature of the ontology, reliance on a single expert's opinion, and the absence of empirical validation with sorters. Future research directions are suggested to address these limitations, which include expert validation of the ontology, real-world testing with textile sorters, exploration of additional data fields, expansion of the ontology's applicability to consumers, and integration of automated data collection technologies. This chapter underlines the ontology's potential as a tool for promoting circularity, while also setting the stage for further research to enhance its relevance and effectiveness.

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To all these individuals, I express my heartfelt thanks. Your support, expertise, and encouragement have been crucial to the success of this research project. To the readers, I hope you enjoy reading my research and that it might inspire you to venture into the world of semantics.

W.F. Goedkoop
Delft, December 2023

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List of Figures and Tables

Acronyms

[CE] : Circular Economy

[DPP] : Digital Product Passport

[EC] : European Commission

[EU] : European Union

[IoT] : Internet of Things

[PLM] : Product Life Cycle Management

[DSR] : Design Science Research

[RDF] : Resource Description Framework

[RDFS] : RDF Schema

[URI] : Uniform Resource Identifier

[URL] : Uniform Resource Locator

[HTTP] : Hypertext Transfer Protocol

[HTML] : Hypertext Markup Language

[W3C] : The World Wide Web Consortium

[OWL] : Web Ontology Language

[SPARQL] : Simple Protocol and RDF Query Language

[SHACL] : Shapes Constraint Language

[BoM] : Bill of Materials

[DTLF] : Digital Transport and Logistics Forum

PART I

Identification of the Problem

1 Problem Identification

1.1 Introduction

Chapter 1, titled "Problem Identification," begins by highlighting the textile industry's substantial environmental impact and its need for sustainable solutions. In Section 1.2, "Subject Introduction," the focus is on the industry's contribution to carbon emissions and the inefficiencies in its recycling processes, setting a backdrop for the necessity of a circular economy. The chapter then transitions to a literature review in Section 1.3, "Research Gap," where it identifies the existing gaps in research related to the use of ontologies in the textile industry. Section 1.4, "Research Objective and Scope," details the goal of developing a prototype ontology tailored to the textile sector, underlining the study's alignment with the TU Delft's Complex Systems Engineering & Management program. This is followed by Section 1.5, "Research Questions and Research Approach," which outlines the key research questions and introduces the Design Science Research methodology guiding the study. Furthermore, section 1.5 introduces the Research Flow Diagram of Figure 1 The chapter concludes with Section 1.6, summarising the importance of this research and its potential contributions.

1.2 Subject Introduction

The global textile industry, a critical component of our economy and culture, is facing a mounting environmental crisis. Its significant impact on environmental degradation is increasingly evident, as the industry accounts for a substantial portion of global carbon emissions – estimated between 8 to 10 percent. This surpasses the combined emissions from international flights and maritime shipping, emphasising the sector's considerable contribution to climate change (Leal Filho et al., 2022; Virta & Räisänen, 2021). Particularly in the European Union, the consumption of textile products in 2020 led to alarming levels of greenhouse gas emissions, with an average of 270 kg of CO_2 emissions per person, totalling 121 million tonnes (European Environment Agency, 2022). Compounding this issue is the inefficient disposal and recycling of clothing; less than half of discarded clothes are collected for reuse or recycling, with a mere 1% being recycled into new garments, largely due to nascent recycling technologies (European Environment Agency, 2022). Furthermore, the industry generates substantial waste, including textile scraps and packaging materials, underscoring an urgent need for sustainable practices and waste reduction across the textile supply chain (Hasanbeigi & Price, 2015; Madhav et al., 2018).

One effective approach to address textile waste is to promote the concept of a circular economy within the industry. Circularity in the textile industry is gaining increasing attention as a sustainable approach to resource management and waste reduction (Koszewska, 2018). The Circular Economy (CE) has garnered significant interest as an economic model that prioritizes resource efficiency through waste reduction and sustainable practices (Clarkson et al., 2010). According to the European Parliament, CE promotes sharing, leasing, reusing, repairing, refurbishing, and recycling materials and products to prolong their life cycle (European Parliament, 2015). CE was developed in response to the harmful "take-make-dispose" approach prevalent in many modern societies, which depletes natural resources, generates waste, and contributes to greenhouse gas emissions. To address these challenges and meet the needs of growing populations, this linear approach to the economy must be replaced with a closed-loop model. At the core of CE lies the understanding that resources are finite and should be managed in a manner that minimises extraction and disposal.

Effective communication among stakeholders is critical for the successful implementation of the Circular Economy, and standardised information exchange is required. In line with these principles the European Commission (EC) has introduced a forward-looking strategy for circular fashion, emphasizing Digital Product Passports (DPP) and clearer information sharing in its forward-looking approach to circular fashion (European Commission, 2022a). These strategies aim to provide comprehensive insights into a product's lifecycle, including details on materials, manufacturing processes, and environmental impact. Additionally, transparent information is a cornerstone of the EU's strategy, ensuring that both consumers and industry stakeholders can access easily understandable and relevant data regarding the environmental footprint of textile products. This leads to the potential role of ontologies in the Circular Economy, which could be beneficial for enhancing clarity and efficiency in information exchange (Cao et al., 2019). Ontologies offer a structured framework to organize and categorize the wealth of data required for Digital Product Passports and initiatives aimed at clearer information dissemination.

An ontology within the context of information communication technology refers to the representation of knowledge and defines the concepts, relations, and constraints within a specific domain for example. This representation is then used to create a shared understanding of the data semantics within the domain by enabling stakeholders to communicate and collaborate efficiently (Pinto et al., 2014). Ontologies can enhance interoperability among diverse stakeholders, including businesses, end users, researchers, and government entities, by establishing a common data communication structure. It will allow stakeholders to collaborate and communicate about resources, goods, processes, and supply chains efficiently, facilitating the move to a circular economy. By improving data consistency, correctness, and availability through the use of ontologies, data input for decision-making is improved, resource use can be optimized, and possibilities for waste reduction and sustainable practices are found. Stakeholders may break down the barriers created by disparate terminologies and incompatible data formats by adopting a shared ontology, enabling a more integrated and cooperative approach to attain the goals of the Circular Economy.

This thesis details the development of a prototype ontology that is designed to encapsulate information about the production processes within the textile industry. The key objective is to utilise this production information to bolster efforts towards circularity. The ontology is specifically structured to provide insights that can inform and improve the industry's circularity initiatives. To evaluate the practical applicability of the ontology, the prototype will be integrated with the logistical upper ontology of FEDeRATED. This integration will allow for a thorough assessment of the ontology's utility in a range of different scenarios.
The rationale for developing this prototype is to investigate the potential of an ontology that is bespoke for the textile industry, leveraging specific use cases given the research's focused scope. The textile industry, with its intricate and multi-faceted nature, demands standardised protocols for product information exchange. It also faces the imperative of enhancing sustainability and maintaining competitiveness (Sandvik & Stubbs, 2019). Addressing environmental concerns, the textile industry is tasked with the sustainable management of its resources. It is critical to emphasize the recovery and recycling of textile materials as a means to counteract the overuse of natural resources (Do Amaral et al., 2018).

Following the problem statement, this thesis will proceed with a literature review that examines the role of ontologies in facilitating the circular use of materials, with a particular focus on the textile industry. It will then synthesise the findings from the literature to define the central research question and its associated sub-questions. These sub-questions will be explored in depth to understand their significance in the context of the research and to establish an appropriate research framework. To provide clarity on the research process, a research flow diagram will be introduced, which will guide the subsequent sections of the thesis. These sections will include a detailed examination of the textile sector, an introduction to ontologies and the Semantic Web, and an in-depth look at the FEDeRATED project.
The thesis will then delve into the methodology for developing the textile ontology itself, defining its scope and domain, and specifying the requirements for the ontology. It will review existing standards and analyse the data requirements of textile sorters. The construction of the ontology will be presented, covering aspects such as classes and properties. An evaluation of the ontology will be conducted, including a discussion of the tools and methods used, numerical metrics, and the validation process. The final structure of the ontology will be presented before the thesis concludes with its findings, societal contribution, scientific contributions and limitations, and suggestions for future research.

1.2.1 Link to MSc Program

This report describes the goals and methodology for developing an ontology for the textile industry as part of the FEDeRATED project during the author's internship at TNO. The study will be submitted as a thesis for the TU Delft's Complex Systems Engineering & Management (CoSEM) programme at TU Delft. The development of an ontology for the textile industry contributes to a complex problem involving multiple stakeholders by creating an information and communications technology (ICT) solution to promote sustainable activities. This solution aligns with the program's values. The development of the ontology for the textile sector, in accordance with the CoSEM approach, includes technical, institutional, and process components. To accurately represent the textile domain, the technical aspect entails designing the ontology's structure, defining classes, properties, and relationships. The institutional component addresses governance policies for the ontology, ensuring proper data management and access. The process component, meanwhile, considers the broader implications of ontology adoption in the textile industry, including the potential for organisational change.

1.3 Research Gap

In this section, our exploration deepens into the existing literature to examine two key areas: firstly, the development of ontologies and their specific contributions to circularity within the manufacturing domain; and secondly, the availability and scope of ontologies that are specifically tailored for the textile industry.
Only peer-reviewed articles from reputable databases will be included in the literature search to ensure the review's reliability and credibility. We can be confident that the articles have undergone rigorous evaluation and scrutiny by experts in the field by focusing on peer-reviewed sources, which improves the quality and validity of the information gathered. This method allows for a thorough examination of existing research and practises in the context of ontologies in the textile industry.
The goal of this section is to conduct a systematic search of peer-reviewed articles to determine the current state of the literature. We use this approach to ensure that we use reliable and authoritative sources to gain a thorough understanding of existing research and practises concerning ontologies in the context of circularity in the textile industry.

1.3.1 Academic Literature Search Method

A systematic search was conducted prior to conducting the literature synthesis to gather relevant sources. Using appropriate search terms and synonyms, this systemic approach involved searching relevant databases containing scientific journals, conference proceedings, and industry reports. The aim was twofold: firstly, to explore the role of ontologies in circular and sustainable production, and secondly, to identify articles that demonstrate the use of ontologies in enhancing circularity and sustainability within the manufacturing sector. By employing this comprehensive and systematic approach, we succeeded in compiling a diverse range of literature that significantly contributes to our understanding of the application of ontologies in circular and sustainable production.

Search terms were constructed by entering rudimentary keywords such as “ontology”, “sustainability”, “circularity” and “textile”. After a quick scan of the articles that resulted from the search, new keywords are found through backwards- snowballing, as described by Wohlin (2014). This resulted in the following key string.

("ontologies" OR "semantic models" OR "knowledge graphs" OR "Ontology") AND ("circularity" OR "circular economy" OR "sustainable systems" OR "closed-loop" OR "Product lifecycle" OR "Circular Manufacturing" OR "CM") AND ("interoperability" OR "Standard*" OR "Data sharing") AND ("Supply chain" OR "Textile" OR "Manufacturing" OR "Textile Supply Chain" OR "Textile Manufacturing")

Our initial search using key strings resulted in identifying 108 articles, with 59 from Scopus and 49 from Web of Science. To concentrate on recent advancements, we first excluded articles published before 2017. However, to ensure that influential papers from earlier years were not overlooked, we included those published between 2009 and 2017 that were cited more than 15 times. This criterion led to the exclusion of 55 articles. Our next step in refining the selection involved discarding articles from unrelated fields, removing those in formats not suitable for our review, and focusing exclusively on papers written in English. After this meticulous process and the elimination of duplicates, our pool was narrowed down to 33 papers. We were mindful of the potential impact of these exclusions and carefully considered how they might affect the comprehensiveness of our review.

In the subsequent stage of examination, we specifically sought articles that presented ontologies relevant to our study. This further scrutiny resulted in a final selection of 16 papers (as shown in Table 1).

1.3.2 Academic context

The synthesis of literature in this study is instrumental in deepening our understanding of ontologies and their role in promoting circularity, particularly within the manufacturing sector. Our analysis focused on how these ontologies can facilitate circular practices in the textile supply chain. By examining the literature, we identified various ontological frameworks and assessed their effectiveness in fostering circular practices. This synthesis was aimed at providing a comprehensive overview of the use of ontologies in the manufacturing industry, with a special emphasis on their application for the textile sector. Table 1 summarises the synthesis articles and highlights key ontology features. The table specifies the author(s) of the paper, the domain of the developed ontologies, the level of operationality, the scope differentiating between ontology developed for a specific domain, focus on multiple specific domains, or covering more general processes applicable to all kinds of domains. Furthermore, the purpose of the developed ontology is checked as well as the availability of the ontology to the public.

Table 1: Articles included in the literature synthesis.

Authors (Year)	Domain and Scope	Development	Scope	Data and Information Exchange	Internet of Things (IoT)	CE Business Model	Product or Material Passport	Available for Reuse?
Li et al. (2023)	Cross-Domain in Manufacturing	-	Cross-Domain	+	+	+	+	No
Ren et al., (2023)	Digital Twin Product Lifecycle Management	Conceptual/ Theoretical	Non-domain specific	+	+			No
Pereira et al. (2023)	Cloud Collaborative Manufacturing	Advanced Development	Domain Specific	+	+			No
Szejka et al. (2022)	Aerospace Manufacturing Processes	Advanced Development	Domain Specific	+	+			No
Matos & Belfo (2022)	Product Information Management	Advanced Development	Non-domain specific	+			+	Yes
Hildebrandt et al. (2020)	Cyber-Physical Manufacturing Systems	Advanced Development	Domain Specific	+	+			Yes
Huang et al. (2020)	Smart Manufacturing	Advanced Development	Domain Specific	+		+		Yes
Sarkar & Šormaz (2019)	Manufacturing Resources Ontology	Advanced Development	Domain Specific	+		+		Yes
Cao et al. (2019)	Condition Monitoring Ontology	Prototype	Non-domain specific	+				Yes
Sauter & Witjes (2017)	Circular Economy Textile Case	Conceptual/ Theoretical	Domain Specific	+			+	No
Arena & Kiritsis (2017)	Ontology-Driven Framework	Advanced Development	Domain Specific	+		+		No
Sriti et al. (2015)	Ontology for Product Process Models	Advanced Development	Non-domain specific	+		+		No
Borsato, (2014)	Product Lifecycle Information Exchange	Conceptual/ Theoretical	Domain Specific	+		+		No
Chungoora et al. (2013)	Sustainability in Manufacturing	Advanced Development	Non-domain specific	+		+		No

Chungoora et al. (2012)	Product Lifecycle Management	Advanced Development	Non-domain specific	+	+	No
Panetto et al. (2012)	Product Data Management within Manufacturing Process Environment	Prototype	Domain Specific	+		No

With the digital transformation fast gaining pace, several challenges arise related to the management and utilization of distributed knowledge gained by the evolution to Industry 4.0 and the implementation of industrial Internet of Things (IoT) (Matos & Belfo, 2022) In recent years, ontologies have drawn a lot of interest as a method of knowledge management across a variety of industries, including manufacturing and sustainability. They offer a formal, machine-computable representation of domain knowledge (Arena & Kiritsis, 2017) Ontologies have been used in the context of the circular economy and sustainability to record and express the ideas, connections, and procedures linked to these domains.

Li et al. (2023) conducted a survey of general ontologies for the cross-industry domain of circular economy (Li et al., 2023). The authors identified several ontologies that cater to different aspects of circular economy, such as resource management, waste management, and sustainable supply chain management. These ontologies provide a structured representation of the relevant concepts and relationships in the circular economy domain, highlighting the potential for broader applications in areas like data and information exchange, IoT integration, and CE business models, which are also pertinent to the textile industry.

Ontologies have been used in the manufacturing industry to formalise domain knowledge and make it machine-understandable (Hildebrandt et al., 2020). Process modelling (Arena & Kiritsis, 2017), condition monitoring (Cao et al., 2019), cyber-physical systems (Hildebrandt et al., 2020), and smart manufacturing (Huang et al., 2020) are just a few of the manufacturing-related areas in which they have been used. In product lifecycle management (PLM), ontologies have also been utilised to promote knowledge-driven decision-making (Chungoora et al., 2012). Ontologies improve the interoperability and knowledge-sharing capabilities of PLM systems by capturing best practise through-life engineering information and facilitating the sharing of manufacturing knowledge across domains (Chungoora et al., 2012).

Ontologies have also been proposed for application in product information management (Chungoora et al., 2012). Ontologies can enhance integration in the value chain by facilitating the interchange and interoperability of product information among various stakeholders and businesses (Panetto et al., 2012). They minimise the loss of semantics by offering a standard paradigm for representing and exchanging product information (Panetto et al., 2012). In order to facilitate successful communication and collaboration across stakeholders with various business domains and experiences, ontology-based techniques have been proposed for the exchange of product information (Sriti et al., 2015).

In light of the aforementioned, the use of ontologies has drawn considerable attention across a range of industries, including manufacturing and sustainability. Nevertheless, despite their extensive use, the body of extant knowledge still lacks a thorough and effective textile ontology designed exclusively for the textile sector. From the analysis of the peer-reviewed databases that were available Sauter & Witjes (2017) present a rudimentary use case for textile that suggests that Linked Spatial Data can serve as an exchange medium for the Circular Economy by establishing connections between product passports and facilitating collaborative exchanges among diverse industry actors. By enhancing spatial awareness and enabling the sharing of relevant information. This research, however, is not operational and requires further research.

The use of ontologies has received significant attention considering the challenges posed by digital transformation and the need for effective knowledge management in the textile industry. Despite their widespread use in a variety of industries, there is still a lack of a comprehensive textile ontology that is tailored specifically to the complexities and sustainability requirements of the textile supply chain.
In response to this gap, this research will embark on the development of a prototype ontology. Given the complexities of the textile sector, such a prototype is a strategic first step. It will concentrate on the most

vital elements required to promote circularity within the industry, creating a scalable framework capable of evolving into a more comprehensive ontology over time.

The initial insights from Sauter & Witjes (2017) on the potential for Linked Spatial Data to facilitate the exchange of information for a circular economy underscore the need for an operational ontology in the textile domain. However, the absence of a fully developed application from their theoretical proposal marks a clear opportunity for this research to contribute a practical tool.

Thus, the focus of this project is to create a foundational ontology that will support sustainable practices and enable effective information sharing among industry stakeholders. This prototype will lay the groundwork for future refinement and growth, ultimately leading to a robust ontology that aligns with the continuous advancements in the textile industry's digital transformation.

1.3.3 Company context

TNO, the Netherlands Organisation for Applied Scientific Research, is a key partner in the FEDeRATED project, an EU initiative for digital cooperation in logistics involving 15 partners across six EU member states. TNO contributes to the project's vision of transitioning to a federated network of data sharing platforms, enhancing transparency and efficiency in the transport ecosystem. Their role includes supporting interoperability, demonstrating the proposed federative platform, initiating its implementation, and identifying conditions for effective stakeholder use. As part of the development multiple sector specific lower ontologies (prototypes) have been developed in order to assess feasibility of structuring the semantic data and aligning the ontology with the FEDeRATED ontology. This report will develop the ontology for the textile sector.

1.4 Research Objective and Scope

In this research, conducted within the framework of the Complex Systems Engineering and Management (CoSEM) program at TU Delft and in collaboration with TNO (Netherlands Organisation of Applied Scientific Research), the primary goal is to synthesize a prototype ontology for the textile industry. This ontology is aimed at enhancing circular practices within the textile industry, a sector marked by its significant environmental footprint and potential for sustainable transformation. The development of this ontology is an effort to create a structured framework for data that will improve information sharing among industry stakeholders and facilitate the creation of digital twins representing products' circular life cycles.

Our approach involves a thorough investigation into the current practices and challenges within the textile industry. This exploration will guide us in identifying the essential ontological concepts and relationships that are crucial for this sector. With this understanding, we aim to develop a prototype ontology tailored to the textile industry, specifically designed to support and enhance circular practices. This ontology is intended to be a true representation of the industry's practices and semantic information, with a focus on sustainable practices and resource management.

Furthermore, the research will involve demonstrating the efficacy and flexibility of the ontology by integrating it with the upper ontology of the FEDeRATED project. This integration is crucial to ensure that the developed lower domain ontology is comprehensive, adaptable, and future-proof, capable of evolving with the industry's needs and technological advancements.

Conducted in coordination with TNO, the Netherlands Organisation for Applied Scientific Research, this research benefits from access to, and collaboration within, the FEDeRATED project, an EU initiative focused on digital cooperation in logistics.
TNO is a key partner in the FEDeRATED project, an EU initiative for digital cooperation in logistics involving 15 partners across six EU member states. TNO contributes to the project's vision of transitioning to a federated network of data sharing platforms, enhancing transparency and efficiency in the transport ecosystem. TNO's contribution to the project centres around supporting interoperability, demonstrating the proposed federative platform, initiating its implementation, and identifying conditions for effective

stakeholder use. As part of the development multiple sector specific lower ontologies have been developed to assess feasibility of structuring the semantic data and aligning the ontology with the FEDeRATED ontology. This research will focus on developing the initial prototype ontology for the textile domain.

In summary, this research aims to optimise semantic data structuring in the textile industry to enhance both interoperability and sustainability. It emphasises the importance of integrating the developed ontology with the FEDeRATED project's upper ontology, leveraging its proven concepts within the field of logistics. Through the development of this prototype ontology, the research aspires to contribute significantly to the sustainable transformation of the textile industry and foster innovation in circular practices.

1.5 Research Questions and Research Approach

The aforementioned goals can be achieved by addressing a series of research questions that will steer this investigation. The primary research question is articulated as follows:

How can we structure a prototype textile-ontology that leverages the FEDeRATED project, to maximise its contribution to providing insights in circular data?

This research aims to create a prototype for the textile ontology to promote circularity by building on the FEDeRATED ontology. Unlike a typical design, this project requires rigorous research methods because it will generate new knowledge and expand an existing knowledge base. The results will be shared with practitioners and researchers, aligning with Design Science Research (DSR) principles (Johannesson & Perjons, 2014). In addition to the DSR principles, we will integrate a detailed step-by-step methodology from Zhou et al. (2016) for the specific stages of ontology development, which will be discussed in Chapter 3.
The proposed artefact, an ontology for the textile supply chain, is situated within the FEDeRATED and circularity research communities. It leverages empirical data and contributes to local practices by offering a dedicated ontology. The project draws from existing knowledge in ontological technologies and circularity practices.

The Johannesson & Perjons (2014) framework is being used as a guiding principle in this report. This study seeks to leverage the systematic problem-solving and solution-creation aspects of the Design Science Research model by using a design-oriented approach inspired by Johannesson & Perjons (2014) and their process model for design science research. By incorporating this framework and supplementing it with the methodology by Zhou et al. (2016), the research project benefits from a structured and methodical approach, ensuring the creation of an ontology that promotes interoperability and provides valuable guidance to stakeholders in the textile industry.
This research follows the steps of (Johannesson & Perjons, 2014) as a guiding principle, all steps are incorporated into our methodological framework even though we have chosen to give it a different structuring and name. For instance, our first sub-question aims to establish the foundational knowledge necessary for ontology development, aligning with the DSR model's emphasis on understanding and defining the problem space. Subsequent sub-questions delve into the requirements gathering and design and development phases of the DSR framework, each building on the insights and outputs of the previous one. By mapping each sub-question to a step in the DSR process, we maintain a clear and consistent trajectory through our research, ensuring that each phase naturally informs and transitions into the next.

To illustrate this alignment more concretely, after presenting a short summary of the research parts, we articulate each corresponding sub-question and the deliverable it targets, clearly indicating its place within the DSR framework. This approach provides transparency in our methodology and ensures that each step of our research is purpose-driven and contributes to the overarching goal of developing a robust and contextually relevant ontology.

PART I: This section includes chapter one. The first chapter introduces the research project, the literature review, After the literature review the main research question is presented. The chapter then continues discussing the research methodology used which correspond to the sub-question which will be presented integrated with the methodology's steps.

PART II: In this section, the focus is on explicating the problem, which is the first step in the design science research process according to (Johannesson & Perjons, 2014) model and the third chapter in our research. The researchers identify the specific challenges and issues they intend to address in the textile industry. This involves a deep dive into the contextual background of the problem, emphasizing the importance of the FEDeRATED project in this context.

Sq 1. What foundational knowledge and contextual understanding are required to construct a textile-ontology that leverages the FEDeRATED project?

Answering this research question is key to formulating a contextual background chapter. This chapter will explicate the most crucial concepts in ontologies, circularity, data semantics, and their relation to the textile sector. It is this exploration and analysis that will provide an answer to the first sub-question.

The significance of PART II lies in its role in laying the groundwork for the research. By examining the problem in its contextual background and exploring the FEDeRATED project, this section not only addresses the first sub-question but also sets the stage for the rest of the research. It ensures that there is a solid understanding of the key concepts and challenges that the research aims to tackle, thereby framing the direction for subsequent steps in the research process.

PART III: This section delves into the process of gathering and analysing requirements for the artefact, which will be developed using a two-pronged methodological approach. Initially, the general framework of Design Science Research (DSR) by Johannesson & Perjons (2014) guides our overarching methodology, ensuring a structured process for artefact creation that is applied throughout the research. However, to address the intricacies of ontology development within the textile sector, we will supplement the DSR framework with a specialized methodology by Zhou et al. (2016). This additional methodology, introduced here and detailed in Chapter 3, provides a granular process with a special emphasis on ontology construction steps such as formulating competency questions and analysing existing taxonomies and ontologies. By integrating this dual methodology approach, we ensure that the developed ontology is robust, effective, and tailored to the latest developments and specific requirements in the textile industry. The chapter is particularly focused on the methodology of translating these identified needs into a structured ontology, presenting a refined scope of the to be developed ontology. To guide the creation of these requirements the sub-question 2 is as follows:

Sq. 2 What are the prerequisites for creating an ontology that handles semantic data in the textile supply chain while integrating with the FEDeRATED ontology?

The intended result of addressing this sub-question is a detailed list of requirements. This list not only specifies the capabilities of the artefact but also considers the environmental and structural needs of the artefact. Additionally, there is an analysis of current standards and similar solutions in the field. This comprehensive approach ensures that the developed ontology is robust, effective, and aligned with the latest developments and requirements in the textile industry.

PART IV: This part of the research transitions into a crucial phase, focusing on the ontology modelling and development stage. This chapter begins by describing the tool used to build the ontology prototype, emphasizing the practical aspects of the design and development phase. It then elaborates on the detailed steps involved in creating the ontology, which includes defining and establishing the necessary classes, properties, and relationships to accurately represent semantical data in the textile industry.

This part of the research is dedicated to answering Sub-question 3:

Sq 3. *How can the various classes, properties, and relationships be structured in such a way that they accurately represent semantical data in the textile industry while also being compatible with the FEDeRATED ontology?*

The creation of the ontology is based on the requirements defined in earlier stages of the research. The chapter progresses to illustrate the evolution of the ontology's structure, presenting the ontology's attributes along with their corresponding hierarchy. Additionally, it provides a clear motivation for why elements within the ontology are structured as they are, ensuring that they align with the needs of the textile industry and are compatible with the FEDeRATED ontology.

Subsequently, the chapter transitions into the integrated demonstration and evaluation phases. This is done jointly in the same part as the development as the development of the ontology is an iterative process, combining these steps of the methodology in the same part mimics the iterative development of the ontology that is happening at the same time as the evaluation and demonstration. In this segment, the research addresses two additional sub-questions:

Sq 4. *To what degree does the developed ontology satisfy the requirements specified in sub question 2, as demonstrated through an evaluation and demonstration?*

Sq 5. *What structure will the final ontology have to represent semantic data in the textile industry while being compatible with the FEDeRATED ontology?*

First sub-question 4 will produce evaluation methods to assess the ontology on its structural metrics and clarity. Next, the content will be checked using demonstration of use cases which will be queried to measure the completeness of the ontology. Finally, after the demonstration and evaluation and iterative improvements of the ontology the final structure can be presented.

PART V: The final section marks the conclusion of the research report, tying together the answers to the research questions raised throughout the report. This final section will provide a clear response to the main question and circle back to the secondary questions. It will also highlight the contributions of the research to both society and the scientific community. To wrap up, we will outline the limitations encountered during the research and suggest areas for future investigation, as informed by the findings and evaluations conducted in this study.

The aforementioned steps have been adjusted for this research to better suit the needs of this report. In Figure 1 the steps are schematically shown grouped by their parts. Below the figure each part is discussed in which also the information elicitation is presented.

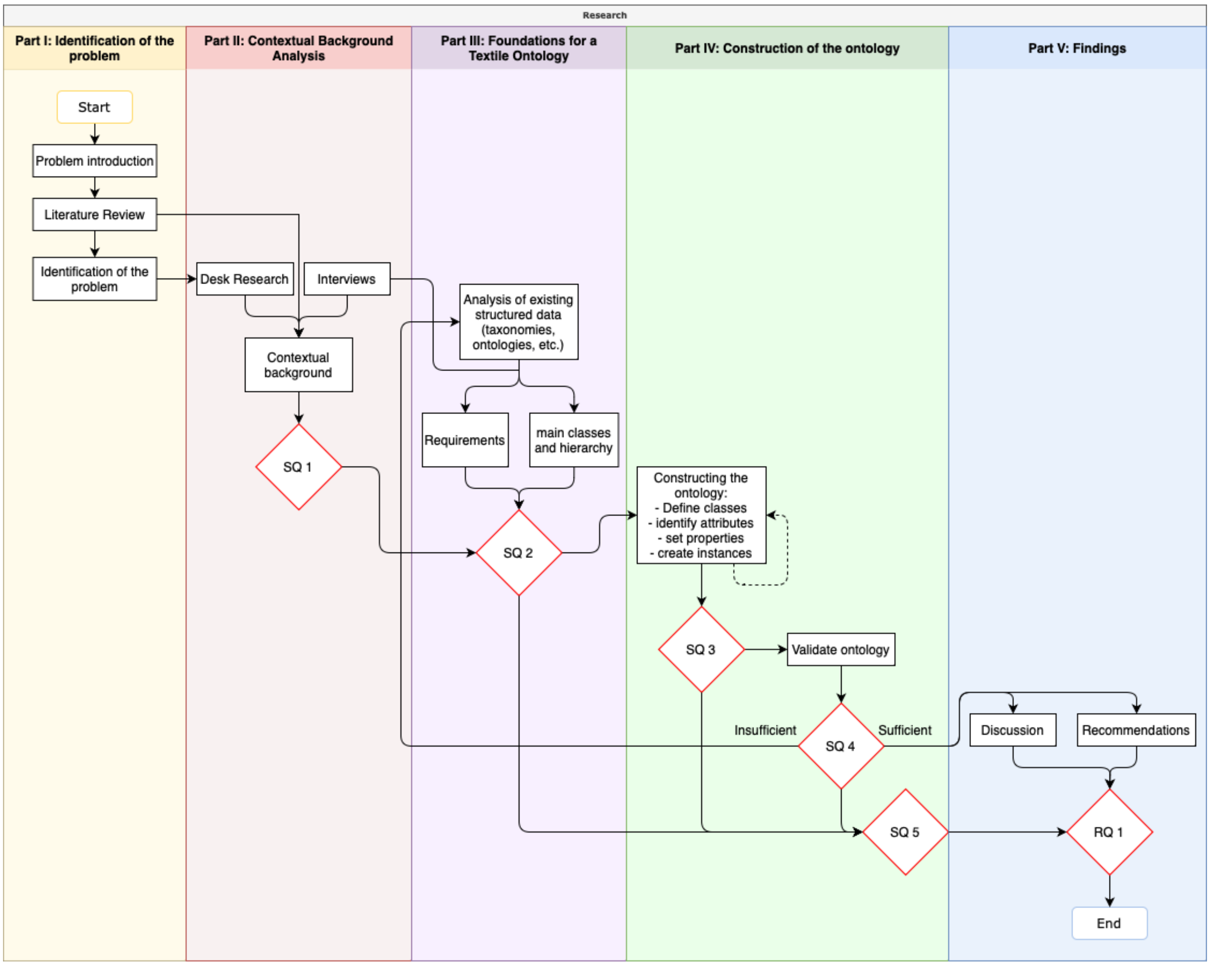

Figure 1: Research Flow Chart

1.6 Conclusion

Chapter 1 of this thesis has established a crucial foundation for the ensuing research by highlighting the significant environmental impact of the textile industry and the urgent need for sustainable solutions. The discussion underscores the industry's role in contributing to global carbon emissions and waste generation, emphasising the necessity for adopting circular economy principles to address these challenges. This chapter's exploration of circularity in the textile industry, underpinned by the concept of ontologies, serves as a prelude to the research's core objective: developing a prototype ontology tailored to the textile industry. The research's aim, as delineated in this chapter, is not only to develop an ontology that encapsulates critical information about textile production processes but also to ensure its adaptability and integration with the FEDeRATED project's broader framework. This overarching goal sets the stage for the comprehensive methodology that will be employed in the subsequent chapters.
The literature review conducted in this chapter forms a vital part of the research, as it helps to identify the gap in current knowledge regarding ontologies specific to the textile industry. This identification of the research gap is instrumental in shaping the direction of the study and formulating the main research question. As we transition to Chapter 2, we delve deeper into the concepts and contexts crucial for understanding and addressing these challenges, exploring the intricacies of the textile sector, the nuances of ontology development, and the significance of the Semantic Web and the FEDeRATED project in this context.

PART II

Contextual Background

2 Exploration & Definition of Background

2.1 Introduction

In this chapter, we address the sub-question 2: *"What foundational knowledge and contextual understanding are required to construct a textile-ontology that leverages the FEDeRATED project?"*
Employing a literature review methodology, we explore key concepts including the textile industry, circularity, digitalization, ontologies, and the FEDeRATED project. This examination will yield a nuanced understanding of these topics, forming the sub-deliverable of this chapter. Starting with Section 2.2, we dissect the environmental challenges inherent to the textile industry, a domain where pollution and resource depletion demand innovative solutions. This environmental context directly informs the need for sustainable practices, where circularity emerges as a key concept, offering a potential remedy to the industry's ecological footprint. Transitioning to Section 2.3, we navigate through the theoretical underpinnings of ontologies, establishing a foundation for representing knowledge that can support the circular economy in the textile industry. The clarity gained from understanding different ontologies informs our approach to constructing a domain-specific ontology that can encapsulate environmental considerations alongside industry-specific knowledge.
In Section 2.4, the Semantic Web is introduced as the technological fabric that enables the practical application of ontologies, creating a web of data where information flows seamlessly across systems, further reinforcing the need for a robust ontology in realizing the vision of a sustainable textile sector.
Concluding the chapter with Section 2.5, we align our discussions with the FEDeRATED project, which embodies an upper ontology that our domain-specific ontology must interface with. This project stands as a testament to the importance of interoperability and the broad applicability of ontologies, extending beyond environmental concerns to the logistics and operations that are critical in the textile industry. By examining these topics—ranging from the environmental footprint of the textile industry to the intricacies of circular economy, and from the theoretical frameworks of ontologies to the operational capabilities of the Semantic Web, culminating in the overarching architecture of the FEDeRATED project—a comprehensive picture emerges. This multifaceted analysis is instrumental in guiding the development of a domain ontology that is well-suited to the textile industry. The aim is to create an ontology that not only encapsulates the unique characteristics and sustainability goals of the industry but also seamlessly integrates into a broader digital ecosystem. The resulting ontology is intended to facilitate knowledge exchange that is vital for industry-wide sustainability and innovation, ensuring relevance and applicability across various facets of the textile sector.

2.2 The textile sector

The textile industry has a significant environmental impact, causing pollution and depletion of resources. Textile manufacturing involves a number of processes that emit harmful chemicals and waste into the environment. The production of yarns and fabrics is one of the most polluting processes in textile manufacturing (Patti et al., 2020). It requires a lot of water to make textiles, as well as a lot of land to grow cotton and other fibres. The worldwide textile and garment sector is projected to have consumed 79 billion m^3 of water in 2015, whereas the EU's whole economy used 266 billion cubic metres in 2017. According to estimates, a single cotton t-shirt requires 2,700 litres of fresh water, which is enough to supply one person's drinking needs for 2.5 years (European Environment Agency, 2022). In 2020, the textile industry was the third greatest contributor of water pollution and land utilisation. Each EU citizen used an average of nine cubic metres of water, 400 m^2 of land, and 391 kilogrammes of raw materials that year for textiles (European Environment Agency, 2022) The textile industry's environmental impact extends beyond the manufacturing stage. The disposal of finished textile goods also has an impact on the environment. Throughout the life cycle of the products, the textile and garment industries generate chemical loading, high water consumption, high energy consumption, air pollution, and solid waste (Islam et al., 2022).

Sustainable practises such as eco-design and recycling are being promoted in the textile industry to reduce environmental impact. Eco-design focuses on minimising a product's environmental impact during the design stage, optimising product function, and making recycling and reuse easier (Islam et al., 2022). Textile waste recycling and reuse can help reduce the volume of solid waste and conserve resources (Patti et al., 2020).

2.2.1 Circularity in the textile sector

The circular economy is a multifaceted concept with various definitions, all sharing a core theme: the closure of material flow loops and the establishment of a system where resources are continually recycled and reused (Kirchherr et al., 2017). This approach seeks to minimise waste, enhance resource efficiency, and foster sustainable economic growth. At its heart are the principles of reducing, reusing, and recycling materials and products to create a self-sustaining cycle (Diéguez-Santana et al., 2021). The overarching goal of the circular economy is to ensure that products contain components that contribute positively to the preservation and enhancement of natural capital, the optimization of resource utilization, and the mitigation of systemic risks (Diéguez-Santana et al., 2021). In essence, it aspires to transform our current linear, wasteful economic model into a regenerative one that harmonizes with the planet's finite resources. It is characterized by the implementation of circular business models, which focus on closing material loops and maximizing the value of resources. Circular business models have been recognized as a key driver for achieving a circular economy (Geissdoerfer et al., 2017).
Nevertheless, it is essential to recognize that the pursuit of circularity entails trade-offs that demand careful consideration (Geissdoerfer et al., 2017). The pursuit of a circular economy presents both opportunities and challenges. Transitioning from a linear to a circular model requires significant upfront investments in new technologies and infrastructure, which can be financially burdensome for businesses (Boons & Lüdeke-Freund, 2013; Geissdoerfer et al., 2020). Additionally, there may be trade-offs between short-term economic gains and long-term environmental benefits, as some companies may prioritize immediate profitability over circular practices. Achieving a fully circular economy also relies on changing consumer behaviour and societal acceptance, which can be a slow and challenging process. As a result, successfully transitioning to a circular economy necessitates strategic planning, embracing change, and addressing these trade-offs and challenges (Geissdoerfer et al., 2020). A fully circular economy also necessitates changes in consumer behaviour and societal acceptance, which can be a slow and difficult process (Sousa et al., 2021). As a result, successfully transitioning to a circular economy necessitates strategic planning, embracing change, and addressing these trade-offs and challenges (Velenturf et al., 2019).

Within this framework of challenges and opportunities in transitioning to a circular economy, a key aspect to consider is the 'replacement rate.' This metric is essential for measuring progress towards achieving a more circular model, especially in resource-intensive sectors like textiles. The replacement rate in the circular economy refers to the rate at which primary raw materials are replaced with secondary ones through recycling, reusing, and remanufacturing processes It is a key metric that measures the extent to which a circular economy is being achieved (Garcés-Ayerbe et al., 2019; Kayal et al., 2019).The goal is to reduce the consumption of virgin resources and minimise waste generation by increasing the replacement rate. By closing material and power loops, the circular economy aims to extend the life cycle of products and materials. In the context of the textile sector, the replacement rate is crucial for reducing the industry's environmental impact. By increasing the replacement rate of primary raw materials with secondary ones, such as recycled fibres, the textile sector can reduce its reliance on virgin resources and minimise waste.

The 9R principles are fundamental within the circular economy framework, guiding the shift from a linear to a circular model. These principles - Reduce, Reuse, Recycle, Repair, Refurbish, Remanufacture, Repurpose, Redistribute, and Recover - emphasize the importance of waste reduction and enhanced resource value (Millar et al., 2019). In relation to the replacement rate in the circular economy, these principles highlight how increasing the replacement rate can be achieved by reducing the use of virgin resources and promoting practices such as reuse, recycling, and remanufacturing (Millar et al., 2019). Strategies like recycling, upcycling, and incorporating recycled materials into manufacturing processes are integral to this approach. Enhancing the replacement rate requires collaborative efforts from stakeholders, adherence to circular economy principles, supportive policies and regulations, and investment in research and development (Millar et al., 2019).

However, increasing the replacement rate in the textile sector presents unique challenges. Textile recycling is still in its nascent stages, with technological barriers and limited research impeding higher recycling rates (Riemens et al., 2021). Moreover, while reuse and recycling are vital, prevention is often considered a more effective strategy. By focusing on reducing waste generation and resource consumption at the source, prevention tactics address overproduction and overconsumption, thereby reducing the reliance on waste management processes like reuse or recycling. This approach leads to more efficient resource utilisation and lessens environmental impact (Riemens et al., 2021).

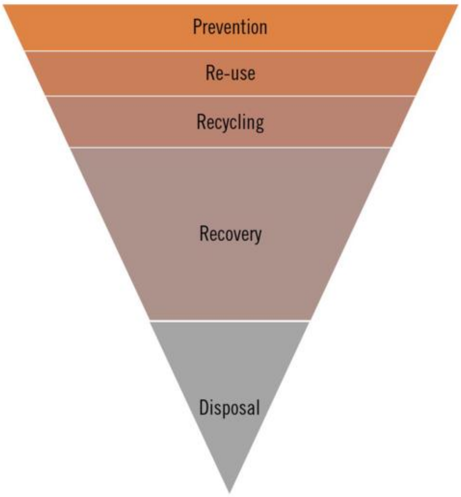

Figure 2: Waste hierarchy, by Keßler et al. (2021)

As illustrated in Figure 2 by Keßler et al. (2021) and in accordance with the waste hierarchy proposed by the same source, this systemic viewpoint emphasises prevention as the primary strategy during the transition to a circular economy. The textile industry can achieve its sustainability goals most effectively when stakeholders prioritise adherence to circular economy principles. To clarify, the recommended priority order should begin with prevention as the primary strategy, ensuring that the generation of waste is minimized from the outset, thereby reducing the overall impact on the environment. Following prevention, the focus should shift to reuse, which involves finding ways to extend the life of textile products and materials through repeated use, repair, or repurposing. Finally, recycling should be considered, which entails processing textiles to recover fibres and other materials for new products. Each layer of the hierarchy builds upon the previous one, creating a comprehensive approach that seeks to maximise resource efficiency and minimise waste.

2.2.2 Digitalisation in the textile sector

Digital transformation has emerged as a crucial driver of change within the textile and apparel industry, prompting a pressing need to accelerate the infusion of digital intelligence into fashion and textile production (Li & Li, 2022). To navigate this transformation effectively, textile firms must harness digital technology, cultivate digital dynamic capabilities, and foster digital innovation (Shen et al., 2022).
In the textile sector, the integration of digital twins is an innovative approach to digitalisation that can significantly contribute to advancing circularity and sustainability goals (Preut et al., 2021). These digital replicas of physical products, processes, or systems are instrumental in preventing overproduction by providing real-time insights and simulations of production processes (Wiegand & Wynn, 2023). By creating digital twins for production lines and facilities, companies can simulate scenarios, identify bottlenecks, and continuously gather data on parameters such as machine performance, energy consumption, and material usage (Alves et al., 2022; Wiegand & Wynn, 2023). This data enables informed decision-making, reduces waste, and aligns production with demand, ultimately contributing to sustainable practices. Additionally, digital twins play a critical role in optimizing production processes, enhancing resource efficiency, and reducing the environmental footprint of textile manufacturing (Alves et al., 2022).
Moreover, digital twins foster collaboration and communication among different stakeholders involved in the production process (Wiegand & Wynn, 2023). By serving as a digital representation of the physical

product and enhancing visibility throughout the production steps, digital twins improve coordination and decision-making, thereby reducing the likelihood of overproduction due to miscommunication or limited visibility.
Digital twins can also play an important role in enhancing traceability and transparency in the textile supply chain, crucial elements for achieving circularity. By integrating data from various stages of the supply chain, such as raw material sourcing, production, distribution, and end-of-life management, digital twins enable tracking and tracing of materials and products (Alves et al., 2022). This ensures the authenticity and quality of materials, facilitates the identification of recycling and reuse opportunities, and enhances overall supply chain transparency. Furthermore, digital twins facilitate the implementation of circular business models, such as product-as-a-service or leasing models. By monitoring product performance and condition through their digital twins, companies can optimise maintenance and repair processes, extend product lifetimes, and enable efficient recovery and remanufacturing at the end of the product's use phase (Alves et al., 2022). In this way, digital twins become integral tools in the pursuit of sustainability and circularity within the textile industry. In Figure 3 is a depiction of how digital twins can integrate with various stages of the textile industry to promote circularity. The diagram demonstrates the flow of both physical products and their digital counterparts throughout the value chain – from material sourcing to end-of-life management. It highlights the role of digital twins in facilitating data exchange between upstream suppliers, manufacturers, retailers, users, and recyclers. The interconnected web of data exchange fosters transparency, traceability, and enhanced decision-making across the supply chain. Furthermore, the figure illustrates how the digital product flow complements the physical product flow, with an emphasis on circular economy loops that include repair, reuse, refurbish, and recycle strategies. This visual representation underscores the potential of digital twins to revolutionise sustainability practices in the textile sector.

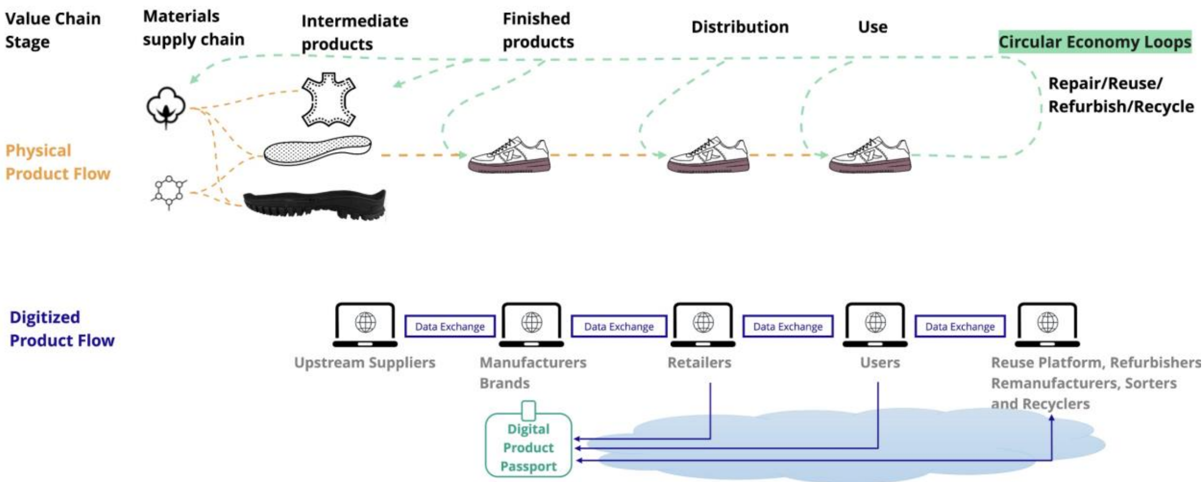

Figure 3: Representation of the value chain in the textile industry with a focus on physical and digitized product flow (adapted from Onto-Deside, 2022)

Ontologies play a crucial role in contributing to digital twins by providing a formal and explicit specification of the domain knowledge related to the digital twin (Meierhofer et al., 2021). They enable semantic modelling, allowing for the definition of entities and their interrelationships within the digital twin (Meierhofer et al., 2021). Ontologies describe the entities and topologies of digital twins through the taxonomy of defined classes and object properties (Meierhofer et al., 2021). Furthermore, ontologies can be utilised to integrate data from heterogeneous sources and information systems, facilitating the organized representation of multi-context data within the digital twin context (Khan et al., 2022). Ontology-based modelling is commonly employed in the definition and modelling phase of digital twins (Göppert et al., 2021). Overall, ontologies are essential for enabling interoperability, semantic understanding, and decision support in digital twin systems (Meierhofer et al., 2021).
Having explored the transformative impact of digitalisation in the textile sector and the critical role played by digital twins, we now turn our attention to the underlying conceptual framework that empowers these digital replicas. Enter the world of ontologies – a foundational element in our journey to harness digital intelligence effectively.

Ontology, in its simplest form, is a structured way to organize and define concepts, their relationships, and properties within a specific domain of knowledge. This organised structure serves as a shared language for humans and computers, making it easier to communicate and collaborate effectively, especially in complex areas like digital twins.

As we transition from a broad discussion on the role of digitalization in enhancing sustainability within the textile sector to the more specialised topic of ontologies, it is essential to understand the important role these conceptual frameworks play. The upcoming sections delve into the intricacies of ontologies, which serve as the backbone of digital twins and are fundamental to achieving the digital transformation that the textile industry is undergoing. Understanding ontologies is crucial because they provide a structured and standardized way to represent knowledge, enabling better communication and collaboration across various stakeholders. They form the underpinnings of digital systems that drive the circular economy forward. As we delve into the more technical aspects of ontologies, it's essential to understand how they shape the sustainable future of textiles. With a grasp of digitalisation's role, we now explore ontologies in detail, equipping us to effectively apply these digital principles within the textile sector.

2.3 What is an ontology?

Gruber's (1993) widely accepted definition characterizes ontology as a statement of conceptualization, serving to convey knowledge and foster consensus among diverse stakeholders, thus facilitating enhanced communication and collaboration (Gruber, 1993; Studer et al., 1998). Borst (1997) underscores the need for formal, machine-readable ontology structures, forged through specialist consensus for cross-domain applicability.
These frameworks play a pivotal role in data integration, knowledge sharing, and semantic interoperability. They enable effective communication, reasoning, and information retrieval, generating structured knowledge representations (Studer et al., 1998; Vidal et al., 2010). Ontologies typically encompass classes, instances, relations, functions, and axioms, providing a comprehensive hierarchy (Uschold & Gruninger, 1996). For example, as illustrated in Figure 4, instances belong to classes such as 'City' being an instance of the class 'Geographical Location', and relations establish connections between entities, such as a country having a land boundary with another country.

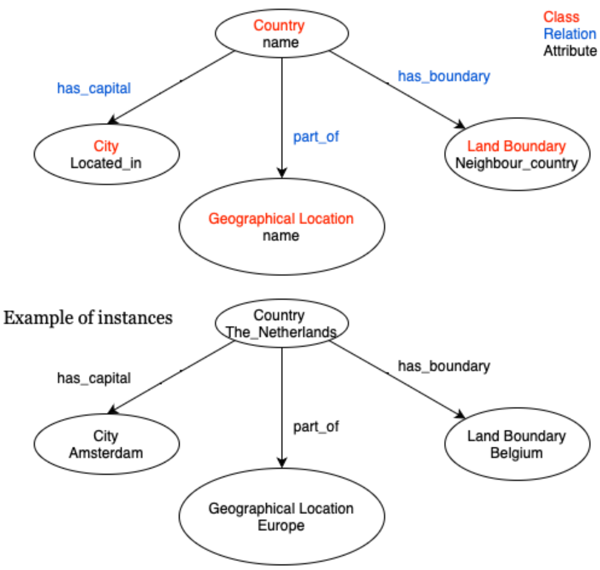

Figure 4: Example of an ontology's components

Semantically, ontologies entail domain-specific knowledge representation (Ameen et al., 2014), defining concepts, relationships, and properties to establish a shared vocabulary for communication and interoperability (Ameen et al., 2014). They ensure consistent, unambiguous terminology for semantic interoperability across systems and domains (Slater et al., 2020). Technically, ontologies can be systematically authored and organized to validate accuracy (Pushpa et al., 2016), while their digital format guarantees uniform machine-readable data formats for seamless system communication.

2.3.1 Classification of ontologies

Ontologies can be categorised into two primary types: **taxonomic** ontologies and **semantic** ontologies. Taxonomic ontologies employ hierarchical relationships to arrange elements based on shared characteristics. They excel in tasks involving categorisation and recording taxonomic relationships, proving valuable in domains such as biology and systematics (Gerber et al., 2017; Senderov et al., 2018). In contrast, semantic ontologies possess a broader scope, capturing intricate meanings and connections between concepts. Their purpose is to provide a more comprehensive understanding of relationships and semantics, rendering them suitable for applications like information retrieval, personalized search, and knowledge management (Jiang & Tan, 2009).
A taxonomic ontology, for instance, could be used in the domain of biology to classify species of animals. In such an ontology, elements like "mammals," "reptiles," and "birds" would be organized hierarchically, with "mammals" further subdivided into "carnivores" and "herbivores," and so on. This hierarchical structure helps categorize and arrange species based on shared characteristics such as their mode of reproduction or physical attribute.
On the other hand, a semantic ontology might be employed in the field of personalised search engines. In this context, the ontology would capture not just the taxonomic relationships between words or concepts but also their nuanced meanings and relationships. For example, it could understand that in the context of a search for "jaguar," the user might be interested in information about the car brand as well as the animal. It would then link these two concepts, providing a more comprehensive understanding of the user's intent and facilitating more relevant search results. Semantic ontologies are versatile in capturing complex meanings and connections between concepts to enhance information retrieval and knowledge management.
Taxonomic and semantic ontologies are used in a variety of fields, including biology, e-commerce, artificial intelligence, and the Internet of Things, because they provide effective frameworks for organizing and analysing information in our linked environment.
In conclusion, ontologies are indispensable tools in knowledge representation, and their various types cater to specific requirements in different domains. The analysis provided by Gómez-Pérez et al. (2004) further distinguishes ontologies based on their conceptualisation and highlights their applications in diverse fields, contributing to a better understanding and utilization of ontological engineering principles:

- **Ontologies for Knowledge Representation (KR):** KR ontologies encapsulate the representation primitives that are utilized to codify knowledge in various KR paradigms. They concentrate on formalising representation primitives used in frame-based languages, such as classes, subclasses, attributes, values, relations, and axioms.
- **Ontologies in general or in common use:** Ontologies in general represent common sense knowledge that can be utilised across fields. They provide terminology for basic ideas such as things, events, time, space, causation, behaviour, and function.
- **Upper-level or top-level ontologies:** Top-level ontologies define very broad concepts and give overarching concepts to which all root terms in current ontologies should be related. These ontologies aim to address the disparity in classification criteria that emerges as a result of differing philosophical orientations.
- **Domain Ontology:** Domain ontologies are tailored to a certain domain, such as medicine, engineering, or law. They give languages to describe concepts and connections that are specific to that area.
- **Tasks Ontology:** Task ontologies concentrate on terminology associated with general tasks or activities. They specialise top-level ontology words to provide a systematic method to problem-solving for various jobs.
- **Domain-Tasks Ontology:** Domain-task ontologies are task ontologies that can be reused within one domain but not across domains. They are application-independent and focus on tasks within a specific domain.

- **Method Ontology:** Method ontologies define the concepts and relationships that are used to specify reasoning processes for completing specified tasks. They are concerned with giving an organized approach to issue solving.
- **Application Ontology:** Application ontologies are application-specific and contain the definitions needed to model knowledge for that application. They augment and specialize the language from domain and task ontologies to meet the application's specific requirements.

In summary, Gómez-Pérez et al. (2004) provide a thorough examination of these various types of ontologies and their applications in knowledge management, e-commerce, and the Semantic Web, allowing researchers and practitioners to better leverage their potential for organizing information and improving decision-making across multiple domains.

As we ventured into the creation of our ontology for the textile industry, it was imperative to survey the landscape of ontology types. This exploration was a necessary step to ensure we chose the right kind of ontology for our needs. We settled on developing a 'Domain Ontology,' which aligns perfectly with the intricate details and specific concepts of the textile industry. This type of ontology allows for an in-depth and shared understanding of the industry's particulars, which is indispensable for effective communication and data handling within the field. At the same time, recognising and explaining other ontology forms in this thesis enriches our discussion and solidifies our decision-making process. For example, our Domain Ontology is designed to work in tandem with the FEDeRATED ontology, which serves as an 'Upper Ontology.' The FEDeRATED ontology operates at a higher level, providing a scaffold that ensures our more detailed domain-specific information can be integrated within a larger, more general framework. This ensures that our work is not only relevant on a micro level but is also interoperable on a macro scale, facilitating broad connections across different systems and industries.

Before delving further into the applications and implications of ontologies in the textile sector, it is essential to lay the groundwork by understanding their basic building blocks. These components—classes, instances, properties, relations, and axioms—are the tools that will later be employed to construct a digital framework that is not only robust but also capable of fostering the kind of semantic interoperability that is critical for advancing the industry's sustainability goals. With this foundation, we will be better equipped to appreciate the application of the ontology in subsequent sections.

Ontology Components

For the structuring of knowledge, multiple representational languages exist. Each of those languages is comprised of different components. However, most ontologies consist of classes, instances, properties and attributes, relations, and axioms (Gruber, 1993; Studer et al., 1998; Globa et al., 2020). The different elements of an ontology can be defined as follows:

- **Classes:** refer to abstract categories or concepts that define a group of similar objects or entities with common characteristics.
- **Instances**: also known as individuals, are specific concrete members or instances of a class. They represent digitalised real-world objects that belong to a particular class.
- **Properties:** or attributes are characteristics or features that describe the members of a class. They define the relationships between classes and instances and can have data type restrictions (e.g., String, Integer, etc.).
- **Relations:** establish connections or associations between different classes or instances in an ontology. These connections represent the interdependencies and interactions between entities.
- **Axioms:** or restrictions are logical statements that impose constraints or rules on the elements of an ontology. They help to define the behaviour and constraints governing the relationships between classes and instances.

2.3.2 The Advantages of Ontologies in Knowledge Structuring

The selection of an appropriate structure is critical in the field of knowledge representation for capturing the complexities of information in a coherent and meaningful manner. An ontology emerges as a convincing solution, differentiated by its ability to model, and integrate diverse concepts within a domain in a comprehensive manner (Achsan et al., 2017). The Resource Description Framework (RDF), a standardised framework for defining and linking digital resources, is at the heart of ontologies. RDF structures create a consistent framework for describing information, ensuring that data is arranged in a way that allows for smooth interconnection. Unlike alternative approaches to knowledge structuring, such as a taxonomy, that may rely on diverse systems or models, RDF-based ontologies provide a consistent structure that allows for easy integration and knowledge sharing (Ma et al., 2016).
Furthermore, the ability of ontologies to inherit properties via subclass connections is an advantage. By designing a new ontology as a sub-class of an existing one, the new ontology can effortlessly acquire all its parent's properties. This feature speeds up ontology development by allowing developers to draw on work done in broader domains and adapt it to accommodate specific idiosyncrasies within tighter domains (Achsan et al., 2017). This practice not only accelerates the generation of ontologies but also promotes the reuse of existing ontologies. Additionally, this inheritance mechanism facilitates the creation of multimodal ontologies or "upper ontologies" that encompass a wide range of concepts and relationships, leading to richer and more versatile knowledge representation through the alignment of lower and upper ontologies. As a result, this approach speeds up the generation of ontologies while maintaining consistency and coherence in the resultant knowledge structure.
The necessity for comprehensive and holistic knowledge representation is greater than ever in an era of quickly expanding information landscapes (Khobreh et al., 2016). Ontologies excel at satisfying this demand by providing a structured framework that can accommodate a wide range of data kinds, relationships, and contextual complexities (Khobreh et al., 2016). This thorough methodology ensures that the final knowledge representations reflect the complexity of the real world, improving processes such as information retrieval & sharing, analysis, and decision-making.

2.4 Introduction to semantic web

Following our exploration of ontologies as the structural backbone of digital information, we now turn to the domain of the Semantic Web. Here, our theoretical discussion becomes practical: the Semantic Web employs ontologies to endow data with meaning and context, enabling computers to process and understand information in a human-like manner. In my research, this technology is pivotal for capturing the complexity and nuances of the textile industry, enhancing collaboration, and facilitating information exchange within this sector.
The best informal definition of the semantic web is perhaps found in the Scientific American article "The Semantic Web" (Berners-Lee et al., 2001, p. 1), which states that " The Semantic Web is not a separate Web but an extension of the current one, in which information is given well-defined meaning, better enabling computers and people to work in cooperation The Semantic Web is not a separate Web but an extension of the current one, in which information is given well-defined meaning, better enabling computers and people to work in cooperation" This idea, introduced by the creator of the World Wide Web, Tim Berners-Lee, along with his team, is intended to resolve a fundamental issue with the current web: While machines can handle data, they lack the ability to interpret it as humans do. The goal is to structure the data and assign it explicit meanings—semantics—so that computers can not only process the web's information but understand it and carry out intricate operations for users. This shift towards the Semantic Web introduces a profound transformation in the way we interact with information and the capabilities of technology. At its core, the Semantic Web aims to enrich data with context and significance, paving the way for a more intelligent and efficient digital landscape.

Linked Data The Semantic Web is designed to link entities in a way that both humans and machines can analyse them. Thus, through the use of connected data, once you've identified an item of interest, you can effortlessly discover more related data (Berners-Lee, 2006). The architecture of the World Wide Web can be described by three fundamental elements, as illustrated in the Figure 5 below.

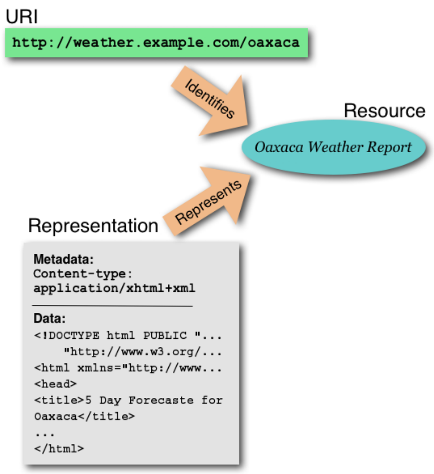

Figure 5: Three elements of WWW by W3C (2004)

URI/URL: A Uniform Resource Identifier (URI) is a string of characters that identifies a resource, whereas a Uniform Resource Locator (URL) is a sort of URI that allows you to find the resource by entering its internet address.
HTTP: Hypertext Transfer Protocol (HTTP) is a protocol that allows data to be transferred over the internet, especially between web servers and clients, allowing the request and delivery of web pages and other resources.
HTML: Hypertext Markup Language (HTML) is the standard language for creating and structuring web page content, with tags defining components such as headings, paragraphs, links, and images.
In essence, the interplay between these three elements harmonizes the retrieval, transmission, and presentation of information on the web. It paves the way for an internet where data is no longer an inert repository but a dynamic fabric of interconnected knowledge, empowering both humans and machines to collaboratively navigate the digital landscape and unlock new dimensions of insight and innovation.
This way of representing information gives rise to a concept that underpins the Semantic Web: Resource Description Framework (RDF). RDF serves as the language of interconnectedness, allowing us to express relationships and attributes about resources in a structured, machine-understandable format. The RDF model encodes data as subject, predicate, and object triples. A triple's subject and object are both URIs that identify a resource, or a URI and a string literal, respectively. The predicate, which is also represented by a URI, specifies how the subject and object are connected (Bizer et al., 2009). In an RDF triple:

- The subject represents the resource under consideration.
- The predicate denotes the property or relationship associated with the resource.
- The object signifies the value, or another resource linked by the predicate.

RDF provides a flexible and extensible foundation for defining resource declarations. Within the semantic web RDF provides the basis for structures such as ontologies and taxonomies. In Figure 6 the semantic web stack is shown, here the place of RDF as one of the pillars of the semantic web is clearly shown.

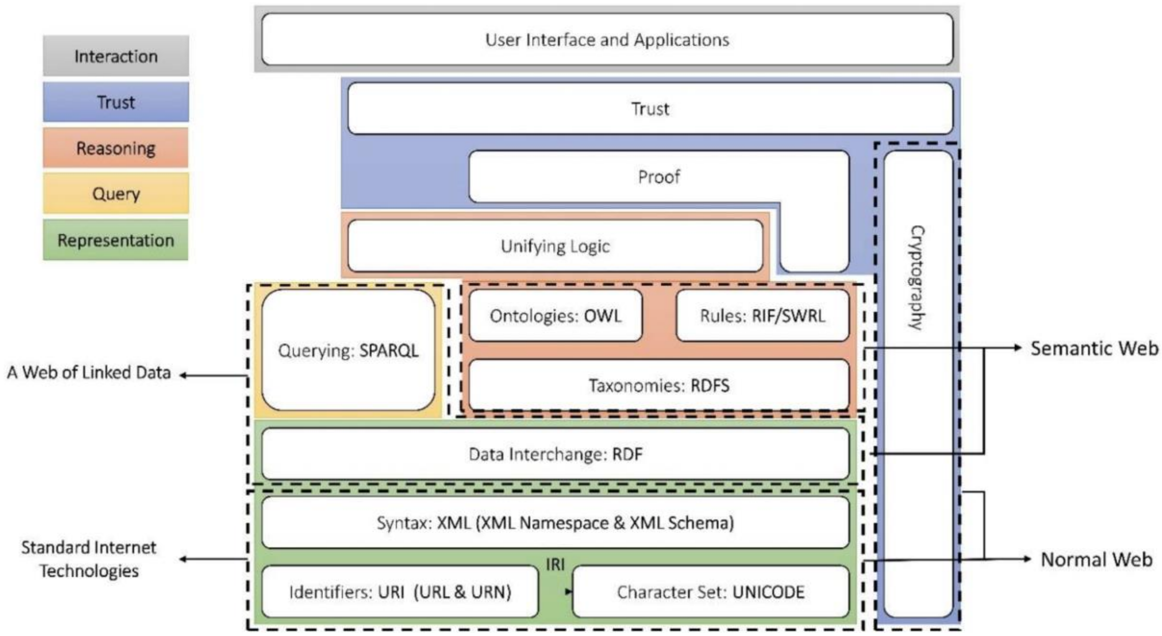

Figure 6: Semantic Web Stack by (Farghaly, 2020)

The web stack comprises multiple layers, including standard internet technologies that deliver data online. The first two layers merge with Cryptography to ensure input reliability via digital signature verification. This foundation forms the basis of a typical web structure. The Resource Description Framework (RDF) layer serves as a graphical representation for semantic web data. Each element in the graph (subject, predicate, object) has a unique URI. RDF graphs can be expressed in various formats like RDF/XML, N-Triples, Turtle, and Notation3. RDF Schema (RDFS) outlines fundamental ontology elements like classes, relationships, and data types derived from RDF triples. Ontologies embody domain knowledge, enabling semantic interoperability by linking external data sources. The Web Ontology Language (OWL) provides richer, more complex ontology expression, enhancing machine interpretability. Simple Protocol and RDF Query Language (SPARQL) are employed for querying and managing RDF data, RDFS, and OWL ontologies. SPARQL offers SQL-like operations to retrieve OWL-based knowledge, forming the foundation for rules and proofs. This framework supports building applications with a high level of trust through rule-based approaches.

2.5 FEDeRATED

In the preceding sections, we explored the role of ontologies in structuring knowledge within a given domain. As we progress, it becomes essential to examine the Semantic Web — a natural extension of these ontologies — which enables a more interconnected and meaningful exchange of information. This technology is crucial in my research as it underpins the creation of a specialised 'textile ontology.' This lower-level domain-ontology will operate within the broader framework set by FEDeRATED's upper-level ontology, facilitating nuanced data exchange and interoperability specifically tailored to the textile industry. The management and use of data have undergone profound changes in recent years as a result of the digitisation of various industries, fundamentally altering business operations and decision-making procedures. This wave of digital transformation has had a particular impact on the logistics and transportation sectors, which are important parts of international trade and commerce. To optimise operations, improve transparency, and enable real-time decision-making, these sectors must have an effective flow of information and data. In response to these needs, the FEDeRATED project emerges as an innovative project supported by the European Union, poised to transform the way data is shared, managed, and used in logistics and smart mobility services within the transportation industry (FEDeRATED, 2022).

The Directorate-General for Mobility and Transport (DG MOVE) of the European Commission is leading the collaborative FEDeRATED project, which includes participants from government, business, and academia. With the proliferation of data and the requirement for seamless data flows within the logistics and transportation sectors, this consortium seeks to address the complex issues that have arisen. The project, which has many facets, aims to improve the logistics chain's overall efficiency, transparency, and decision-making capabilities in addition to its focus on enhancing data sharing mechanisms (FEDeRATED, 2022).

FEDeRATED Architecture The core principles of the FEDeRATED architecture are centred on the concept of data sovereignty, which is designed to align seamlessly with the EU Data Policy and draws on the insights of the EU Digital Transport and Logistics Forum (DTLF). The European Commission established the DTLF as an expert group to advance the digital transformation of Europe's transport and logistics sectors. The DTLF's mission includes providing technical assistance for the implementation of Regulation (EU) 2020/1056 on Electronic Freight Transport Information as well as developing Corridor Freight Information Systems to facilitate interoperable data sharing among all stakeholders in multimodal freight transport and logistics chains. While the FEDeRATED architecture has traditionally focused on transport and logistics events, my project extends its scope by integrating the specific characteristics of textiles in relation to the Circular Economy (CE). This expansion allows for a nuanced approach to data sharing that not only covers multimodal transport and logistics but also addresses the unique properties and lifecycle of textile products, ensuring a more comprehensive data sovereignty within the textile sector. This addition is crucial for promoting sustainability and resource efficiency, key components of the CE, by enabling the tracking and analysis of textiles through their entire value chain. (FEDeRATED, 2022)

The FEDeRATED integration of semantic web technologies and ontologies is a key aspect of the architecture. The architecture makes use of concepts from the semantic web to build a structured framework for data sharing, allowing users to browse data via links while preserving data semantics. Each pertinent dataset has a distinct link, or Uniform Resource Locator (URL), which enables data processing and interpretation independent of the data storage server. The idea of "linked open data" improves the understanding and accessibility of data. To address the complexity of multimodal logistics chains and data sovereignty, the architecture also uses semantic models and ontologies. The architecture creates a standardised "language" for interoperability by defining pertinent concepts and their properties for data sharing within supply and logistic chains. While maintaining semantic consistency, this modularized approach allows for extensibility to accommodate new functionalities and innovations. Three intertwined layers—conceptual, functional, and technical—define the FEDeRATED Reference Architecture (FEDeRATED, 2022).

- **Conceptual Layer:** The architecture takes into account the necessity of constant digital connectivity between data users and holders at the conceptual level. The architecture paves the way for successful business cases, contracts, transactions, compliance procedures, and legislative adherence by facilitating countless interactions and harmonised data interoperability. This emphasizes the need for understanding data at its fundamental meaning, which is a key aspect of data semantics.
- **Functional Layer:** In the functional layer, the architecture emphasizes technical interoperability, vital for efficient logistics operations. It relies on agreed-upon functionalities, reflecting the structured patterns of stakeholder participation, akin to a business's transactional model when dealing with partners. These functionalities are closely tied to a shared semantic model, underlining the significance of data semantics in ensuring seamless communication and coordination among stakeholders in the logistics network. This approach harmonises data exchange and supports multimodal transportation, fostering organisational interoperability.
- **Technical Layer:** In the technical layer, the architecture prioritizes "freedom of choice" for organizations in implementing it. It establishes a protocol stack encompassing connectivity, security, presentation, linked event data, and business protocols, all while adhering to agreed-upon interfaces. This stack facilitates multimodal transportation and enables organizational interoperability. Data semantics play a critical role in ensuring that organisations can effectively choose, implement, and communicate within this technical framework, fostering interoperability.

The FEDeRATED architecture features a central multi-modal upper ontology that encompasses a wide spectrum of logistics, business, and industrial processes. These processes are portrayed in a manner that allows for versatile applicability. Through the creation or alignment of specific "lower-ontologies" that align with this upper-ontology, the system achieves the capability to interlink various industries (DTLF Subgroup 2, 2023). To complement this ontology, several data sharing standards and initiatives have been established, contributing distinct concepts and data specifications. This matching process enables organisations to harmonize their data with the upper ontology and the associated standards.
The alignment of existing ontologies and/or the representation of the concepts and properties of current standards are both necessary for the successful realisation of a multimodal ontology. This strategy effectively makes use of recent developments by providing integrated semantics that are customised for organisations (DTLF Subgroup 2, 2023). The concept is visually depicted in Figure 7

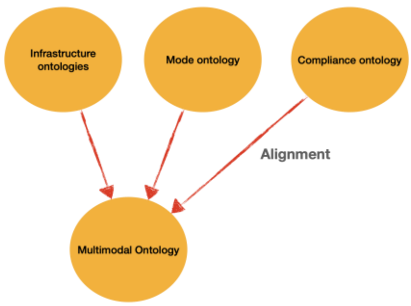

Figure 7: Taken from (DTLF Subgroup 2, 2023, p. 10)

To accommodate the different standards and structures present within different communities the multimodal ontology provides an alignment framework consisting of 'Digital Twin' and 'event'.

2.5.1 Digital Twin

In the realm of data sharing within the textile sector, the concept of a "Digital Twin" can be envisioned as a versatile and scalable representation of real-world objects, such as a piece of clothing like a shirt (Trauer et al., 2020). Think of a Digital Twin as a comprehensive digital counterpart of this shirt, capturing not just its physical attributes but also its entire lifecycle. This digital representation can flexibly accommodate a wide range of information, from design specifications and manufacturing processes to materials used and even maintenance history. It enables businesses to customize and specify the level of detail they need for their shirts, accommodating variations in design, materials, and production methods (Trauer et al., 2020). These Digital Twins are organized into named graphs, allowing for easy reference and retrieval of information related to specific shirts, facilitating standardized data sharing among various stakeholders in the textile industry (Trauer et al., 2020). Whether tracking a shirt's production, supply chain journey, or consumer interactions, Digital Twins provide a dynamic and adaptable framework for data sharing and collaboration in this sector.

2.5.2 Association Events

Association events capture the relationships between various real-world entities or digital concepts, allowing us to understand how these entities interact over time and in specific contexts. These events are critical building blocks for developing structured knowledge because they allow us to model, document, and analyse the relationships between objects, processes, or activities (TNO & TU Delft, 2023).
Consider the construction of a t-shirt as a business activity in the textile industry. The concept of start and end states, along with event associations, can be used effectively in this context. The initial phase corresponds to the start state, where a Bill of Materials (BoM) specifies the expected assembly components, such as fabric, buttons, and thread. The necessary materials and quantities are defined in this BoM using event associations. In contrast, the end state represents the finished product, the identifiable t-shirt, which includes details such as size, colour, and branding elements, all of which are encapsulated by event associations. The use of named graphs based on ontology within a triple store facilitates managing these start and end states, allowing for comprehensive documentation of the entire manufacturing process. An arrival event, for example, could denote the start state, indicating the planned arrival of materials and fabrics, whereas the end state would indicate the physical presence of these materials, indicating the start of the assembly process. This method enables the textile industry to track and manage the t-shirt assembly process effectively.

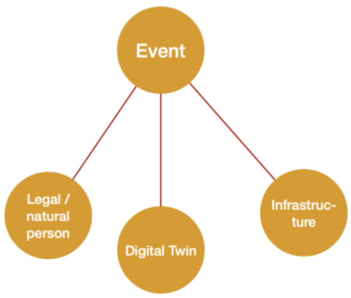

Figure 8: Digital twins in context of events (DTLF Subgroup 2, 2023, p. 18)

2.5.3 Interactions patterns

Interaction patterns are fixed static structures that govern how actors share data in the textile sector to synchronise conditions, prices, and business activities. These patterns define the ideal order of activities in a business transaction, such as payment timing and ownership changes (for example, the transfer of ownership of a specific textile product). They can also reflect how business activities are organised, such as manufacturing to order or manufacturing to stock, and can be generic or organisation specific. Interaction patterns, importantly, include fail-safe mechanisms for dealing with non-compliant behaviour (TNO & TU Delft, 2023).

Interaction patterns, such as the one governing the process of invoice payment, act as blueprints delineating the ideal sequence of interactions for diverse business transactions. Within such a pattern, when an invoice is issued to a customer by a supplier, it prescribes a set of procedural steps. The customer starts by scrutinizing the invoice for accuracy and verifying that the goods or services have been received as per the agreement. Should any inconsistencies be identified, the customer engages in dialogue with the supplier to rectify or clarify the issues. Satisfaction with the invoice details leads the customer to commence the payment, which could be executed via various methods including online transactions, checks, or bank transfers. This interaction pattern is completed once the supplier confirms receipt of the payment.

In the context of communities, choreographies or interaction patterns can be specified to define the synchronization of actions between two stakeholders without explicitly modelling the underlying business processes. Choreographies support stakeholders in designing and implementing their own business processes while maintaining data sharing concepts derived from the upper ontology. Data sharing between any two stakeholders can be represented using choreographies as diverse event types, such as those associating Digital Twins, locations, and organizations for a business activity or representing various interactions and business documents. Additionally, an ontology governs the principles of data sharing, with each natural or legal person having specific business objectives connected to data sharing concepts (DTLF Subgroup 2, 2023).

2.5.4 Alignment

Semantic interoperability and effective communication across diverse domains and industries rely heavily on alignment. At its core, alignment involves the seamless integration of distinct ontologies, each tailored to specific areas of expertise, into a unified framework. This integration serves as the foundation for establishing a shared comprehension of concepts, relationships, and data, transcending industry boundaries. Figure 9 illustrates the process where queries, represented as named graphs, are specified through the upper ontology for data sharing. The upper ontology encompasses fundamental concepts, which are then used to select aligned ontologies related to specific application sectors. In a parallel manner, profiles are constructed by employing named graphs based on the upper ontology and its aligned counterparts. This visualization (Figure 9) sheds light on how the textile ontology fits into the broader context of the FEDeRATED project.

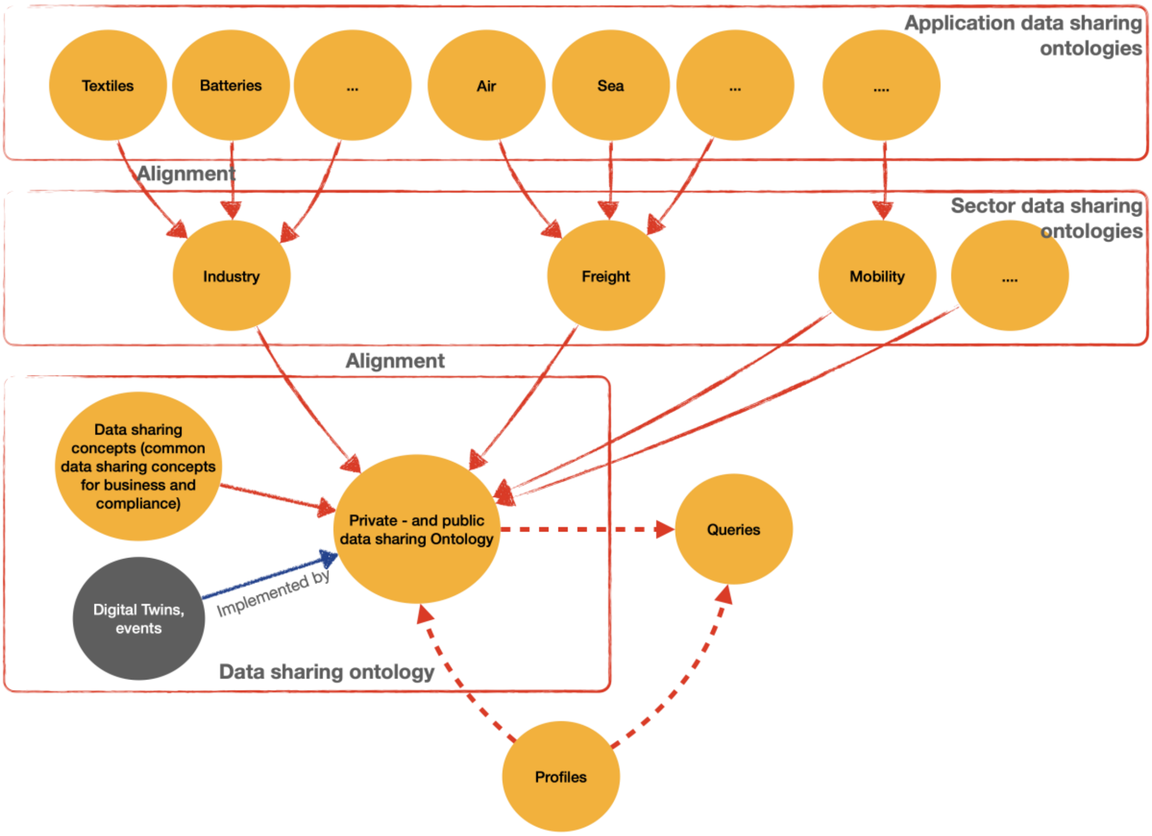

Figure 9: Overview of Data Sharing Ontology and Related Concepts (TNO & TU Delft, 2023, p. 71)

Consider the delivery of shirts as an example of a transport activity to better understand the functionality of the data sharing ontology. This ontology allows for the comprehensive modelling of various stages of the transportation process, including order placement, planning, execution, and delivery. Specific interactions and data states are involved in each phase. For example, during the order placement phase, interactions between order creation and order validation may occur, resulting in a distinct state transition indicating order acceptance. During the transportation planning phase, analogous interactions can occur, influencing the state of the planned route.

2.6 Conclusion

In Chapter 2, we addressed the sub-question, "What does comprehensive background knowledge of ontologies and the FEDeRATED project entail?" Our exploration revealed that a deep understanding of these areas is crucial for developing a textile ontology that supports environmental sustainability and interoperability in the industry. We identified the critical environmental impacts of the textile sector and the necessity for sustainable practices, such as eco-design and recycling. The concept of circularity emerged as a key strategy to address these challenges. The integration of digitalization, particularly through digital twins, was recognized as an innovative approach to enhance resource efficiency and waste management. Understanding various ontologies and their application, especially within the framework of the Semantic Web, was found to be vital. This background knowledge forms the cornerstone for developing a domain-specific ontology within the textile industry, aimed at enhancing data exchange and sustainability practices. The alignment with the FEDeRATED project's upper ontology is essential for ensuring broad applicability and interoperability across different industry segments. Building upon this foundational knowledge, Chapter 3 focuses on the prerequisites for creating an effective ontology for the textile supply chain, which integrates with the FEDeRATED ontology. This next step involves defining the specific requirements and methodologies for ontology development, ensuring it effectively manages semantic data and supports the circular economy within the textile industry.

PART III

Foundations for a Textile Ontology

3 Laying the Foundations for a Textile Ontology

3.1 Introduction

In this chapter, we address the sub-question 3: "*What are the prerequisites for creating an ontology that handles semantic data in the textile supply chain while integrating with the FEDeRATED ontology?*" While adhering to the overarching Design Science Research (DSR) framework, we employ a complementary, specialized methodology by Zhou et al. (2016) exclusively for this chapter. This methodology is particularly focused on the construction of ontologies, including the formulation of competency questions and the analysis of existing taxonomies and ontologies, to ensure a tailored approach to the needs of the textile industry. We begin with Section 3.2, outlining the ontology development methodology, followed by Section 3.3 which defines the domain and scope, identifies stakeholders, and presents competency questions that guide the ontology's structure. The chapter concludes with Section 3.4, which discusses the data requirements of textile sorters, and Section 3.5, which reviews existing standards and taxonomies.

3.2 Methodology for the Development of the Ontology

In structuring the methodology for this chapter on ontology design, the overarching research is steered by the comprehensive framework provided by Johannesson & Perjons (2014) which lays out a structured process for artifact creation. This framework guides the entire research and is applied across all chapters. Within the specific context of this chapter, which focuses on the construction of the ontology for the textile industry, an additional, more focused methodology is incorporated. The steps outlined by Zhou et al. (2016) are particularly useful here, offering a refined approach with a special emphasis on the nuances of ontology development, such as the formulation of competency questions and the analysis of existing taxonomies and ontologies.

The application of Zhou et al. (2016) methodology in this chapter serves a dual purpose: it complements the broader research framework by Johannesson & Perjons (2014) and addresses the detailed requirements of ontology design. By integrating the steps of Zhou et al. (2016) steps, this chapter ensures that the ontology developed is not only methodologically robust but also specifically tailored to the needs of the textile industry. This methodology acknowledges the bespoke nature of ontology construction, thus providing the adaptability required to meet the unique challenges presented in this domain. Consequently, the use of Zhou et al.'s methodology is confined to this chapter, where it serves to enhance the artifact design principles set out by Johannesson & Perjons (2014), ensuring that the ontology is both comprehensive and contextually relevant. The steps adopted from Zhou et al. (2016) have been introduced in chapter 1.5 are detailed as follows:

1. **Identify scope:** Analyse stakeholders to identify and assess their interests and needs, which in turn will guide the formulation of competency questions. These questions will help determine the ontology's purpose and scope, encompassing aspects like intended use, user base, and information inclusion criteria. Through this process, functional, structural, and environmental requirements should be delineated.
2. **Review existing sources:** Utilising existing ontologies, taxonomies, or sources at an early stage is used as a time-saving approach, involving the review and incorporation of relevant sources from the textile domain.
3. **Class definition and hierarchy:** This step includes two parts: identifying main classes and creating the class hierarchy. Three strategies are available: bottom-up, middle-out, and top-down. The bottom-up approach can introduce irrelevant concepts, while the top-down approach may yield less meaningful higher-level abstractions. The middle-out strategy is preferred as it focuses on frequently used classes and addresses issues found in the other two approaches (Zhou et al., 2016).

4. **Construct Ontology:** An ontology editor is selected. The process within an ontology editor involves defining classes, establishing relationships, identifying attributes, and creating instances, ultimately resulting in a preliminary ontology.
5. **Evaluate and refine ontology:** Ontology evaluation, encompassing verification and validation, ensures that the ontology aligns with requirements and intended purposes. Verification, an internal process, focuses on consistency and redundancy checks, while validation involves assessing conformity to competency questions from Step 1.

3.3 Defining the Scope and the Domain

The first step of developing the ontology entails setting the domain and scope of the artefact. This was predominantly done in chapters 1 & 2. The identification of problems in the textile sector revealed its significant environmental impact, particularly when considering the challenges associated with increasing recycling rates. Digitalisation offers a promising solution. Specifically, the introduction of digital twins in the textile industry can play a pivotal role in advancing circularity and sustainability. Yet, despite the transformative potential of digitalisation, there remains a glaring lack of a comprehensive ontology that addresses the intricate nuances and sustainability needs of the textile industry. To address this gap, this research aims to create and implement an ontology that effectively represents and organises the domain knowledge of the textile industry, fostering sustainable practices and facilitating information exchange among stakeholders. This segment will provide a detailed overview of the intended purpose and the extent of the solution. It will outline the stakeholders within the targeted field, delineate the goals and targets, define the scope of the project, and specify the criteria that have been established.

3.3.1 Stakeholder analysis

Within the framework of projects and problem-solving, stakeholders are individuals or groups with the potential to influence or be impacted by the project's decisions and outcomes (Freeman et al., 2010). Their role is paramount, as they have the power to shape the trajectory and outcomes of a project, ensuring that it aligns with their interests and expectations (Aaltonen, 2011). Stakeholders often have specific goals and objectives related to a project. These goals can either align with the project's objectives or diverge based on their unique perspectives and interests. Their feedback and insights are essential in refining and tailoring project requirements, ensuring a comprehensive approach that caters to diverse needs (Yang et al., 2011).

The early identification and engagement of stakeholders are crucial. Recognizing their needs and concerns at the outset can lead to more informed decision-making, fostering an environment conducive to project success (Yang et al., 2011). The evolving nature of technology and insights from previous research, such as understanding the dynamic status of stakeholders, play a pivotal role in this identification process (Perrault, 2017; Salado & Nilchiani, 2013).

Stakeholders bring a mix of constraints and goals to a project. Their varied sustainability viewpoints can be harnessed to guide the project towards better outcomes. However, it's also essential to be aware that conflicts among stakeholders can introduce challenges, especially concerning project timelines and budgets (Herazo & Lizarralde, 2016; Irfan et al., 2019). The following stakeholders have been identified in this project Table 2.

Table 2: Stakeholders present in textile products' life cycle.

#	Stakeholder	Description	Goal(s)	Constraints
1	Student	Master student of TU Delft, responsible for designing and developing domain ontology	- Fulfilling internship requirements - Acquiring masters' degree	- 6 months of project duration
2	Consumers	End users of textile	- Make informed sustainable choices	- Limited access to comprehensive product information
3	Government entities	Regulate and oversee textile industry.	- Develop and enforce sustainable textile policies	- Political challenges, resource allocation
4	Apparel producers	Producers of textile products and apparel	- Increase sustainability, reduce waste, adopt circular practices, improve product transparency.	- Economic constraints - supply chain complexities. - resistance to change. - cost of sustainable practices.
5	Retailers and Brands	Companies that sell textile products to consumers, either under their own brand or as resellers	- Increase sales. - Maintain brand reputation. - Respond to consumer demand for sustainable products	- Balancing costs and sustainability - Managing supply chain complexities - Consumer price sensitivity
6	Textile sorters	Involved in textile waste sorting and recycling.	- Enhance textile waste recycling efficiency, reduce landfill waste, promote circular practices.	- Limited access to comprehensive waste data - economic viability of recycling - technology constraints.

3.3.2 Competency questions

Competency questions are an important part of artefact design and needs determination (Suárez-Figueroa et al., 2009) These questions help in identifying and specifying the required skills, knowledge, and abilities for an artefact to achieve its intended purpose and needs (Suárez-Figueroa et al., 2009), aligning with the problem identification phase of Design Science Research as described by Johannesson & Perjons (2014). They ensure that the object is developed in a way that corresponds with the expected skills and contribute to the iterative refinement of the artefact, resonating with the evaluation phase of the methodology. In the context of artefact design, competency questions can be utilized to determine the specific competencies that the artefact should possess to fulfil its intended function (Drechsler, 2017).

Furthermore, competency questions contribute significantly to the development of requirements for the artefact. For instance, they facilitate the bridging of job and knowledge elements, aiding in the identification of knowledge shortages and mismatches between tasks and knowledge domains, which are crucial for defining the artefact's requirements (Khobreh et al., 2016). Additionally, these questions enable the testing of ontology requirements, ensuring that the artefact fulfils the competency questions (Ren et al., 2014). They can be used to assess whether an artefact meets the required competencies and to identify areas for improvement (Fahrenbach, 2022). By formulating competency questions, ontology developers can gain a deeper understanding of the domain and the relationships between concepts. These questions can help in identifying the key concepts and their informal semantics, which can then be formalized and represented in the ontology (Shiang et al., 2018). The use of informal competency questions in ontology development allows for a more flexible and intuitive approach. It enables ontology developers to capture the nuances and context-specific aspects of the domain, which may not be easily expressed through formal representations alone (Shiang et al., 2018). The competency questions were refined to reflect the sustainable and circular focus of the EU Textiles Strategy, which emphasizes durability, reparability, and recyclability of textile products (European Commission, 2023).

Competency questions were identified in accordance with the research thesis's goal, scope, and stakeholder demands. To make the competency questions well organised they have been divided into modules. This modular approach also defines more clearly the main pillars that the requirements are to be built on, enhancing the ontology's consistency, applicability, and preventing inconsistencies (Guardia et al., 2012; Nazir et al., 2014). Informed by the EU Strategy for Sustainable and Circular Textiles, the competency questions have been further shaped by the European Green Deal's legislative proposals and the objectives of the Circular Economy Action Plan (European Commission, 2022b). The legislative proposal under the European Green Deal aims to establish a comprehensive framework for setting Ecodesign requirements across various product groups in the EU. This will enhance their environmental sustainability, particularly in aspects like circularity and energy performance. The framework will introduce a wide array of product standards, covering durability, reparability, material efficiency, and environmental impact. Additionally, it will promote transparency through information requirements like a Digital Product Passport (European Commission, 2022b). The Ecodesign strategies are set to transform the textile industry, among others, with a vision set for 2030 and are directly influencing the development of competency questions for artefacts in this sector.

Moreover, the competency questions will be inspired by existing standards for data in the textile industry such as the Circularity.ID standard (Circular.fashion, 2020), which promotes circular practices through an Open Data Standard, reflecting over seven years of industry research, design, and end-of-life considerations for fashion products. This should provide us with competency questions that offer a forward look while also adhering to current standards and facilitating circular design and closed-loop recycling processes (Circular.fashion, 2020).

Product Identification and Specifications:

- What's the name and brand of this textile product?
- What type and category does this textile item fall under?
- When was this textile product first put up for sale?
- What colours does this product have?
- What size and country code does this product have?
- What kind of design strategy does this product have?
- What materials make up this textile product and in what amounts?
- What gender does the product have?

Supplier, Manufacturing, and Logistics:

- Where was this textile product made or sourced from?
- What category does the manufacturer classify this product under?
- Are there any specific assembly details for this textile product?
- Do we have packaging or delivery information for this textile item?
- What content does the raw material have and what percentage?

Care, Maintenance, and Use:

- How should you care for this textile product, in terms of washing, drying, and ironing?
- Does this textile product contain recycled materials?
- How sustainable is this textile product in design and purpose?

Pricing, Sales, and Visual Representation:

- How is this textile product described and named on online shopping platforms?
- Are there pictures of this textile product? If yes, how many are there?
- What is the recommended selling price and currency of the product?

3.4 Requirements of the ontology

The design of ontologies in the textile industry, particularly when focusing on circularity, calls for a thorough understanding of various requirements. These requirements can be divided into three categories: functional, structural, and environmental as Johannesson & Perjons (2014) state:

Functional requirements are essential to the artefact's operations and actions. They ensure that the artefact effectively addresses specific problems and fulfils the needs and expectations of stakeholders. These requirements are directly linked to the functionality of the artefact, defining what it must do to solve the identified issue.

Structural requirements focus on the internal architecture and design of the artefact. Their purpose is to ensure coherence, sustainability, and ease of maintenance. These requirements impact the artefact's overall structure, influencing factors like modularity, scalability, and maintainability.

Environmental requirements are concerned with the external conditions and contexts in which the artefact will operate. They emphasize platform compatibility, adaptability, and smooth integration with existing systems or environments. These requirements ensure that the artefact functions effectively in its intended setting and can adapt to changes in the environment.

Crafting the requirements for an ontology is a complex process. Zhou et al. (2016) highlight the challenges inherent in this task, noting that building a comprehensive domain-specific ontology can be both time-intensive and susceptible to mistakes. To enhance efficiency, precision, and relevance while minimising the potential for errors, this project will incorporate a taxonomy developed by a domain expert, this is further elaborated in chapter 3.5.2. This approach draws upon established knowledge frameworks and models, ensuring that the ontology is grounded in expert understanding and insight. Due to confidentiality commitments, the identity of the contributing expert is protected under a Non-Disclosure Agreement (NDA). Nonetheless, the expertise they bring to the development of this taxonomy is recognized and valued by the supervising body, TNO, and the graduation committee overseeing this thesis.

Table 3: Requirements for the ontology.

CATEGORY	*REQUIREMENT ID*	*REQUIREMENT DESCRIPTION*	*SOURCE*
FUNCTIONAL	1.1	The ontology should encompass domain knowledge necessary for circular practices, such as material categorization and lifecycle data, to support sorting processes.	Internal Project Meeting
	1.2	The ontology should facilitate circular activities, ensuring accurate representation of semantic data for processes like recycling and upcycling.	Internal Project Meeting
	1.3	The ontology should be adaptable to accommodate new trends and technologies.	Hepp, 2007
	1.4	Should provide cross-industry operability to facilitate efficient data exchange and collaboration across different sectors.	Internal Project Meeting
	1.5	Should provide textile sorters with data to make better informed decisions	Internal Project Meeting
STRUCTURAL	2.1	The ontology's structure should facilitate an intuitive and detailed representation of semantic data, adhering to established modelling principles.	Chaware & Rao, 2010
	2.2	Should have a clearly defined, explained, and documented set of terms and names used in ontologies.	Chaware & Rao, 2010
	2.3	Should allow for easy extension and integration with other ontologies or data sources.	Quinn et al., 2018
	2.4	Definitions for all concepts and relationships within the ontology must be clear, consistent, and validated by industry experts.	Jackson et al., 2019

	2.5	Should be structured to logically inherit properties from parent concepts.	Jackson et al., 2019
	2.6	Should support reasoning and querying capabilities to extract valuable insights from the data.	Jackson et al., 2019
	2.7	Must ensure that relationships between concepts are well-defined and easily traceable	Jackson et al., 2019
	2.8	Establish a top-class in the ontology that fully aligns with the FEDeRATED ontology, ensuring cross-industry operability.	Internal Project Meeting
	2.9	The ontology must conform to established standards and expert-derived taxonomies to ensure a structured and accurate representation within the textile domain.	Internal Project Meeting
	2.10	The ontology should be clear and to the point, including only the information that's necessary and avoiding any extra, unneeded details.	Internal Project Meeting
ENVIRONMENTAL	3.1	The ontology should support technical interoperability within the FEDeRATED standards framework and comply with general standards such as OWL and RDF for seamless integration with various industrial domain ontologies.	Boeker et al., 2013
	3.2	The ontology's content must be regularly updated and curated to ensure cross-domain applicability and facilitate knowledge reuse within the FEDeRATED project's scope.	Hartung et al., 2013
	3.3	Provide comprehensive documentation and guidelines for the ontology's use, maintenance, and extension, with a defined update and versioning protocol.	Boeker et al., 2013
	3.4	Ensure compatibility with prevalent ontology languages and modelling tools to facilitate use in standard ontology environments.	MaduraiMeenachi & Sai Baba, 2012

3.5 Review of existing standards and textile sorters

As stated in the method section of this chapter, reviewing current standards, common practices, and existing sources in the textile industry related to data and circularity is crucial. This analysis not only helps to set the scope and accelerate development by building on previous work but also paves the way for refining or augmenting existing ontologies, taxonomies, and other sources to encapsulate the necessary knowledge for our task. In the following sections, we will delve into the role of textile sorters in the recycling process, their specific data needs, and the importance of modelling an ontology tailored to these needs. We will also discuss the crucial data requirements for textile sorters, the application of a structured taxonomy for categorizing textile data, and the potential integration of other standards and metrics that could enhance the efficiency and accuracy of textile sorting processes. As Annamalai et al. (2011) highlighted, a standardized ontology facilitates clear communication among researchers and practitioners, which is vital for fostering the inception and implementation of effective methods and tools tailored to the textile industry's unique challenges.

3.5.1 Textile sorters

Textile sorters play a pivotal role in the textile recycling process, ensuring that materials are appropriately categorized based on their type, quality, and potential for reuse or recycling. The process of sorting textiles is intricate and demands a keen understanding of the material properties, potential applications, and the current market demand. As emphasized by Nørup et al. (2019), textile sorting centres play a significant role in ensuring high reuse rates, highlighting their importance in accurately modelling textile waste management.

In the broader context of textile circularity, sorters act as gatekeepers. They determine which textiles can be reintroduced into the production cycle, which can be repurposed for alternative uses, and which are destined for disposal. Their decisions directly impact the amount of waste generated, the energy consumed in recycling processes, and the overall carbon footprint of the textile industry. In a related study, Nørup et al., (2018) established a method for sorting and quality assessment of textiles in household waste, further underscoring the importance of this process through dialogue with professional textile sorting centres.

Given the notable role of textile sorters in the realm of circularity, it becomes clear that modelling an ontology which includes their data needs can significantly impact circular processes, making it very beneficial. The intricate process of sorting textiles, as described by Nørup et al., (2018), involves a deep understanding of material properties, potential applications, and market demand. An ontology that provides life cycle data or even digital twins of the textile production process can significantly enhance the efficiency and accuracy of textile sorters. Such a digital representation can offer insights into the environmental impact, potential reuse applications, and market value of textiles, thereby aiding sorters in making informed decisions. Moreover, Sandvik & Stubbs (2019) emphasised the potential of digital technologies in enhancing sorting and recycling technology within the fashion supply chain. An ontology that offers life cycle data or digital twins of the textile production process can be a game-changer for sorters, aiding them in making informed decisions. Figure 10 is a schematic view that elucidates the textile selecting process for circularity, as devised by Nørup et al. (2018):

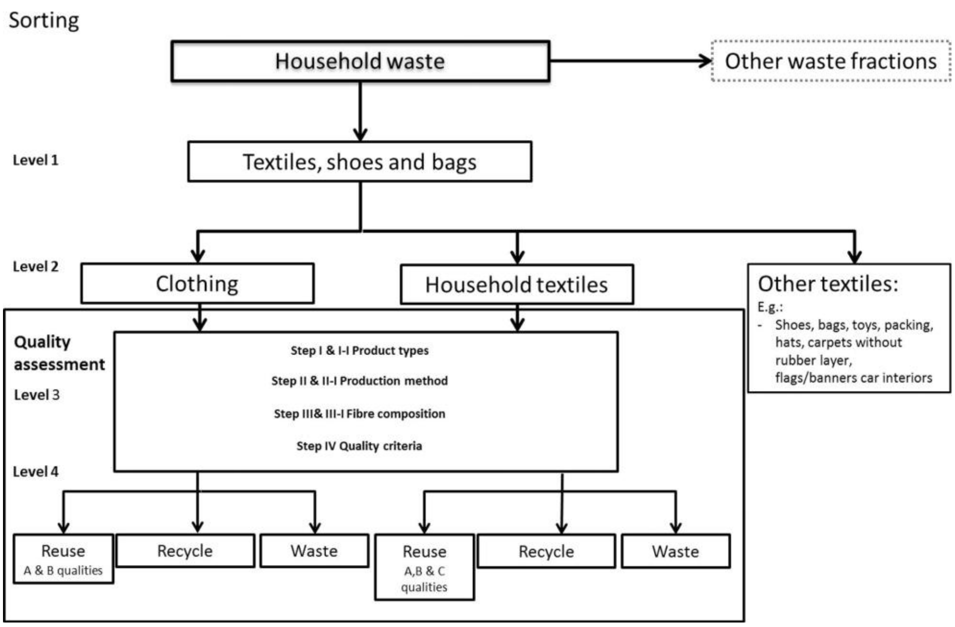

Figure 10: schematic view of the textile selecting process for circularity, by (Nørup et al., 2018)

The schematic presents a hierarchical structure that begins with the broader category of 'Household waste'. From this, textiles, shoes, and bags are segregated. As we delve deeper into the schematic, textiles are further categorized into 'Clothing', 'Household textiles', and 'Other textiles'. The process entails a stepwise quality assessment which evaluates textiles based on product types, production methods, fibre combinations, and then finally, specific quality criteria. These criteria decide the fate of the textile, categorizing them into potential 'Reuse', 'Recycle', or 'Waste' buckets. Notably, 'Reuse' has been further differentiated into categories A, B, and C, with each signifying varying levels of quality and potential applications.

In the textile world, the quality of clothing and household items determines their next journey: reuse, recycling, or waste.

Reuse is categorised into three:

- **Category A:** Perfect condition items ready for immediate reuse.
- **Category B:** Functional items with minor defects, like stains or broken zippers, often destined for the international low-quality market.
- **Category C**: Rags or wipers, which, despite stains, still serve a purpose.

Products unsuitable for reuse, classified as Category A and B, may be repurposed through recycling if their fibre content, manufacturing technique, and dimensions are appropriate. Items that are neither reusable nor recyclable are designated as waste, falling under Category C. Yet even products tainted by incorrect disposal may preserve their capacity for reuse or recycling.
The textile's fate is determined through a two-step process: sorting and quality assessment. Sorting involves separating textiles from waste and categorizing them. Quality assessment, a more detailed process, identifies the product type, manufacturing method, fibre composition, and overall condition. This systematic approach ensures textiles get a chance at a new life, whether through reuse, recycling, or, if necessary, being treated as waste (Nørup et al., 2018, 2019).

3.5.2 Data requirements of Textile sorters

Highlighting the significance of ensuring that the ontology's data aligns with the data requirements for textile sorters is paramount. Sorting companies play an important role in enabling a reverse supply chain for apparel and textiles. The majority of collected post-consumer waste is processed by sorting firms, which determine if a garment can be resold or recycled, and then who will receive the tailored feedstock. Today, sorting is mostly manual, relying on a sorter's eye perception as well as their senses of touch and smell. The exact feedstock needs of cutting-edge fibre-to-fibre recycling systems are strongly reliant on the quality of the sorted materials (Circular.fashion, 2019).
The compatibility and relevance of the ontology's data, especially in terms of product data and life cycle data, can greatly influence the efficiency and accuracy of sorting processes. Detailed product data provides insights into the material composition, origin, and manufacturing processes of textiles, while life cycle data sheds light on the environmental impact, usage, and end-of-life considerations of textile products. Together, these datasets can offer a comprehensive view that can greatly enhance the sorting process.

During our investigation, we discovered that the information obtained from our internal project meetings aligned closely with the open data standard from circularity.ID (Circular.fashion, 2019). Consequently, we decided to utilise the circularity.ID standard as it is not only well-documented and accessible but also supported by our expert's insights. This standard focuses on facilitating traceability and transparency, supporting intelligent sorting solutions, and providing verified data, all of which are essential for the efficient and accurate operations of textile sorters. The applicability and relevance of our ontology are bolstered by the congruence between our expert's insights and the open standard in question. The standard came to our attention in a meeting with the domain expert, detailed in Appendix A. While delineating the scope and elucidating the requirements with the expert, the discussion facilitated a thorough examination of potential inclusions and their implications.

To ensure that our understanding of these data requirements is both thorough and accurate, we have based our investigations on two primary sources: literature research and Internal project meetings with domain experts on semantics and textiles. Delving into existing literature will allow us to tap into the wealth of knowledge and findings from previous studies and research in the field. On the other hand, the project meetings provided us with first-hand insights and practical examples from professionals who are actively involved in the circular textile industry. This dual approach will not only enhance the depth and breadth of our understanding but also ensure that our ontology is tailored to meet the real-world needs of textile sorters. Based on these methods Table 4 was produced.

Table 4: Data requirements for textile sorters based of literature and expert information.

Data Field	Description	Data Type	Subject
product_name	Display name for the product on e-commerce platforms.	String	Product
product_description	Description of the product intended for consumers.	String	Product
year_of_sale	The year the product is intended for sale.	Integer	Product
brand_name	Name of the fashion brand or manufacturer.	String	Product
product_category	General category of the product (e.g., clothing, footwear).	String	Product
product_type	Specific type of product (e.g., pants, shirt, dress).	String	Product
product_images	Collection of images representing the product.	String	Product
assigned_colour_category	Color categories associated with the product.	Array	Product
size	Dimensions or size of the product.	String	Product
size_country_code	Size metric standard used (e.g., EU, US).	Array	Product
service_type	Types of circular design associated with the product.	Array	Product
country_of_origin	Country where the product was manufactured or produced.	String	Product
country	Country associated with various steps of product creation.	String	Product
assembly	Information related to the product's assembly.	String	Product
name	Name associated with a particular component or material.	String	Assembly
materials	Information about the materials used in the product.	String	Assembly
name	Name of the specific material used.	String	Material
components	Details about the components of the product.	String	Material
content	Type of fibres used in the material (e.g., Cotton, Polyester).	String	Material
percentage	Proportion of each component present in the material.	Integer	Material
is_recycled	Indicator if the material contains recycled materials.	Boolean	Material
country	Origin country of the raw material.	String	Material
assigned_colour_category	Color categories associated with the material.	Array	Material
category	Type of material (e.g., fabric, yarn, trim).	String	Material
step_type	Type of step in the material's creation or supply chain.	String	Material
country	Country associated with a particular step in the material's lifecycle.	String	Material

3.5.3 Internal Project Meetings

Throughout the development of the prototype ontology for the textile product lifecycle, we facilitated a series of internal project meetings aimed at harnessing expert knowledge and fostering a collaborative environment for idea exchange. These meetings were important in determining the scope of my research and refining the structure of the ontology.

Each session was structured as an hour-long brainstorming dialogue, engaging with the domain expert on the textile industry's complexities and the semantic detail necessary for the ontology's construction. Central to these discussions was a domain expert in textiles. Our consistent collaboration ensured that the discussions were grounded in practical industry knowledge.
The composition of these meetings varied, with additional expertise brought in as needed. On several occasions, we were joined by a colleague from the DATAPIPE project at TU Delft, providing valuable perspectives on data management and the critical role of traceability in the circular economy. Their contributions were particularly influential in structuring our ontology to support traceability and compliance within the textile sector. Additionally, a semantical expert from TNO was often present, contributing significant expertise in data semantics, which was crucial for the ontology's design.

The unstructured nature of these meetings was deliberate, designed to create a space where ideas could be exchanged freely, and innovative solutions could emerge organically. We engaged in wide-ranging

discussions about the ontology's scope, principles of circularity, data practices in the textile sector, and semantic frameworks.
Important aspects of these discussions were recorded, with the most influential insights included in Appendix A. Furthermore, some of the questions that were discussed during the project meetings are included in Appendix B to provide a better insight into the nature of the meetings.

3.5.4 Taxonomy

The taxonomy, obtained and utilized through project meetings with a domain expert, underpins the structured categorisation necessary for an accurate representation of the textile domain. While specific details about the owner's identity remain confidential due to a non-disclosure agreement, it's essential to emphasize the validation of their expertise and contributions by various reputable entities, including the thesis supervisor, the graduation committee, and TNO.

The owner of this taxonomy is a seasoned textile expert with a wealth of experience in the textile industry. Their professional focus has been primarily centred on advancing sustainability and circularity initiatives within the textile sector. In recent times, they have dedicated significant efforts to harnessing information and communication technology (ICT) and data-driven solutions to bolster circularity endeavours. This has translated into active involvement in numerous digital product passport and supply chain tracking projects aimed at fostering transparency and sustainability throughout the textile industry.

Incorporating this taxonomy in the accelerates the ontology development by providing an already structured and validated classification system. This incorporation is poised to ensure that the ontology aligns well with established knowledge structures and standards within the textile industry. The taxonomy serves as a solid foundation upon which the ontology's classes and hierarchies can be defined, thus facilitating the accurate representation of domain-specific knowledge. The emphasis on addressing the data requirements of textile sorters contributes to enhancing circularity within the textile industry. The taxonomy provides a structured way to categorize textile data, which is crucial for textile sorters who play a pivotal role in the textile recycling process. From the taxonomy mainly structural elements were taken such as the classification into the different segments. Furthermore, as was addressed by the expert, we have chosen to incorporate other relevant data fields, namely, Colour brightness, Gender, Production material, the aforementioned segments and their names. By aligning the ontology with the taxonomy, the ontology is better positioned to cater to the functional, structural, and environmental requirements highlighted in the text, thereby promoting sustainability and improved data communication among stakeholders in the textile industry.

3.5.5 Other standards

In the process of developing Table 4, which serves as a guideline for the ontology's data inclusion, insights from internal project meetings have been instrumental. These discussions highlighted several data fields that, while not currently in widespread use by textile sorters, hold potential for future utility or integration. In the prevailing system, economic factors predominantly guide the sorting process, with metrics like production year, size, and recommended selling price being pivotal. However, the internal project meetings suggested a range of emerging metrics that may influence future sorting and recycling decisions, such as material quality certificates, yarn characteristics, and standardized product classification codes like FEDAS. These indicators, among others not listed here, were identified as having significant promise. The feasibility of incorporating these metrics will be subject to further examination in subsequent phases of the research or could be proposed as areas for future investigation.

3.6 Conclusion

In Chapter 3, we effectively addressed the sub-question, "What are the prerequisites for creating an ontology that handles semantic data in the textile supply chain while integrating with the FEDeRATED ontology?" The exploration and application of a specialized methodology led to the establishment of a foundational framework for the ontology. Through stakeholder analysis, competency questions, and a detailed review of existing standards and sorters' requirements, we identified the essential components necessary for constructing a relevant and effective textile ontology. This process not only highlighted the diverse needs within the textile industry but also underscored the importance of creating an ontology that is adaptable, scalable, and capable of facilitating semantic interoperability, especially in the context of the FEDeRATED project. With the groundwork laid in Chapter 3, Chapter 4 delves into the actual construction of the ontology. It focuses on structuring the various classes, properties, and relationships in a way that accurately represents the semantical data unique to the textile industry, while ensuring compatibility with the overarching framework of the FEDeRATED ontology. This next step is crucial in translating the identified prerequisites into a functional and coherent ontology model.

PART IV
Construction of the Ontology

4 Construction of the Ontology

4.1 Introduction

In addressing the sub-question 4: *"How can the various classes, properties, and relationships be structured in such a way that they accurately represent semantical data in the textile industry while also being compatible with the FEDeRATED ontology?"*. The deliverable of this chapter is a preliminary ontology, with a clear presentation of its classes, properties, instances, and the rationale behind their structuring. The ensuing sections provide a roadmap of the ontology creation process: Section 4.2 introduces the tools employed, Section 4.3 discusses the language selection, Section 4.4 delves into the ontology building, and Sections 4.4.1, 4.4.2, and 4.4.3 detail the classes, properties, and instances of the ontology, respectively. Each section contributes to the overarching goal of establishing an ontology that encapsulates the semantic richness of the textile domain and integrates smoothly with the FEDeRATED project's ontology.

4.2 Tools

For the development of the ontology, it was chosen to make use of a tool called Protégé. This was done instead of other popular methods of developing such as manual coding. Protégé, developed by Stanford University's Centre for Biomedical Informatics Research, is a free, open-source platform renowned for its suite of tools designed to construct domain models and knowledge-based applications with ontologies. It has been a cornerstone in the ontology engineering field, supporting the creation, editing, and visualization of ontologies in various formats. Notably, Protégé offers effective ontology visualization (Subramaniyaswamy & Chenthur Pandian, 2012) and collaborative features akin to platforms like Google Docs, allowing users to share and edit ontologies online (Musen, 2015). Its modular design has fostered a rich ecosystem of plugins, enhancing its capabilities from visualization tools to intricate reasoning engines (Gennari et al., 2003). By choosing the use of the tool over other ways of constructing the ontology such as coding by hand comes with several benefits to this project.

Automation & Collaboration: Protégé offers automated ontology creation, streamlining the process for intricate domains like textiles. Its collaborative features also enhance communication among dispersed domain experts (Gacitua et al., 2009).

Knowledge Sharing: Protégé promotes easy sharing of knowledge, fostering community contributions and ensuring the ontology remains updated for the evolving textile sector (Danial-Saad et al., 2013).

Robustness: The tool ensures ontologies are free from logical errors and adhere to quality standards, vital for the nuanced textile domain (Jackson et al., 2019).

Modularity: Protégé's design encourages modular ontologies, facilitating reuse of knowledge, especially beneficial given the diverse sub-domains in textiles (Sanya & Shehab, 2015).

4.3 Language

The Web Ontology Language (OWL), developed by the World Wide Web Consortium (W3C), is a powerful knowledge representation language tailored for authoring ontologies. It is designed to represent rich and complex knowledge about things, groups of things, and relations between things. OWL is pivotal in the Semantic Web vision, providing a mechanism for defining structured, web-based ontologies that can be leveraged by algorithms and applications for more intelligent data querying and interoperability. In this research OWL is selected as the formal language to present the ontology for the following reasons:

Expressiveness: OWL's expressiveness allows for the representation of complex relationships and constraints, making it suitable for intricate domains such as textiles (Harris & Pemberton, 1995).

Reasoning Capabilities: OWL is designed to work seamlessly with ontology reasoners, enabling automated knowledge inference, consistency checking, and other advanced features that ensure the ontology's logical soundness (Vidal et al., 2012).

Interoperability: Being a W3C standard, OWL ensures that ontologies are interoperable across different systems and applications, a crucial feature for the global textile industry with its diverse stakeholders (Smith et al., 2004).

Evolution and Scalability: OWL ontologies are inherently designed to evolve over time, accommodating new knowledge and changes, which is essential given the dynamic nature of the textile sector (Allemang & Hendler, 2011).

Integration with Protégé: OWL's compatibility with tools like Protégé ensures a seamless ontology development experience, combining the strengths of both the language and the tool for a comprehensive ontology engineering process (Musen, 2015).

4.4 Building the ontology

This subchapter focusses on presenting the classes, properties, instances, and other relevant concepts of the ontology. We will also explain the rationale behind the structuring of classes and properties. We will start off with presenting the classes and their hierarchy or subclasses. Outlining the classes in such a format aid in segmenting the core concepts and classifying the knowledge. As said in chapter 4 by Zhou et al. (2016) there are multiple approaches for tackling the construction of the ontology, such as bottom-up or top-down approach. This research has chosen for the middle-out strategy which is preferred as it focuses on frequently used classes and addresses issues found in the other two approaches. This strategy allows us to make the most use of the taxonomy and the structuring of its concepts and the data requirements for circularity in the textile sector using the top-down approach. Simultaneously, it also allows us the benefit of the bottom-up approach, structuring the ontology as an event- artifact ontology allowing us to incorporate the production steps in the textile industry as events and thus also allowing the ontology to better align with the event-based architecture of the FEDeRATED ontology.

4.4.1 Classes

In shaping the ontology, of which the classes and the inferred hierarchy are detailed in Table 5, we've meticulously aligned them with the data requirements specified in Table 4. This alignment ensures that the ontology aptly reflects the critical data fields identified from the data standard and the internal project meetings —fields that underpin circular practices in the textile industry. The rationale behind combining terms like *Price_And_Currency* and *Material_And_Percentage* is to synthesize related data requirements into cohesive entities, thus simplifying the ontology's structure and enhancing its practical utility. For example, by merging price and currency into a single term, we encapsulate all financial aspects related to a textile product, streamlining the data for sorters and recyclers. These integrated classes have drawn inspiration from concepts from Catena-X, a battery pass domain ontology. Catena-X provides a precedent for how different data elements can be effectively integrated, and we've drawn upon its methodology to inform our own ontology's development, particularly in areas such as material classification which is crucial for recycling processes.
The hierarchical levels presented in Table 5 originate from a combination of the expert-derived taxonomy and the data requirements of the textile sorting process.
The 'top class' – *Segment_Finished_Product* – in our ontology is established as a central concept, akin to a trunk from which branches of subclasses can extend. This design facilitates the straightforward inheritance of properties to subclasses, creating an organized and efficient hierarchical structure. Moreover, positioning the top class at the apex of our ontology's structure enables seamless integration with the upper-level ontology of the FEDeRATED project. It provides a clear pathway for establishing parent-child relationships between the broader FEDeRATED ontology and our more specialized textile ontology. By doing so, we ensure that our ontology can interoperate within the larger ecosystem of the FEDeRATED

project, maintaining consistency and coherence across different applications and domains involved in the textile lifecycle.

Table 5: Classes and Hierarchy of the ontology

Topclass	*1st Level*	*2nd Level*	*3rd Level*	*4th Level*
owl:Thing	Category			
	Price_And_Currency			
	Material_And_Percentage			
	Content_And_Percentage			
	Production_Step_Raw_Material	Pre-Tanning		
		Production		
		Spinning		
		Tanning		
		Printing		
		Dyeing		
		Finishing		
	Production_Step_Finished_Product	Cut_Make_Trim		
		Dyeing		
		Embellishing		
		Finishing		
		Full_Garment_Supply		
		Laundry		
		Packaging_&_Shipping		
		Printing		
	Assigned_Colour			
	Colour_Brightness			
	Country_Of_Origin			
	Currency			
	Gender			
	Segment_Finished_Product	Segment_Finished_Product_Accessories	Accessories	
			Backpacks	
		Segment_Finished_Product_Apparel	Bottoms	Denim
				Pants
				Skirt
			Full_Outfits	Dress
				Overall
			Tops	Blazer
				Blouse
				Jacket
				Knitwear
				Polo
				Shirt
				Sweater
				T-Shirt
				Top
		Segment_Others		
		Segment_Production_Material	Button	
		Segment_Raw_Material		
	Service_Type			
	Size	Size_And_Size_Country_Code	Size_country_Code	

Figure 11: Classes of the ontology with asserted hierarchy

4.4.2 Properties

Object properties are fundamental constructs in the realm of ontology and conceptual modelling. They serve as the backbone for defining and elucidating the relationships between different entities within a domain of interest. By establishing clear connections, object properties enable a more comprehensive and detailed understanding of the domain, allowing for the creation of robust and meaningful models (Bechhofer et al., 2004; Horridge, 2011). These properties are instrumental in linking classes to other classes or individuals, thereby facilitating the representation of complex relationships in a structured manner (Allemang & Hendler, 2011).

Object properties in ontologies are like the threads that connect different concepts or items together, defining relationships and organizing knowledge in a systematic and meaningful way. They are fundamental in various fields, from mapping information and solving problems to understanding complex ideas like the laws of nature (Hadar & Soffer, 2006; Wheeler et al., 2018).
For instance, in the textile industry, the object property "*hasMaterialAndPercentage*" links a finished product, such as a T-shirt, to the specific materials used in its creation and their respective proportions. This property acts as a bridge, providing valuable information about the composition of the product, which can affect everything from comfort and durability to care instructions and environmental impact (Sentilles et al., 2016).

Consistent with the recommendations of Allemang & Hendler (2011) and Horridge (2011) object properties are typically prefixed with terms like "has" or "is" to enhance understandability and conform with naming conventions followed by standards such as W3C. These prefixes aid in clarity and ensure that the properties are intuitively graspable (Sadeghi et al., 2015).

Table 6: Object properties of the ontology

Property Name	*Domain*	*Range*	*Explanation*
has_Circualr_R_Service_Type	Segment_Finished_Product	Service_Type	Specifies the type of service associated with the finished product
hasCategory	Segment_Raw_Material	Category	Defines the category of the raw material (yarn, leather, etc.)
hasColor	Segment_Finished_Product	Assigned_Colour	Indicates the assigned color of the finished product
hasColorBrightness	Assigned_Colour	Colour_Brightness	Specifies the brightness level of the assigned color
hasContent	Segment_Raw_Material	Content_And_Percentage	Details the content and its percentage in the raw material
hasCountryOfOrigin	Production_Step_Finished_Product	Country_Of_Origin	Identifies the country of origin in the production step of the finished product
hasCurrency	Price_And_Currency	Currency	Specifies the currency used in pricing
hasGender	Segment_Finished_Product	Gender	Indicates the gender for which the finished product is intended
hasMaterialAndPercentage	Segment_Finished_Product	Material_And_Percentage	Details the material used in the finished product and its percentage
hasPriceAndCurrency	Segment_Finished_Product	Price_And_Currency	Specifies the price and currency of the finished product
hasProduction_Material	Segment_Finished_Product	Segment_Production_Material	Details the garments used in the production of the finished product

hasSegment_Raw_Material	Segment_Finished_Product	Segment_Raw_Material	Associates the finished product with a particular segment of raw material
hasSize	Size_And_Size_Country_Code	Size	Indicates the size of the product
hasSizeAndSize_Country_Code	Segment_Finished_Product	Size_And_Size_Country_Code	Details the size and the country code related to the size standards
hasSize_Country_Code	Size_And_Size_Country_Code	Size_country_Code	Specifies the country code related to the size standards
involvesFinishedProduct	Production_Step_Finished_Product	Segment_Finished_Product	Indicates the involvement of the finished product in a production step
involvesRawMaterial	Production_Step_Raw_Material	Segment_Raw_Material	Indicates the involvement of raw material in a production step

Data properties are integral to ontologies and conceptual modelling, serving to define and characterize the attributes of individual entities. Unlike object properties, which establish relationships between entities, data properties assign specific values or characteristics to entities, enriching the ontology with detailed and precise information.

Data properties often hold literal values, such as numbers, dates, or textual descriptions. For example, in a textile ontology, the data property "*ArticleName*" within the domain "*Segment_Finished_Product*" has a range of "string", providing the name of the finished product. Similarly, "*Content_Percentage*" in the domain "*Content_And_Percentage*" has a range of "integer", indicating the percentage of a specific content within a raw material. These properties provide essential details about the entities they describe, enabling a nuanced representation of information (Baader et al., 2007)

Data properties are crucial for detailed information representation and are often used for attributes that require quantification or precise description. For instance, "Percentage" in the domain "*Material_And_Percentage*" is an integer value representing the percentage of a specific material in the finished product. "*Product_Description*" in the domain "*Segment_Finished_Product*" is a textual description of the product, providing a detailed narrative of its features (Hadar & Soffer, 2006).

Furthermore, data properties play a significant role in facilitating complex queries and data retrieval within ontologies. By providing specific and detailed information about entities, data properties enable more refined and targeted searches, thereby improving the efficiency and effectiveness of information retrieval (Wheeler et al., 2018). The data properties of the preliminary ontology are depicted in Table 7.

Table 7: Data properties of the ontology

Property Name	*Domain*	*Range*	*Explanation*
ArticleName	Segment_Finished_Product	string	The name of the finished product
BrandName	Segment_Finished_Product	string	The brand associated with the finished product
Content_Precentage	Content_And_Percentage	integer	The percentage of a specific content within a raw material
CountryofOrigin	Country_Of_Origin	string	The country where the product or its key components were produced
Gender	Gender	string	The gender for which the finished product is intended
MaterialName	Material_And_Percentage	string	The name of the material used in the finished product
Percentage	Material_And_Percentage	integer	The percentage of a specific material in the finished product
Product_Description	Segment_Finished_Product	string	A textual description of the finished product
Product_Image	Segment_Finished_Product	string	A visual representation (image) of the finished product
Product_Name	Segment_Finished_Product	string	The official name of the finished product
RecommendedPrice	Price_And_Currency	decimal	The suggested retail price for the finished product
isRecycled	Segment_Raw_Material	boolean	Indicates whether the raw material used is recycled
yearOfSale	Segment_Finished_Product	dateTime	The year when the finished product is intended to be sold

4.4.3 Instances

In the context of the ontology construction as detailed in this chapter, the process of creating individuals—or specific instances of classes—serves the purpose of populating the ontology with concrete examples that illustrate the use and behaviour of the classes in real-world scenarios. Although the complete list of individuals is extensive and beyond the scope of presentation in tabular form, their development is a critical step in validating the ontology's design.

Individuals in the ontology represent tangible elements within the textile industry, such as specific garments, materials, or production steps. They are instantiated with attributes and relationships defined by the data and object properties, respectively, which reflect the knowledge embedded within the ontology. This instantiation is guided by the data requirements outlined in Table 4, ensuring that each individual aligns with the practical needs of textile sorters and the broader objectives of circularity in the industry.

Creating these individuals helps demonstrate the ontology's practical applicability and tests its robustness by mirroring real-world data interactions. This step also plays a vital role in the ontology's evaluation phase, as it allows for the assessment of the ontology's capacity to handle diverse and complex data reflective of the textile sector. The list of individuals that were created for this ontology can be found in Appendix E: Individuals due to its size.

4.5 Conclusion

In Chapter 4, we successfully navigated the complexities of constructing a preliminary ontology, addressing the sub-question 4: "How can the various classes, properties, and relationships be structured in such a way that they accurately represent semantical data in the textile industry while also being compatible with the FEDeRATED ontology?". The ontology was meticulously crafted using tools like Protégé and the OWL language, ensuring a rich, modular structure capable of representing the nuanced relationships within the textile industry. The classes, properties, and instances were aligned with the unique requirements of the textile domain, ensuring relevance and practical utility. The adoption of a middle-out strategy facilitated the incorporation of essential data for textile sorters and recyclers, demonstrating a keen understanding of the industry's needs. This chapter's deliverable, a preliminary ontology, stands as a testament to the careful consideration of industry-specific semantics and the strategic goal of integrating with the FEDeRATED project's ontology, thereby laying a robust foundation for practical implementation and interoperability within the textile domain. Transitioning to Chapter 5, the focus shifts to the evaluation phase, where the developed ontology undergoes rigorous scrutiny. We aim to answer the pertinent questions: "To what degree does the developed ontology satisfy the requirements specified in sub-question 2, as demonstrated through an evaluation and demonstration?" and "What structure will the final ontology have to represent semantic data in the textile industry while being compatible with the FEDeRATED ontology?". This phase is crucial for validating the ontology's accuracy, adaptability, and overall effectiveness, ensuring that it not only meets theoretical expectations but also stands up to practical applications and challenges within the textile industry.

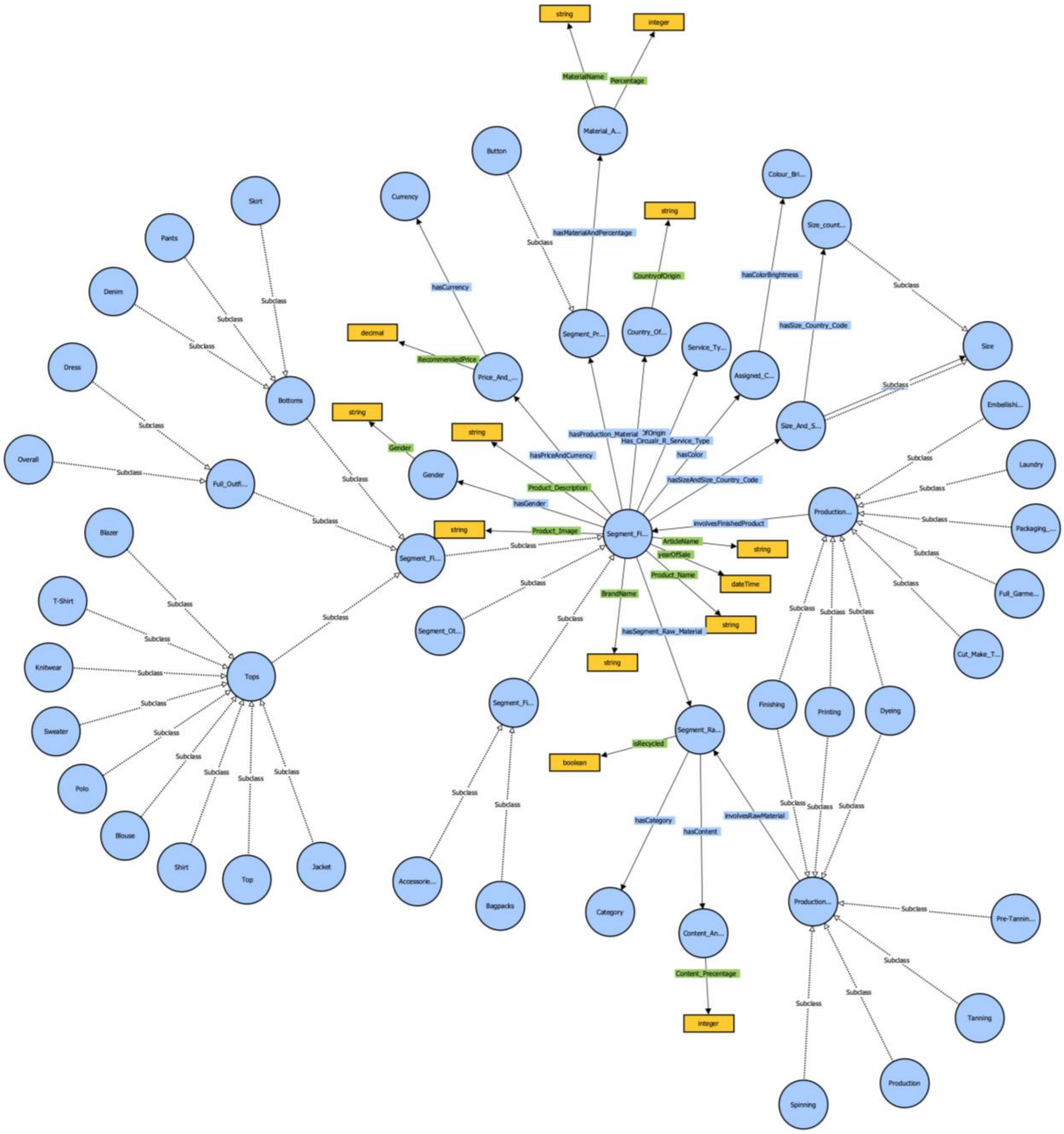

Figure 12: Preliminary ontology visualised using VOWL.

5 Evaluation

5.1 Introduction

In Chapter 5, we address the sub-questions 4: "To what degree does the developed ontology satisfy the requirements specified in sub-question 2, as demonstrated through an evaluation and demonstration?" and sub-question 5 "What structure will the final ontology have to represent semantic data in the textile industry while being compatible with the FEDeRATED ontology?" This chapter utilises an evaluation framework alongside validation methods to examine the ontology. The deliverables of this chapter include a comprehensive assessment of, among others, the ontology's accuracy, adaptability, clarity, completeness, and consistency in the context of the textile industry and its alignment with the FEDeRATED ontology. Specifically, we will guide the reader through the process of ontology evaluation and validation, detailing the criteria and methods in Sections 5.1 and 5.2, the application of these methods in Section 5.3, and concluding with a discussion on the final structure of the ontology in Section 5.4. This structured approach ensures that the ontology's design principles are thoroughly evaluated and validated, thereby confirming its practical applicability and interoperability within the textile domain.

5.2 Evaluation Framework

Ontology evaluation is a pivotal step in determining the quality and accuracy of an ontology, guided by specific evaluation criteria (Amith et al., 2018). Various methodologies and techniques exist for this purpose, each with its distinct set of criteria (Degbelo, 2017; Kim & Oh, 2019).
Evaluation criteria and metrics are essential tools in this process. Criteria such as consistency, conciseness, completeness, adaptability, and clarity are often employed. These metrics help in pinpointing potential issues or misapplications within the ontology, offering a quality assessment that augments expert opinions (Goldstein et al., 2021; Sicilia et al., 2012). Some frameworks suggest specific evaluation methods depending on the ontology's intended use (Goldstein et al., 2021), while others rely on established standards from the ontology evaluation literature, like consistency and conciseness (Jabla et al., 2021).

The evaluation of the ontology centres on three principal criteria that have been selected for their direct relevance to the ontology's utility in the textile industry. Structural Integrity is assessed to ensure that the ontology accurately captures the intricate relationships and processes critical to textile recycling and circularity. This is vital as the ontology must represent the domain's complexities in a manner that machines can process, enabling efficient data analysis and decision-making. Content Alignment with set competencies of Table 4 ensures the ontology contains all necessary domain-specific information, reflecting the data sorters require for circular practices. This adherence to detailed content is crucial for maintaining the ontology's relevance and accuracy. Lastly, Compatibility with the FEDeRATED ontology is evaluated to guarantee that the ontology can integrate and operate within a cross-industry framework, enabling it to support a wide array of use cases beyond its initial scope. Each criterion has been chosen not only for its significance in ontology development but also for its specific applicability to the project's goals—ensuring that the ontology not only conforms to technical best practices but also aligns with the strategic objectives of enhancing sustainability within the textile industry.

5.2.1 Criteria

In Section 3.4, we outlined the functional, strategic, and environmental requirements for the textile ontology. Drawing inspiration from Degbelo (2017) and Kim & Oh (2019), we have chosen specific evaluation criteria, detailed in Table 8. These criteria are intrinsically linked to the requirements and are selected based on a rationale that incorporates insights from internal project meetings, literature, and the alignment with our competency questions. The connection between these criteria and the requirements is further explained in Table 9, which provides a structured overview and justifies our methodological choices. The upcoming section will introduce the evaluation methods employed to assess these criteria, ensuring a thorough and methodical evaluation process.

Table 8: Evaluation criteria (adapted from (Degbelo, 2017; Kim & Oh, 2019))

Criterion	*Definition*
Accuracy	Refers to the correctness and precision of the information represented in the ontology.
Adaptability	Assesses the ability of an ontology to be easily modified or extended to accommodate changes in the domain or requirements.
Clarity	Evaluates the clarity and understandability of the ontology's concepts, relationships, and definitions.
Completeness	Measures the extent to which the ontology covers all the relevant concepts and relationships within the domain.
Conciseness	Evaluates the ontology's ability to represent the necessary information without unnecessary redundancy or verbosity.
Consistency	Assesses the absence of contradictions or conflicts within the ontology, ensuring that the concepts and relationships are logically coherent.
Reusability	Evaluates the extent to which the ontology can be reused in different contexts or integrated with other ontologies or systems.

Furthermore, we refined the structure described in Table 3, specifying the requirements of the ontology, and presented the updated format in Table 9. Notably, we have kept the original ID numbers of the requirements to maintain clarity and avoid confusion. Our primary objective is to categorise each demand and identify which criterion it wants to meet. To be clear, and as Johannesson & Perjons (2014) emphasise:

- **Functional requirements:** These are determined by the specific problem being addressed as well as the needs of stakeholders.
- **Structural Requirements:** These refer to the design of the final solution.
- **Environmental Requirements:** These pertain to the larger environment and serve as more general recommendations for solution design.

Table 9: Requirements linked to criteria.

Requirement No.	*Category*	*Criteria*	*Requirement*
1.1	Functional	Completeness	The ontology should encompass domain knowledge necessary for circular practices, such as material categorization and lifecycle data, to support sorting processes.
1.2	Functional	Completeness	The ontology should facilitate circular activities, ensuring accurate representation of semantic data for processes like recycling and upcycling.
1.3	Functional	Adaptability	The ontology should be adaptable to accommodate new trends and technologies.
1.4	Functional	Completeness	Should provide cross-industry operability to facilitate efficient data exchange and collaboration across different sectors.
1.5	Functional	Accuracy	Should provide textile sorters with data to make better informed decisions
2.1	Structural	Accuracy	The ontology's structure should facilitate an intuitive and detailed representation of semantic data, adhering to established modelling principles.
2.2	Structural	Clarity	Should include a defined, explained, and documented vocabulary of terms and names.
2.3	Structural	Adaptability	Should allow for easy extension and integration with other ontologies or data sources.
2.4	Structural	Accuracy	Definitions for all concepts and relationships within the ontology must be clear, consistent, and validated by industry experts.
2.5	Structural	Clarity	Should be structured to logically inherit properties from parent concepts.
2.6	Structural	Completeness	Should support reasoning and querying capabilities to extract valuable insights from the data.

2.7	Structural	Clarity	Must ensure that relationships between concepts are well-defined and easily traceable
2.8	Structural	Accuracy	Establish a top-class in the ontology that fully aligns with the FEDeRATED ontology, ensuring cross-industry operability.
2.9	Structural	Completeness	The ontology must conform to established standards and expert-derived taxonomies to ensure a structured and accurate representation within the textile domain.
2.10	Structural	Conciseness	The ontology should be clear and to the point, including only the information that's necessary and avoiding any extra, unneeded details.
3.1	Environmental	Reusability	The ontology should support technical interoperability within the FEDeRATED standards framework and comply with general standards such as OWL and RDF for seamless integration with various industrial domain ontologies.
3.2	Environmental	Reusability	The ontology's content must be regularly updated and curated to ensure cross-domain applicability and facilitate knowledge reuse within the FEDeRATED project's scope.
3.3	Environmental	Completeness	Provide comprehensive documentation and guidelines for the ontology's use, maintenance, and extension, with a defined update and versioning protocol.
3.4	Environmental	Accuracy	Ensure compatibility with prevalent ontology languages and modelling tools to facilitate use in standard ontology environments.

5.2.2 Methods

Table 10: Criteria with matching evaluation methods

Criteria	*Qualitative Method*	*Quantitative Method*
Accuracy	Use Case, Queries	
Adaptability		Numerical Metrics
Clarity	Use Case, OOPS	
Completeness	OOPs, Queries, Use cases	
Conciseness	OOPs, Reasoner	
Consistency	OOPs, Reasoner	
Reusability	OWL, Use case	

Accuracy

Now that the requirements have been linked to the criteria, we will select evaluation methods to evaluate the criteria, taking care to align our methods with the information presented in Table 10. Evaluating an ontology across various criteria ensures its robustness and applicability in diverse scenarios. For accuracy, the ontology can be tested against the specific data needs essential for fibre-to-fibre textile recycling. By comparing the ontology's representation against these data needs, one can assess its correctness and precision in capturing the necessary information for the domain. This can be achieved by developing use cases that will allow testing of the accurate representation of information in the knowledge graph. This can be done using SPARQL queries and via the Semantic TreeHouse tool by TNO, which will also serve to evaluate reusability by ensuring that the ontology can interface effectively with the FEDeRATED project's upper ontology, thus demonstrating its capability to be reused in different contexts.

Adaptability

Numerical metrics, particularly those rooted in algorithms like the de Vries algorithm, are invaluable for gauging the depth, breadth, and structure of ontologies. These metrics focus on graph-based measurements, analysing node connectivity, depth of hierarchies, and the distribution of relationships to offer insights into the ontology's adaptability (Orme et al., 2007; Yang et al., 2006). For instance, a balanced depth-to-breadth ratio might indicate an ontology that is both detailed and broad, making it adaptable to various applications (Kumar et al., 2017). Conversely, an ontology with excessive depth could be highly specialized, making adaptability more challenging. Such metrics, when applied, not only provide quantitative data on the ontology's structure but also serve as indicators of its potential adaptability and usability in diverse contexts (Franco et al., 2020; Manouselis et al., 2010).

Clarity and conciseness

For clarity, the ontology's concepts, relationships, and definitions should be clear to users, ensuring that there's no ambiguity. The OOPS! (OntOlogy Pitfall Scanner!) tool emerges as a solution, offering an automated mechanism to detect and rectify pitfalls in ontologies. Specifically, OOPS! aids in enhancing ontology quality by identifying potential modelling errors, ensuring that ontologies are robust and reliable (Poveda-Villalón et al., 2014). The web-user interface of OOPS! (OntOlogy Pitfall Scanner!) can be employed to evaluate aspects such as consistency, clarity, understanding, language, and requirements completeness. Moreover, by identifying and suggesting the elimination of unnecessary or redundant concepts, OOPS! contributes to the ontology's conciseness, ensuring that it represents the necessary information without superfluous content. This attribute is particularly relevant to conciseness and consistency (Poveda-Villalón et al., 2014). Furthermore, the evaluation of ontology technology, such as OOPS!, facilitates its seamless integration with other software platforms, ensuring a smooth transition from academic research to practical applications (Sure et al., 2004). However, it's essential to approach these tools with caution, as some aspects of ontology development might inadvertently introduce challenges rather than solutions. In essence, while the landscape of ontology development is complex, tools like OOPS! provide invaluable support, ensuring clarity, consistency, conciseness, and high-quality outcomes in ontology creation. Figure 13 further illustrates the many pitfalls that the OOPS! tool is able to identify in ontology development.

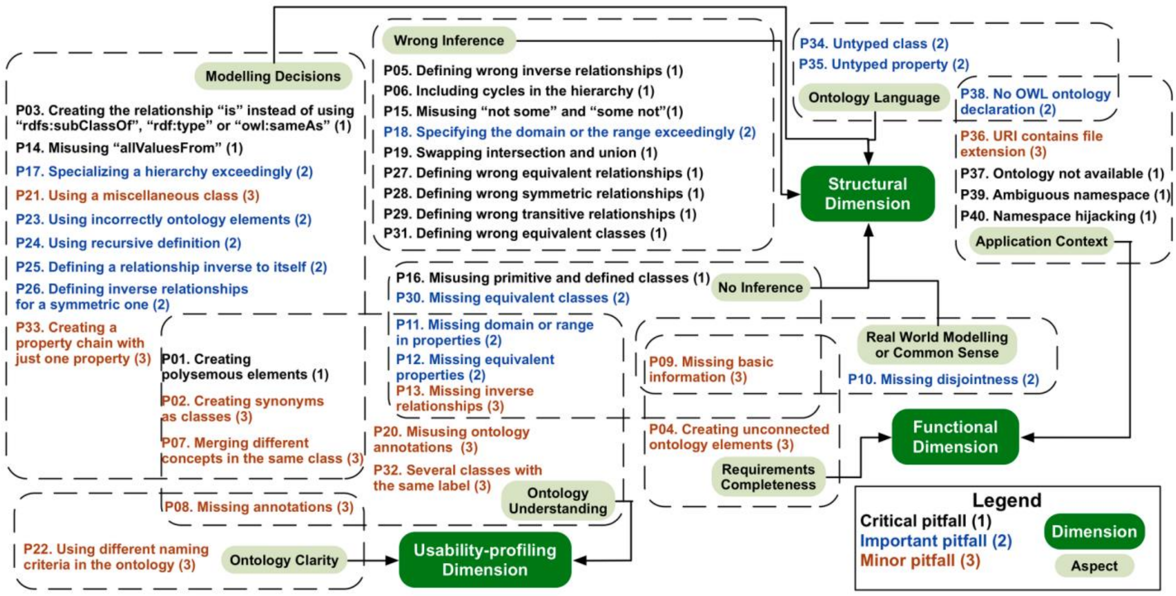

Figure 13: OOPS! Pitfall classification (Retrieved from: (Poveda-Villalón et al., 2014)

<u>Completeness</u>

For the completeness of the ontology, the alignment of the domain ontology with the upper ontology was facilitated using the Semantic TreeHouse tool. This alignment, crucial for ensuring that the ontology comprehensively covers all necessary domain-specific information, is outlined in detail in Section 5.4. After this alignment, Docker was employed to provide a stable environment for executing SPARQL queries derived from competency questions. These queries were instrumental in evaluating how thoroughly the ontology encapsulates the intended domain, highlighting areas well covered and identifying any gaps. This process ensures the ontology's completeness, affirming its capability to support the necessary functions and applications within the textile industry (Glimm et al., 2015; Jing et al., 2009; Valencia-García et al., 2011).

<u>Consistency</u>

Consistency within the ontology is primarily ensured by employing the reasoner in Protégé, which facilitates automatic classification and checks for logical coherence, as outlined by Horridge (2011). This foundational consistency check is crucial for establishing that the ontology's definitions and interrelations are mutually coherent. However, the OOPS! tool extends the evaluation scope by detecting common modelling errors that a standard reasoner might not uncover. Such errors can range from missing annotations to labelling inconsistencies, and misuse of ontology elements, which, while not necessarily affecting the ontology's logic, can impede its usability and interoperability. OOPS! thus offers a comprehensive quality check, ensuring adherence to best practices in ontology development and enhancing the ontology's clarity and practical applicability across various systems. This holistic assessment is vital for an ontology's robustness, particularly when considering its alignment with other ontologies, such as the FEDeRATED ontology, and its integration into diverse applications, thereby also evaluating its reusability. The combination of Protégé's reasoner and OOPS! ensures that the ontology is not only logically sound but also well-structured and user-friendly, as indicated in Table 10.

Reusability
The ontology's reusability is assessed not only through its ability to integrate with the FEDeRATED project's upper ontology but also in its development within Protégé using standardized languages such as OWL and RDF. This adherence to standards ensures the ontology can be reused in different contexts or integrated with other systems, as indicated in Table 10. By confirming that the ontology aligns with these general standards, we establish its capacity for technical interoperability within the FEDeRATED standards framework and cross-domain applicability.

5.3 Evaluation

5.3.1 Tool evaluation

As a first evaluation the reasoner was ran to see if there are any inconsistencies that appear, doing this as a first evaluation allows us to ensure there are no logical errors before starting functional testing using queries and use cases. For the reasoner the built in HermiT tool from Protégé was used. The reasoner did not yield and illogical constraints or errors.

In order to further investigate the preliminary structure of the ontology the OntOlogy Pitfall Scanner! (OOPS!) was also used. The OOPS tool scans the structure for pitfalls, Poveda-Villalón et al. (2014) classify the pitfall as one of the following:

- **Critical**: It is crucial to correct the pitfall. Otherwise, it could affect the ontology consistency, reasoning, applicability, etc.
- **Important:** Though not critical for ontology function, it is important to correct this type of pitfall.
- **Minor:** It is not really a problem, but by correcting it we will make the ontology nicer.

The results from the first entry that were obtained can be seen in Figure 14. The first results contain 2 critical errors, 4 important errors of which 2 are relevant and multiple minor errors which can be mostly attributed to untidiness. Nonetheless, the pitfalls that were detected will be fixed as best as possible as discussed below.

Results for P07: Merging different concepts in the same class.	4 cases	Minor
Results for P08: Missing annotations.	82 cases	Minor
Results for P10: Missing disjointness.	Ontology*	Important
Results for P13: Inverse relationships not explicitly declared.	17 cases	Minor
Results for P19: Defining multiple domains or ranges in properties.	2 cases	Critical
Results for P22: Using different naming conventions in the ontology.	Ontology*	Minor
Results for P24: Using recursive definitions. 1 case	1 case	Important
Results for P30: Equivalent classes not explicitly declared. 1 case	1 case	Important
Results for P41: No license declared.	Ontology*	Important

Figure 14: Pitfalls from the first entry in OOPS!

From the critical error P19 as shown in Figure 14, the domain of the properties (relationships and attributes) *hasMaterialAndPercentage* and *hasCountryOfOrigin* is defined by stating more than one *rdfs:domain* or statement. In OWL multiple *rdfs:domain* or *rdfs:range* axioms are allowed, but they are interpreted as conjunction, being, therefore, equivalent to the construct *owl:intersectionOf*. This is a pitfall that we accept in our ontology as it enables us to not have redundant properties specifying new object properties for all domain that share properties. In this case P19 is a pitfall that we will accept.

For the pitfalls classified as important there is one pitfall that claims that the ontology metadata omits information about the license that applies to the ontology (P41). While our ontology is currently in the preliminary stage of development, we understand the importance of establishing clear licensing from the outset. This practice aligns with best practices in software and data management and ensures that there will be no ambiguity about the terms of use as the ontology evolves (García & Gil, 2009). Although the immediate need for a license may not seem pressing, we recognize that the status of the ontology could change in the future. It may become an asset that we wish to share or collaborate on with external parties. By including a license in the final version, we prepare the groundwork for potential wider distribution, making the transition smoother should the decision to release the ontology publicly be made. A clear license will also avoid any retrospective legal complications or misunderstandings about ownership and usage rights (García & Gil, 2009).

Moving on to the missing disjointness (P10). If disjointness is not defined, you could encounter scenarios where an item is ambiguously classified as both "Male" and "Female" or is assigned contradictory colours like "Black" and "White" at the same time. Defining disjointness between these categories would prevent such unrealistic overlaps, ensuring clarity and accuracy in the classification of textile products. However, it also puts restrictions on combinations of colours or genders for example. To ensure we have a versatile system the disjointness is not modelled in our ontology. After the development of our ontology for the textile system, we can utilize SHACL (Shapes Constraint Language) to ensure that no unrealistic overlaps occur. By defining SHACL shapes that reflect the constraints and relationships of our ontology, we can validate the RDF graphs representing our data. This validation process will help us maintain the integrity and consistency of the data within our textile system, even as the ontology evolves and the system scales. Implementing SHACL will enable us to enforce these constraints automatically, ensuring that our data remains accurate and reliable.
Moreover, the pitfall classified as a single case of recursive definition (P24), we found that the data property ***https://ontology.tno.nl/Textile#Gender*** was self-referential in its domain definition, which could lead to logical inconsistencies and was not aligned with best practices in ontological modelling. Recognizing the nature of 'Gender' in our ontology as an entity with a finite set of possible values, we decided to model 'Gender' as a class with individuals—namely 'male', 'female', 'unisex', 'gender-neutral', 'genderless' —rather than as a data property. This allowed us to represent 'Gender' as a concept with specific instances, each

corresponding to a possible gender value. To correct the initial error, we eliminated the self-referential data property altogether. Instead, we introduced 'Gender' as a class with enumerated individuals. This approach clarified the ontology's structure, ensuring that 'Gender' is now used semantically correct as a class that other entities can reference, thereby reflecting real-world distinctions accurately.

Finally, we encountered the pitfall classified as important of potentially having duplicated concepts (P30) without defining equivalent classes using *owl:equivalentClass*. Specifically, the classes ***https://ontology.tno.nl/Textile#Tops*** and ***https://ontology.tno.nl/Textile#Top*** were identified as candidates for this kind of equivalence relationship due to their similar names and possible meanings. However, we consciously chose not to align these classes as equivalent within our ontology framework. This decision was grounded in the specialized taxonomy provided by a textile expert whose categorizations are integral to the structure of our ontology. Additionally, we aligned our terminology with the open data standard set forth by Circularity.id, ensuring that our ontology reflects the precise distinctions and nuances articulated by these authoritative sources (see section 3.4).
By adhering to the taxonomy and the established data standard, we maintain a clear and deliberate semantic distinction between the classes in question, which supports the specific use cases and domain requirements of our ontology.

The minor pitfalls that were identified consisted mostly of missing annotations of properties and classes (P08). Wherever the annotations of classes and properties were missing they were added to the ontology. Furthermore, OOPS! Pointed out that we were missing inverse properties (P13), although not necessary for the ontology we decided to add the inverse properties nonetheless to improve structuring and clarity in the ontology.
Another minor pitfall is P07 which mentions that our ontology merges different concepts in the same class. While this is true as we have argued the only solution would be to separate all the classes again and establish relationship between them, this would be the opposite of what we have argued earlier when we explained structuring different concepts together such as *Material_And_Percentage* this way as it is beneficial for the event driven ontology that we are creating.

5.3.2 Numerical Metrics

In the construction of an ontology for the textile sector, assessing its structural quality is an important step in the evaluation. An ontology's structure significantly impacts its effectiveness in semantic searches, knowledge representation, and information retrieval. The structural metrics of average depth, average breadth, relationship richness, inheritance richness, and attribute richness offer a multifaceted evaluation, addressing the ontology's hierarchy, complexity, and the detail of its conceptualization. This allows us to measure the criteria adaptability.

Average Depth and Breadth

Average depth is a metric indicative of the ontology's hierarchical complexity. It is calculated by averaging the path lengths from the root node to every other node within the ontology (Gangemi et al., 2005). A deeper ontology may suggest a more detailed categorization, beneficial in a domain like textiles where specific classifications (e.g., fabric types, weaves, and treatments) are crucial. Conversely, a shallow depth could imply a more general overview, potentially overlooking finer details vital in textile categorization.

The average breadth refers to the number of sibling concepts at each level of the ontology (Gangemi et al., 2005). This metric provides insight into the ontology's horizontal spread, which is particularly relevant in the textile industry where a wide range of categories must be managed at a single hierarchical level, such as various material types or production techniques.

Relationship, Inheritance, and Attribute Richness

Relationship richness (RR) at the schema level is defined by the formula:

$$RR = \frac{P}{SC + P}$$

Where P is the number of relationships and SC is the number of subclasses, i.e., the inheritance relationships (Tartir et al., 2005). At the class level, it compares the number of relationships used by instances of a class to the number defined at the schema level. In the textile ontology, this metric could evaluate how well the ontology represents the complex relationships between different textile concepts.
Inheritance richness (IR) offers an average measure of subclasses per class. The schema level inheritance richness (IRs) provides an overview of the ontology's generalization capabilities:

$$IRs = Average\ number\ of\ subclasses\ per\ class$$

For a specific class C_i, it is:

$$IRc = Average\ number\ of\ subclasses\ per\ class\ in\ the\ subtree\ rooted\ at\ C_i$$

The more general an ontology is, the higher its inheritance richness, which may be desirable in the textile sector to accommodate a broad spectrum of classifications and hierarchies for materials, processes, and products.
Attribute richness (AR) is calculated as the average number of attributes per class:

$$AR = Average\ number\ of\ attributes\ per\ class$$

This reflects the ontology's capacity to describe its classes with relevant properties (Tartir et al., 2005). For the textile ontology, a rich set of attributes is essential to capture the diverse and detailed characteristics of textiles, such as thread count, dye techniques, or material properties.

The selection of these metrics is motivated by their capacity to collectively offer a comprehensive picture of the textile ontology’s structure. In the textile domain, where the diversity of concepts and their interrelations is vast and complex, these metrics provide critical insights into the ontology’s ability to model the domain effectively. They allow for the evaluation of the ontology's depth in terms of conceptual hierarchy, its breadth in capturing a wide range of categories, and its richness in detailing relationships, inheritance, and attributes necessary for a nuanced representation of concepts of the textile sector.

Figure 15: Metrics as portrayed in Protégé.

Table 11: Numerical metrics of the preliminary ontology

Metric (Preliminary Version)	*Value*	*Calculation Detail*
Average Depth (AD)	2.32	$AD = \frac{123}{53}$
Average Breadth (AB)	13.25	$AB = \frac{53}{4}$
Relationship Richness (RR)	0.429	$RR = \frac{(17 + 13)}{(40 + (17 + 13))}$
Inheritance Richness (IRs)	0.755	$IRs = \frac{40}{53}$
Attribute Richness (AR)	0.245	$AR = \frac{13}{53}$

Average Depth:
The ontology's average depth of 2.32 conveys a moderately detailed hierarchical structure. It demonstrates that while there is some depth to the classification system, it doesn't become overly intricate, potentially avoiding the pitfalls of excessive complexity which can hinder usability and understanding. A depth of this level suggests an ontology that is nuanced enough to capture essential distinctions within the domain yet remains straightforward to navigate.

Average Breadth:
The breadth of 13.25 suggests a wide-ranging horizontal expansion, reflecting an ontology with a broad spectrum of concepts at each hierarchical level. This extensive breadth may be indicative of an ontology designed to encapsulate the vast range of categories inherent in a domain as diverse as textiles, from fibres to fabric construction techniques. It denotes a capacity for comprehensive classification, crucial for domains where various sub-categories must be managed concurrently.

Relationship Richness (RR):
An RR of 0.429 indicates a balanced level of concept interconnectivity, which is neither overly simplistic nor excessively convoluted. This could imply that while the ontology has a solid base of relationships, there is room to further elaborate on these connections to better represent the intricate interdependencies typical in domains like textiles, where the relationships between different materials, weaves, and finishes are complex and multifaceted.

Inheritance Richness (IRs):
The Inheritance Richness (IRs) score stands at about 0.7547, reflecting a well-articulated hierarchical structure with a significant number of subclasses per class. This suggests a mature categorization schema within the ontology, which is advantageous for capturing the diverse subcategories typical in the textile industry. The higher IRs score indicates that the ontology can effectively represent the layered complexity inherent in the sector, which is essential for applications requiring detailed hierarchical information.

Attribute Richness (AR):
Lastly, the Attribute Richness (AR) score of approximately 0.2453 points to a modest attribution of properties to the classes within the ontology. While this may indicate a shortfall in descriptive detail—attributes such as material types, thread counts, and dye techniques are essential in textiles—it may be adequate for general purposes. However, for more intricate applications where detailed attributes are crucial, enriching the ontology with a broader array of properties per class would be beneficial to increase its utility and specificity.

In sum, the ontology exhibits a balanced structure, with a tendency towards modesty in depth and well expanded in breadth. While it has a solid hierarchical foundation, there is an opportunity to augment its descriptive richness to enhance its adaptability and applicability across various textile-related contexts. Evaluating the completeness of the ontology will allow us to contemplate further additions to improve numerical values.

5.3.3 Querying of competency questions

For the last evaluation part, this research ran queries to assess whether all the competency question could be answered using this ontology and the corresponding queries. The design and setup of the queries was done simultaneously with the validation of the use cases. Therefore, the steps that were followed to run the queries are further explained in section 5.4. During the querying of the competency questions the approach was relatively simple, if a competency question was not able to be queried using the current state of the ontology, the ontology was altered to include elements that allowed for the querying. During this final evaluation of the ontology structural problems and other small altercations that were discovered during the querying were also altered. The full queries and their outcomes can be found in Appendix H: Queries and Results for Use Cases.

5.4 Validation

Following the initial evaluation steps, carried out in section 5.3.1 & 5.3.2, the Semantic Treehouse provides an advanced method for assessing the ontology's capability in semantic interoperability within the textile domain. Semantic Treehouse is a practical tool for querying and applying ontologies to real-world scenarios, thereby gauging its accuracy, clarity, and completeness.
Semantic Treehouse functions as a sophisticated vocabulary hub, assisting in the visualization, customization, and validation of ontology-based data exchange schemas. By enabling the design of message schemas and API specifications rooted in shared domain ontologies, Semantic Treehouse presents a unique opportunity to evaluate the textile industry ontology against practical data space requirements. The tool's wizard facilitates the formulation of competency questions into queries, offering a practical means to assess the ontology's accuracy and completeness (TNO, 2022).
Moreover, the Semantic Treehouse's capabilities extend to testing the interoperability of the textile ontology with upper-level ontologies and other domain-specific ontologies. The inclusion of the FEDeRATED project's upper ontology and the Catena-X battery pass ontology within the Semantic Treehouse framework allows for an evaluation of cross-domain applicability, a key attribute of the developed ontology. This step is essential for ensuring semantic coherence and data exchange fluidity between various industry sectors, which in our requirements table refers to the completeness.
The ability of the textile ontology to align with the FEDeRATED project's upper ontology and to interface effectively with the Catena-X battery pass ontology demonstrates its well-constructed semantic foundation. It highlights the ontology's potential to act as a versatile mediator in the semantic data space, enabling efficient data exchange and interoperability across different domains. By facilitating these connections, Semantic Treehouse ensures that the textile ontology can serve a broader array of applications, proving its adaptability and completeness beyond its initial scope.
The detailed use cases, along with the corresponding queries crafted for their execution, are comprehensively documented in Appendices F, G & H. These use cases are constructed with mock data that is designed to closely resemble actual scenarios. This approach is intended to demonstrate the practical effectiveness of the ontology, although the data and examples are not sourced from real-world instances.

5.4.1 Procedure

First, we needed to load the ontology into the Semantic Treehouse. This is done by setting up the Message Model using the provided wizard. The wizard assists in creating a project that, at its core, consists of a title, a description, and various versions of the message model. Each version is accompanied by status information, such as whether it's a concept or final, along with other metadata including dates, documentation, and acknowledgements (TNO, 2022).
To ensure connectivity of the generated output schemata, namespaces are employed. Each message model is required to import at least one versioned ontology. For our purposes, we selected the 'FEDeRATED' upper-ontology along with the 'Catena-X' battery pass. These will be presented as graph trees, facilitating the subsequent composition of messages. Figure 16 schematically depicts the role of Semantic Treehouse's wizard in connecting ontologies and requesting data.

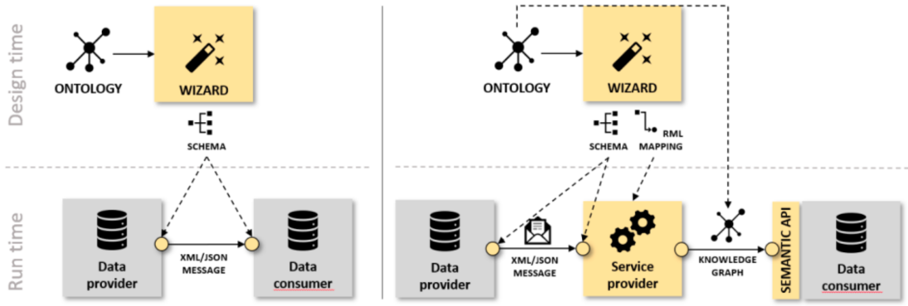

Figure 16: (a) syntax bindings in a single stack, (b) syntax bindings and rml mappings in a dual stack, by (TNO, 2022)

After the initial set-up we align the ontology to the FEDeRATED ontology by selecting the root class of our domain ontology, which is structured as such in our ontology that it allows for easy subclassing.
As depicted in Figure 17 FEDeRATED upper ontology property "*involvesDigitalTwin*" has the range set to "*Segment_Finished_Product*", as the *Segment_Finished_Product* is considered a sub class of Digital Twin Product, it can now be included in FEDeRATED events.

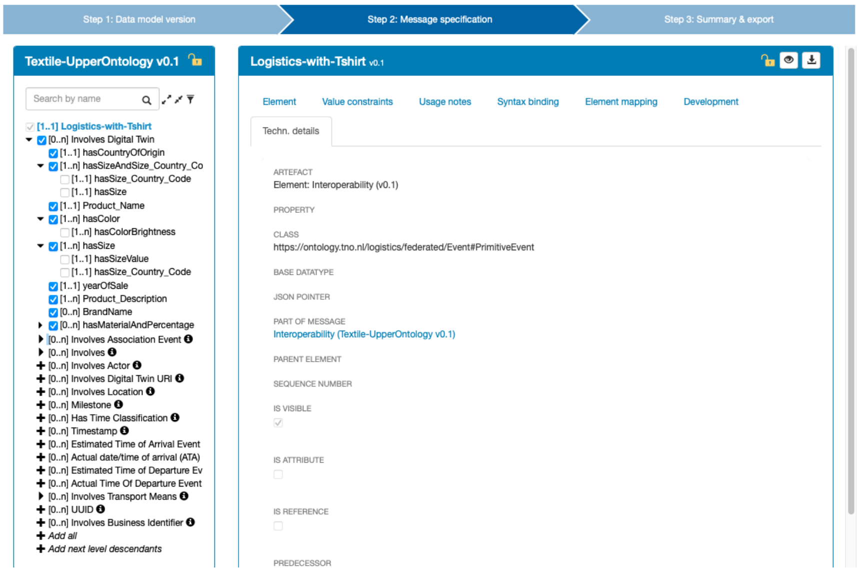

Figure 17: Set-up of the domain ontology with the FEDeRATED ontology

The properties of the root class, both incoming and outgoing, were successfully loaded from the ontology and presented as potential elements for addition as children of the message's root element. During this step, customization can be carried out, such as application of additional restrictions beyond the default ontological specifications to form a more customized message specification, for instance, certain properties had their cardinality changed from [0..n] to [1..n] to introduce further restrictions. This was also discussed in the OOPS! analysis where we chose to not model restrictions in our ontology itself.

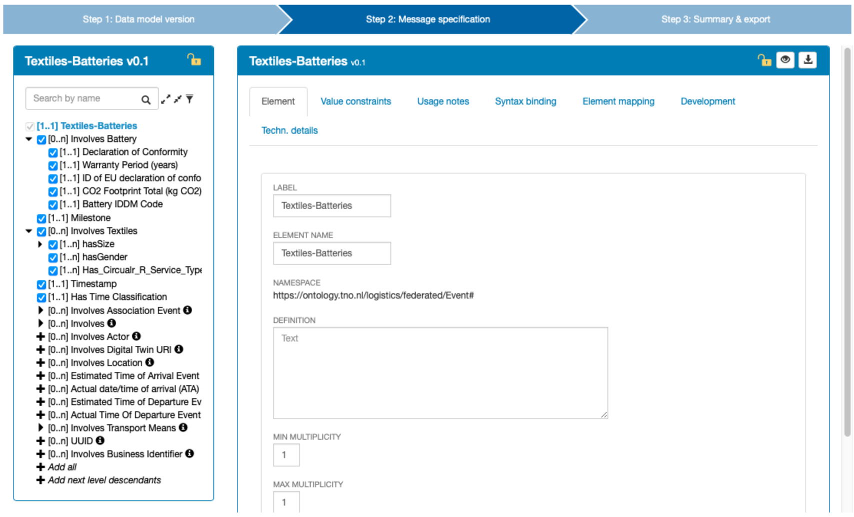

Figure 18: Set-up of the textile ontology for cross-domain querying with the Catena-X ontology.

With the set-up complete the constructed use cases were given mock-up data closely resembling actual data. With the querying of this data we were able to show, a) that the ontology was functional and well structured, b) that it covered the competency questions set out earlier c) that it was able to connect with other ontologies through the FEDeRATED project being able to query data with both the textile ontology as the battery ontology as shown in Figure 17 & Figure 18. The use cases, the mock-up data and the queries with their results can be found respectively in appendix F, G & H.

5.5 Evaluating the ontology after refinement

During the evaluation and validation additions and refinements were made, this means that the pitfalls and numerical metrics from the preliminary version of the ontology no longer are correct. To assess the changes that have been made the OOPS! pitfall scanner and the numerical metrics have been ran again. Furthermore, the HermiT reasoner native to Protégé was ran again obtaining nu further errors.
After having left out the pitfalls in the scan that were argumented to not be relevant for our ontology in section 5.3.1 the results of the scan can be seen in Figure 19. The evaluation results that one pitfall, P22 remains. This pitfall is a minor one and is mostly related to conciseness. During the development we have tried to keep the naming conventions as similar as possible but as the development of the ontology was an iterative process some inconsistencies in the naming conventions have been produced.
The numerical metrics were also recalculated to obtain the new values and the percentage of change. What may stand out is that 3 metrics score lower than before, this is mainly due to the refinement of the ontology during the evaluation, it became clear that some classes were better of structured as a data property instead of a class to improve the overall structure and clarity of the ontology. This resulted in less classes and thus lower scores. This also depicts the limitations of the metrics quite well as the ontology has not lost any of its functionality, in fact it has gained some functionality during the validation, but it won't show in the metrics. Another metric that stands out is the large increase in relationship richness, this is the opposite of the choices we've made structuring some of the classes as properties. Furthermore, this large change can be mainly attributed to solving the pitfall of not having inverse properties, while not critical to the functionality, we agreed with OOPS! that it would improve structuring and clarity to also add inverse properties more clearly delineating the properties and the domains.

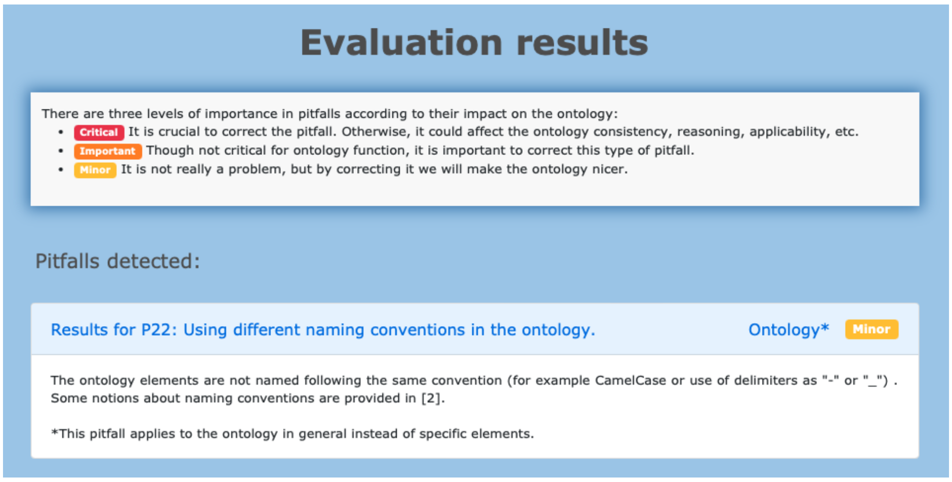

Figure 19: OOPS! (Ontology Pitfall Scanner!) after refinements

Table 12: Metrics of the final version of the ontology and the percentage of change

Metric	*Value of preliminary version*	*Value of final version*	*Percentage change (%)*
Average Depth (AD)	2.32	2.31	-0.43%
Average Breadth (AB)	13.25	13.0	-1.89%
Relationship Richness (RR)	0.429	0.542	+26.34%
Inheritance Richness (IRs)	0.755	0.731	-3.18%
Attribute Richness (AR)	0.245	0.25	+2.04%

5.6 Evaluation and validation conclusion

This subchapter discusses the results of the evaluation and the validation. This evaluation started off with the HermiT reasoner, this was constantly ran throughout the development, it proved an easy way to ensure that the ontology remains concise and consistent. The evaluation of the ontology with the OOPS! pitfall scanner provided us with valuable information on mistakes, inconsistencies, and element we might have forgotten. In most cases it proved an easy fix and some like the inverse property required a bit more work, all in all the tool has helped in providing a more consistent, clear, concise, and complete ontology. The numerical metrics turned out a bit bleak regarding some of the score, nonetheless, it was able to help form an opinion on the structure. Beforehand we knew due to the scope of our research the ontology would not be the most granular, as was intended, as we had chosen to model it on the most necessary data for sorters to increase circularity. However, the metrics proved that out model has a structure that is well suited for adaptability and with this in mind it should be able to easily extend the developed ontology to include more classes in the future as research, standards and commitment will provide more relevant and mandatory data fields to increase the circularity.
For the validation of the ontology the mock-up data showed that out ontology can cover elements commonly found in textile products. The queries showed that all the competency questions have been covered addressing the criteria of accuracy and completeness. The ontology cannot be complete as the work in this dynamic and changing sector will most likely never be done. Even though the queries have proven that this ontology adheres to the scope and the standards that were research and therefore has a satisfying completeness.
Moreover, the use cases provided an example of how the ontology can be integrated with the FEDeRATED ontology proving the usability of cross-domain querying. This aligns with our completeness goal of developing an ontology that is suited for cross-domain querying by aligning it to the FEDeRATED ontology. Table 13 summarises the validation of each requirement.

Table 13: Validation of the requirements

Requirement No.	*Category*	*Criteria*	*Requirement*	*Validated*
1.1	Functional	Completeness	The ontology should encompass domain knowledge necessary for circular practices, such as material categorization and lifecycle data, to support sorting processes.	✓
1.2	Functional	Completeness	The ontology should facilitate circular activities, ensuring accurate representation of semantic data for processes like recycling and upcycling.	✓
1.3	Functional	Adaptability	The ontology should be adaptable to accommodate new trends and technologies.	✓
1.4	Functional	Completeness	Should provide cross-industry operability to facilitate efficient data exchange and collaboration across different sectors.	✓
1.5	Functional	Accuracy	Should provide textile sorters with data to make better informed decisions	✓
2.1	Structural	Accuracy	The ontology's structure should facilitate an intuitive and detailed representation of semantic data, adhering to established modelling principles.	✓
2.2	Structural	Clarity	Should have a clearly defined, explained, and documented set of terms and names used in ontologies.	✓
2.3	Structural	Accuracy	Should allow for easy extension and integration with other ontologies or data sources.	✓
2.4	Structural	Accuracy	Definitions for all concepts and relationships within the ontology must be clear, consistent, and validated by industry experts.	X
2.5	Structural	Clarity	Should be structured to logically inherit properties from parent concepts.	✓
2.6	Structural	Completeness	Should support reasoning and querying capabilities to extract valuable insights from the data.	✓
2.7	Structural	Clarity	Must ensure that relationships between concepts are well-defined and easily traceable	✓
2.8	Structural	Accuracy	Establish a top-class in the ontology that fully aligns with the FEDeRATED ontology, ensuring cross-industry operability.	✓
2.9	Structural	Completeness	The ontology must conform to established standards and expert-derived taxonomies to ensure a structured and accurate representation within the textile domain.	✓
2.10	Structural	Conciseness	The ontology should be clear and to the point, including only the information that's necessary and avoiding any extra, unneeded details.	✓
3.1	Environmental	Reusability	The ontology should support technical interoperability within the FEDeRATED standards framework and comply with general standards such as OWL and RDF for seamless integration with various industrial domain ontologies.	✓
3.2	Environmental	Reusability	The ontology's content must be regularly updated and curated to ensure cross-domain applicability and facilitate knowledge reuse within the FEDeRATED project's scope.	X
3.3	Environmental	Completeness	Provide comprehensive documentation and guidelines for the ontology's use, maintenance, and extension, with a defined update and versioning protocol.	X
3.4	Environmental	Accuracy	Ensure compatibility with prevalent ontology languages and modelling tools to facilitate use in standard ontology environments.	✓

Table 13 indicates that requirements 2.4, 3.2, and 3.3 were not validated. The domain expert, while instrumental in defining the scope and requirements, encountered difficulties in evaluating the ontology for semantic precision. This was primarily due to the expert's limited experience with the intricacies of data semantics, a nuance that was not anticipated at the outset of the project. Consequently, while the expert contributed significantly to the conceptual framework of the ontology, an independent evaluation of the ontology's semantic accuracy was not feasible within the timeframe of this study.

Additionally, validating the ontology based solely on content coverage against the expert's own recommendations could introduce a bias, as the standard and data fields originated from his advisement. This form of circular validation would not provide the objective assessment required for academic rigor. To mitigate this, we relied on competency questions derived from the data requirements to validate the content, ensuring that the ontology met its intended functional specifications.

The integration of environmental requirements 3.2 and 3.3 was beyond the scope of this study. Their inclusion during the requirement specification phase was challenging yet deliberate, intended to outline the ontology's aspirational criteria more precisely. Should the ontological study extend beyond its current confines and the ontology be deployed practically, it would be important to re-examine these requirements to facilitate the ontology's ongoing refinement and applicability.

5.7 Final structure

Having concluded the evaluation and validation phases, we now present the definitive version of the prototype ontology. Despite the inability to validate each requirement exhaustively, it is our conviction that the ontology we have devised is sufficiently comprehensive for the intended scope. It stands as a constructive instrument in furthering the adoption of circular practices within the textile industry. The delineation of classes, properties, and individuals is methodically documented in Appendices C, D & E.

5.8 Conclusion

Chapter 5 delves deeply into evaluating and validating the ontology developed to answer sub-question 4: "To what degree does the developed ontology satisfy the requirements specified in sub-question 2?" Utilising a blend of qualitative tools such as the HermiT reasoner and the OntOlogy Pitfall Scanner (OOPS!), along with quantitative metrics, the chapter scrutinizes the ontology's structural integrity, consistency, and clarity. These methodologies provided critical insights into the ontology's logical coherence and adaptability, as well as its capacity to represent the textile industry's semantic data accurately and align with the FEDeRATED ontology. Validation through querying competency questions and practical use-case scenarios further affirmed the ontology's completeness and practical applicability, demonstrating its readiness for real-world implementation. This rigorous evaluation and validation process not only affirmed the ontology's capabilities in managing semantic data within the textile supply chain but also laid a solid foundation for Chapter 6. At the end of this chapter we were able to present the final structure of the ontology which can be found in Appendices C, D & E, answering providing an answer to sub-question 5: "*What structure will the final ontology have to represent semantic data in the textile industry while being compatible with the FEDeRATED ontology?*". In the final chapter, these findings will be synthesized to address the overarching research question, exploring the ontology's broader societal and scientific contributions, its limitations, and avenues for future research.

PART V

Findings

6 Conclusion

6.1 Introduction

In the concluding Chapter 6 of this thesis, the full scope of the research is summarised, and key findings are presented. This chapter revisits and answers the five sub-questions and the main research question outlined in Chapter 1, thoroughly examining their implications. Additionally, this chapter delves into the societal and scientific contributions of the research, discusses its limitations, and suggests directions for future research. This chapter continues after the introduction with revisiting the sub-questions leading to the main research question in 6.2. Furthermore, sections 6.3 and 6.4 discuss the societal impacts and scientific advancements achieved through this research, respectively, while also acknowledging the study's constraints. Lastly, Section 6.5 outlines recommendations for extending this research domain, paving the way for ongoing scholarly exploration.

6.2 Findings

In addressing the overarching aim of this research, which was to make a substantive contribution to advancing circularity within the textile industry, this thesis has underscored the criticality and immediacy of mitigating climate change through innovative and sustainable practices. By investigating the current landscape of the textile sector alongside the development of ontologies, this work sought to identify key areas where the greatest impact could be realised. To guide this search the following main research question was presented in chapter 1 with 5 sub-questions to accompany the overarching research question. In addressing these sub-questions, this research makes a significant scientific contribution by systematically circling back to the knowledge gap found in the literature review, particularly in the exploration and development of specific ontologies for the textile industry. These findings not only add depth to the existing literature but also pave new pathways for future research in this area. To further elucidate the findings the sub-questions are revisited.

Sq 1. What foundational knowledge and contextual understanding are required to construct a textile-ontology that leverages the FEDeRATED project?

In addressing the first sub-question regarding the foundational knowledge and contextual understanding required to construct a textile ontology leveraging the FEDeRATED project, the research unearthed several key insights. Firstly, it highlighted the substantial environmental impact of the textile industry, emphasizing the need for sustainable practices such as eco-design and recycling, which are crucial for reducing the industry's ecological footprint. This understanding forms a core part of the ontology's focus. Secondly, the principles of circular economy emerged as pivotal in shaping the ontology, advocating for a shift from linear to sustainable, regenerative practices within the textile sector. Thirdly, the integration of digitalization, particularly through digital twins, was identified as a significant driver in advancing sustainability. This aspect underlines the importance of incorporating digital replication of physical systems into the ontology to enhance efficiency and transparency. Furthermore, the role of ontologies in fostering semantic web technologies was recognized as essential for ensuring data interoperability and effective knowledge sharing, which are key to the digital transformation of the textile industry. Finally, aligning with the FEDeRATED project, the research underscored the importance of developing an ontology that supports data sovereignty and interoperability within logistics and transportation and manufacturing industry, ensuring seamless integration with broader digital ecosystems. These findings collectively inform the construction of a textile domain-specific ontology that is not only environmentally conscious and digitally advanced but also aligns with the broader objectives of the FEDeRATED project, thus setting a robust foundation for future enhancements and adaptations in the evolving landscape of textile industry sustainability. The findings from this sub-question reveal that constructing a textile ontology requires a multifaceted approach, integrating environmental sustainability, circular economy principles, digitalization strategies, and semantic web technologies. These elements collectively form the basis of an ontology that not only addresses the specific needs of the textile industry but also aligns with the overarching goals of the FEDeRATED project. Such an ontology is poised to facilitate effective data management, promote sustainable practices, and support the evolving digital landscape of the textile sector.

Sq. 2 What are the prerequisites for creating an ontology that handles semantic data in the textile supply chain while integrating with the FEDeRATED ontology?

In addressing the sub-question regarding the prerequisites for creating an ontology that handles semantic data in the textile supply chain while integrating with the FEDeRATED ontology, the focus on standards and the perspective of textile sorters emerged as a critical consideration. The standard that was used is recognized for its thorough documentation and accessibility, making it a valuable resource for ensuring traceability and transparency within the industry. The choice to adopt the circularity.ID standard was reinforced through collaborative meetings with a textile expert and was largely influenced by its support for intelligent sorting solutions and its provision of verified data. These aspects are crucial for textile sorters who are integral to the reverse supply chain, determining the potential for reuse or recycling of textile products.

The focus on textile sorters was strategic. As gatekeepers in the circular economy, sorters make critical decisions that affect the lifecycle of textiles. Their role is essential in categorizing textiles for reuse or recycling, thus reducing waste and promoting sustainability. The ontology, therefore, needed to be designed with the perspective of textile sorters in mind, ensuring that it includes data fields relevant to their operations, such as material composition, country of origin, and recycling potential.

To accurately capture these requirements, internal project meetings with a textile expert and semantical experts were conducted. This expert brought a wealth of industry experience, particularly in advancing sustainability and circularity through the use of information and communication technology. These discussions were invaluable in identifying the specific data fields and structural elements of the taxonomy that are critical for sorters, such as colour brightness, gender, production material, and various other segments relevant to the sorting process, in addition to the standard.

The input from this textile expert was not only informed by their extensive knowledge but also by their direct involvement in digital product passport initiatives and supply chain tracking projects. Their insights helped to ensure that the ontology would not only be theoretically sound but also practically applicable, addressing the real-world data needs of textile sorters and aligning with the latest industry practices for sustainability and transparency.

Moreover, these meetings with experts led to the generation of competency questions, which are designed to test the ontology's capacity to meet specific knowledge requirements. These questions helped in shaping the ontology’s requirements and identifying the detailed data necessary for sorters. For instance, questions about material properties, product lifecycle, and recycling processes were devised to ensure the ontology would facilitate efficient sorting and decision-making.

Sq 3. How can the various classes, properties, and relationships be structured in such a way that they accurately represent semantical data in the textile industry while also being compatible with the FEDeRATED ontology?

The ontology was developed using the open-source tool Protégé, supported by the Web Ontology Language (OWL). Protégé, thanks to its visual interface and collaborative capabilities, allowed for the streamlined and intuitive development of the ontology construction. The tool's functionality extends to automation, collaborative editing akin to Google Docs, and modularity, which facilitates the reuse of knowledge through a rich plugin ecosystem.

OWL was chosen for its expressiveness, reasoning capabilities, interoperability, and its ability to evolve and scale alongside dynamic sectors like textiles. The language's compatibility with ontology reasoners ensures automated knowledge inference and consistency checks, important for maintaining the ontology's logical structure.

The construction of the ontology started with establishing classes and their hierarchies, adopting a middle-out strategy. This approach balanced the taxonomy's structure and the data requirements for circularity in the textile sector. It allowed the ontology to utilise a top-down approach for organizing frequently used classes while leveraging a bottom-up strategy to incorporate production steps as events, aligning with the event-based architecture of the FEDeRATED ontology.
The classes were structured to reflect the taxonomy obtained from internal project meetings, integrating circularity data needs. This integration was supported by modelling certain concepts after existing ontologies to enhance structure and eliminate redundancies. For example, combining terms like Price_And_Currency and Material_And_Percentage was inspired by the Catena-X battery pass ontology's approach, which also aligns with FEDeRATED's event-driven architecture.
Object properties were defined to express the relationships between entities, such as linking finished products to materials and their percentages, while data properties assigned specific values to entities, such as the material names and their percentages in finished products. These properties are essential for detailed knowledge representation and complex querying within the ontology.
In summary, the ontology was constructed to be semantically rich and logically consistent, ensuring accurate representation of the textile industry's data. The use of Protégé and OWL, along with a balanced middle-out strategy for structuring classes, properties, and relationships, laid a solid foundation for an ontology that aligns with the FEDeRATED project's standards and supports the sector's movement towards sustainability and circularity. The key findings from this development process include the effective use of Protégé and OWL for handling complex semantic data, the successful adoption of a middle-out strategy for ontology structuring, and the preliminary alignment with the FEDeRATED ontology. This alignment points towards standardization and adaptability within the textile sector, facilitating a comprehensive framework capable of representing diverse data accurately. The semantic richness and logical consistency achieved are expected to be instrumental in supporting complex decision-making processes and data querying, further contributing to the textile industry's digital transformation and sustainability efforts.

Sq 4. To what degree does the developed ontology satisfy the requirements specified in sub question 2, as demonstrated through an evaluation and demonstration?

The developed ontology underwent a detailed evaluation to validate its adherence to the requirements specified in sub-question 2, using a combination of quantitative and qualitative approaches. First, tools such as the HermiT reasoner, native to the protégé tool, ensured logical coherence, while the OntOlogy Pitfall Scanner (OOPS!) identified critical pitfalls for correction. For instance, the ontology's preliminary design faced critical pitfalls in defining domain properties, which, although initially considered for revision, were ultimately accepted as part of the ontology's structural design. Conversely, minor pitfalls such as missing annotations were rectified to enhance clarity and understanding. The ontology's clarity and consistency were enhanced by addressing feedback from OOPS! including the addition of inverse properties to improve structuring and clarity, despite not being essential for functionality. This proactive response to the OOPS! feedback reflects a commitment to achieving a high-quality ontological framework.
Throughout this iterative evaluation process, the ontology was refined to better align with established criteria such as accuracy, adaptability, and clarity. Specific structural metrics provided quantitative insights into the ontology's organization, with particular attention given to average depth and breadth, relationship richness, inheritance richness, and attribute richness. The average depth of 2.32 and breadth of 13.25 suggested a balanced hierarchical structure and extensive horizontal expansion, deemed suitable for the textile domain's varied categories. However, subsequent refinements during validation led to a slight decrease in some of these metrics, this was not due to the loss of functionality but rather stipulated the limitations of the metrics and their dependence on the context.
Queries against competency questions confirmed the ontology's completeness in covering domain knowledge necessary for circular practices, such as material categorization and lifecycle data. It showed adaptability to new trends and technologies and supported efficient data exchange across industries, satisfying several functional requirements. Structural requirements were largely met, as the ontology provided a detailed representation of semantic data, a clear vocabulary, and maintained logical inheritance of properties. However, requirement 2.4, concerning the validation of definitions by industry experts, was not met due to the absence of such a validation using the correct experts.

Validation through practical application in the Semantic Treehouse illustrated the ontology's interoperability with the FEDeRATED ontology and its ability to function well in cross-domain querying, as evidenced by successful integration with the Catena-X battery pass ontology, which was used as example in this case due to its easy availability. Despite these advancements, the ontology's, maintenance, as outlined in environmental requirements 3.2 and 3.3, remained unvalidated within the scope of this study.
The final version of the ontology, though not without areas for future enhancement, presents a solid framework that supports the textile industry's shift towards circularity. It demonstrates a balance between detailed domain representation and adaptability for cross-domain application, paving the way for future extensions and updates that will undoubtedly be necessitated by the evolving landscape of circular economy practices.

In the evaluation of the ontology, several key findings were identified, providing valuable insights into its design and functionality. The use of tools like HermiT and OOPS! was instrumental in identifying and addressing both critical and minor issues, ensuring the ontology's logical coherence and clarity. The iterative refinement process, informed by quantitative metrics and feedback, enhanced the ontology's alignment with criteria such as accuracy, adaptability, and clarity. The validation exercises, including queries against competency questions and practical application scenarios, demonstrated the ontology's completeness and its ability to cover essential domain knowledge for circular practices. These exercises also highlighted the ontology's adaptability to new trends and its capability for efficient data exchange across various industries. Although certain aspects, like validation by industry experts, were not fully realized, the ontology's successful integration with the FEDeRATED ontology and its functionality in cross-domain querying were affirmed. The final ontology, while presenting areas for future enhancement, stands as a robust framework that supports the textile industry's move towards circularity, offering a balance of detailed domain representation and adaptability.

Sq 5. What structure will the final ontology have to represent semantic data in the textile industry while being compatible with the FEDeRATED ontology?

The final structure of the ontology was obtained after the evaluation and validation of the preliminary ontology. It is important to note that this is the final version of the ontology for this research, as said earlier. While the development of the ontology, especially for the complex textile industry, is hardly ever fully complete, this version serves the current research needs effectively. The detailed structure of the ontology, which includes classes, properties, and individuals tailored to the textile industry, is thoroughly documented in Appendices C, D & E.

The comprehensive and robust nature of the ontology, as revealed in these appendices, demonstrates its capacity to accurately represent semantic data within the textile industry while being compatible with the FEDeRATED ontology. This compatibility is crucial for ensuring seamless integration into broader data ecosystems, facilitating interoperability and data exchange. The practical use cases detailed in the appendices highlight the ontology's functionality in real-world scenarios, showcasing its ability to handle complex data representations and queries. These examples underline the ontology's versatility and relevance to the industry's evolving digital landscape.
The current version of the ontology, though considered complete for this research, provides a solid foundation for future enhancements. As the textile industry continues to evolve with advancements in digitalization and sustainability, the ontology can be adapted and expanded to meet new challenges and requirements. This adaptability ensures that the ontology will remain a relevant and effective tool for promoting circularity and sustainability in the textile industry.
In summary, the final version of the ontology presents a well-structured and adaptable framework that supports the textile industry's transition towards more integrated and sustainable practices. It aligns with the broader objectives of the FEDeRATED project, marking a significant step towards standardizing and enhancing semantic data representation in the textile sector. This ontology not only demonstrates a balance between detailed domain representation and adaptability for cross-domain application but also sets the stage for future extensions and updates in line with the evolving landscape of circular economy practices.

How can we structure a prototype textile-ontology that leverages the FEDeRATED project, to maximise its contribution to providing insights in circular data?

To address the main research question on structuring a prototype textile ontology that leverages the FEDeRATED project to maximize its contribution to providing insights into circular data, the focus was particularly on the role of textile sorters. The ontology's development was steered by the critical role of textile sorters in the industry, whose work is foundational for efficient recycling and waste reduction, pivotal for the circular economy. This was chosen as the core focus due to the sorters' key position in classifying textiles for subsequent lifecycle stages, thereby directly influencing the potential for reuse, recycling, and waste reduction.
The ontology aimed to provide a structured approach to data to support sorters and other stakeholders by offering a systematic way to identify and categorize textiles more effectively for circular practices. It was designed to be adaptable, allowing for updates as industry practices evolve and new data becomes relevant. This adaptability is crucial, ensuring that the ontology can remain a relevant and effective tool for promoting circularity in the textile industry as regulations and societal expectations change.
Moreover, aligning with regulatory standards, particularly the European Commission's ESPR Ecodesign regulations, the ontology can be easily maintained to keep relevance and compliance within the industry. It detailed critical product information vital for sorters' decision-making processes and supported the assessment of textiles' suitability for various circular pathways.
The structured data approach of the ontology also aimed to improve transparency and traceability within the industry, which has societal implications for consumer trust and ethical considerations. While the ontology primarily focused on satisfying the data needs of textile sorters, it also had the potential to provide relevant information for consumers.
This research has made notable scientific contributions by directly addressing the previously identified knowledge gaps in the literature review. Through the development and evaluation of a prototype ontology tailored for the textile industry, this study advances our understanding of how ontologies can be leveraged to promote circularity in manufacturing, particularly in the textile sector. This significant advancement in the field demonstrates the importance of domain-specific ontological frameworks and sets the stage for future developments in this rapidly evolving area of research.

Enhancements to this research included rigorous testing of the ontology in real-world scenarios, validating its effectiveness in various practical applications. The detailed structure of the ontology, as outlined in the appendices, captures the complexities of the textile industry, ensuring its accuracy and compatibility with the FEDeRATED project. The ontology’s adaptability and compliance with regulatory standards such as the European Commission's ESPR Ecodesign regulations highlight its potential for future enhancements. Furthermore, the ontology’s structured data approach significantly contributes to improving industry transparency and traceability, underlining its societal impact.

6.3 Societal Contribution

The societal relevance of the domain-specific ontology developed for the textile industry is notably significant in the context of global sustainability efforts. By structuring data to support textile sorters and other industry stakeholders, the ontology serves as a foundational tool for advancing circular economy practices within the textile sector, demonstrating its applicability beyond mere textile management.
The critical role of informed and efficient textile sorting is central to achieving a circular economy, a key aspect addressed by this ontology. The focus on improving data management through the ontology directly supports textile sorters in making well-informed decisions, crucial for enhancing reuse, recycling, and waste reduction practices. This direct impact of the ontology on textile sorting operations is a clear demonstration of its utility in environmental sustainability within the industry. These informed decisions contribute to lowering environmental impact by optimizing resource usage and minimizing landfill accumulation.
The development of this ontology specifically addresses the need for improved data handling in the textile sorting process, directly contributing to more sustainable practices. The ontology's role in facilitating better decision-making in textile sorting directly impacts the industry's environmental footprint by supporting effective recycling and material conservation strategies. This reflects the ontology’s practical contribution to reducing the reliance on virgin resources and minimizing waste generation in the textile industry.

In terms of economic implications, the ontology's implementation in textile sorting processes can enhance the efficiency of material recovery, thereby indirectly contributing to more sustainable and potentially cost-effective textile production methods. This tangible outcome of the ontology supports the industry's efforts towards a circular economy by enabling a more efficient and sustainable use of resources.
The ontology's structured approach to data also plays a crucial role in enhancing transparency and traceability within the textile industry. This is directly aligned with the research's objective to improve data management in the industry, thereby contributing to increased consumer awareness and industry accountability. While the primary focus of the ontology is to address the data needs of textile sorters, its structured data approach inherently promotes greater transparency in the textile production cycle.

Lastly, the ontology's adaptability to evolving industry standards and societal expectations is a key contribution from a societal perspective. This adaptability, highlighted in the research, ensures the ontology's continued relevance and effectiveness in the rapidly changing textile industry landscape. Aligning with regulatory standards, such as the European Commission's Ecodesign regulations, the ontology not only adheres to current compliance requirements but also reflects the industry's broader commitment to sustainability.

- Enhanced Circular Economy Practices: Demonstrated the ontology's role as a foundational tool in advancing circular economy practices within the textile sector.

- Informed Decision Making: Supported textile sorters in making well-informed decisions, crucial for enhancing reuse, recycling, and reducing waste, thus optimizing resource usage, and minimising landfill accumulation.

- Sustainable Practices Contribution: Addressed the need for improved data handling in textile sorting, contributing to effective recycling and material conservation strategies.

- Economic Implications: Enhanced material recovery efficiency, indirectly contributing to more sustainable and cost-effective textile production methods.

- Transparency and Traceability: Played a crucial role in enhancing industry transparency and traceability, contributing to increased consumer awareness and industry accountability.

- Adaptability to Evolving Standards: Showcased adaptability to evolving industry standards and societal expectations, ensuring ongoing relevance and effectiveness.

- Alignment with Regulatory Standards: Aligned with regulatory standards like the Ecodesign regulations, reflecting the industry's commitment to sustainability.

In conclusion, this ontology's societal impact is grounded in its direct contributions to enhancing sustainability practices within the textile industry. Its role in supporting environmentally responsible decisions, improving resource efficiency, enhancing industry transparency, and adapting to evolving standards demonstrates its tangible impact on promoting a more sustainable textile industry. While the ontology's primary aim is to address specific industry needs, its broader implications underscore the importance of structured data management in fostering sustainable practices within the textile industry.

6.4 Scientific Contribution

Within the textile industry's journey toward a circular economy, the development of a domain-specific ontology, particularly for textile sorters, is a considered step in enhancing the management of crucial data. This ontology is designed not as a cure-all for the industry's environmental challenges but as a facilitative tool to improve the organization and accessibility of data, addressing the identified knowledge gap concerning data fragmentation and unavailability. Its primary aim is to assist sorters by providing a systematic approach to data that may help in identifying and categorizing textiles for recycling or repurposing more efficiently. This directly addresses the lack of comprehensive textile ontologies tailored to the sector's complexities and sustainability requirements.

The determination of data requirements for the ontology drew upon a combination of expert opinion and insights from ongoing ontological research within the textile industry. This methodological approach correlates with the research's aim to fill the identified knowledge gap by creating a well-structured and applicable ontology. The ontology is structured to offer clearer semantics, thus potentially improving data management and exchange. This directly contributes to reducing the knowledge gap in data semantics in circular systems.

The project's scope was crafted in response to the identified lack of academic focus on ontological needs for circularity. These factors led to a strategic focus on textile sorters, acknowledging their pivotal position in sorting and classifying textiles for subsequent stages of the product lifecycle.

In aligning the ontology with regulatory standards, particularly the European Commission's ESPR Ecodesign regulations, the ontology takes a step toward not only maintaining relevance but also advancing compliance within the industry. This alignment directly addresses the regulatory challenges identified in the literature review, demonstrating the ontology's practical application in navigating the evolving landscape of circular economy legislation.

The ontology details critical product information—such as the steps of production, size, colour, material content, and country of origin—which are vital for sorters in their decision-making process. By organizing and presenting this information systematically, the ontology directly addresses the need for improved decision-making processes in textile sorting, as identified in the literature review.

The design for adaptability is a key feature of the ontology, intentionally avoiding an overemphasis on minutiae in favour of a more generalised structure. This design choice is a direct response to the evolving nature of the textile industry and the need for flexible data management tools, as identified in the research.

In conclusion, while the ontology offers a modest yet substantive contribution to the scientific community, it is primarily a practical tool for the textile industry. It addresses the specific knowledge gaps and challenges identified in the literature review, setting a foundation for ongoing research and gradual development, supporting the industry's incremental shift towards more sustainable circular practices. Following are the key scientific contributions of this research:

- Developed a specialised ontology for textile sorters, directly addressing the identified knowledge gap by providing a structured approach to crucial data management in the textile industry's transition to a circular economy.

- Integrated expert opinions and existing research to shape the data requirements for the ontology, advancing the application of domain-specific knowledge structures within the textile sector.

- Structured the ontology to enhance data semantics and management, contributing scientifically to the field of data management and potentially serving as a reference model for other industries.

- Alignment with European regulatory standards underscores the ontology's practical application in navigating evolving legislation in the circular economy, demonstrating a scientific approach to legal compliance integration within industry-specific data management tools.

- Systematised detailing of critical product information, contributing to the science of product lifecycle management and decision support systems.

- Designed the ontology for adaptability, considering the evolving data needs and industry practices, showcasing a scientific strategy for future-proofing data management tools.

- Laid the groundwork for future scientific research and development in the textile industry towards sustainable and circular practices.

6.5 Limitations and Recommendations for Future Research

The journey of developing this ontology has been both enlightening and challenging. Each decision we made not only influenced our research outcomes but also brought important limitations to light. These limitations, inherent in our research process, have offered crucial insights that will guide future explorations.

At present, the ontology developed in this research is in a prototype phase. This state can be attributed to several key factors: the project's inherent time constraints, the multifaceted nature of the textile sector, and the limited availability of comprehensive data and literature. These challenges have not only defined the scope of our current model but also underscored the difficulties in fully capturing the textile industry's complexity within the ontology framework. As a prototype, the ontology is operational, yet it retains a conceptual dimension. This means that while it can function in practical scenarios, it might not yet encapsulate the complete range of data needed for an exhaustive representation of the textile sector. Therefore, the prototype serves as an initial model, offering valuable insights and a foundational understanding but still requiring further refinement and expansion to meet the industry's nuanced needs more effectively.

The research benefited significantly from the collaboration with a highly qualified textile expert. However, due to confidentiality agreements, the expert's identity remains undisclosed. Relying on a single, anonymous source could potentially impact the perceived credibility of our findings and might introduce a certain level of bias or limit the diversity of perspectives. To bolster the research's credibility and breadth, it will be crucial to validate and enhance the data with inputs from additional field experts, while respecting confidentiality constraints.

Our evaluation of the ontology's usefulness and effectiveness did not involve direct engagement with textile sorters. Instead, it was shaped by expert opinions, existing literature, and projected legislative changes. This approach, while informative, lacks empirical validation from the end-users in the sorting process, which may question the ontology's practical utility. It suggests that the ontology might not be fully aligned with the real-world needs and challenges faced by textile sorters, indicating a need for further empirical testing and refinement in actual sorting environments.

The initial ambition of this research was to create an ontology that would cater to a wide range of stakeholders within the circular textile economy. However, due to my novice status in both ontology design and the textile sector, coupled with the project's tight timeframe, we had to narrow our focus to the stakeholder deemed most critical for achieving circularity. While this decision was made to ensure the project's feasibility, it implies that the ontology might not be as versatile or comprehensive as initially intended. Future expansions should aim to encompass a broader spectrum of stakeholder needs, thereby enhancing its relevance and utility across the sector.

The limited engagement with textile sorters and the focused attention on this specific group means that the ontology's relevance to other stakeholders in the circular textile economy remains underdeveloped. This suggests that the current ontology might not fully address the diverse requirements and processes of other stakeholders such as manufacturers, retailers, or consumers. Future developments should aim to extend the ontology's scope to include these additional industry players.

As we transition from discussing these limitations to contemplating future directions, it's important to consider specific recommendations for further research. These recommendations, informed by our experiences and the challenges encountered during this study, are intended to refine and broaden the ontology's effectiveness and relevance within the textile industry.

Reflecting on the course of this project, it becomes clear that our approach to expert validation had certain limitations. We realised the importance of involving experts not just with domain knowledge but also with proficiency in data semantics. This dual expertise is crucial for a comprehensive and accurate evaluation of the ontology. We encountered challenges in fully validating requirement 2.4, partly due to our initial scope, which did not completely account for the complexities of semantic intricacies. This led to an over-reliance on our domain expert, whose expertise in semantic details was limited. To avoid the risk of circular validation, where the ontology is assessed based solely on the input of this expert, we employed competency questions derived from the data requirements. This approach facilitated a more objective assessment, ensuring the ontology met its intended functional specifications, although the validation was not as in-depth as we had initially hoped.

Recognising this, future research should prioritize engaging experts with a strong background in semantic content validation. This will enhance the robustness of the developed ontology. Furthermore, given the rapidly evolving nature of the textile industry, a continuous update plan for the ontology is essential. Regular updates will be crucial to maintain its relevance and accuracy, keeping pace with current industry standards and practices. In this context, the role of TNO in the FEDeRATED project is invaluable. Their extensive expertise, particularly in textiles, positions them ideally to manage the ongoing update process effectively.
In advancing the application of the ontology as outlined in this thesis, there are two main directions to consider. Firstly, implementing real-world testing with a focus on textile sorters is essential. This step extends beyond theoretical analysis, providing tangible evidence of the ontology's utility in a practical setting. By integrating the ontology into the daily operations of textile sorters, we can gather direct feedback on its functionality. This feedback is critical as it offers insights into how the ontology performs under actual working conditions, highlighting its strengths and identifying areas that may need modification. This real-world application is key to transitioning the ontology from a conceptual model to a practical tool within the textile industry.

Secondly, expanding the ontology's application to encompass a wider range of stakeholders is an important progression. The need for improved access to information for decision-making, as highlighted in chapter 3, applies to more stakeholders than just textile sorters. Expanding the applicability of the ontology opens up opportunities for broader impact and relevance. By exploring its use for consumers and retailers, the ontology can offer insights beyond operational efficiency; it can contribute to sustainable practices, product care, and supply chain transparency. Understanding the specific needs and potential benefits for these new user groups through targeted research is crucial. Such an expansion not only broadens the ontology's scope but also enhances its practicality, making it a more comprehensive and versatile tool that caters to the diverse needs of the textile industry.

Both these steps are essential to ensure that the ontology developed not only aligns with academic rigor but also proves robust in practical applications, catering to the dynamic needs of the textile industry. Building on the idea of inclusive development, a collaborative, multi-stakeholder approach is paramount, considering the societal impact of this research. It is crucial for government bodies, academic research institutions, industry associations, NGOs, and private sector companies to collaborate in championing these endeavours. This collective action is necessary to foster an ecosystem that supports sustainable and circular practices, thereby establishing them as the norm in the textile industry. Such a comprehensive approach ensures that various perspectives and expertise are considered, facilitating the creation of robust, universally applicable solutions that can drive significant change in the industry. The synergy from this multi-faceted collaboration is essential to make sustainable practices more pervasive and effective in addressing the environmental challenges facing the textile sector. The FEDeRATED project already fosters such collaborative effort, making it an ideal testbed for further testing and development of the ontology.

Building upon the foundation laid by previous steps, future research must also concentrate on expanding data fields to enhance transparency and efficiency. The addition of more comprehensive data fields is a pivotal area for exploration. By including information that enhances supply chain transparency, such as specifics of labour involvement, consumers will be better equipped to make informed decisions. Moreover, integrating complex metrics like FEDAS codes and yarn twist details could significantly improve the efficiency and cost-effectiveness of the sorting process for textile sorters. Investigating these expansions is crucial to maximize the ontology's functionality and bolster sustainability efforts within the textile industry.
Furthermore, the development process of the ontology has underscored the necessity for enhanced accessibility to information on material information and assembly processes. Future research initiatives should focus on improving the availability of this information. A key area should be the establishment of

effective disassembly protocols, which would facilitate product repair and enable fibre-to-fibre recycling. Essential to this approach is the emphasis on material traceability, crucial for verifying material quality and determining their genuine potential for recovery. Collaborative efforts between research institutions and industry innovators are necessary to develop these strategies. Such collaboration has the potential to bring about transformative changes in the way products are designed and recycled in the textile sector, aligning with broader sustainability goals, and advancing the industry towards a more circular economy.

Furthermore, the intersection of this ontology with emerging technologies presents another exciting frontier. Recognizing that ontologies are a part of the solution, their integration into broader frameworks like the FEDeRATED project, which focuses on cross-domain data exchange, is essential. Additionally, staying attuned to advancements in technologies like generative AI and large language models (LLMs) is imperative. These technologies might not only enhance the ontology but also offer more efficient solutions. Guided by the overarching objective of minimizing the environmental impact of the textile industry, these research endeavors should seek to leverage new technologies to complement and enhance the existing ontology, ensuring that the field remains at the forefront of innovation and sustainability.

In conclusion, these recommendations for future research address the limitations of the current study and propose a collaborative approach involving various stakeholders. By engaging a diverse group of leaders from government, academia, industry, and technology sectors, future research can significantly advance the ontology's development, making it a more dynamic and impactful tool in the textile industry.

7 Bibliography

Aaltonen, K. (2011). Project stakeholder analysis as an environmental interpretation process. *International Journal of Project Management*, *29* (2), 165–183. https://doi.org/10.1016/J.IJPROMAN.2010.02.001

Achsan, H. T. Y., Suhartanto, H., & Wibowo, W. C. (2017). Ontology enrichment for multi-domain knowledge and expertise representation. *Annals of DAAAM and Proceedings of the International DAAAM Symposium*, 1170–1177. https://doi.org/10.2507/28TH.DAAAM.PROCEEDINGS.162

Allemang, D., & Hendler, J. (2011). Semantic Web for the Working Ontologist. *Semantic Web for the Working Ontologist*. https://doi.org/10.1016/C2010-0-68657-3

Alves, L., Ferreira Cruz, E., Lopes, S. I., Faria, P. M., & Rosado da Cruz, A. M. (2022). Towards circular economy in the textiles and clothing value chain through blockchain technology and IoT: A review. *Waste Management & Research : The Journal of the International Solid Wastes and Public Cleansing Association, ISWA*, *40*(1), 3–23. https://doi.org/10.1177/0734242X211052858

Ameen, A., Khan, K. U. R., & Rani, B. P. (2014). Extracting knowledge from ontology using Jena for semantic web. *2014 International Conference for Convergence of Technology, I2CT 2014*. https://doi.org/10.1109/I2CT.2014.7092025

Amith, M., He, Z., Bian, J., Lossio-Ventura, J. A., & Tao, C. (2018). Assessing the practice of biomedical ontology evaluation: Gaps and opportunities. *Journal of Biomedical Informatics*, *80*, 1–13. https://doi.org/10.1016/J.JBI.2018.02.010

Annamalai, G., Hussain, R., Cakkol, M., Roy, R., Evans, S., & Tiwari, A. (2011). An Ontology for Product-Service Systems. *Functional Thinking for Value Creation*, 231–236. https://doi.org/10.1007/978-3-642-19689-8_41

Arena, D., & Kiritsis, D. (2017). A methodological framework for ontology-driven instantiation of petri net manufacturing process models. *IFIP Advances in Information and Communication Technology*, *517*, 557–567. https://doi.org/10.1007/978-3-319-72905-3_49

Baader, F., Calvanese, D., Mcguinness, D., Nardi, D., & Patel-Schneider, P. (2007). *The Description Logic Handbook: Theory, Implementation, and Applications*.

Bechhofer, S., Harmelen, F., Hendler, J., Horrocks, I., Mcguinness, D., Patel-Schneider, P., & Stein, L. (2004). *OWL Web Ontology Language Reference*.

Berners-Lee, T. (2006). *Linked Data - Design Issues*. W3C. https://www.w3.org/DesignIssues/LinkedData.html

Berners-Lee, T., Hendler, J., & Lassila, O. (2001). The Semantic Web A new form of Web content that is meaningful to computers will unleash a revolution of new possibilities. *Scientific American*, *284*(5), 34–43. https://www-sop.inria.fr/acacia/cours/essi2006/Scientific%20American_%20Feature%20Article_%20The%20Semantic%20Web_%20May%202001.pdf

Bizer, C., Heath, T., & Berners-Lee, T. (2009). Linked data - The story so far. *International Journal on Semantic Web and Information Systems*, *5*(3), 1–22. https://doi.org/10.4018/JSWIS.2009081901

Boeker, M., Jansen, L., Grewe, N., Röhl, J., Schober, D., Seddig-Raufie, D., & Schulz, S. (2013). Effects of Guideline-Based Training on the Quality of Formal Ontologies: A Randomized Controlled Trial. *PLOS ONE*, *8*(5), e61425. https://doi.org/10.1371/JOURNAL.PONE.0061425

Boons, F., & Lüdeke-Freund, F. (2013). Business models for sustainable innovation: state-of-the-art and steps towards a research agenda. *Journal of Cleaner Production*, *45*, 9–19. https://doi.org/10.1016/J.JCLEPRO.2012.07.007

Borsato, M. (2014). Bridging the gap between product lifecycle management and sustainability in manufacturing through ontology building. *Computers in Industry*, *65*(2), 258–269. https://doi.org/10.1016/J.COMPIND.2013.11.003

Borst, W. (1997). *Construction of Engineering Ontologies for Knowledge Sharing and Reuse*. https://research.utwente.nl/en/publications/construction-of-engineering-ontologies-for-knowledge-sharing-and-

Cao, Q., Zanni-Merk, C., & Reich, C. (2019). Ontologies for manufacturing process modeling: A survey. *Smart Innovation, Systems and Technologies*, *130*, 61–70. https://doi.org/10.1007/978-3-030-04290-5_7

Chaware, S., & Rao, S. (2010). Integrated Approach To Ontology Developement Methodology With Case Study. *International Journal of Database Management Systems*, *2*(3), 13–19. https://doi.org/10.5121/IJDMS.2010.2302

Chungoora, N., Gunendran, G. A., Young, R. I. M., Usman, Z., Anjum, N. A., Palmer, C., Harding, J. A., Case, K., & Cutting-Decelle, A. F. (2012). Extending product lifecycle management for manufacturing knowledge sharing. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, *226*(12), 2047–2063. https://doi.org/10.1177/0954405412461741

Chungoora, N., Young, R. I., Gunendran, G., Palmer, C., Usman, Z., Anjum, N. A., Cutting-Decelle, A. F., Harding, J. A., & Case, K. (2013). A model-driven ontology approach for manufacturing system interoperability and knowledge sharing. *Computers in Industry*, *64*(4), 392–401. https://doi.org/10.1016/J.COMPIND.2013.01.003

Circular.fashion. (2019). *CIRCULARITY.ID The transformation to data-driven circularity in fashion*. https://circularity.id/static/circular.fashion_circularityID_white_paper_2021.pdf

Circular.fashion. (2020). *CIRCULARITY.ID® OPEN DATA STANDARD SCHEMA V 4.0*. https://circularity.id/open-data-standard.html#

Clarkson, J. J., Hirt, E. R., Jia, L., & Alexander, M. B. (2010). When Perception Is More Than Reality: The Effects of Perceived Versus Actual Resource Depletion on Self-Regulatory Behavior. *Journal of Personality and Social Psychology*, *98*(1), 29–46. https://doi.org/10.1037/A0017539

Danial-Saad, A., Kuflik, T., Weiss, P. L., & Schreuer, N. (2013). Building an ontology for assistive technology using the Delphi method. *Disability and Rehabilitation. Assistive Technology*, *8*(4), 275–286. https://doi.org/10.3109/17483107.2012.723238

Degbelo, A. (2017). A snapshot of ontology evaluation criteria and strategies. *ACM International Conference Proceeding Series*, *2017-September*, 1–8. https://doi.org/10.1145/3132218.3132219

Diéguez-Santana, K., Rodríguez Rudi, G., Acevedo Urquiaga, A. J., Muñoz, E., & Sablón-Cossio, N. (2021). An assessment tool for the evaluation of circular economy implementation. *Academia Revista Latinoamericana de Administracion*, *34*(2), 316–328. https://doi.org/10.1108/ARLA-08-2020-0188

Do Amaral, M. C., Zonatti, W. F., Da Silva, K. L., Junior, D. K., Neto, J. A., & Baruque-Ramos, J. (2018). Industrial textile recycling and reuse in Brazil: case study and considerations concerning the circular economy. *Gestão & Produção*, *25*(3), 431–443. https://doi.org/10.1590/0104-530X3305

Drechsler, A. (2017). *Designing for Change and Transformation: Exploring Artefact Generativity*. https://doi.org/10.26686/WGTN.13088396.V1

DTLF Subgroup 2 - Corridor Information Systems. (2023). *Data Sharing Architecture for freight data*.

European Commission. (2022a). *European Commission-Press release Green Deal: New proposals to make sustainable products the norm and boost Europe's resource independence*. https://ec.europa.eu/commission/presscorner/detail/en/ip_22_2013

European Commission. (2022b). *Ecodesign for sustainable products*. https://commission.europa.eu/energy-climate-change-environment/standards-tools-and-labels/products-labelling-rules-and-requirements/sustainable-products/ecodesign-sustainable-products-regulation_en

European Commission. (2023). EU strategy for sustainable and circular textiles. https://environment.ec.europa.eu/strategy/textiles-strategy_en

European Environment Agency. (2022). *Textiles and the environment: the role of design in Europe's circular economy*. https://doi.org/10.2800/578806

European Parliament. (2015). *Circular economy: definition, importance and benefits | News | European Parliament*. https://www.europarl.europa.eu/news/en/headlines/economy/20151201STO05603/circular-economy-definition-importance-and-benefits

Fahrenbach, F. (2022). A design science approach to developing and evaluating items for the assessment of transversal professional competences. *Education and Training*, *64*(1), 21–40. https://doi.org/10.1108/ET-03-2020-0056/FULL/PDF

Farghaly, K. (2020). *Building Information Modelling and Asset Management: Semantic and Syntactic Interoperability*.

FEDeRATED. (2022). *FEDeRATED REFERENCE DATA SHARING ARCHITECTURE under development Serves as Annex 1 to FEDeRATED MILESTONE 10*. www.federatedplatforms.eu

Franco, M., Vivo, J. M., Quesada-Martínez, M., Duque-Ramos, A., & Fernández-Breis, J. T. (2020). Evaluation of ontology structural metrics based on public repository data. *Briefings in Bioinformatics*, *21*(2), 473–485. https://doi.org/10.1093/BIB/BBZ009

Freeman, R. E., Harrison, J. S., Wicks, A. C., Parmar, B., & de Colle, S. (2010). Stakeholder theory: The state of the art. *Stakeholder Theory: The State of the Art*, 1–343. https://doi.org/10.1017/CBO9780511815768

Gacitua, R., Casteleiro, M. A., Sawyer, P., Des, J., Perez, R., Ferández-Prieto, M. J., & Paniagua, H. (2009). A collaborative workflow for building ontologies: A case study in the biomedical field. *Proceedings of the 2009 3rd International Conference on Research Challenges in Information Science, RCIS 2009*, 121–128. https://doi.org/10.1109/RCIS.2009.5089275

Gangemi, A., Catenacci, C., Ciaramita, M., & Lehmann, J. (2005). A theoretical framework for ontology evaluation and validation. *CEUR Workshop Proceedings*, *166*.

Garcés-Ayerbe, C., Rivera-Torres, P., Suárez-Perales, I., & Hiz, D. I. L. D. La. (2019). Is it possible to change from a linear to a circular economy? An overview of opportunities and barriers for european small and medium-sized enterprise companies. *International Journal of Environmental Research and Public Health*, *16*(5). https://doi.org/10.3390/IJERPH16050851

García, R., & Gil, R. (2009). Copyright Licenses Reasoning an OWL-DL Ontology. *Frontiers in Artificial Intelligence and Applications*, *188*(1), 145–162. https://doi.org/10.3233/978-1-58603-942-4-145

Geissdoerfer, M., Pieroni, M. P. P., Pigosso, D. C. A., & Soufani, K. (2020). Circular business models: A review. *Journal of Cleaner Production*, *277*, 123741. https://doi.org/10.1016/J.JCLEPRO.2020.123741

Geissdoerfer, M., Savaget, P., Bocken, N. M. P., & Hultink, E. J. (2017). The Circular Economy – A new sustainability paradigm? *Journal of Cleaner Production*, *143*, 757–768. https://doi.org/10.1016/J.JCLEPRO.2016.12.048

Gennari, J. H., Musen, M. A., Fergerson, R. W., Grosso, W. E., Crubezy, M., Eriksson, H., Noy, N. F., & Tu, S. W. (2003). The evolution of Protégé: an environment for knowledge-based systems development. *International Journal of Human-Computer Studies*, *58*(1), 89–123. https://doi.org/10.1016/S1071-5819(02)00127-1

Gerber, A., Morar, N., Meyer, T., & Eardley, C. (2017). Ontology-based support for taxonomic functions. *Ecological Informatics*, *41*, 11–23. https://doi.org/10.1016/J.ECOINF.2017.06.003

Glimm, B., Kazakov, Y., Kollia, I., & Stamou, G. (2015). Lower and Upper Bounds for SPARQL Queries over OWL Ontologies. *Proceedings of the AAAI Conference on Artificial Intelligence*, *29*(1), 109–115. https://doi.org/10.1609/AAAI.V29I1.9192

Globa, L. S., Novogrudska, R. L., Zadoienko, B. O., & Junfeng, Y. (2020). ONTOLOGY OF SCIENTIFIC AND EDUCATIONAL INSTITUTIONS INFORMATION. *Information and Telecommunication Sciences*, *0*(2), 86–91. https://doi.org/10.20535/2411-2976.22020.86-91

Goldstein, A., Fink, L., & Ravid, G. (2021). A Framework for Evaluating Agricultural Ontologies. *Sustainability 2021, Vol. 13, Page 6387*, *13*(11), 6387. https://doi.org/10.3390/SU13116387

Gómez-Pérez, A., Fernández-López, M., & Corcho, O. (2004). *Ontological engineering : with examples from the areas of knowledge management, e-commerce and the Semantic Web*. 403.

Göppert, A., Grahn, L., Rachner, J., Grunert, D., Hort, S., & Schmitt, R. H. (2021). Pipeline for ontology-based modeling and automated deployment of digital twins for planning and control of manufacturing systems. *Journal of Intelligent Manufacturing*, *34*(5), 2133–2152. https://doi.org/10.1007/S10845-021-01860-6

Gruber, T. R. (1993). A translation approach to portable ontology specifications. *Knowledge Acquisition*, *5*(2), 199–220. https://doi.org/10.1006/KNAC.1993.1008

Guardia, G. D. A., Vêncio, R. Z. N., & de Farias, C. R. G. (2012). A UML profile for the OBO relation ontology. *BMC Genomics*, *13 Suppl 5*(5), 1–19. https://doi.org/10.1186/1471-2164-13-S5-S3/FIGURES/8

Hadar, I., & Soffer, P. (2006). Variations in Conceptual Modeling: Classification and Ontological Analysis. *Journal of the Association for Information Systems*, *7*(8), 568–592. https://doi.org/10.17705/1JAIS.00096

Harris, M., & Pemberton, M. (1995). Online Writing Labs (OWLs): A taxonomy of options and issues. *Computers and Composition*, *12*(2), 145–159. https://doi.org/10.1016/8755-4615(95)90003-9

Hartung, M., Groß, A., & Rahm, E. (2013). COnto–Diff: generation of complex evolution mappings for life science ontologies. *Journal of Biomedical Informatics*, *46*(1), 15–32. https://doi.org/10.1016/J.JBI.2012.04.009

Hasanbeigi, A., & Price, L. (2015). A technical review of emerging technologies for energy and water efficiency and pollution reduction in the textile industry. *Journal of Cleaner Production*, *95*, 30–44. https://doi.org/10.1016/J.JCLEPRO.2015.02.079

Hepp, M. (2007). Possible ontologies: How reality constrains the development of relevant ontologies. *IEEE Internet Computing*, *11*(1), 90–96. https://doi.org/10.1109/MIC.2007.20
Herazo, B., & Lizarralde, G. (2016). Understanding stakeholders' approaches to sustainability in building projects. *Sustainable Cities and Society*, *26*, 240–254. https://doi.org/10.1016/J.SCS.2016.05.019
Hildebrandt, C., Kocher, A., Kustner, C., Lopez-Enriquez, C. M., Muller, A. W., Caesar, B., Gundlach, C. S., & Fay, A. (2020). Ontology Building for Cyber-Physical Systems: Application in the Manufacturing Domain. *IEEE Transactions on Automation Science and Engineering*, *17*(3), 1266–1282. https://doi.org/10.1109/TASE.2020.2991777
Horridge, M. (2011). *A Practical Guide To Building OWL Ontologies Using Protégé 4 and CO-ODE Tools Edition 1.3*.
Huang, Z., Jowers, C., Dehghan-Manshadi, A., & Dargusch, M. S. (2020). Smart manufacturing and DVSM based on an Ontological approach. *Computers in Industry*, *117*, 103189. https://doi.org/10.1016/J.COMPIND.2020.103189
Irfan, M., Thaheem, M. J., Gabriel, H. F., Malik, M. S. A., & Nasir, A. R. (2019). Effect of stakeholder's conflicts on project constraints: a tale of the construction industry. *International Journal of Conflict Management*, *30*(4), 538–565. https://doi.org/10.1108/IJCMA-04-2019-0074
Islam, M. T., Iyer-Raniga, U., & Trewick, S. (2022). Recycling Perspectives of Circular Business Models: A Review. *Recycling*, *7*(5), 79. https://doi.org/10.3390/RECYCLING7050079/S1
Jabla, R., Khemaja, M., Buendia, F., & Faiz, S. (2021). Automatic Ontology-Based Model Evolution for Learning Changes in Dynamic Environments. *Applied Sciences 2021, Vol. 11, Page 10770*, *11*(22), 10770. https://doi.org/10.3390/APP112210770
Jackson, R. C., Balhoff, J. P., Douglass, E., Harris, N. L., Mungall, C. J., & Overton, J. A. (2019). ROBOT: A Tool for Automating Ontology Workflows. *BMC Bioinformatics*, *20*(1), 1–10. https://doi.org/10.1186/S12859-019-3002-3/FIGURES/1
Jiang, X., & Tan, A. H. (2009). Learning and inferencing in user ontology for personalized Semantic Web search. *Information SciencesInformatics and Computer Science, Intelligent Systems, Applications: An International Journal*, *179*(16), 2794–2808. https://doi.org/10.1016/J.INS.2009.04.005
Jing, Y., Jeong, D., & Baik, D. K. (2009). SPARQL graph pattern rewriting for OWL-DL inference queries. *Knowledge and Information Systems*, *20*(2), 243–262. https://doi.org/10.1007/S10115-008-0169-8/METRICS
Johannesson, P., & Perjons, E. (2014). An introduction to design science. *An Introduction to Design Science*, *9783319106328*, 1–197. https://doi.org/10.1007/978-3-319-10632-8/COVER
Kayal, B., Abu-Ghunmi, D., Abu-Ghunmi, L., Archenti, A., Nicolescu, M., Larkin, C., & Corbet, S. (2019). An economic index for measuring firm's circularity: The case of water industry. *Journal of Behavioral and Experimental Finance*, *21*, 123–129. https://doi.org/10.1016/J.JBEF.2018.11.007
Keßler, L., Matlin, S. A., & Kümmerer, K. (2021). The contribution of material circularity to sustainability—Recycling and reuse of textiles. *Current Opinion in Green and Sustainable Chemistry*, *32*, 100535. https://doi.org/10.1016/J.COGSC.2021.100535
Khan, R., Tomar, R., Hartmann, T., Ungureanu, L., Chacón, R., & Ibrahim, A. (2022). *Platology: A Digital Twin Ontology Suite for the Complete Lifecycle of Infrastructure*. 290–299. https://doi.org/10.7146/AUL.455.C219
Khobreh, M., Ansari, F., Fathi, M., Vas, R., Mol, S. T., Berkers, H. A., & Varga, K. (2016). An Ontology-Based Approach for the Semantic Representation of Job Knowledge. *IEEE Transactions on Emerging Topics in Computing*, *4*(3), 462–473. https://doi.org/10.1109/TETC.2015.2449662
Kim, S., & Oh, S. G. (2019). Extracting and applying evaluation criteria for ontology quality assessment. *Library Hi Tech*, *37*(3), 338–354. https://doi.org/10.1108/LHT-01-2019-0012/FULL/XML
Kirchherr, J., Reike, D., & Hekkert, M. (2017). Conceptualizing the Circular Economy: An Analysis of 114 Definitions. *SSRN Electronic Journal*. https://doi.org/10.2139/SSRN.3037579
Koszewska, M. (2018). Circular Economy - Challenges for the Textile and Clothing Industry. *Autex Research Journal*, *18*(4), 337–347. https://doi.org/10.1515/AUT-2018-0023
Kumar, S., Baliyan, N., & Sukalikar, S. (2017). Ontology Cohesion and Coupling Metrics. *International Journal on Semantic Web & Information Systems*, *13*(4), 1–26. https://doi.org/10.4018/IJSWIS.2017100101
Leal Filho, W., Perry, P., Heim, H., Dinis, M. A. P., Moda, H., Ebhuoma, E., & Paço, A. (2022). An overview of the contribution of the textiles sector to climate change. *Frontiers in Environmental Science*, *10*. https://doi.org/10.3389/FENVS.2022.973102

Li, H., Abd Nikooie Pour, M., Li, Y., Lindecrantz, M., Blomqvist, E., & Lambrix, P. (2023). A Survey of General Ontologies for the Cross-Industry Domain of Circular Economy. *ACM Web Conference 2023 - Companion of the World Wide Web Conference, WWW 2023*, 731–741. https://doi.org/10.1145/3543873.3587613

Li, W., & Li, C. (2022). Path Analysis of the Impact of Digital Transformation on Export Performance of Textile and Apparel Companies. *Open Journal of Business and Management*, *10*(6), 2903–2914. https://doi.org/10.4236/OJBM.2022.106143

Ma, Z., Capretz, M. A. M., & Yan, L. (2016). Storing massive Resource Description Framework (RDF) data: a survey. *The Knowledge Engineering Review*, *31*(4), 391–413. https://doi.org/10.1017/S0269888916000217

Madhav, S., Ahamad, A., Singh, P., & Mishra, P. K. (2018). A review of textile industry: Wet processing, environmental impacts, and effluent treatment methods. *Environmental Quality Management*, *27*(3), 31–41. https://doi.org/10.1002/TQEM.21538

MaduraiMeenachi, N., & Sai Baba, M. (2012). Web Ontology Language Editors for Semantic Web - A Survey. *International Journal of Computer Applications*, *53*(12), 12–16. https://doi.org/10.5120/8472-2398

Manouselis, N., Sicilia, M. A., & Rodríguez, D. (2010). Exploring ontology metrics in the biomedical domain. *Procedia Computer Science*, *1*(1), 2319–2328. https://doi.org/10.1016/J.PROCS.2010.04.260

Matos, A. I., & Belfo, F. P. (2022). Use of Ontologies in Product Information Management: A Proposal for a Multinational Engineering and Technology Company. *Procedia Computer Science*, *204*, 599–609. https://doi.org/10.1016/J.PROCS.2022.08.073

Meierhofer, J., Schweiger, L., Lu, J., Züst, S., West, S., Stoll, O., & Kiritsis, D. (2021). Digital Twin-Enabled Decision Support Services in Industrial Ecosystems. *Applied Sciences 2021, Vol. 11, Page 11418*, *11*(23), 11418. https://doi.org/10.3390/APP112311418

Millar, N., McLaughlin, E., & Börger, T. (2019). The Circular Economy: Swings and Roundabouts? *Ecological Economics*, *158*, 11–19. https://doi.org/10.1016/J.ECOLECON.2018.12.012

Musen, M. A. (2015). The protégé project: a look back and a look forward. *AI Matters*, *1*(4), 4–12. https://doi.org/10.1145/2757001.2757003

Nazir, S., Motla, Y. H., Abbas, T., Khatoon, A., Jabeen, J., Iqra, M., & Bakhat, K. (2014). A process improvement in requirement verification and validation using ontology. *Asia-Pacific World Congress on Computer Science and Engineering, APWC on CSE 2014*. https://doi.org/10.1109/APWCCSE.2014.7053837

Nørup, N., Pihl, K., Damgaard, A., & Scheutz, C. (2018). Development and testing of a sorting and quality assessment method for textile waste. *Waste Management*, *79*, 8–21. https://doi.org/10.1016/J.WASMAN.2018.07.008

Nørup, N., Pihl, K., Damgaard, A., & Scheutz, C. (2019). Evaluation of a European textile sorting centre: Material flow analysis and life cycle inventory. *Resources, Conservation and Recycling*, *143*, 310–319. https://doi.org/10.1016/J.RESCONREC.2019.01.010

Onto-Deside. (2022). *Use Case Needs Analysis and Circular Value Flow Mapping-Report v1*. https://ontodeside.eu/

Orme, A. M., Yao, H., Etzkorn, L. H., Orme, A. M., Yao, H., & Etzkorn, L. H. (2007). Indicating ontology data quality, stability, and completeness throughout ontology evolution. *Journal of Software Maintenance and Evolution: Research and Practice*, *19*(1), 49–75. https://doi.org/10.1002/SMR.341

Panetto, H., Dassisti, M., & Tursi, A. (2012). ONTO-PDM: Product-driven ONTOlogy for Product Data Management interoperability within manufacturing process environment. *Advanced Engineering Informatics*, *26*(2), 334–348. https://doi.org/10.1016/J.AEI.2011.12.002

Patti, A., Cicala, G., & Acierno, D. (2020). Eco-Sustainability of the Textile Production: Waste Recovery and Current Recycling in the Composites World. *Polymers 2021, Vol. 13, Page 134*, *13*(1), 134. https://doi.org/10.3390/POLYM13010134

Pereira, J., Pimenta, D., Dias, D., Monteiro, P., Morais, F., Santos, N., Mendonça, J. P., Pereira, F., & Carvalhal, J. P. (2023). Implementing Semantic Interoperability in Cloud Collaborative Manufacturing: A Demonstration Case for an Ontology-Based Asset Efficiency Testbed. *Proceedings of the I-ESA Conferences*, *10*, 83–92. https://doi.org/10.1007/978-3-030-90387-9_8/FIGURES/6

Perrault, E. (2017). A 'Names-and-Faces Approach' to Stakeholder Identification and Salience: A Matter of Status. *Journal of Business Ethics*, *146*(1), 25–38. https://doi.org/10.1007/S10551-015-2929-1

Pinto, V. A., de Rezende Rohlfs, C. L., & Parreiras, F. S. (2014). Applications of ontologies in enterprise modelling: A systematic mapping study. Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), 8823, 23–32. https://doi.org/10.1007/978-3-319-12256-4_3/COVER

Poveda-Villalón, M., Gómez-Pérez, A., & Suárez-Figueroa, M. C. (2014). OOPS! (OntOlogy Pitfall Scanner!): An on-line tool for ontology evaluation. *International Journal on Semantic Web and Information Systems*, *10*(2), 7–34. https://doi.org/10.4018/IJSWIS.2014040102

Preut, A., Kopka, J.-P., Clausen, U., Adrodegari, F., Cristina, D., Pigosso, A., & Bressanelli, G. (2021). Digital Twins for the Circular Economy. *Sustainability 2021, Vol. 13, Page 10467*, *13*(18), 10467. https://doi.org/10.3390/SU131810467

Pushpa, C., Deepak, G., Thriveni, J., & Venugopal, K. (2016). A Hybridized Framework for Ontology Modeling incorporating Latent Semantic Analysis and Content based Filtering. *International Journal of Computer Applications*, *150*(11), 33–41. https://doi.org/10.5120/IJCA2016911665

Quinn, S., Bond, R., & Nugent, C. (2018). A two-staged approach to developing and evaluating an ontology for delivering personalized education to diabetic patients. *Informatics for Health and Social Care*, *43*(3), 264–279. https://doi.org/10.1080/17538157.2017.1364246

Ren, Y., Parvizi, A., Mellish, C., Pan, J. Z., Van Deemter, K., & Stevens, R. (2014). Towards competency question-driven ontology authoring. *Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, *8465 LNCS*, 752–767. https://doi.org/10.1007/978-3-319-07443-6_50/COVER

Ren, Z., Shi, J., & Imran, M. (2023). Data Evolution Governance for Ontology-Based Digital Twin Product Lifecycle Management. *IEEE Transactions on Industrial Informatics*, *19*(2), 1791–1802. https://doi.org/10.1109/TII.2022.3187715

Riemens, J., Lemieux, A. A., Lamouri, S., & Garnier, L. (2021). A Delphi-Régnier Study Addressing the Challenges of Textile Recycling in Europe for the Fashion and Apparel Industry. *Sustainability 2021, Vol. 13, Page 11700*, *13*(21), 11700. https://doi.org/10.3390/SU132111700

Sadeghi, Z., McClelland, J. L., & Hoffman, P. (2015). You shall know an object by the company it keeps: An investigation of semantic representations derived from object co-occurrence in visual scenes. *Neuropsychologia*, *76*, 52–61. https://doi.org/10.1016/J.NEUROPSYCHOLOGIA.2014.08.031

Salado, A., & Nilchiani, R. (2013). Contextual- and Behavioral-Centric Stakeholder Identification. *Procedia Computer Science*, *16*, 908–917. https://doi.org/10.1016/J.PROCS.2013.01.095

Sandvik, I. M., & Stubbs, W. (2019). Circular fashion supply chain through textile-to-textile recycling. *Journal of Fashion Marketing and Management*, *23*(3), 366–381. https://doi.org/10.1108/JFMM-04-2018-0058

Sanya, I. O., & Shehab, E. M. (2015). A framework for developing engineering design ontologies within the aerospace industry. *International Journal of Production Research*, *53*(8), 2383–2409. https://doi.org/10.1080/00207543.2014.965352

Sarkar, A., & Šormaz, D. (2019). Ontology Model for Process Level Capabilities of Manufacturing Resources. *Procedia Manufacturing*, *39*, 1889–1898. https://doi.org/10.1016/J.PROMFG.2020.01.244

Sauter, E. M., & Witjes, M. (2017). *Linked Spatial Data for a Circular Economy -- Exploring its potential through a Textile Use Case*. https://ceur-ws.org/Vol-2044/paper10/paper10.html

Senderov, V., Simov, K., Franz, N., Stoev, P., Catapano, T., Agosti, D., Sautter, G., Morris, R. A., & Penev, L. (2018). OpenBiodiv-O: Ontology of the OpenBiodiv knowledge management system. *Journal of Biomedical Semantics*, *9*(1). https://doi.org/10.1186/S13326-017-0174-5

Sentilles, S., Papatheocharous, E., Ciccozzi, F., & Petersen, K. (2016). A Property Model Ontology. *Proceedings - 42nd Euromicro Conference on Software Engineering and Advanced Applications, SEAA 2016*, 165–172. https://doi.org/10.1109/SEAA.2016.26

Shen, L., Zhang, X., & Liu, H. (2022). Digital technology adoption, digital dynamic capability, and digital transformation performance of textile industry: Moderating role of digital innovation orientation. *Managerial and Decision Economics*, *43*(6), 2038–2054. https://doi.org/10.1002/MDE.3507

Shiang, C. W., Tee, F. S., Halin, A. A., Yap, N. K., & Hong, P. C. (2018). Ontology reuse for multiagent system development through pattern classification. *Software - Practice and Experience*, *48*(11), 1923–1939. https://doi.org/10.1002/SPE.2595

Sicilia, M. A., Rodríguez, D., García-Barriocanal, E., & Sánchez-Alonso, S. (2012). Empirical findings on ontology metrics. *Expert Systems with Applications: An International Journal*, *39*(8), 6706–6711. https://doi.org/10.1016/J.ESWA.2011.11.094

Slater, L. T., Gkoutos, G. V., & Hoehndorf, R. (2020). Towards semantic interoperability: finding and repairing hidden contradictions in biomedical ontologies. *BMC Medical Informatics and Decision Making*, *20*(10), 1–13. https://doi.org/10.1186/S12911-020-01336-2/FIGURES/4

Smith, M., Welty, C., & Mcguiness, D. (2004). *W3C Proposed Recomendation: OWL Web Ontology Language Guide*.

Sousa, P. M., Moreira, M. J., de Moura, A. P., Lima, R. C., & Cunha, L. M. (2021). Consumer Perception of the Circular Economy Concept Applied to the Food Domain: An Exploratory Approach. *Sustainability 2021, Vol. 13, Page 11340*, *13*(20), 11340. https://doi.org/10.3390/SU132011340

Sriti, M. F., Assouroko, I., Ducellier, G., Boutinaud, P., & Eynard, B. (2015). Ontology-based approach for product information exchange. *International Journal of Product Lifecycle Management*, *8*(1), 1–23. https://doi.org/10.1504/IJPLM.2015.068011

Studer, R., Benjamins, V. R., & Fensel, D. (1998). Knowledge engineering: Principles and methods. *Data & Knowledge Engineering*, *25*(1–2), 161–197. https://doi.org/10.1016/S0169-023X(97)00056-6

Suárez-Figueroa, M. C., Gómez-Pérez, A., & Villazón-Terrazas, B. (2009). How to write and use the ontology requirements specification document. *Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, *5871 LNCS*(PART 2), 966–982. https://doi.org/10.1007/978-3-642-05151-7_16

Subramaniyaswamy, V., & Chenthur Pandian, S. (2012). Effective tag recommendation system based on topic ontology using Wikipedia and WordNet. *International Journal of Intelligent Systems*, *27*(12), 1034–1048. https://doi.org/10.1002/INT.21560

Sure, Y., Staab, S., & Studer, R. (2004). On-To-Knowledge Methodology (OTKM). *Handbook on Ontologies*, 117–132. https://doi.org/10.1007/978-3-540-24750-0_6

Szejka, A. L., Mas, F., & Junior, O. C. (2022). Towards Knowledge-Based System to Support Smart Manufacturing Processes in Aerospace Industry Based on Models for Manufacturing (MfM). *IFIP Advances in Information and Communication Technology*, *640 IFIP*, 425–437. https://doi.org/10.1007/978-3-030-94399-8_31/COVER

Tartir, S., Arpinar, I., Moore, M., Sheth, A., & Aleman-Meza, B. (2005, November). *OntoQA: Metric-Based Ontology Quality Analysis*.

TNO, & TU Delft. (2023). *D2.1. A Diagnostic Problem Analysis Report A Diagnostic Problem Analysis Report for Extended Data Pipeline in the Context of the Automotive Industry (Draft)*.

TNO. (2022). *The Vocabulary Hub to configure data space connectors*. https://www.opendei.eu/

Trauer, J., Schweigert-Recksiek, S., Engel, C., Spreitzer, K., & Zimmermann, M. (2020). WHAT IS A DIGITAL TWIN? - DEFINITIONS and INSIGHTS from AN INDUSTRIAL CASE STUDY in TECHNICAL PRODUCT DEVELOPMENT. *Proceedings of the Design Society: DESIGN Conference*, *1*, 757–766. https://doi.org/10.1017/DSD.2020.15

Uschold, M., & Gruninger, M. (1996). Ontologies: principles, methods and applications. *The Knowledge Engineering Review*, *11*(2), 93–136. https://doi.org/10.1017/S0269888900007797

Valencia-García, R., García-Sánchez, F., Castellanos-Nieves, D., & Fernández-Breis, J. T. (2011). OWLPath: An OWL ontology-guided query editor. *IEEE Transactions on Systems, Man, and Cybernetics Part A:Systems and Humans*, *41*(1), 121–136. https://doi.org/10.1109/TSMCA.2010.2048029

Velenturf, A. P. M., Jensen, P. D., Purnell, P., Jopson, J., & Ebner, N. (2019). A Call to Integrate Economic, Social and Environmental Motives into Guidance for Business Support for the Transition to a Circular Economy. *Administrative Sciences 2019, Vol. 9, Page 92*, *9*(4), 92. https://doi.org/10.3390/ADMSCI9040092

Vidal, J. C., Lama, M., & Bugarín, A. (2012). Toward the use of Petri nets for the formalization of OWL-S choreographies. *Knowledge and Information Systems*, *32*(3), 629–665. https://doi.org/10.1007/S10115-011-0451-Z

Vidal, V. M. P., Pinheiro, J. C., Sacramento, E. R., Macêdo, J. A. F. de, & Lóscio, B. F. (2010). An Ontology-Based Framework for Heterogeneous Data Sources Integration. *Revista de Informática Teórica e Aplicada*, *16*(2), 61–64. https://doi.org/10.22456/2175-2745.12570

Virta, L., & Räisänen, R. (2021). Three futures scenarios of policy instruments for sustainable textile production and consumption as portrayed in the finnish news media. *Sustainability (Switzerland)*, *13*(2), 1–16. https://doi.org/10.3390/SU13020594

W3C. (2004). Architecture of the World Wide Web, Volume One. https://www.w3.org/TR/webarch/#use-namespaces

Wheeler, T. S., Michael Vallis, T., Giacomantonio, N. B., & Abidi, S. R. (2018). Feasibility and usability of an ontology-based mobile intervention for patients with hypertension. *International Journal of Medical Informatics*, *119*, 8–16. https://doi.org/10.1016/J.IJMEDINF.2018.08.002
Wiegand, T., & Wynn, M. (2023). Sustainability, the Circular Economy and Digitalisation in the German Textile and Clothing Industry. *Sustainability 2023, Vol. 15, Page 9111*, *15*(11), 9111. https://doi.org/10.3390/SU15119111
Wohlin, C. (2014). Guidelines for snowballing in systematic literature studies and a replication in software engineering. *ACM International Conference Proceeding Series*. https://doi.org/10.1145/2601248.2601268
Yang, L. R., Huang, C. F., & Wu, K. S. (2011). The association among project manager's leadership style, teamwork and project success. *International Journal of Project Management*, *29*(3), 258–267. https://doi.org/10.1016/J.IJPROMAN.2010.03.006
Yang, Z., Zhang, D., & Ye, C. (2006). Evaluation metrics for ontology complexity and evolution analysis. *Proceedings - IEEE International Conference on e-Business Engineering, ICEBE 2006*, 162–169. https://doi.org/10.1109/ICEBE.2006.48
Zhou, Z., Goh, Y. M., & Shen, L. (2016). Overview and Analysis of Ontology Studies Supporting Development of the Construction Industry. *Journal of Computing in Civil Engineering*, *30*(6), 04016026. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000594

8 Appendix

Appendix A: Internal project Meetings

Table 14: Schedule of internal project meetings

Meeting No.	*Date*	*Meeting*	*Subject*
1	04/08/2023	Teams	Detailed explanation of the platform by the Textile Expert. A follow-up meeting was scheduled to further clarify project visions.
2	18/08/2023	Teams	Continued discussions to align project deliverables. Explored different aspects and perspectives to enhance mutual understanding.
3	21/08/2023	Teams	Progress made through collaborative efforts. Initiated exploration of the textile taxonomy system.
4	08/09/2023	Teams	Collaborative session to define project requirements with the team. Received valuable project-related data for analysis.
5	18/09/2023	Teams	Ontology draft review led to positive feedback and actionable revisions. Discussed the integration of circularity within the textile taxonomy and achieved alignment on project direction. Development progresses with a focus on sorter system requirements.
6	04/10/2023	Teams	Enhanced understanding of the textile taxonomy vision through a visualization of the preliminary ontology. Engaged in discussions about expanding the project scope and establishing evaluation metrics.
7	18/10/2023	Teams	Confirmed the project scope regarding textile sorters. Agreed upon modelling based on specific data requirements.

Appendix B: Structure and Insights of Internal Project Meetings

Overview

This appendix provides a detailed account of the internal project meetings and their contributions to the thesis research. It outlines the adaptive and exploratory approach taken during these sessions, facilitating a natural progression of ideas and fostering an in-depth understanding of the research topics.

Methodological Approach to Meetings

The sessions were structured with flexibility to encourage open-ended discussions, rather than a rigid interview format. This allowed for spontaneous and nuanced conversations with the textile expert, leading to a richer depth of insight.

Prepared Questions for Discussions

The following is a sample of the broader topics and specific questions prepared to guide the discussions:

- How does your company approach data sharing within the supply chain, and what are the perceived benefits?
- What are the key industry challenges that a data-driven approach could potentially mitigate or solve?
- How is the taxonomy structured to organize the industry's diverse aspects, and what methodology was employed in its creation?
- Can you discuss the main categories within the taxonomy and their roles in enhancing industry circularity?
- What challenges were encountered in developing the taxonomy, and how were they resolved to ensure accuracy and comprehensiveness?
- To which part of the supply chain can increased data sharing and knowledge interoperability contribute most significantly to circularity?
- What are the key challenges in collecting and integrating data from different industry stakeholders?
- How can structured knowledge and data optimize manufacturing processes and reduce waste?
- What criteria are used to evaluate the ontology's effectiveness in representing the textile supply chain's complexities?

Thematic Exploration of Discussions

The internal project meetings encompassed a series of interconnected themes that evolved over time, each contributing to the research and development of the thesis:

Initial Framework and Clarification of Objectives:

- Began with laying out the foundational elements of the project and clarifying the overarching goals, setting a clear direction for the subsequent discussions.

Deliberation on Project Deliverables and Perspectives:

- Discussions aimed at aligning the project deliverables with the envisioned outcomes and exploring different aspects to enhance mutual understanding, reflecting a deeper dive into the project's complexity.

Collaborative Development of Taxonomy:

- Progressed through collaborative efforts to initiate the practical development of the textile taxonomy system, focusing on how its structure could support the goals of sustainability and circularity within the industry.

Defining Requirements and Analysing Data:

- A focused session on defining detailed project requirements and analysing data for actionable insights, ensuring that the project stayed aligned with real-world needs and applications.

Refinement of Ontology and Integration of Circularity:

- Examined the draft ontology, leading to revisions that integrated principles of circularity, signifying a shift towards more sustainable practices and alignment with industry trends.

Expansion of Scope and Establishment of Metrics:

- Discussions expanded the project scope, considering broader implications and establishing metrics for evaluation, indicating a maturing of the project's conceptual framework.

Finalization of Project Scope and Data-Driven Modelling:

- The concluding sessions confirmed the project scope and focused on data modelling, solidifying the ontology's practical applicability and readiness for implementation.

Reflection on the meetings

The internal project meetings were essential in shaping the thesis. Initially, we planned more structured interactions, hence the developed questions, but as the discussions unfolded, they organically shifted to better accommodate the flow of information from the textile expert. This less formal approach allowed for a more thorough exploration of complex topics and a deeper understanding of the industry's intricacies.

The expertise shared by the domain expert was critical, providing practical insights that directly informed the taxonomy and ontology development. Their perspectives revealed the real-world applications and challenges of data sharing and sustainability in the textile industry, which were integral to my research.

Overcoming the challenges of integrating such rich, detailed insights into an academic framework required a straightforward, adaptable approach. The result was a series of meetings that built upon one another, leading to significant enhancements to the research objectives and questions.

Appendix C: Classes

Table 15: Classes of the final ontology with their annotations.

Number	Class	rdfs:Comment
1	Accessories	In the context of textiles, accessories may include additional decorative or functional items used to complete or enhance garments, such as belts, scarves, and jewelry.
2	Assigned Colour	Represents a class that defines various colors or color options available for textile products.
3	Bagpacks	Represents a class that categorizes and defines textile products specifically as backpacks, allowing for structured classification and organization within the category of bags and accessories.
4	Blazer	A blazer is a type of jacket resembling a suit jacket but cut more casually, typically worn with non-matching trousers or skirts.
5	Blouse	A Blouse is a type of top usually with buttons
6	Bottoms	Bottoms refer to a general categorisation for pants and other textile items alike
7	Button	Represents a class that defines and categorizes textile components specifically as buttons, allowing for structured classification and organization within the category of textile accessories and fasteners.
8	Category	Type of material (fabric, yarn, trim ...)
9	Colour Brightness	Represents a class that categorizes and defines the brightness or lightness levels of colours used in textile products, allowing for classification based on the intensity of colour shades.
10	Content And Percentage	This class specifies the content and the percentage of raw material present in a product, it denotes the presence of raw materials in a product such as bamboo or mycelium, it is different from the production material
11	Currency	Refers to the currency used to denote the price of a textile item
12	Cut Make Trim	CMT refers to a common production strategy in the textile industry where a client provides the design and materials to a factory, which then cuts the fabric, assembles the product, and adds the finishing trims.
13	Denim	Denim is a type of bottom, usually rugged and in a shade of blue
14	Dress	A dress is a one-piece garment for women or girls that covers the body and extends down over the legs.
15	Dyeing	Dyeing is the application of colour to textiles using specific chemical processes to achieve durable and vibrant hues.
16	Embellishing	Embellishing is the art of enhancing the visual appeal of textile products by adding decorative elements such as sequins, beads, embroidery, lace, or appliqué. This process is often used to add value and distinctiveness to garments and other fabric-based items.
17	Finishing	Finishing refers to the various treatments applied to textile products to enhance their appearance, performance, or hand feel. These treatments can include processes like softening, shrinking, stain resistance, and wrinkle reduction
18	Full Garment Supply	Full Garment Supply as a production step entails the complete assembly of a garmen
19	Full Outfits	Full Outfits as a clothing category encompasses single-piece garments like overalls and dresses that constitute a complete attire on their own.
20	Gender	Denotes the gender classification that a particular textile product is designed for.
21	Jacket	A jacket is a garment for the upper body, typically having sleeves and a fastening down the front, worn outdoors or as part of an outfit or uniform.
22	Knitwear	Knitwear refers to clothing made from knitted fabric, offering stretch, comfort, and warmth, and includes items such as sweaters, cardigans, and dresses.
23	Laundry	As a production step, laundry involves cleaning, drying, and often treating garments to achieve desired textures, finishes, or softness before they are sold.
24	Material And Percentage	Represents a class that combines information about the material (finished production materials like yarn) composition and the percentage of each material used in a textile product.
25	Overall	An overall is a garment typically worn over other clothing to protect it; it's a one-piece suit or combination of trousers and a jacket with or without sleeves.
26	Packaging and Shipping	Refer to the final stages in product distribution where goods are wrapped, boxed, and dispatched to their destination.
27	Pants	Pants are a piece of clothing worn from the waist to the ankles, covering both legs separately.
28	Polo	Represents a class that categorizes and defines textile products specifically as polo shirts, allowing for structured classification and organization within the clothing category.
29	Pre-Tanning	Pre-tanning refers to the preparatory steps in leather processing before the actual tanning, including rehydration and removal of unwanted components.

30	Price And Currency	Represents a class that combines information about the price of a textile product and the currency in which the price is denoted.
31	Printing	Printing, as a production step, involves the application of designs or patterns onto fabric through various techniques.
32	Production	Production as a step refers to the actual manufacturing phase where textile fibers are transformed into finished textile products through processes such as weaving, knitting, or assembly.
33	Production Step Finished Product	Serves as an overarching category that supervises all the individual processes involved in the final assembly and completion of textile goods.
34	Production Step Raw Material	Covers the initial stages in the textile supply chain, including the sourcing, processing, and preparation of natural or synthetic fibers for subsequent manufacturing.
35	Segment Finished Product	Represents a class that categorises and segments finished textile products, providing a structured classification system for different types of textile items.
36	Segment Finished Product Accessories	Represents a class that further categorises and segments finished textile products into the category of bags, facilitating the classification of different types of textile bags and accessories.
37	Segment Finished Product Apparel	Represents a class that further categorises and segments finished textile products into the category of apparel, aiding in the classification of various clothing items within the textile domain.
38	Segment Others	Segment others classifies product that do not fall into the other categories.
39	Segment Production Material	Represents a class that categorises and segments production materials used in the textile industry, encompassing a variety of materials including buttons, zippers, and other components, providing a structured classification system for different types of materials and resources.
40	Segment Raw Material	Represents a class that categorises and segments raw materials used in the textile industry, providing a structured classification system for different types of materials, such as fibres, threads, and fabrics.
41	Service Type	Represents a class that categorizes and defines types of circular economy services associated with textile products, such as repair, reuse, recycling, or rental services, promoting sustainability and resource efficiency within the textile industry.
42	Shirt	A shirt is a garment for the upper body, typically with a collar, sleeves with cuffs, and a full vertical opening with buttons or snaps.
43	Size	Refers to the dimensions or measurements that define the fit of a garment or textile product.
44	Size And Size Country Code	Represents a class that combines information about the size or dimensions of a textile product and the associated country code denoting sizing standards for that region or country, facilitating precise size information and international sizing context.
45	Size country Code	Indicates the regional or national sizing system a garment's measurements conform to, such as US, UK, EU, etc.
46	Skirt	A skirt is a garment that hangs from the waist and covers part of the lower body, varying in length and style.
47	Spinning	Spinning is the process of turning raw fibres like cotton or wool into yarn or thread, which serves as the foundation for fabric production.
48	Sweater	A sweater is a knitted garment intended to cover the upper body and arms, typically made from wool or synthetic fibres for warmth.
49	T-Shirt	A T-shirt is a style of fabric shirt named after the T shape of its body and sleeves, traditionally made of cotton and characterized by its round neckline.
50	Tanning	Tanning is the process of treating animal skins to produce leather, making them more durable and less susceptible to decomposition.
51	Top	Refers to any garment worn on the upper body, usually lighter and less formal than a shirt, and can include items like blouses and tank tops.
52	Tops	Represents a class that categorizes and defines textile products specifically as shirts, allowing for structured classification and organization within the clothing category.

Appendix D: Properties

Table 16: Object Properties of the Final Ontology

#	PROPERTY	DOMAIN	RANGE
1	Has_Circular_R_Service_Type	Segment_Finished_Product	Service_Type
2	hasCategory	Segment_Raw_Material	Category
3	hasColor	Segment_Finished_Product	Assigned_Colour
4	hasColorBrightness	Assigned_Colour	Colour_Brightness
5	hasContent	Segment_Raw_Material	Content_And_Percentage
6	hasCurrency	Price_And_Currency	Currency
7	hasGender	Segment_Finished_Product	Gender
8	hasMaterialAndPercentage	Segment_Finished_Product	Material_And_Percentage
9	hasPriceAndCurrency	Segment_Finished_Product	Price_And_Currency
10	hasProduction_Material	Segment_Finished_Product	Segment_Production_Material
11	hasSegment_Raw_Material	Segment_Finished_Product	Segment_Raw_Material
12	hasSize	Segment_Finished_Product	Size_And_Size_Country_Code
13	hasSizeValue	Size_And_Size_Country_Code	Size
14	hasSize_Country_Code	Size_And_Size_Country_Code	Size_country_Code
15	involvesFinishedProduct	Production_Step_Finished_Product	Segment_Finished_Product
16	involvesRawMaterial	Production_Step_Raw_Material	Segment_Raw_Material
17	isCategoryOf	Category	Segment_Raw_Material
18	isColorBrightnessOf	Colour_Brightness	Assigned_Colour
19	isColorOf	Assigned_Colour	Segment_Finished_Product
20	isContentOf	Content_And_Percentage	Segment_Raw_Material
21	isCurrencyOf	Currency	Price_And_Currency
22	isGenderOf	Gender	Segment_Finished_Product
23	isHas_Circular_R_Service_TypeOf	Service_Type	Segment_Finished_Product
24	isInvolvedInFinishedProduct	Segment_Finished_Product	Production_Step_Finished_Product
25	isInvolvedInRawMaterial	Segment_Raw_Material	Production_Step_Raw_Material
26	isMaterialAndPercentageOf	Material_And_Percentage	Segment_Finished_Product
27	isPriceAndCurrencyOf	Price_And_Currency	Segment_Finished_Product
28	isProduction_MaterialOf	Segment_Production_Material	Segment_Finished_Product
29	isSegment_Raw_MaterialOf	Segment_Raw_Material	Segment_Finished_Product
31	isSizeValueOf	Size	Size_And_Size_Country_Code
32	isSize_Country_CodeOf	Size_country_Code	Size_And_Size_Country_Code

Table 17: Data Properties of the Final Ontology

#	Property	Domain	Range
1	ArticleName	Segment_Finished_Product	string
2	BrandName	Segment_Finished_Product	string
3	Care_Guide	Segment_Finished_Product	string
4	Content_Precentage	Content_And_Percentage	integer
5	MaterialName	Material_And_Percentage	string
6	Percentage	Material_And_Percentage	integer
7	Product_Description	Segment_Finished_Product	string
8	Product_Image	Segment_Finished_Product	string
9	Product_Name	Segment_Finished_Product	string
10	RecommendedPrice	Price_And_Currency	decimal
11	hasCountryOfOrigin	Production_Step_Finished_Product	string
12	isRecycled	Content_And_Percentage	boolean
13	yearOfSale	Segment_Finished_Product	dateTime

Appendix E: Individuals

Table 18: Individuals of the Final Ontology

Number	Individual	Resource Class	Number	Individual	Resource Class
1	Beige	Assigned_Colour	65	Organic_Linen	Content_And_Percentage
2	Black	Assigned_Colour	66	Pineapple_Fiber	Content_And_Percentage
3	Blue	Assigned_Colour	67	Post_Consumer_Recycled_Cotton	Content_And_Percentage
4	Brown	Assigned_Colour	68	Pre_Consumer_Recycled_Cotton	Content_And_Percentage
5	Burgundy	Assigned_Colour	69	Ramie	Content_And_Percentage
6	Coral	Assigned_Colour	70	Recycled_Cotton	Content_And_Percentage
7	Gold	Assigned_Colour	71	Recycled_Others	Content_And_Percentage
8	Green	Assigned_Colour	72	Seashell	Content_And_Percentage
9	Indigo	Assigned_Colour	73	Sisal	Content_And_Percentage
10	Khaki	Assigned_Colour	74	Soy	Content_And_Percentage
11	MultiColoured	Assigned_Colour	75	Stone	Content_And_Percentage
12	Navy	Assigned_Colour	76	Stone_Nut	Content_And_Percentage
13	Nude	Assigned_Colour	77	Vegetable_Ivory	Content_And_Percentage
14	Off-White	Assigned_Colour	78	Wood	Content_And_Percentage
15	Orange	Assigned_Colour	79	EURO	Currency
16	Pink	Assigned_Colour	80	Other_Currency	Currency
17	Purple	Assigned_Colour	81	YEN	Currency
18	Red	Assigned_Colour	82	US$	Currency
19	Rose	Assigned_Colour	83	Anti_Soiling_Treatment	Finishing
20	Silver	Assigned_Colour	84	Antimicrobial_Treatment	Finishing
21	Taupe	Assigned_Colour	85	Antistatic	Finishing
22	Teal	Assigned_Colour	86	Bio_Polishing	Finishing
23	Turquoise	Assigned_Colour	87	Debossing	Finishing
24	Uncoloured	Assigned_Colour	88	Embossing	Finishing
25	White	Assigned_Colour	89	Embroidery	Finishing
26	Yellow	Assigned_Colour	90	Enzyme_Washing	Finishing
27	other	Assigned_Colour	91	Flame_Retardant_Treatment	Finishing
28	Black_&_White	Assigned_Colour	92	Garment_Dyeing	Finishing
29	Fabric	Category	93	Laser_Cutting_Engraving	Finishing
30	Leather	Category	94	Napping_And_Sueding	Finishing
31	Leather_Alternative	Category	95	Optical_Brighteners	Finishing
32	Trim	Category	96	Shrinkage_Control	Finishing
33	Yarn	Category	97	Stain_Repellent	Finishing
34	Dark	Colour_Brightness	98	Unkown	Finishing
35	Light	Colour_Brightness	99	Untreated	Finishing
36	Neon	Colour_Brightness	100	Wax	Finishing
37	Normal	Colour_Brightness	101	Wrinkle_Free_Treatment	Finishing

38	Other	Colour_Brightness	102	Female	Gender
39	Pastell	Colour_Brightness	103	Male	Gender
40	Very_Dark	Colour_Brightness	104	Unisex	Gender
41	Abaca	Content_And_Percentage	105	gender-neutral	Gender
42	Bamboo	Content_And_Percentage	106	genderless	Gender
43	Banana	Content_And_Percentage	107	Batik_Printed	Printing
44	Bee_Wax	Content_And_Percentage	108	Digital_Printed	Printing
45	Coconut	Content_And_Percentage	109	Hand_Printed	Printing
46	Cork	Content_And_Percentage	110	Inkjet_Printed	Printing
47	Corozo	Content_And_Percentage	111	Roller_Printed	Printing
48	Cotton	Content_And_Percentage	112	Screen_Printed	Printing
49	Food_Crop_Waste	Content_And_Percentage	113	Transfer_Printed	Printing
50	Fungi	Content_And_Percentage	114	Other_Service_Type	Service_Type
51	Hemp	Content_And_Percentage	115	Redesign	Service_Type
52	Jute	Content_And_Percentage	116	Rental	Service_Type
53	Kapok	Content_And_Percentage	117	Repair	Service_Type
54	Lignin	Content_And_Percentage	118	Resell	Service_Type
55	Linen	Content_And_Percentage	119	Take_Back_For_Reuse	Service_Type
56	Manila_Hemp	Content_And_Percentage	120	Take_back_for_Recycling	Service_Type
57	Mother_Of_Pearl	Content_And_Percentage	121	Large	Size
58	Mycelium	Content_And_Percentage	122	Medium	Size
59	Natural_Latex	Content_And_Percentage	123	Small	Size
60	Natural_Rubber	Content_And_Percentage	124	XL	Size
61	Nettle	Content_And_Percentage	125	OtherRegion	Size_country_Code
62	Nuts	Content_And_Percentage	126	Ru	Size_country_Code
63	Organic_Cotton	Content_And_Percentage	127	UK/AU/NZ	Size_country_Code
64	Organic_Hemp	Content_And_Percentage	128	US_&_Canada	Size_country_Code

Appendix F: Use cases

Use Case 1: Product Categorization

- A textile sorter is working through a new shipment and identifies a product as a "GreenWeave Eco-Tee" from the brand "EcoFab Textiles."
- The sorter classifies this item under the "T-Shirt" category within "Tops." The T-shirt features a design that aligns with circular fashion principles,meaning its designed to take back for reuse.
- The material composition is tagged as "100% Cotton." The 'Content_And_Percentage' detail specifies "95% Organic Cotton" as the fiber content, and the sorter identifies the remaining "5% as Recycled Polyester" involved in the material's production.
- The product tag also indicates the colour as "Green," colour brightness "Light", and the size is marked as "Medium (M)," with a country code "PT" for Portugal.
- The product was first put up for sale in May 2021, as indicated by the date on the manufacturer's tag.

Use Case 2: Origin and Material Sorting

- The textile sorter examines the country-of-origin label on a "GreenWeave Eco-Pants" and notes it was made in Portugal (PT).
- The category "Denim" under "Bottoms" is confirmed as per the manufacturer's label.
- The sorter references the product's supply chain records to confirm the materials were sourced from Turkey and recycled cotton from a facility in Spain.
- The product's detailed assembly instructions are included in the manufacturer's documentation, it shows that the product has undergone the production step Laundry for finished materials to give it a nice finish.

Use Case 3: Care and Maintenance Sorting

- As the sorter processes various garments, they come across the "GreenWeave Eco-Tee" and check its care instructions.
- They note the cold wash and low-heat drying guidelines, which are important for the garment's longevity and recyclability.
- The label advises against ironing to preserve the integrity of the recycled polyester.
- The sorter verifies the gender classification on the care label, indicating that the "GreenWeave Eco-Tee" is designed for "Unisex" wear.

Use Case 4: Sales and Presentation Sorting

- While sorting, the textile sorter refers to an online listing to understand how the "GreenWeave Eco-Tee" is marketed.
- They note the T-shirt is listed under "Tops" with several high-quality images indicating its premium status.
- The sorter confirms that there are five images available on the listing site, consisting of URLs.
- The selling price is listed as 29.99 Euros (EURO).
- Upon inspecting a "GreenWeave Eco-Tee," they find that it is designed for Repair indicating that the product should be easily repairable.

Use Case 5: Cross-Industry Event

- During a sorting event, the textile sorter is responsible for preparing a batch of "GreenWeave Eco-Tees" in the "Tops" category for transport, alongside a shipment of electric batteries.

- The sorter ensures that the T-shirts are packed with materials that prevent damage during transport and logs the details of the textiles and batteries to facilitate cross-industry tracking and accountability. Noting that the finished product has underwent the production step Packaging and shipping.

Appendix G: Mock-up Data for Use Cases

Data for use case 1:

```
@prefix textile: <https://ontology.tno.nl/Textile#> .
@prefix xsd: <http://www.w3.org/2001/XMLSchema#> .
@prefix ex: <http://example.com/base#> .

# The T-Shirt
ex:GreenWeaveEcoTee a textile:TShirt ;
    textile:articleName "Eco-Friendly Green Tee"^^xsd:string ;
    textile:brandName ex:EcoFabTextiles ;
    textile:has_circular_R_Service_Type textile:Take_Back_For_Reuse ;
    textile:hasMaterialAndPercentage ex:Material100PercentCotton ;
    textile:hasContent ex:Content95PercentOrganicCotton,
                                ex:Content5PercentRecycledCotton ;
    textile:hasColor "Green"^^xsd:string ;
    textile:hasColorBrightness "Light"^^xsd:string ;
    textile:hasSize "Medium (M)"^^xsd:string ;
    textile:hasSize_Country_Code "PT"^^xsd:string ;
    textile:yearofSale "2021-05-01"^^xsd:dateTime .

# The brand
ex:EcoFabTextiles a textile:Brand ;
    textile:brandName "EcoFab Textiles"^^xsd:string .

# The material composition with MaterialAndPercentage class
ex:Material100PercentCotton a textile:MaterialAndPercentage ;
    textile:MaterialName "Cotton"^^xsd:string ;
    textile:percentage 100.0 .

# The content composition with ContentAndPercentage class
ex:Content95PercentOrganicCotton a textile:ContentAndPercentage ;
    textile:hasContentName "Organic Cotton"^^xsd:string ;
    textile:hasCategory "Fiber"^^xsd:string ;
    textile:content_percentage 95 ;
    textile:isRecycled false .

ex:Content5PercentRecycledCotton a textile:ContentAndPercentage ;
    textile:hasContentName "Recycled Cotton"^^xsd:string ;
    textile:hasCategory "Yarn"^^xsd:string ;
    textile:content_percentage 5 ;
    textile:isRecycled true .
```

Data for use case 2:

```
@prefix textile: <https://ontology.tno.nl/Textile#> .
@prefix xsd: <http://www.w3.org/2001/XMLSchema#> .
@prefix ex: <http://example.com/base#> .
@prefix rdfs: <http://www.w3.org/2000/01/rdf-schema#> .

# The T-Shirt (now EcoPants)
ex:GreenWeaveEcoPants a textile:Denim ;
    textile:hasSize_Country_Code "PT"^^xsd:string ;
    textile:involvesContent ex:MaterialRecycledCottonSpain ;
    textile:hasProductionStep ex:LaundryStep ;
    textile:brand ex:EcoFabTextiles .
```

```
# Denim is a subclass of Bottoms
textile:Denim rdfs:subClassOf textile:Bottoms .

# Material sourced from Turkey
ex:MaterialSourcedTurkey a textile:Content_And_Percentage ;
    textile:hasContent "Recycled Cotton"^^xsd:string ;
    textile:hasCountryOfOrigin "Turkey"^^xsd:string .

# Recycled cotton from Spain
ex:MaterialRecycledCottonSpain a textile:Material_And_Percentage ;
    textile:materialName "Cotton"^^xsd:string ;
    textile:hasCountryOfOrigin "Spain"^^xsd:string ;
    textile:isRecycled true .

# Production step - Laundry
ex:LaundryStep a textile:Production_Step_Finished_Product ;
    textile:production_step_finished_material "Laundry"^^xsd:string .

# Brand
ex:EcoFabTextiles a textile:Brand ;
    textile:brandName "EcoFab Textiles"^^xsd:string .
```

Data for use case 3:

```
@prefix textile: <https://ontology.tno.nl/Textile#> .
@prefix xsd: <http://www.w3.org/2001/XMLSchema#> .
@prefix ex: <http://example.com/base#> .

# The "GreenWeave Eco-Tee"
ex:GreenWeaveEcoTee a textile:TShirt ;
    textile:articleName "GreenWeave Eco-Tee"^^xsd:string ;
    textile:Care_Guide "Cold wash only; Low-heat drying; Do not iron"^^xsd:string
;
    textile:hasGenderClassification ex:Unisex .

# Gender classification
ex:Unisex a textile:Gender .
```

Data for use case 4:

```
@prefix textile: <https://ontology.tno.nl/Textile#> .
@prefix xsd: <http://www.w3.org/2001/XMLSchema#> .
@prefix ex: <http://example.com/base#> .

# The "GreenWeave Eco-Tee"
ex:GreenWeaveEcoTee a textile:Top ;
    textile:Product_Description "Premium quality GreenWeave Eco-Tee, designed for
durability and repair."@en ;
    textile:Product_Image <http://example.com/images/greenweave-eco-tee-1.jpg>,
                          <http://example.com/images/greenweave-eco-tee-2.jpg>,
                          <http://example.com/images/greenweave-eco-tee-3.jpg>,
                          <http://example.com/images/greenweave-eco-tee-4.jpg>,
                          <http://example.com/images/greenweave-eco-tee-5.jpg> ;
    textile:hasPriceAndCurrency ex:GreenWeaveEcoTeePrice ;
    textile:has_circular_R_Service_Type textile:Repair .

# Price Information
ex:GreenWeaveEcoTeePrice a textile:RecommendedPrice ;
    textile:RecommendedPrice "29.99"^^xsd:decimal ;
```

```
    textile:hasCurrency "EURO"^^xsd:string .

# Individual "Repair" of the class "Service_Type"
textile:Repair a textile:Service_Type .
```

Data for use case 5:

```
@prefix textile: <https://ontology.tno.nl/Textile#> .
@prefix battery: <https://ontology.catenary-x.com/Battery#> .
@prefix xsd: <http://www.w3.org/2001/XMLSchema#> .
@prefix ex: <http://example.com/base#> .

# Electric Batteries
ex:ElectricBatteries a battery:Battery ;
    battery:batteryIDDMCode "IDDM12345"^^xsd:string ;
    battery:co2FootprintTotal "20.5"^^xsd:float ;
    battery:warrantyPeriod 5 .

# GreenWeave Eco Tees
ex:GreenWeave_Eco_Tees a textile:Tops ;
    textile:productionStep textile:Packaging_and_Shipping ;
    textile:material [
        a textile:Material_And_Percentage ;
        textile:MaterialName "cotton"^^xsd:string ;
        textile:Percentage "100"^^xsd:float
    ] ;
    textile:gender ex:Unisex .

# Batteries
ex:Batteries a battery:Battery ;
    battery:batteryIDDMCode "IDDM123456789"^^xsd:string ;
    battery:co2FootprintTotal "50.0"^^xsd:float ;
    battery:DeclarationOfConformity [ ] ;  # Ensure this is correctly represented
as per your ontology
    battery:warrantyPeriod 2 .

# Gender Classification
ex:Unisex a textile:Gender .
```

Appendix H: Queries and Results for Use Cases

Use case 1:

```
PREFIX textile: <https://ontology.tno.nl/Textile#>
PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>

PREFIX ex: <http://example.com/base#>
SELECT
  ?articleName
  ?materialName
  ?materialPercentage
  (GROUP_CONCAT(DISTINCT CONCAT(?contentName, " (", STR(?contentPercentage), "%)");
separator=", ") AS ?contentDetails)
  (GROUP_CONCAT(DISTINCT STR(?isRecycled); separator=", ") AS ?recycledStatuses)
  ?yearOfSale
  ?size
  ?color
  ?colorBrightness
  ?circularServiceType
WHERE {
  ex:GreenWeaveEcoTee a textile:TShirt .
  OPTIONAL { ex:GreenWeaveEcoTee textile:articleName ?articleName }
  ex:GreenWeaveEcoTee textile:hasMaterialAndPercentage ?material .
  ?material textile:MaterialName ?materialName .
  ?material textile:percentage ?materialPercentage .

  ex:GreenWeaveEcoTee textile:hasContent ?content .
  ?content textile:hasContentName ?contentName .
  ?content textile:content_percentage ?contentPercentage .
  ?content textile:isRecycled ?isRecycled .

  OPTIONAL { ex:GreenWeaveEcoTee textile:yearofSale ?yearOfSale }
  OPTIONAL { ex:GreenWeaveEcoTee textile:hasSize ?size }
  OPTIONAL { ex:GreenWeaveEcoTee textile:hasColor ?color }
  OPTIONAL { ex:GreenWeaveEcoTee textile:hasColorBrightness ?colorBrightness }
  OPTIONAL { ex:GreenWeaveEcoTee textile:has_circular_R_Service_Type
?circularServiceType }
}
GROUP BY ?articleName ?materialName ?materialPercentage ?yearOfSale ?size ?color
?colorBrightness ?circularServiceType
```

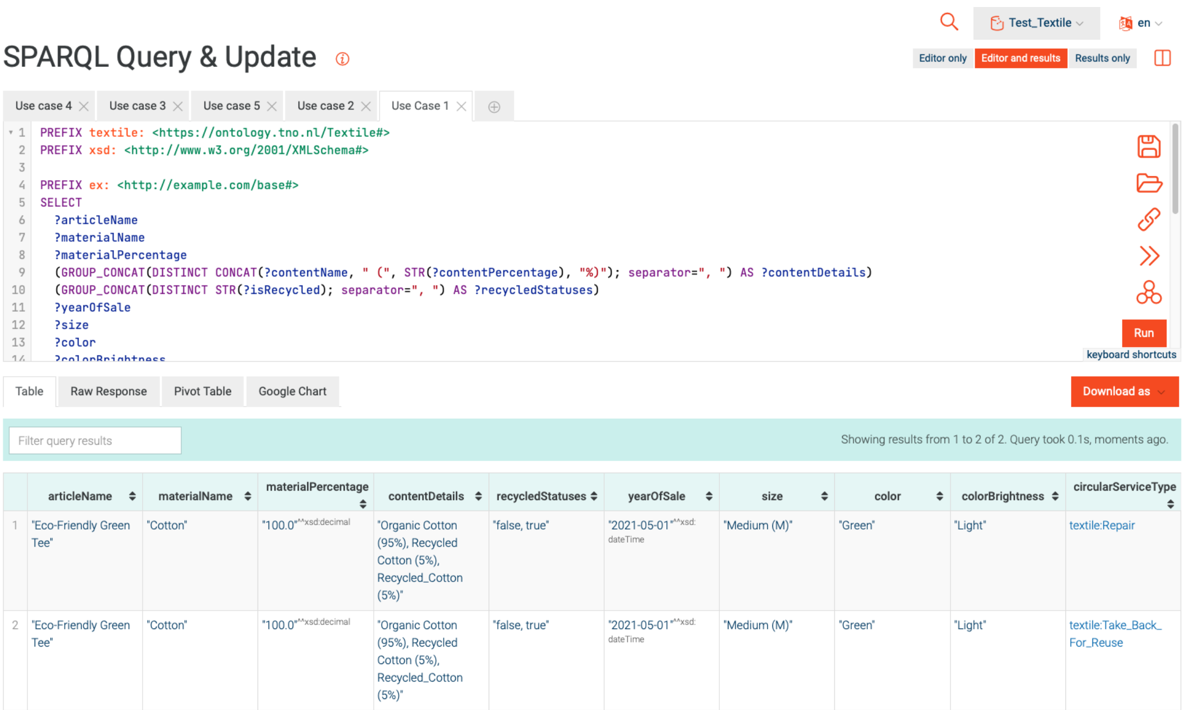

Figure 20: SPARQL Query Result 1

Use case 2:

```
PREFIX textile: <https://ontology.tno.nl/Textile#>
PREFIX ex: <http://example.com/base#>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>

SELECT  ?item  ?type  ?sizeCountryCode  ?materialName  ?countryOfOrigin  ?isRecycled
?productionStepName WHERE {
    {
        ?item a textile:Denim .
        BIND("Denim" AS ?type)
    } UNION {
        ?item a ?type .
        ?type rdfs:subClassOf textile:Bottoms .
    }
    OPTIONAL { ?item textile:hasSize_Country_Code ?sizeCountryCode }
    OPTIONAL {
        ?item textile:involvesContent ?materialResource .
        ?materialResource textile:materialName ?materialName ;
                          textile:hasCountryOfOrigin ?countryOfOrigin ;
                          textile:isRecycled ?isRecycled .
    }
    OPTIONAL {
        ?item textile:hasProductionStep ?productionStepResource .
        ?productionStepResource          textile:production_step_finished_material
?productionStepName .
    }
}
```

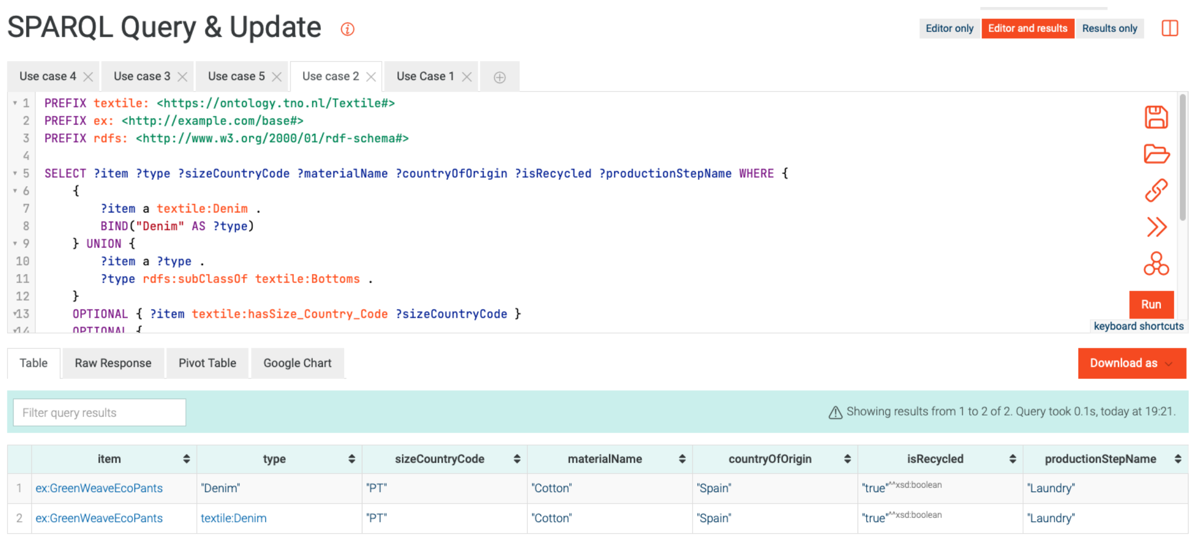

Figure 21: SPARQL Query Result 2

Use case 3:

```
PREFIX textile: <https://ontology.tno.nl/Textile#>
PREFIX ex: <http://example.com/base#>
PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>

SELECT ?articleName ?careGuide ?gender WHERE {
  ex:GreenWeaveEcoTee a textile:TShirt .
  ex:GreenWeaveEcoTee textile:articleName ?articleName .
  ex:GreenWeaveEcoTee textile:Care_Guide ?careGuide .
  OPTIONAL {
    ex:GreenWeaveEcoTee textile:hasGenderClassification ?gender .
    FILTER (?gender = ex:Unisex)
  }
}
```

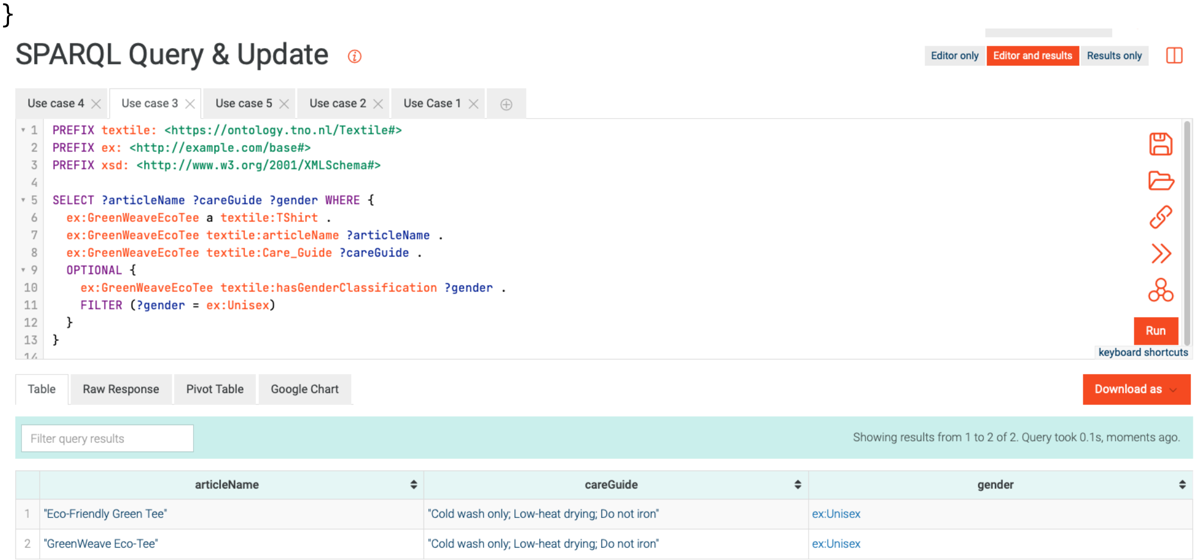

Figure 22: SPARQL Query Result 3

Use case 4:

```
PREFIX textile: <https://ontology.tno.nl/Textile#>
PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>
PREFIX ex: <http://example.com/base#>

SELECT ?description ?image ?price ?currency WHERE {
  ex:GreenWeaveEcoTee textile:Product_Description ?description .
  ex:GreenWeaveEcoTee textile:Product_Image ?image .
  ex:GreenWeaveEcoTee textile:hasPriceAndCurrency ex:GreenWeaveEcoTeePrice .

  ex:GreenWeaveEcoTeePrice textile:RecommendedPrice ?price .
  ex:GreenWeaveEcoTeePrice textile:hasCurrency ?currency .

  FILTER EXISTS { ex:GreenWeaveEcoTee textile:has_circular_R_Service_Type textile:Repair }
}
```

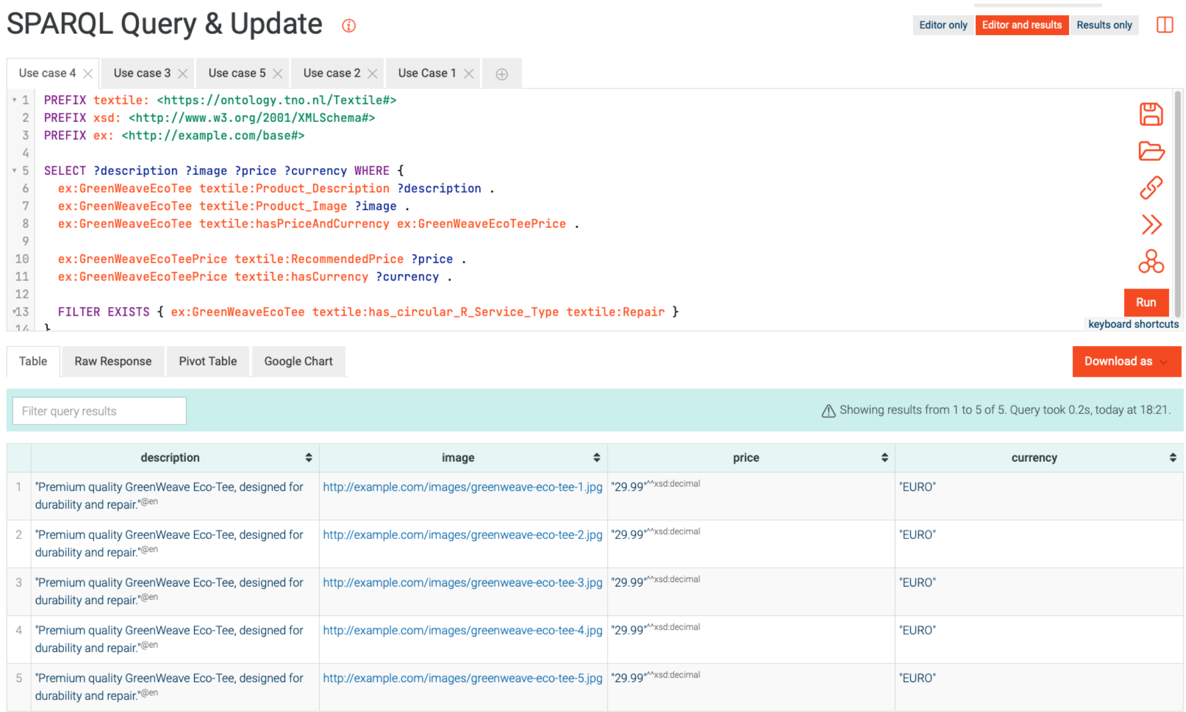

Figure 23: SPAQRL Query Result 4

Use case 5:

```
PREFIX textile: <https://ontology.tno.nl/Textile#>
PREFIX battery: <https://ontology.catenary-x.com/Battery#>
PREFIX ex: <http://example.com/base#>

SELECT ?item ?type ?co2Footprint ?material ?percentage ?gender ?warrantyPeriod
WHERE {
    {
        ?item a battery:Battery .
        ?item battery:co2FootprintTotal ?co2Footprint .
        ?item battery:warrantyPeriod ?warrantyPeriod .
        BIND("Battery" AS ?type)
        BIND("N/A" AS ?material)
        BIND("N/A" AS ?percentage)
```

```
            BIND("N/A" AS ?gender)
        }
        UNION
        {
            ?item a textile:Tops .
            ?item textile:material ?materialNode .
            ?materialNode textile:MaterialName ?material ;
                               textile:Percentage ?percentage .
            ?item textile:gender ?gender .
            BIND("Textile" AS ?type)
            BIND("N/A" AS ?co2Footprint)
            BIND("N/A" AS ?warrantyPeriod)
        }
}
```

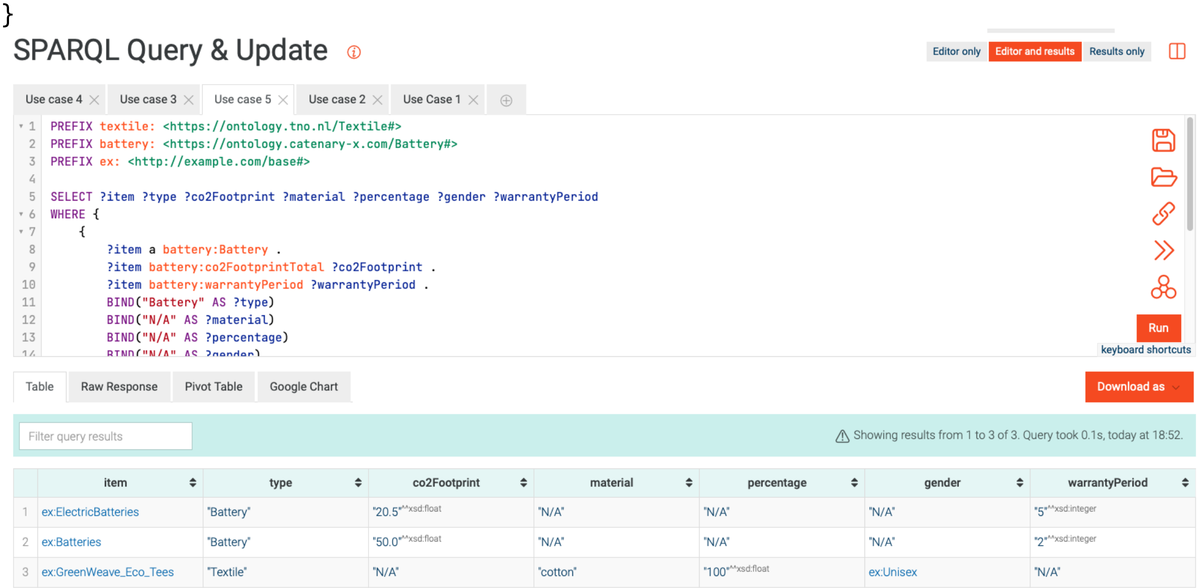

Figure 24:SPARQL Query Result 5