WOOD2WOOD

A Wood-to-Wood Cascade Upcycling Valorisation Approach

» Deliverable 4.4

Data sharing model, FAIR digital assets and digital passports principles

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SEN	Sensitive — limited under the conditions of the Grant Agreement	X

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GLOSSARY OF ACRONYMS

Acronym	Extended Definition
AI	Artifical Intelligence
C&D	Construction and Demolition
DSM	Data Sharing Models
DPP	Digital Product Passport
ESPR	Ecodesign for Sustainable Products Regulation
EU	European Union
FAIR	Findability, Accessibility, Interoperability, Reusability
GDPR	General Data Protection Regulation
LCA	Life Cycle Assessment
P2P	Peer-to-Peer
VOC	Volatile Organic Compound
W2W	Wood2Wood

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EXECUTIVE SUMMARY

The W2W (wood2wood) project, funded by the EU's Horizon RIA program, addresses the pressing need for sustainable wood resource management. With rising demand for wood in construction, furniture, energy production, and the chemical industries, European wood production is predicted to fall short of meeting demand by 2030. Simultaneously, a significant amount of wood is discarded in construction and demolition (C&D) waste and furniture, offering a potentially cost-effective source of raw materials. However, the presence of pollutants and contaminants complicates recycling efforts.

W2W aims to tackle these challenges by promoting a circular economy for wood through advanced technologies, including sorting, upcycling, and digital management of material flows. The project emphasizes a holistic approach that integrates innovation, sustainable material usage, and policy support to foster a more circular economy.

Deliverable 4.4 plays a key role in creating a standardized digital infrastructure that supports sustainable wood recycling through the development of a Data Sharing Model (DSM). The DSM is based on FAIR digital asset principles and Digital Product Passports (DPP), ensuring transparency and traceability across the wood material lifecycle. This work package sets the groundwork for establishing DPPs, digital tools for circular flow management, and stakeholder communication, thus contributing to high-quality, low-risk outcomes and long-term sustainability in wood management.

The DSM developed under the project enables a seamless exchange of information across the wood value chain. By leveraging the FAIR principles, the model ensures that wood-related data is discoverable, accessible, interoperable, and reusable, thereby fostering more efficient material flows and improving collaboration among stakeholders. The integration of digital ontologies within the DSM allows for the standardized representation of data across different platforms and stakeholders, reducing barriers to data sharing and enhancing the accuracy of information exchange. These advancements are critical for achieving the W2W project's objective of establishing a more sustainable wood management system. Through the successful implementation of **Deliverable 4.4**, the project contributes to the broader goal of achieving sustainability in the wood sector, with far-reaching implications for industries across Europe and beyond.

1. INTRODUCTION

The depletion of natural resources and the environmental consequences of traditional production methods have accelerated the global shift towards sustainable practices. In Europe, wood, a renewable yet limited resource, plays a vital role in various industries, including construction, furniture, energy production, and chemicals. However, the dominant linear economic model—where materials are taken, used, and disposed of—has led to inefficiencies, waste, and unsustainable wood consumption patterns. This linear model poses significant risks to forest ecosystems, leading to deforestation, biodiversity loss, and increased carbon emissions. Against this backdrop, the W2W project emerges as a timely and essential initiative aimed at transforming the wood industry into a more sustainable, circular economy.

The W2W project, funded by the EU's Horizon RIA program, seeks to address the critical challenges surrounding wood consumption and waste management. It proposes a circular approach to wood use, focusing on recycling and upcycling waste and discarded wood products such as furniture. The project's objective is to revolutionize the way wood materials are managed by promoting their reuse and recycling, thus reducing the need for virgin wood extraction and minimizing environmental harm.

By 2030, European wood production is anticipated to fall short of meeting industry demands. This projection highlights the urgent need for alternative solutions, as wood demand continues to rise across various sectors. Simultaneously, large quantities of wood are embedded in C&D waste, representing an untapped source of valuable material. However, challenges such as contamination, the presence of pollutants, and additives in discarded wood complicate the recycling process. W2W aims to overcome these challenges through innovative technologies, advanced sorting processes, and digital tools that facilitate efficient material flow management.

At the heart of the W2W project is its focus on Work Package 4 and Task 4.4 which addresses the need for a DSM to support sustainable wood management. This work package involves the creation of a digital infrastructure that enhances the transparency and traceability of wood materials throughout their lifecycle. A key component of this infrastructure is the development of DPPs, based on FAIR digital asset principles. These passports provide a detailed record of a product's lifecycle—from its initial production to its end-of-life phase—capturing critical information on material composition, production processes, and environmental impact.

The FAIR principles ensure that wood-related data is easily accessible and usable across the value chain, facilitating collaboration between stakeholders such as manufacturers, recyclers, suppliers, and policymakers. By adopting these principles, the W2W project promotes a standardized and interoperable system that supports the efficient exchange of data and materials. This, in turn, enhances resource efficiency and reduces the environmental footprint of wood products.

In summary, the W2W project represents a comprehensive effort to transform the wood industry through innovation and collaboration. By addressing the challenges of wood waste management and developing advanced digital and technological solutions, W2W aims to create a resilient, sustainable, and circular wood economy. The focus on DSM, FAIR principles, and DSMs ensures that stakeholders can efficiently manage wood materials throughout their lifecycle, contributing to long-term sustainability in Europe's wood-based industries. Task 4.4 will establish DPP principles and define the necessary digital data to facilitate the FAIR use of these passports, promoting transparency and traceability across the material lifecycle. By ensuring data quality and enabling effective communication among stakeholders, T4.4 aims to contribute to the project's goal of high-quality, low-risk outcomes and long-term sustainability.

2. BACKGROUND

2.1. Overview of DPP

The DPP is a robust and dynamic digital framework that provides a detailed, end-to-end record of a product's lifecycle, from its inception through manufacturing, usage, and eventual disposal or recycling. It captures critical information related to the product's material composition, origin, production processes, and environmental sustainability. This holistic approach allows the DPP to serve as a centralized hub of information, ensuring transparency and traceability at every stage of the product's life. By consolidating this wealth of data, the DPP enables various stakeholders—manufacturers, suppliers, regulators, consumers, and recyclers—to access and utilize the information for decision-making, ensuring the product is managed in a way that optimizes its value and minimizes its environmental impact. The DPP's structured documentation helps to address various challenges within the product lifecycle. For example, the DPP can enhance sustainability by providing insights into a product's environmental footprint, such as energy consumption, emissions during manufacturing, and the potential for recycling or reprocessing. Additionally, it can aid in compliance with regulatory standards, certifications, and sustainability goals by offering a transparent view of a product's adherence to laws and industry-specific requirements.

One of the DPP's primary strengths lies in its adaptability to different products and industries. The level of detail captured within the passport is adjusted to the product's complexity, lifecycle intricacy, and potential risks. Products that are highly complex or hazardous may require more extensive tracking of materials, manufacturing processes, and disposal options, while simpler or non-hazardous products may require less. This flexibility ensures that the DPP remains a valuable tool across a wide range of industries and product types, whether it's used for consumer goods, industrial machinery, or electronic devices. By capturing real-time data across multiple stages, the DPP also facilitates greater accountability and fosters collaboration across the value chain. Manufacturers can ensure the transparency of their sourcing practices, while end-users can track the performance and maintenance needs of their products. At the end-of-life stage, recyclers can access detailed information on the materials and components, making it easier to recycle or reprocess products in an environmentally responsible manner. This continuous flow of information helps optimize resource efficiency, reduce waste, and extend the product's usable life, all of which contribute to a more circular economy. The specific requirements for a product's DPP are shaped by a range of factors, including the product's overall value, the complexity of its design, and the potential environmental or safety hazards it may pose. As a result, the DPP can play a critical role in ensuring that high-value or high-risk products are handled with the appropriate care throughout their lifecycle, protecting not only the environment but also public health and safety. [1, 2]

The DPP encompasses various types of data, which can be categorized as follows [3]:

Manufacturing Data

Manufacturing data is a critical component of the DPP, capturing all relevant information about the product's creation. This includes detailed documentation of the manufacturing process, design parameters, material composition, and technical specifications of individual components. Information about the manufacturers and their specific manufacturing processes is also included. This data ensures transparency in the production phase and enables stakeholders to trace the product's origin and manufacturing history.

Usage Data

During the product's operational life, all modifications and updates should be meticulously recorded in the DPP. This includes data on usage patterns, repairs, replacement of parts, maintenance activities, and any modifications made to the product. Historical product data and ownership status are also tracked. The responsibility for updating this data lies with the individual or organization implementing the changes. Additionally, feedback from stakeholders is collected to inform future product improvements and support services.

End-of-Life Data

The DPP also contains detailed information pertinent to the product's end-of-life phase. This includes documentation on collection methods, sorting procedures, and recycling or reprocessing techniques. By integrating these data with user feedback, waste management processes can be optimized, leading to more efficient and sustainable end-of-life solutions.

Lifecycle Data

Lifecycle data in the DPP provides a holistic view of the product's environmental, social, and legal impacts throughout its entire lifespan. This includes information on sustainability assessments, supply chain traceability, and details about suppliers. Logistics information, certifications, compliance with standards and regulations, and alignment with sustainability development goals are also documented. This data supports stakeholders in making informed decisions that align with legal requirements and sustainability objectives.

2.2. Product Life Cycle

The W2W project focuses on the life cycle of wood products, emphasizing upcycling as a key mechanism to support the EU's Circular Economy Action Plan. This plan aims to enhance resource efficiency by 30% by 2030, reducing environmental impacts while promoting sustainable production, consumption, and waste management. The project's lifecycle approach is illustrated in the accompanying figure, which maps out the stages of product life from resources to the end-of-life phase. At the outset, the **Resources** phase highlights the use of sustainably sourced timber from certified forests, predominantly low-durable woods from the Northern Hemisphere and some undervalued tropical wood species. The project aims to enhance the sustainable use of these resources by minimizing waste and reducing reliance on virgin materials. This aligns with the project's objective of integrating sustainable material use right from the source. Following resource extraction, the wood enters the **Processing** stage, where energy (from gas, electricity, etc.), water, and other resources are consumed. This phase involves generating emissions such as CO_2 and CH_4, alongside volatile organic compounds (VOCs) and wastewater. The W2W project aims to optimize this stage by promoting technological innovations that minimize emissions and resource use, ensuring that wood processing becomes more environmentally friendly and efficient. The next phase, **Distribution**, though not detailed in the figure, is an important part of the life cycle. The project envisions optimizing logistics and transportation through AI-based dynamic tracking tools, ensuring efficient movement of materials with minimal environmental impact.

During the **Setting Up & Period of Use** phase, wood products such as wood flooring and structural components (like wood houses) are subject to wear and tear. VOCs, leachates, and other emissions may occur, requiring proper management to reduce environmental harm. The W2W project addresses this by proposing innovations in maintenance and weathering practices that prolong the lifespan of wood products, reducing the frequency of replacements and repairs. The **End-of-Life** stage in the diagram is particularly critical to the project's goals. Here, the wood waste can follow one of three pathways: *Recycling*, *Incineration* or *Landfilling*. The W2W project emphasizes the importance of diverting wood waste from incineration and landfilling, both of which contribute to carbon emissions and pollution. Instead, the project promotes *Recycling*, which involves recovering usable materials from waste and transforming them into valuable products through innovative processes. Figure 1 shows how this pathway aligns with carbon storage goals and contributes to the circular economy by keeping valuable materials out of landfills.

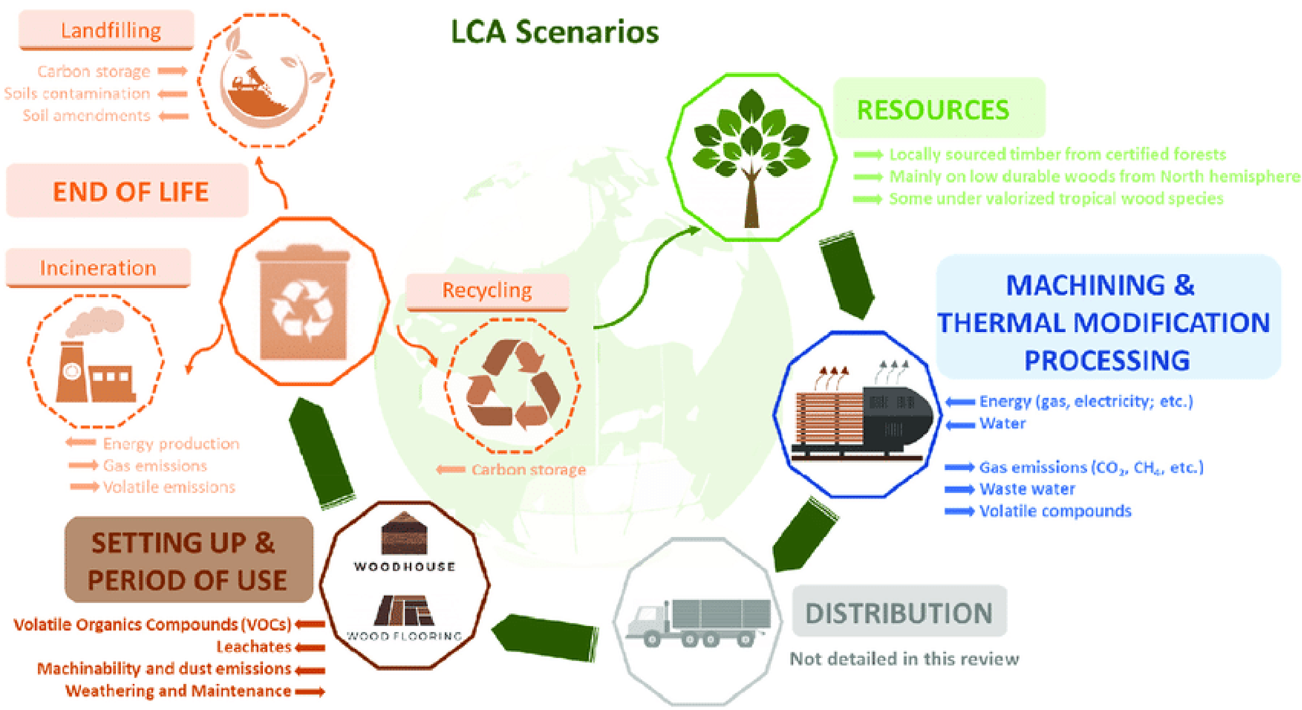

Figure 1 Life cycle assessments of thermally modified wood according to [4].

One of the key aspects of the project is the development of new separation and dissolving processes that allow for the recovery of usable components even from contaminated or composite wood materials, such as laminated flooring, which often contains adhesives and plastics. These processes enable the extraction of cellulose, depolymerization of lignin, and separation of inorganic materials, allowing for the reuse of wood in new products rather than disposal. The integration of digital tools such as dynamic Life Cycle Assessment (LCA) and DSMs will enable real-time monitoring of the environmental and economic impacts of wood recycling and upcycling. These tools will guide decision-making, ensuring that every stage of the product life cycle contributes to the broader goal of sustainability. [5]

2.2.1. Stakeholders

The DPP is designed to serve a broad range of stakeholders, which can be categorized into two main groups: material flow-related stakeholders and strategy-oriented stakeholders. These groups are distinguished by the nature of their engagement with the DPP, the type of information they provide or utilize, and their specific objectives in interacting with the system.

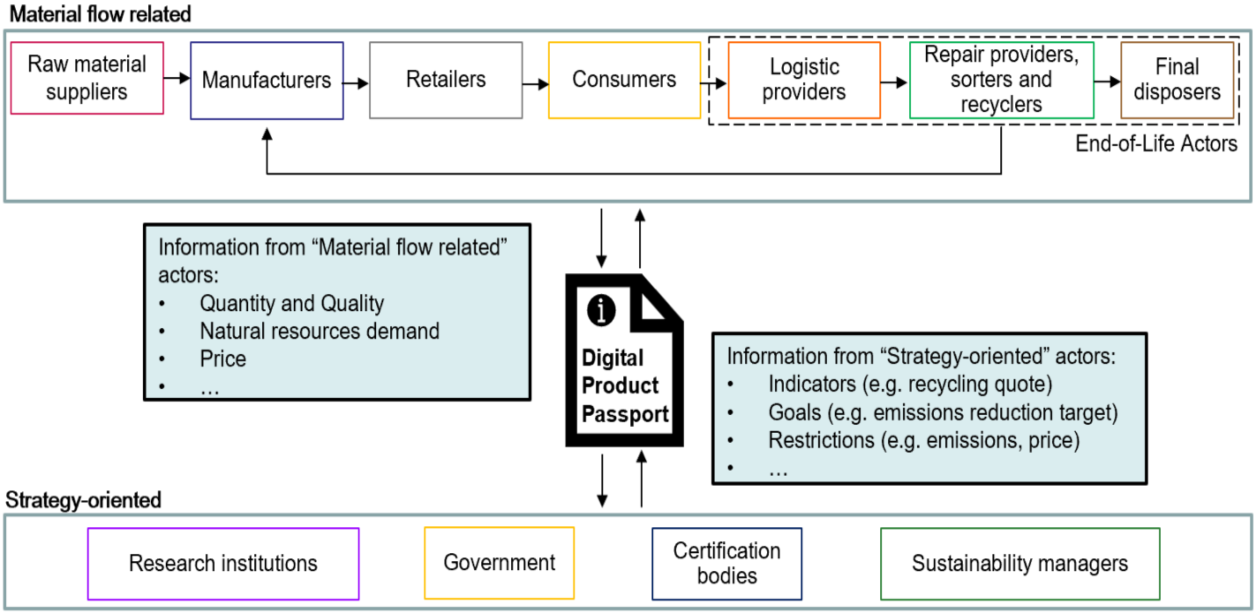

Figure 2: Potential users of the DPP

Material Flow-Related Stakeholders are those who physically interact with the product and materials throughout its lifecycle. This group includes raw material suppliers, manufacturers, retailers, logistic providers, repair providers, sorters, recyclers, and final disposers. These stakeholders are responsible for the handling, transformation, and movement of materials and products. They provide key data to the DPP such as the quantity, quality, and composition of materials, as well as information related to energy, water, and raw material requirements during manufacturing processes. The DPP helps these actors manage and optimize the flow of resources through various stages of production and distribution, while also supporting more efficient logistics and end-of-life recycling efforts. For instance, manufacturers and suppliers can input detailed information about the product's composition and resource usage, allowing logistics and recycling partners to handle materials more effectively and sustainably. Repair providers, sorters, and recyclers can use this data to optimize the reuse and upcycling of materials, reducing waste and supporting circular economy practices. The DPP facilitates communication across the value chain, ensuring that information flows back to upstream actors, allowing for improvements in resource efficiency and material recovery.

On the other hand, **Strategy-Oriented Stakeholders** — including research institutions, government bodies, certification authorities, and sustainability managers — interact with the DPP from a strategic perspective. These stakeholders are focused on long-term sustainability goals, regulations, and market compliance. They leverage data from the DPP to make informed decisions related to environmental policy, product certification, and corporate sustainability initiatives. For instance, governments might use DPP data to monitor compliance with emissions regulations, while certification bodies assess whether products meet industry standards for resource efficiency or eco-friendliness. Sustainability managers and research institutions may analyse the DPP data to identify trends in resource usage, measure the environmental impacts of production processes, or set emissions reduction targets. By having access to real-time information on a product's lifecycle, strategy-oriented actors can also develop future programs or initiatives that drive further resource efficiency, emissions reductions, or circular economy principles.

2.2.2. Guiding Principles

The successful implementation of the DPP across the industrial ecosystem is guided by eight core principles. These principles ensure that the system remains efficient, transparent, and adaptable while addressing the needs of various stakeholders and supporting the broader goals of sustainability and circular economy practices. These practices are according to [6].

1. DPP Requirements Principle

This principle emphasizes the importance of clearly defining the criteria and requirements of the DPP at the system level. It involves explaining the objectives and theoretical foundations underlying the DPP to all relevant parties and users. By ensuring that all stakeholders understand the goals and rationale of the DPP, this principle fosters alignment and effective participation across the industrial ecosystem.

2. DPP Design Principle

The DPP should be designed as a modular, interoperable, and transparent system, using open-source, decentralized infrastructures that prioritize data protection and scalable adoption. This design allows for flexibility in how the DPP is integrated into different systems while ensuring that the data shared across platforms remains secure and transparent. This principle supports the creation of an open infrastructure where all users can trust that their data will be handled responsibly.

3. DPP Technology Principle

The DPP must utilize a common, democratically organized technological infrastructure that is accessible to all stakeholders within the industrial ecosystem. This principle advocates for the selection of digital technologies that are easy to implement and use, ensuring that all participants—regardless of their position in the supply chain—can contribute and benefit from the DPP. By standardizing the technology, the DPP can promote collaboration and interoperability across different industrial systems.

4. DPP Implementation Principle

For the DPP to succeed, it must be fully integrated into business models that align with its objectives. This principle focuses on ensuring that businesses adopt the DPP in a way that improves material flow efficiency, benefiting both upstream suppliers and downstream customers. The alignment between the DPP and business models will also lead to measurable financial benefits, as companies become more resource-efficient and reduce waste through improved data sharing and analysis.

5. DPP Impact Assessment Principle

The sustainability impact of a product must be thoroughly assessed, taking into account potential rebound effects—where efficiency gains lead to increased consumption. This principle ensures that the DPP not only tracks material flows but also evaluates the broader environmental impact of a product. It highlights the importance of assessing the DPP’s contribution to sustainability innovations and determining whether those innovations achieve their intended outcomes.

6. DPP Governance Principle

Effective governance is essential for managing the DPP system. This principle calls for the establishment of a framework for cooperation, formalized through contractual agreements that specify how data will be shared, who has access to the data, and under what circumstances it can be accessed. Additionally, it outlines the incentives, restrictions, and obligations that parties must agree to, ensuring clarity and fairness in the use of DPP data.

7. DPP Regulation Principle

The success of the DPP also depends on engaging with regulators to advocate for policies that support the development of fair and effective DPP systems. This principle emphasizes the importance of collaboration with regulatory bodies to influence policies that align with the DPP's goals of promoting transparency, sustainability, and resource efficiency.

8. DPP Improvement Principle

Continuous improvement is at the heart of the DPP’s long-term success. This principle encourages the involvement of all stakeholders in improving the DPP system over time. By fostering collaboration among users, the DPP can evolve to meet new challenges, incorporate feedback, and remain relevant in an ever-changing industrial landscape.

2.3. Data Sharing Models

DSM define the frameworks and methodologies by which data is exchanged between entities, ensuring that the right data is available to the right stakeholders at the right time. These models are pivotal in sectors such as healthcare, finance, supply chain management, and manufacturing, where timely and accurate data exchange can significantly impact operational efficiency and strategic decision-making. DSM encompass a range of architectures and protocols designed to facilitate data exchange while addressing concerns related to security, privacy, interoperability, and compliance with regulatory standards. The primary models include centralized, decentralized, federated, and peer-to-peer systems, each with its unique advantages and challenges.

DSM are fundamental to how information is exchanged and managed across various platforms and organizations. One common approach is centralized data sharing, where data is collected, stored, and managed in a single central repository. This model simplifies data management and ensures consistency since all information resides in one location. However, it also introduces risks such as single points of failure, scalability issues, and potential bottlenecks. Moreover, centralized systems can raise concerns about data sovereignty and control, as participants might be reluctant to relinquish their data to a central authority. On the other hand, decentralized data sharing distributes data across multiple nodes or participants, eliminating the need for a central authority. This approach enhances resilience and reduces the risk associated with single points of failure. Technologies like blockchain exemplify decentralized data sharing by enabling transparent and immutable records without centralized control. Despite these advantages, decentralized systems can face challenges in achieving consensus, ensuring data integrity, and managing scalability. [7]

Achieving the balance between centralized and decentralized models, federated data sharing allows data to remain within the control of individual entities while enabling sharing through standardized interfaces and protocols. In this model, data isn't moved to a central repository; instead, queries are executed across federated databases, and results are aggregated. An example of this is federated learning in artificial intelligence, where models are trained across multiple decentralized devices holding local data samples without exchanging them. Finally, peer-to-peer (P2P) data sharing facilitates direct data exchange between participants without intermediaries. This model promotes autonomy and reduces dependency on central servers, enhancing robustness and scalability. P2P networks are utilized in file-sharing applications and distributed computing projects. However, they can present challenges in managing data consistency, security, and establishing trust among participants.

2.3.1. The Role of Data Sharing Models in DPPs

The effective implementation of DPPs relies heavily on robust DSM that ensure seamless, secure, and efficient exchange of product data among manufacturers, suppliers, retailers, consumers, and recyclers. The chosen data sharing framework must address key considerations such as data interoperability, security, privacy, and compliance with regulatory requirements like the General Data Protection Regulation (GDPR). One common approach is the centralized DSM for DPPs, which involves a central platform where all product information is stored and managed. This model simplifies data access and management by providing a single source of truth for all stakeholders. However, it may raise concerns about data monopolization, vendor lock-in, and vulnerability to cyber-attacks. Central authorities overseeing such platforms must ensure high levels of security and build trust to encourage participation from all stakeholders. Alternatively, decentralized models—particularly those leveraging blockchain technology—offer promising solutions for DPPs. Blockchain's immutable ledger and distributed nature enhance transparency and trust among participants. Each transaction or update to a product's passport is recorded on the blockchain, providing an auditable trail that is virtually tamper-proof. Smart contracts can further automate processes such as compliance checks and ownership transfers. Despite these advantages, challenges persist, including scalability issues, energy consumption concerns associated with certain blockchain consensus mechanisms, and the need for standardization to ensure interoperability between different blockchain platforms.

Federated DSMs present another viable option by allowing organizations to maintain control over their data while still participating in the DPP ecosystem. Through standardized interfaces and data formats, interoperability is achieved without requiring data to leave the organization's domain, thus enhancing privacy and security. This model facilitates collaboration without necessitating full data disclosure, which is particularly important when dealing with proprietary or sensitive information. Lastly, peer-to-peer (P2P) models can enable direct data exchange between stakeholders in the DPP ecosystem. By eliminating intermediaries, this approach can reduce latency and improve efficiency. However, ensuring data integrity, authenticity, and trust in a P2P environment requires robust mechanisms—potentially combining elements of blockchain or other verification technologies—to validate transactions and secure communications.

2.3.2. Challenges and Considerations

Achieving interoperability is crucial for the success DPPs. Diverse stakeholders often use different systems and standards, making it essential to adopt common data models, formats, and communication protocols. Implementing standards such as ISO 10303 (STEP) for product data representation and exchange can facilitate seamless interoperability, ensuring that all parties can access and interpret product information accurately. Protecting sensitive information while enabling data sharing presents significant challenges in the context of DPPs. DSMs must incorporate robust security measures, including encryption, access control, and authentication mechanisms, to safeguard data integrity and confidentiality. Compliance with data protection regulations like the General Data Protection Regulation (GDPR) is mandatory, necessitating careful handling of personal and sensitive data to prevent unauthorized access and ensure legal adherence.

Scalability is another critical consideration for DSMs supporting DPPs. The chosen technologies and architectures must be capable of accommodating the vast amount of data associated with products throughout their lifecycle. This includes supporting growth in data volume, the number of participants, and transaction frequency without compromising system performance. Scalable solutions ensure that as the DPP ecosystem expands, the infrastructure remains robust and efficient. Building trust among participants and establishing effective governance are essential for the widespread adoption of DPPs. Clear governance structures, transparent policies, and fair data usage agreements can encourage stakeholder participation by outlining roles, responsibilities, and expectations. In decentralized models, establishing consensus mechanisms and dispute resolution processes becomes critical to maintain cooperation and resolve conflicts, thereby fostering a trustworthy environment.

Cost and infrastructure implications play a significant role in the implementation and maintenance of DSMs for DPPs. Stakeholders must consider the financial aspects, including technology investments, operational expenses, and potential fees associated with platform usage. Balancing these costs against the benefits of improved data sharing, compliance, and sustainability is crucial for the long-term viability of DPP initiatives. Regulatory and standardization efforts are shaping the future of data sharing for DPPs. Regulatory bodies and industry groups are actively working towards establishing standards and regulations to facilitate data exchange. The EU's Sustainable Products Initiative, for example, aims to make sustainable products the norm, with DPPs playing a key role in this transformation. Standards organizations are developing frameworks to support data interoperability, security, and governance, which will guide stakeholders in implementing effective and compliant DSMs.

2.4. FAIR PRINCIPLES IN W2W

The FAIR principles serve as comprehensive guidelines for the management and exchange of scientific data. Designed to enhance the discovery and reuse of data by third parties, these principles outline the essential characteristics that information resources, tools, vocabularies, and infrastructures should possess. Although each component of the FAIR principles is distinct, they are inherently interconnected, working together to support a cohesive data ecosystem. [10]

Findability refers to the ease with which data can be located by both humans and machines. This involves assigning globally unique and persistent identifiers to data, providing rich metadata descriptions, and indexing data in searchable resources. By ensuring that data is easily discoverable, researchers and other stakeholders can efficiently locate the information they need.

Accessibility ensures that once data is found, it can be accessed appropriately, possibly through well-defined authentication and authorization procedures. This principle acknowledges that while some data may be open access, other data might require controlled access due to privacy or security considerations. Clear protocols and metadata about access procedures are essential components of this principle.

Interoperability focuses on the ability of data to be integrated with other data and to interoperate with applications or workflows for analysis, storage, and processing. This is achieved through the use of shared vocabularies, ontologies, and standardized formats that enable diverse systems to understand and use the data coherently. Interoperability is crucial for collaborative research and for combining datasets from different sources.

Reusability emphasizes that data should be well-described and documented so that it can be replicated, combined, or used in new contexts beyond its original purpose. This includes providing clear usage licenses, detailed provenance information, and adhering to community standards for data and metadata. By facilitating reuse, the FAIR principles support innovation and the advancement of knowledge.

By adopting the FAIR principles, organizations and researchers can improve the quality and efficiency of data management practices. The interconnected nature of these principles means that advancements in one area often support progress in others. For instance, enhancing metadata for findability can also improve interoperability and reusability. Ultimately, the FAIR principles aim to foster a data environment where information is more readily available, usable, and valuable to the broader scientific community.

Table 1: FAIR Principles derived from [8, 9]

FAIR	Description	FAIR principles
Findable	The first step in (re)using data is to find them. Metadata and data should be easy to find for both humans and computers. Machine-readable metadata are essential for automatic discovery of datasets and services, so this is an essential component of the FAIRification process.	F1. (meta)data are assigned a globally unique and persistent identifier
		F2. Data are described with rich metadata (defined by R1 below)
		F3. Metadata clearly and explicitly include the identifier of the data they describe
		F4. (Meta)data are registered or indexed in a searchable resource
Accessible	Once the user finds the required data, she/he/they need to know how they can be accessed, possibly including authentication and authorisation.	A1. (Meta)data are retrievable by their identifier using a standardised communications protocol
		A1.1 The protocol is open, free, and universally implementable
		A1.2 The protocol allows for an authentication and

		authorisation procedure, where necessary
		A2. Metadata are accessible, even when the data are no longer available
Interoperable	The data usually need to be integrated with other data. In addition, the data need to interoperate with applications or workflows for analysis, storage, and processing.	I1. (Meta)data use a formal, accessible, shared, and broadly applicable language for knowledge representation.
		I2. (Meta)data use vocabularies that follow FAIR principles
		I3. (Meta)data include qualified references to other (meta)data
Reusable	The ultimate goal of FAIR is to optimise the reuse of data. To achieve this, metadata and data should be well-described so that they can be replicated and/or combined in different settings.	R1. (Meta)data are richly described with a plurality of accurate and relevant attributes
		R1.1. (Meta)data are released with a clear and accessible data usage license
		R1.2. (Meta)data are associated with detailed provenance
		R1.3. (Meta)data meet domain-relevant community standards

2.5. Other EU Projects

1. CIRPASS

CIRPASS (Collaborative Initiative for a Standards-based DSM for Stakeholder-Specific Sharing of Product Data for a Circular Economy) is an EU-funded project with the aim of developing DPPs in accordance with the Eco-design Sustainable Product Regulations (ESPR), which was finalised in March 2024. In three value chains - textiles, electronics and batteries - CIRPASS focussed primarily on the creation of roadmaps for DPP prototypes. In addition, the promotion of an open DPP data exchange protocol, the description of product identification requirements and the creation of a cross-sectoral product data model are the main objectives of CIRPASS [11].

2. Digital Product Pass

The Digital Product Pass (DPP) application is an open source project developed as part of the Eclipse Tractus-X initiative, whose main goal is to provide a user interface for customers to obtain and display battery passports from manufacturers using the standardized components and technologies of the Catena-X network. This DPP project allows users to retrieve battery data by scanning QR codes or by entering the manufacturer or product ID via Eclipse database connectors through the Catena-X network, with the format being human-readable only for logged-in users [12].

3. CISUTAC Project (Circular and Sustainable Textiles and Clothing.)

The CISUTAC project (Circular and Sustainable Textiles and Clothing), funded under the Horizon Europe framework, plays a pivotal role in advancing circular economy practices within the textile and clothing sector. A core focus of the project is to enhance transparency, traceability, and sustainability across the textile value chain through innovative solutions such as DPPs. DPPs serve as digital records that contain comprehensive information about a product's material composition, manufacturing process, lifecycle, and end-of-life options [13]. CISUTAC supports the development and implementation of DPPs by promoting data collection on textile products and integrating digital tools that manage this data effectively [14]. By providing detailed information on the recyclability, reuse potential, and circularity of textiles, DPPs foster informed decision-making among stakeholders and consumers, aligning with CISUTAC's goals to reduce waste and enhance sustainability in the textile industry [15]. Furthermore, CISUTAC's emphasis on designing for circularity, developing new recycling technologies, and engaging stakeholders in sustainable practices directly contributes to the data needed for DPPs to function effectively. This integration not only supports compliance with upcoming EU regulations mandating digital transparency for products but also encourages a shift towards more sustainable consumption patterns [16]. Overall, the synergy between CISUTAC and the DPP framework demonstrates a comprehensive approach to addressing environmental challenges in the textile sector through digital innovation and circular economy principles.

3. REQUIREMENTS FOR DATA SHARING MODELS

3.1. Essential Requirements

The DSM is a fundamental component in realizing the goals set forth by the ESPR. It plays a crucial role in enabling effective management and exchange of product data throughout the entire lifecycle, from design and manufacturing to use and end-of-life disposal. The essential requirements for the DSM are driven by the need for transparency, interoperability, and adherence to regulatory standards. These requirements ensure that product information is accessible, accurate, and secure, facilitating a circular economy where products are designed for longevity, repairability, and recyclability. Below are the key essential requirements for a DSM based on the ESPR:

3.1.1. Interoperability and Standardization

For the DSM to be effective, it must enable seamless data exchange across various systems and platforms used by different stakeholders. Interoperability ensures that all parties can communicate and share information without technical barriers, which is vital for a functioning circular economy. The DSM should support:

- Open Standards: Utilizing open standards is essential to ensure that data can be read, processed, and interpreted by various stakeholders—such as manufacturers, suppliers, recyclers, and regulatory bodies—without being restricted by proprietary systems or vendor lock-in. Open standards promote compatibility and facilitate collaboration across different software and platforms, enabling a more integrated and efficient supply chain [17].

- Machine-Readable Formats: Data should be available in formats that can be automatically processed by computers, enhancing the usability of the information across digital systems. Machine-readable formats enable automation, reduce the likelihood of human error, and allow for real-time data analysis and decision-making. This is critical for applications such as supply chain management, compliance monitoring, and sustainability assessments [18].

3.1.2. Decentralized Data Storage and Access

Secure, accessible, and resilient data storage is imperative for the DSM to function reliably. Decentralizing data storage mitigates the risks associated with centralized systems, such as single points of failure or bottlenecks. Key requirements include:

- Decentralized Data Storage: Data should be stored either with Responsible Economic Operators (REOs) or independent certified third-party providers. This approach distributes data storage across multiple locations and entities, enhancing data security and resilience. Decentralization ensures that if one node fails or is compromised, the data remains accessible from other sources, thereby preventing disruptions in the supply chain or data loss [19].

- Free and Easy Access to Specific Data Points: Stakeholders throughout the supply chain must have unobstructed access to essential product data. This means eliminating barriers such as excessive fees, restrictive licensing, or cumbersome access procedures. Easy access to data empowers stakeholders to make informed decisions, comply with regulations, and contribute to sustainability goals. For instance, recyclers need access to material composition data to process products correctly, while consumers may seek information on product durability or repair options [20].

3.1.3. Data Privacy and Usage Control

Protecting the privacy and interests of all stakeholders is a critical aspect of the DSM. Robust data usage controls are necessary to prevent misuse of sensitive information and to comply with legal and ethical standards. This includes:

- No Secondary Data Use Without Consent: Data shared within the DSM should be used solely for its intended purpose unless explicit consent is obtained from the data owner for additional uses. This provision safeguards against unauthorized exploitation of data, such as selling user data to third parties or using proprietary information for competitive advantage. It ensures transparency and builds trust among stakeholders by respecting their rights and intentions [21].

- Role-Based Access Control: Implementing role-based access control means that access to data is granted based on the user's role and responsibilities within the organization or supply chain. Only authorized entities with a legitimate interest should have access to specific data sets. This minimizes the risk of sensitive information being exposed to unauthorized parties and helps maintain data integrity and confidentiality. For example, a manufacturer may have access to detailed design specifications, while a retailer might only access pricing and inventory data [22].

3.1.4. Persistent and Unique Product Identification

Assigning a persistent and unique identifier to each product is essential for tracking and managing products throughout their lifecycle. This requirement facilitates:

- Traceability Across the Product Lifecycle: A persistent unique product identifier allows for continuous tracking of a product from manufacturing through to end-of-life recycling. It ensures that each product can be uniquely identified and associated with its relevant data within the DSM. This is crucial for activities such as warranty claims, recalls, maintenance, and recycling processes.

Traceability enhances transparency and accountability, enabling stakeholders to monitor product performance, origin, and compliance with regulations [23].

3.1.5. Consumer and Stakeholder Transparency

Transparency empowers consumers and stakeholders by providing them with the information needed to make sustainable and informed decisions. The DSM must facilitate:

- Real-Time Visibility into Key Product Attributes: Providing up-to-date information on product characteristics—such as environmental impact, energy efficiency, material composition, and repairability—enables consumers to choose products that align with their values and sustainability goals. This transparency fosters consumer trust and encourages manufacturers to improve product sustainability to meet market demands [24].

- Public or Restricted Access Conditions: The DSM should differentiate between data that is publicly accessible and data that requires restricted access due to its sensitive nature. Public data might include general product information and environmental performance metrics, while restricted data could involve proprietary manufacturing processes or trade secrets. Establishing clear access conditions balances the need for transparency with the protection of confidential business information [25].

3.1.6. Compliance with Legal and Ethical Standards

Adhering to legal and ethical standards is non-negotiable for the DSM to function responsibly and effectively. This includes:

- Compliance with Data Protection Regulations: The DSM must comply with existing data protection laws, such as the GDPR in the EU. This involves implementing appropriate technical and organizational measures to protect personal data, ensuring lawful processing, and upholding individuals' rights over their data. Compliance reduces legal risks and reinforces ethical data handling practices [26].

- Alignment with ESPR Technical, Semantic, and Organizational Requirements: The DSM must meet the technical specifications, semantic standards, and organizational protocols outlined in the ESPR. This ensures consistency in how data is structured, interpreted, and managed across different platforms and stakeholders. Aligning with these requirements enhances interoperability, data quality, and the overall effectiveness of sustainability initiatives.

3.2. TECHNICAL REQUIREMENTS

The technical requirements for the DSM under the ESPR are designed to ensure efficient, secure, and transparent sharing of product data throughout its lifecycle. These requirements are essential for the effective implementation of the DPP, which is a key component of the ESPR's objectives to foster circularity and sustainability in product design and consumption. An effective DSM enables stakeholders—including manufacturers, suppliers, regulators, consumers, and recyclers—to access and share vital product information. This facilitates better decision-making, compliance monitoring, and promotes sustainable practices across the product's lifecycle. Below is an expanded and detailed guide on the key technical requirements for the DSM based on the ESPR.

3.2.1. Interoperability and Data Formats

To meet the goals of the ESPR, the DSM must ensure full interoperability between various stakeholders, systems, and platforms involved in the product lifecycle. Interoperability is critical for seamless data exchange, reducing barriers, and enhancing collaboration among different entities. Key technical requirements include:

Open Standards (Article 9, Paragraph 1d ESPR):

- Avoiding Vendor Lock-In: Data must be shared using open standards to prevent dependency on specific vendors or proprietary systems. This ensures that data can be accessed and used by any stakeholder, regardless of the software or platform they employ.
- Compatibility Across Systems: Open standards facilitate compatibility across different systems, industries, and countries, enabling global interoperability. This is essential for multinational supply chains and for products that are traded internationally.
- Examples of Open Standards: Utilizing formats like XML, JSON, or industry-specific standards like ISO 10303 (STEP) for product data representation.

Machine-Readable Data Carriers (Article 9, Paragraphs 1b & 1c ESPR):

- Data Accessibility: The DSM must support machine-readable data carriers such as QR codes, RFID tags, or NFC chips that can be affixed to products. These carriers allow for easy retrieval and interpretation of data by all stakeholders using standard devices like smartphones or RFID readers.
- Ease of Use: Machine-readable formats enable quick access to product information without the need for specialized equipment or extensive manual data entry.
- Dynamic Updates: Some data carriers can be reprogrammed to update the information stored, which is useful for reflecting changes in product status or specifications throughout its lifecycle.

3.2.2. Decentralized and Secure Data Storage

In line with ESPR requirements, product data must be stored in a decentralized manner to ensure accessibility, security, and resilience. Centralized systems can be vulnerable to single points of failure, whereas decentralization distributes the risk and enhances system robustness. Technical requirements for data storage include:

Decentralized Data Storage (Article 10, Points c & d ESPR):

- REOs: Data related to products must be stored by REOs or certified third-party service providers authorized to store data on behalf of manufacturers. This ensures that the data is managed by entities accountable for its integrity and availability.
- Accessibility: Decentralization ensures that data remains accessible even if one entity becomes unavailable due to technical failures, cyber-attacks, or business discontinuity.
- Data Redundancy: By having multiple storage locations, the DSM mitigates the risk of data loss and ensures continuity of access for all stakeholders.

Data Integrity and Security:

- Encryption Mechanisms: Data must be secured using strong encryption both during transmission (in transit) and when stored (at rest) to prevent unauthorized access or tampering. Encryption protocols like TLS/SSL for data in transit and AES-256 for data at rest are commonly used.
- Compliance with GDPR and ESPR's Data Usage Control Measures (Article 9, Paragraph 1da ESPR): The DSM must ensure that data is used only for its intended purpose and that personal data is handled in compliance with data protection regulations. This includes implementing data anonymization or pseudonymization where necessary.
- Access Control: Implementing robust authentication and authorization mechanisms to ensure that only authorized users can access sensitive data.

3.2.3. Role-Based Access and Consent Management

To comply with ESPR's data control requirements, the DSM must implement strict access control mechanisms. This ensures that sensitive information is protected and that data privacy is maintained across the system.

Role-Based Access Control (RBAC) (Article 9, Paragraph 1da ESPR):

- Defining User Roles: The DSM must define various user roles (e.g., manufacturer, supplier, regulator, consumer) and assign access permissions based on these roles.
- Attribute-Based Access Control (ABAC): In some cases, ABAC may be used to provide more granular control by considering user attributes, environmental conditions, or resource attributes.
- Protecting Sensitive Information: Sensitive data such as proprietary manufacturing processes, trade secrets, or personal consumer data must remain accessible only to authorized personnel.

No Secondary Use Without Consent:

- Purpose Limitation: Data collected and shared within the DSM must not be used for purposes beyond its original intent without explicit consent from the relevant parties.
- Consent Management: The DSM should incorporate mechanisms for obtaining, recording, and managing user consents, preferences, and permissions.
- Regulatory Compliance: This is critical for compliance with ESPR and data protection laws like GDPR, which mandate that data subjects have control over how their data is used.

3.2.4. Real-Time Data Exchange and Versioning

To ensure the integrity and timeliness of the data shared through the DSM, the system must support real-time data updates and robust version control.

Real-Time Data Updates (Article 9, Paragraph 3a ESPR):

- Timeliness: The DSM must facilitate immediate updates to data points as products evolve throughout their lifecycle. This is essential for reflecting changes such as product recalls, updates in regulatory compliance, or modifications in environmental impact assessments.
- Event-Driven Architecture: Implementing an event-driven architecture can enable real-time data synchronization across the system when changes occur.

- Stakeholder Notifications: Automated notifications can alert relevant stakeholders about critical updates, ensuring that everyone has the most current information.

Version Control:

- Traceability and Accountability: A robust version control system must manage updates to product data, allowing for tracking of who made changes, what changes were made, and when they occurred.
- Historical Data Access: Stakeholders should be able to access both current and historical data points for each product, which is important for audits, compliance checks, and analysing product performance over time.
- Conflict Resolution: Version control mechanisms help in resolving conflicts that may arise when multiple parties attempt to modify the same data concurrently.

3.2.5. Dynamic and Public/Restricted Information Points

The ESPR emphasizes the importance of providing both static and dynamic product information, with appropriate access controls based on the sensitivity of the data.

Dynamic Information Points:

- Static Data: Includes unchanging information such as product identification details, manufacturer information, and material composition.
- Dynamic Data: Encompasses information that may change over time, such as environmental impact metrics, energy consumption data, or maintenance records.
- Data Refresh Mechanisms: The DSM must support mechanisms for regularly updating dynamic data to ensure accuracy and relevance. [26]

Public and Restricted Access:

- Public Data: Certain data points should be openly available to the general public, such as environmental impact data, energy efficiency ratings, and basic product information. This transparency empowers consumers to make informed decisions.
- Restricted Data: Sensitive information, such as proprietary manufacturing processes or detailed supply chain data, should be accessible only to authorized stakeholders with legitimate interests.
- Access Rights Management: The DSM must implement policies and technologies to manage and enforce access rights, ensuring compliance with legal and contractual obligations.

3.2.6. Backup, Archiving, and Redundancy

To ensure data persistence, integrity, and accessibility, the DSM must include robust mechanisms for secure backup, archiving, and redundancy.

Backup and Archiving:

- Automatic Backup Processes: The DSM should have automated processes for regularly backing up data to prevent loss due to system failures, cyber-attacks, or human errors.
- Certified Independent Third-Party Providers: Utilizing certified third-party service providers for backup storage ensures that data is preserved in secure, compliant environments.

- Long-Term Archiving: Data should be archived in a manner that ensures it remains accessible and readable over extended periods, which is important for compliance with regulatory requirements and for historical analysis. [26]

Redundancy:

- System Resilience: Employing redundant data storage techniques, such as data replication across multiple servers or locations, enhances system resilience and availability.
- Failover Mechanisms: Implementing failover strategies ensures that if one component fails, another can take over without disrupting service.
- Minimizing Downtime: Redundancy helps minimize the risk of data loss or inaccessibility, ensuring continuous operation of the DSM even in the event of technical failures.

3.3. Design principles for data sharing models

The following table outlines a set of design principles intended to guide the development and operation of data sharing Communities of Practice. These principles aim to enhance collaboration, standardize practices, and create mutual value among community members engaged in shared data management initiatives. The principles are organized into three key areas: Domain of Interest, Community, and Shared Practice. Each design principle includes a specific aim, the mechanism for achieving it, and the context in which it should be applied, as referenced in sources [27] and [28].

Table 2: Design Principles for Data Sharing [22] [23]

Communities of Practice	Design Principle	Description
Domain of Interest	DP 1 – Case for action	Aim: To identify the data sharing community's scope and shared domains of interest Mechanism: Community members should pinpoint their shared data management challenges in a "case for action." Context: In the design phase
	DP 2 – Value proposition	Aim: To communicate the data sharing community's value and impact Mechanism: The value proposition of shared data management should describe its expected direct and indirect benefits, as well as the methods for measuring its impact Context: In the design and the operating phases
Community	DP 3 – Community charter and guidelines	Aim: To clarify the institutional framework for the community Mechanism: Community guidelines and procedures should include a roadmap with deliverables, as

		well as the collaboration and participation mechanisms Context: In the design phase
	DP 4 – Community members as prosumers	Aim: To ensure all the community members contribute actively to the shared practice Mechanism: Community members should endorse the roles of providers and consumers of the data assets in the data pool, thereby acting as data prosumers Context: In the building and the operating phases
	DP 5 – Community support	Aim: To facilitate community operations in a trusted environment Mechanism: A neutral intermediary should provide organizational and technical support, and report the successes and KPIs regularly Context: In the building, operating, and supporting phases
Shared Practice	DP 6 – Shared semantics	Aim: To standardize the community members' norms, practices, and terminologies Mechanism: A common business vocabulary and rulebook should be developed, accepted, and used by all the community members Context: In the building and the operating phases
	DP 7 – Shared data assets	Aim: To expand the volume of share data assets Mechanism: The intermediary should provide periodic updates and communications about the community's data landscape, as well as communicate the external data sources that are relevant for enriching the pool Context: In the building and the operating phase
	DP 8 – Data management practices	Aim: To grow the community and its benefits Mechanism: Community members should continuously refine the required data management practices that need to be implemented on the data sharing platform Context: In the building and the operating phases

4. STRUCTURE OF DATA SHARING MODEL – ONTOLOGY CREATION

To implement DPPs and facilitate seamless data exchange among diverse stakeholders, a well-structured DSM is imperative. Central to this model is the creation of an ontology—a formal representation of knowledge within a specific domain that defines the relationships between concepts and data elements. Ontology creation enables standardized communication by providing a common vocabulary and framework, ensuring that disparate systems can interoperate and share information accurately. This section delves into the structure of DSMs with a focus on ontology creation, highlighting how it enhances interoperability, data consistency, and the overall efficiency of data management in the context of DPPs.

4.1. Ontology Tools

Ontologies provide a common vocabulary for the visualisation and integration of data from many sources, representing concepts and relationships in a domain [29,30]. The semantic web relies heavily on ontologies, which provide a framework for integrating and expressing data from different sources, helping to overcome the difficulties caused by data heterogeneity and facilitating data sharing, integration and reuse [30,30,31].

In [14], ontology tools are analysed with regard to the visualisation methods used, user interaction techniques, Web Ontology Language and their suitability. Based on the results of [31], an ontology tool is selected for this task and the following table summarises the results of the study.

Table 3: Available and working tools

Available and working tools	Description
CropCircles	CropCircles is a visualisation tool that is only accessible via the "fly the mothership" command in the SWOOP ontology editor and offers a simple implementation of Euler diagrams with limited functionality.
Graffoo	Graffoo is a manual drawing tool that is not suitable for most use cases, with the exception of splitting and is accessible as a palette profile for the yEd Graph Editor and cannot be imported or exported to an Web Ontology Language (OWL) format.
Jambalaya	Jambalaya is a complex visualisation plugin for Protégé 3, which is a flexible tool and not for Protégé 4 or newer versions.
KC-Viz	KC-Viz is integrated in Neon Toolkit which offers an innovative way to visualize and navigate ontologies—an OWL ontology IDE similar to Protégé.
NavigOWL	NavigOWL is a visualisation tool for researching semantic networks, Protégé 4 Plugin.
Neon Toolkit ontology visualizer	Neon Toolkit is an ontology development platform that, like Protégé, is based on the Eclipse environment and offers all entities in one window, separated under folder-like top-level nodes.
OLSVis	OLSVis is a web application that is limited to displaying a few preconfigured ontologies with a biological focus.
Ontodia	Ontodia is a open source ontology and semantic information visualisation tool with additional features for sharing and

	distributing the created diagrams and is weak for learning but very powerful for the other use cases.
OntoGraf	OntoGraf is a visualization plugin integrated in Protégé 4 that facilitates interactively exploring the links across OWL ontologies.
OntoStudio	OntoStudio is an ontology modelling environment and commercial software.
OWLViz	The visualization plugin OWLViz was created to be used in conjunction with Protégé 3.
OWLGrEd	OWLGrEd is a stand-alone programme that is compatible with Protégé 4.
Protégé Entity Browser	Protégé is an open-source platform for ontology development, or an ontology editor, with a design that facilitates the creation of plugins.
SOVA	SOVA is a visualization plugin for Protégé 4.
TGViz	TGViz is a visualisation plug-in for the Protégé version with limited functionality and is no longer supported.
TopBraid Composer	TopBraid Composer is a commercial software and an ontology editor like Protégé or Neon Toolkit.
WebVOWL	WebVOWL is an online tool for the user-oriented visualisation of ontologies that uses the Visual Notation for OWL Ontologies (VOWL) by providing graphical representations of OWL constituents.

Protégé Entity Browser

Protégé Entity Browser is an ontology editor or open-source platform for the creation of ontologies, whose development began in the 1980s and is still ongoing. Its architecture facilitates the creation of plugins as a development platform. The graphical user interface (UI) of Protégé's Entity Browser contains a basic ontology display with indented lists. Class, data type property, object property, annotation property and individual properties of an entity are displayed in different windows, the so-called entity browsers, which each contain an indented list and can be displayed indented under the parent element, the subclasses and the sub-properties after clicking on the parent element. Simple geometric shapes are used to represent the elements: a circle for classes, a rectangle for data type, object and annotation attributes and a diamond to represent people with different colours to identify the different element types. Next to the form is a label which, depending on the user's preference, can contain the name of the transferred entity, the designation or the value of an additional annotation property. In Protégé, the indented list can be used to select which entity you want to change or which sub-entity you want to create. Once an entity has been selected, all additional relationships and property values are displayed in text form in a separate window; only the hierarchy is displayed in the list. In terms of sharing, the Entity Browser is poor, but in the other use-case areas it is excellent. [31]

4.2. Best Practices for Ontology Creation

Creating an effective ontology is a complex but rewarding endeavor that requires a systematic approach to ensure it is well-defined, consistent, and interoperable across different systems and domains. Ontologies serve as foundational elements in areas like semantic web technologies, artificial intelligence, data integration, and knowledge management. They provide a structured framework to model domain knowledge, enabling machines to interpret and reason about data in a human-like manner. Therefore, an expanded and detailed guide is provided that synthesizes general principles with specific guidance from authoritative sources, including the "Best Practices of Ontology Development" white paper by [32] and [33], and other relevant literature. This guide aims to provide comprehensive insights into the 10 best practices of ontology development.

1. Define the Purpose, Scope, and Objectives; Follow a Step-by-Step Development Process

Begin by clearly defining the purpose of the ontology. Determine whether it is intended to facilitate data integration, enable semantic search, support decision-making, or model complex processes. Identify specific use cases that the ontology will support; for example, in healthcare, an ontology might standardize patient data across different hospitals to improve interoperability. Understanding the needs of the intended users—researchers, practitioners, or systems—is crucial to ensure the ontology meets their requirements. Focus on the domain by limiting the scope to essential concepts and relationships. An overly broad ontology can become unmanageable and less effective. Decide on the level of detail, considering whether the ontology will be high-level and abstract or include detailed specifications. Establish clear boundaries to prevent scope creep; for instance, an ontology for e-commerce should concentrate on products, customers, and transactions, not peripheral areas like logistics unless necessary. Create a detailed development plan outlining the objectives, timeline, and resources required. Formulate competency questions that the ontology should be able to answer, guiding the development process. Compile a list of relevant terms and concepts from literature, experts, and existing ontologies, critically assessing each term for relevance and clarity. Prioritize clarity over complexity by ensuring each entity is distinct and not conflated with others, and avoid circular definitions.

2. Engage Stakeholders and Domain Experts; Provide Training and Support Materials

Assemble an interdisciplinary team that includes domain experts, ontology engineers, and stakeholders. Clearly define the roles and responsibilities of each team member to streamline the development process. Implement iterative development with regular feedback sessions to refine the ontology, and conduct workshops or meetings with stakeholders to validate concepts and relationships. Develop tutorials to help new users understand and apply the ontology. Offer training sessions such as webinars and workshops to facilitate adoption. Maintain comprehensive documentation, including FAQs and troubleshooting guides, and set up forums or mailing lists for user support and community interaction.

3. Adopt a Multi-Tiered Architectural Approach; Develop Modular and Scalable Ontologies

Implement a domain-neutral top-level ontology like the Basic Formal Ontology (BFO) [34], Descriptive Ontology for Linguistic and Cognitive Engineering (DOLCE), or the General Formal Ontology (GFO). Define broad categories such as 'Entity', 'Process', 'Agent', and 'Quality' to provide a universal framework. A top-level ontology ensures consistency and facilitates interoperability across various domains and systems. Develop mid-level ontologies that represent general concepts within a broader domain, acting as intermediaries between the top-level ontology and specialized ontologies. Create lower-level ontologies to model specific areas in detail, ensuring hierarchical consistency. Divide the ontology into modules based on content areas (e.g., 'CustomerModule', 'ProductModule'). Each module should be self-contained and focus on a specific aspect of the domain. Define clear interfaces and relationships between modules to ensure seamless integration, and consider that modules can be reused in different ontologies or projects, enhancing scalability.

4. Use Established Standards and Reuse Existing Ontologies; Implement Ontology Design Patterns

Utilize OWL to ensure interoperability and compatibility with existing tools and systems. OWL provides rich expressive power for defining classes, properties, individuals, and data types. Incorporate established ontologies like Dublin Core (metadata), FOAF (social networks), or schema.org (web data) to promote interoperability and avoid duplication of efforts. Ensure that reused terms maintain their original meanings to prevent semantic inconsistencies. Apply established ontology design patterns (ODPs) to address common modeling challenges. Access pattern libraries like the Ontology Design Patterns portal for reusable solutions. Using ODPs promotes consistency across different parts of the ontology and with other ontologies.

5. Ensure Ontological Realism; Adopt Clear Naming Conventions and Provide Definitions

Model the ontology based on entities as they exist in reality, not merely as data constructs [5]. Represent entities independently of how data about them is stored or managed in databases. By focusing on real-world entities, different systems can align their data more effectively, facilitating the integration of heterogeneous data sources by providing a common understanding of entities. Use clear and descriptive names for classes, properties, and individuals—for example, 'PatientRecord' instead of 'PR'. Apply consistent naming conventions throughout the ontology, such as CamelCase for classes and lowerCamelCase for properties. Supply clear, concise, and unambiguous definitions for each term to prevent misinterpretation, and use language that is accessible to both domain experts and non-experts, avoiding jargon.

6. Ensure Ontology Consistency and Single Inheritance; Utilize Ontology Development Tools

Utilize automated reasoners to detect inconsistencies or logical errors, and regularly perform consistency checks during development to catch issues early. Organize classes such that each subclass has only one direct superclass to maintain hierarchical clarity. Ensure properties and relationships are inherited correctly, maintaining the integrity of the hierarchy. If multiple inheritance is necessary, document and justify its use clearly to prevent confusion. Use ontology editors like Protégé, an open-source tool that supports OWL and RDF, and employ visualization tools to understand the ontology's structure and relationships. Use automated reasoners to validate logical consistency and infer implicit knowledge, and implement SPARQL queries to test retrieval and reasoning capabilities.

7. Provide Clear Documentation and Annotations; Version Control and Governance

Use annotation properties like `rdfs:label`, `rdfs:comment`, and `skos:definition` to provide additional information. Include version numbers, authorship, and change history within annotations. Provide illustrative instances or examples of how classes and properties are used in real-world scenarios, and develop user guides or manuals explaining how to navigate and utilize the ontology. Implement semantic versioning (e.g., MAJOR.MINOR.PATCH) to track changes and updates, and maintain detailed logs of changes, including additions, deletions, and modifications. Define who has the authority to make changes to the ontology and establish procedures for reviewing and approving changes. Implement mechanisms for resolving disagreements among team members to ensure smooth governance.

8. Test with Real Data and Scenarios; Monitor and Evaluate Ontology Quality

Map real or simulated data to the ontology to test its applicability, and create realistic scenarios to evaluate how the ontology performs in practical situations. Use the feedback from these tests to identify areas for improvement and refine the ontology accordingly. Monitor performance metrics like query response times and reasoning efficiency [32]. Assess whether the ontology adequately covers the domain concepts and relationships, and monitor the complexity to ensure it remains manageable. Compare the ontology against others in the same domain to identify strengths and weaknesses, and evaluate reasoning and query performance under different conditions to ensure optimal functionality.

9. Promote Accessibility and Reusability; Ensure Internationalization and Localization

Share the ontology on open platforms like BioPortal, Linked Open Vocabularies (LOV), or GitHub, and choose appropriate licenses (e.g., Creative Commons) to facilitate reuse while protecting intellectual property. Encourage community contributions and collaborations to enhance the ontology's quality and coverage, and provide channels for users to report issues or suggest improvements. Use language tags in annotations to support multiple languages, and be mindful of cultural differences that may affect term meanings or usage. Ensure the ontology supports Unicode to accommodate international characters, enhancing its global accessibility. [32]

10. Address Ethical and Legal Considerations; Plan for Maintenance and Evolution

Ensure the ontology complies with data protection regulations like GDPR, and design it to support data anonymization techniques when necessary. Properly attribute any reused content or terms from other ontologies, and be aware of and comply with any licensing restrictions of integrated ontologies. Consider how the ontology will be maintained over time, including resource allocation for sustainability. Establish processes for regular updates and incorporation of new knowledge. Build a user community that can contribute to the ontology's growth and maintenance, and provide training and support to users and contributors to foster ongoing development. [26]

4.3. FAIR Ontology for DPPs in W2W

The integration of the FAIR principles into an ontology for DPPs aims to enhance the management and exchange of product information across the entire lifecycle. By adopting a FAIR-aligned ontology in the W2W context, we can facilitate efficient data sharing among diverse stakeholders, promote sustainable practices, and unlock the full potential of product data. This section delves into the methodologies for implementing such an ontology, discusses the benefits it brings to the circular economy, and addresses the challenges that may arise during its adoption.

At the core of the ontology is the Product class, representing items within the W2W system. This class is a subclass of `gr:ProductOrService` and is further divided into PhysicalProduct (tangible items) and ServiceProduct (intangible offerings). Each product is associated with detailed attributes such as `productName`, `modelNumber`, `serialNumber`, and `batchNumber`, which are essential for identification and traceability. The Material class denotes the components or ingredients used in products. It includes subclasses like WoodMaterial, MetalMaterial, and PlasticMaterial, categorizing materials based on their source. Materials have properties such as `materialType`, `quantity`, `source`, and `certification`, providing insights into their composition and origin. To represent the actions involved in the product lifecycle, the ontology defines the Process class, aligned with `prov:Activity`. Subclasses such as ManufacturingProcess, LogisticsProcess, and RecyclingProcess detail specific activities. These processes are linked to products and lifecycle stages, capturing how items are produced, transported, and recycled. The LifecycleStage class models the different phases a product undergoes, including ResourceStage, ProcessingStage, UseStage, and EndOfLifeStage. The EndOfLifeStage has specific options like Recycling, Landfilling, and Incineration, indicating the possible disposal or repurposing methods for products at the end of their use. Information about products is encapsulated in the InformationEntity class, which includes subclasses like Documentation, Instruction, ComplianceInformation, and EnvironmentalImpact. These classes provide critical data such as usage instructions, maintenance guidelines, safety compliance, and environmental impact metrics like `carbonFootprint` and `resourceConsumption`. This information supports users in proper product handling and promotes sustainability practices. Relationships between classes are established through object properties. For instance, hasMaterial links a product to the materials it comprises, while isManufacturedBy associates a product with the partner organization responsible for its production. The hasProcess property connects lifecycle stages to the processes occurring within them, and hasDocumentation ties products to their relevant informational resources. The ontology integrates the FAIR principles by annotating classes and properties with the `adheresToFAIRPrinciple` attribute, ensuring adherence to best practices in data management. By referencing external vocabularies like `schema.org`, `GoodRelations`, and `PROV-O`, it enhances interoperability and aligns with established standards.

Figure 3 Structure of the Ontology

Class: Schema:Place

The class `schema:Place`, from Schema.org, represents physical locations within ontology, particularly for specifying the `factoryLocation` in the `ManufacturingProcess` class. Its inclusion allows for detailed descriptions of manufacturing sites, such as addresses and geographic coordinates, enhancing supply chain transparency, environmental impact assessment, and regulatory compliance.By using `schema:Place`, the ontology leverages a standardized vocabulary that promotes interoperability and reusability, aligning with the FAIR principles. This ensures location data can be easily accessed and used by various stakeholders, supporting the W2W project's goals of sustainability and efficient data exchange.

Class: 'Information Entity'

The Information Entity class represents abstract entities that provide critical information about other entities within the ontology, such as products, materials, or processes. It serves as a general category for various types of documentation and compliance-related data, ensuring that essential knowledge about the lifecycle and characteristics of a product is captured and accessible.

Several key subclasses of Information Entity include:

- Documentation: This class contains detailed documents that provide information about products, including usage instructions, maintenance guidelines, and installation manuals.

- Compliance Information: This subclass encompasses information related to regulatory and safety standards, ensuring that products meet required legal and industry standards.
- Environmental Impact: Focused on capturing data about a product's environmental and social impacts, this subclass supports sustainability reporting and life-cycle assessments.

Relationships are modeled through object properties such as `hasDocumentation`, which links a Product to its relevant Documentation, and `hasComplianceInformation`, connecting a product to its compliance records. This structure allows for a clear, organized flow of information between physical entities like products and the abstract informational entities that describe them, promoting transparency, accountability, and adherence to standards across the product's lifecycle.

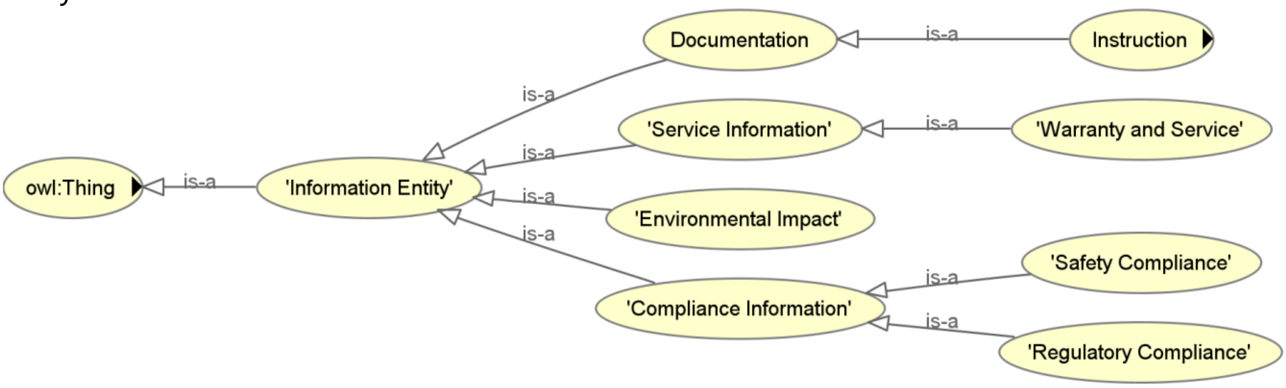

Figure 4 Structure of 'Information Entity'

Class: Schema:Organization

The class `schema:Organization` represents any structured group or entity, typically involved in business, government, or non-profit activities, within the ontology. It is part of the broader Schema.org vocabulary, which is designed to provide a standard way to describe entities and relationships in web contexts. In this ontology, `schema:Organization` is subclassed by more specific entities such as `Organization` and `Partner`, where it helps model organizations participating in the W2W system. This class allows for the definition of key attributes like the organization's name, address, and role in the project, ensuring that interactions between different entities in the W2W system are clearly captured and understood within the DSM framework.

Additionally, `schema:Organization` is extended by more specific subclasses, such as `Partner`, which represents organizations that are direct partners in the W2W system. This hierarchical structure enables the ontology to capture the various roles and responsibilities that organizations play in the lifecycle of products, from manufacturing to recycling, and their participation in the sustainable management of materials.

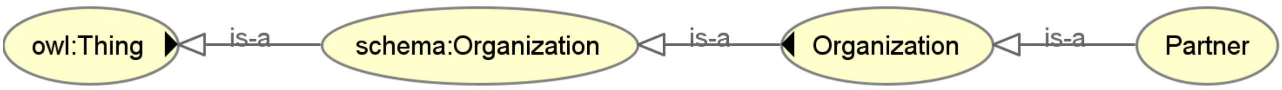

Figure 5 Structure of 'schema Organization'

Class: Actor

The `Actor` class in the ontology represents entities capable of performing actions within the W2W system. It serves as a general category, encompassing various participants involved in product creation, processing, and lifecycle management. `Actor` has important subclasses such as `Organization`, which refers to entities like manufacturers, suppliers, and partners. The `Partner` class is a further specialization of `Organization`, denoting specific organizations that collaborate or contribute directly to the W2W project.

Relationships between the `Actor` class and other entities are essential for modeling the interactions in the system. For instance, an `Actor` can be linked to products through object properties like `isManufacturedBy`, which associates a `Product` with the `Partner` responsible for its creation. This relationship allows for the traceability of products back to their creators, promoting transparency and accountability within the supply chain. Similarly, actors may be involved in processes, linking them to various lifecycle stages and contributing to activities such as manufacturing, logistics, or recycling. Through these relationships, the `Actor` class plays a central role in defining the roles and responsibilities of participants across the product lifecycle.

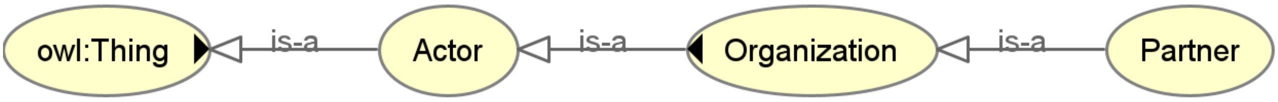

Figure 6 Structure of 'class: Actor'

Class: 'Physical Entity'

The PhysicalEntity class represents tangible objects in the real world within the ontology, encompassing products, materials, and other physical elements involved in the lifecycle of a product. It serves as a parent class to more specific subclasses, such as `Product`, `Material`, and `Packaging`, which further categorize physical objects based on their role in the W2W system.

Relationships:

- `PhysicalEntity` is linked to other entities through various object properties. For example, the `hasMaterial` property connects a `Product` (a subclass of `PhysicalEntity`) to its constituent `Material`, representing the physical ingredients used in its production.

- Additionally, `PhysicalEntity` is related to processes through properties like `isProducedBy`, which links products to the manufacturing processes that created them.

- It also interacts with lifecycle stages via the `hasLifecycleStage` property, allowing physical entities like products to be traced through different stages such as production, use, and end-of-life.

These relationships enable the ontology to model the entire lifecycle of physical objects, from raw materials to finished products and their eventual disposal or recycling.

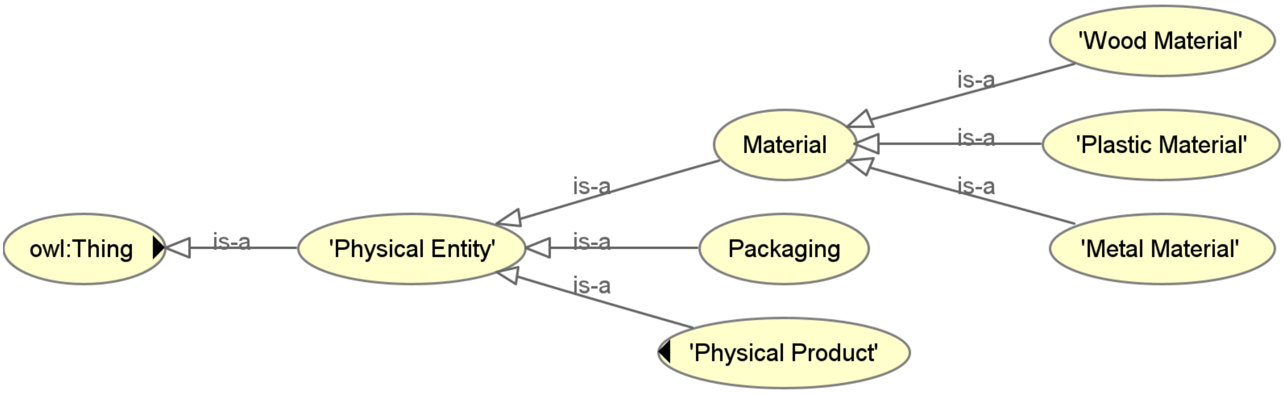

Figure 7 Structure of 'class: Physical Entity'

Class: prov:Activity

The class `prov:Activity` is a core concept in the PROV ontology, representing an action or set of actions that occur over a specific period and result in changes to entities. In the context of the W2W ontology, `prov:Activity` serves as a superclass for various processes, such as `ManufacturingProcess`, `LogisticsProcess`, and `RecyclingProcess`, which describe the activities involved in the lifecycle of a product. Activities are typically linked to other entities through several key relationships. For example, an activity can be associated with a product through object properties like `isProcessOf`, indicating that the activity (e.g., manufacturing or recycling) is part of a specific product's lifecycle stage. Similarly, activities can produce outcomes (e.g., products or byproducts), track resource consumption, or involve actors like organizations or partners.

By modeling processes as subclasses of `prov:Activity`, the ontology enables a structured representation of the dynamic actions that occur throughout a product's lifecycle, ensuring traceability, accountability, and transparency in data related to those activities.

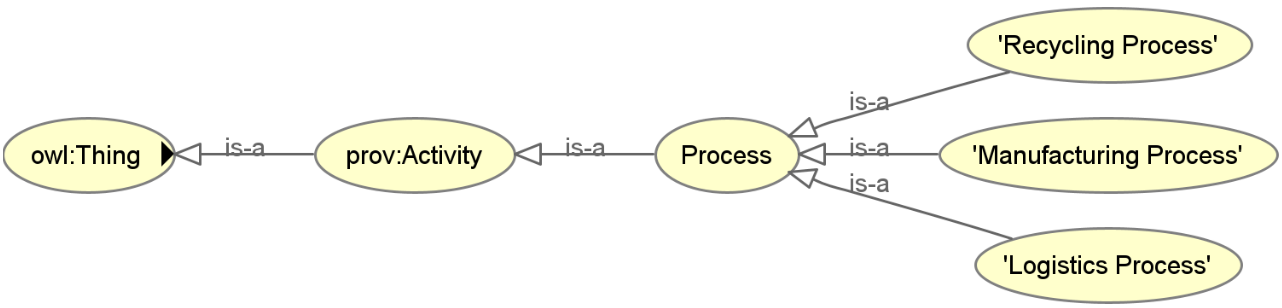

Figure 8 Structure of 'class: prov:Activity'

Class: gr:ProductorService

The class `gr:ProductOrService`, derived from the GoodRelations ontology, represents any item that can be offered in a commercial transaction, including both physical products and non-physical services. This class is central to describing products or services in e-commerce, business processes, and supply chain management. It encompasses a broad range of offerings, allowing flexibility in modeling both goods and services in digital ecosystems.

In the W2W ontology, `gr:ProductOrService` serves as a superclass for `Product`, ensuring that each product instance is aligned with standard commercial representations. The relationships associated with `gr:ProductOrService` include connections to lifecycle stages (`hasLifecycleStage`), processes (`isProducedBy` or `producesProduct`), and materials (`hasMaterial`). These relationships enable detailed modeling of the product's journey from production to end-of-life, capturing key aspects of manufacturing, usage, and disposal, thus supporting comprehensive product data management and traceability across the value chain.

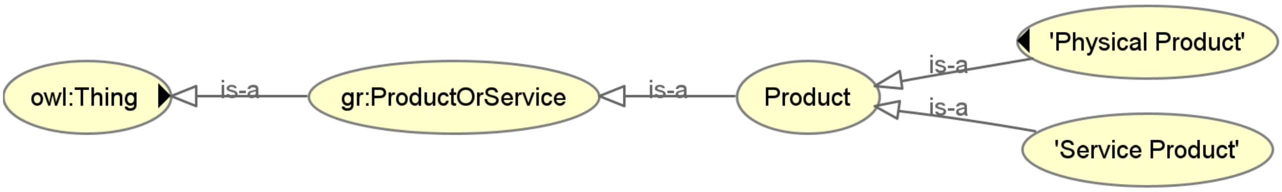

Figure 9 Structure of 'class: gr:ProductOrService`

Class: QuantityValue

The `QuantityValue` class represents a measurable quantity associated with an entity in the ontology, typically used for expressing values such as weight, volume, length, or any other quantitative attribute. This class is aligned with the QUDT (Quantities, Units, Dimensions, and Data Types) schema, ensuring that measurements are represented consistently and interoperably within the ontology. In the W2W ontology, `QuantityValue` is linked to various data properties that define measurable characteristics of entities, such as `productWeight`, `resourceConsumption`, `carbonFootprint`, and `waterUsage`. Each of these properties uses `QuantityValue` to specify both the numerical value and the unit of measurement, providing clear and standardized information about the entity's physical and environmental attributes. For example, the `productWeight` property on the `Packaging` class uses `QuantityValue` to express the product's weight, allowing users to accurately assess logistical needs, such as shipping requirements. Similarly, environmental data like `carbonFootprint` or `resourceConsumption` rely on `QuantityValue` to capture precise metrics, supporting sustainability assessments and reporting. The consistent use of `QuantityValue` across different classes ensures that all measurements within the ontology adhere to the same standards, promoting data interoperability and clarity.

Class: 'LifecycleStage'

The 'Lifecycle Stage' class represents the various phases a product undergoes throughout its existence, from resource acquisition to end-of-life. It provides a structured way to model the different stages in a product's lifecycle, including specific subclasses such as the 'Resource Stage', 'Processing Stage', 'Use Stage', and 'End of Life Stage'. These stages allow for a clear representation of each phase, aiding in traceability and analysis of the product's lifecycle. The 'Lifecycle Stage' class is linked to the 'Product' class through the object property 'hasLifecycleStage', indicating that a product progresses through one or more lifecycle stages. Conversely, the 'isLifecycleStageOf' property denotes the lifecycle stage associated with a specific product. Additionally, lifecycle stages are connected to processes like manufacturing or recycling through the 'hasProcess' and 'isProcessOf' properties, allowing for detailed tracking of actions within each stage. These relationships help provide a comprehensive view of the product's journey, facilitating better management, sustainability assessments, and compliance monitoring throughout its lifecycle.

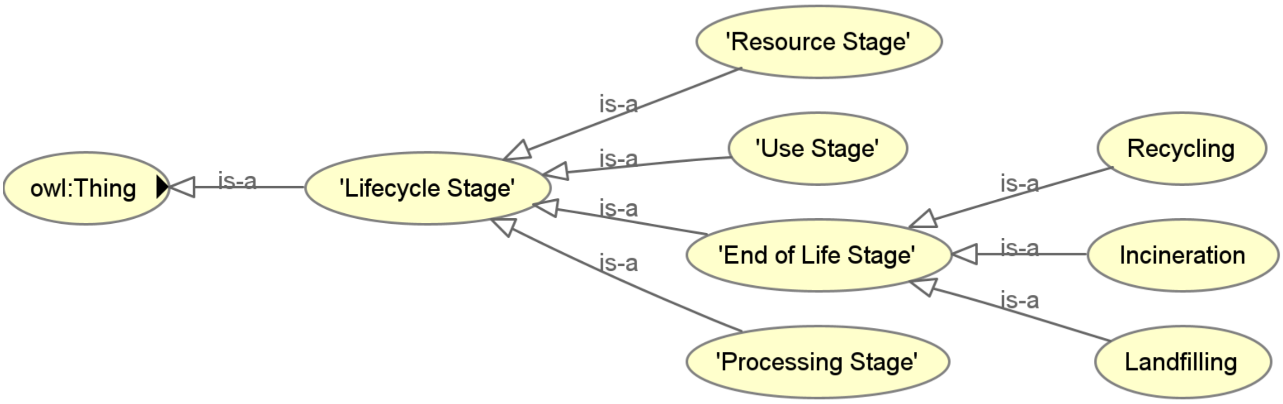

Figure 10 Structure of 'class: LifecycleStage'

4.4. Data Properties

In the ontology, data properties are used to define specific attributes or characteristics of the various entities modeled within the system. These data properties establish a relationship between a class, known as the *domain*, and a type of value, referred to as the *range*. The domain specifies the class to which a data property applies, while the range defines the type of value that the property can have, such as a string, number, or unit of measurement. Data properties serve as essential tools for describing the detailed features of different entities. For example, in the context of a product, a data property like `productName` would have the domain of `Product`, meaning it applies to all instances of that class, and the range of `xsd:string`, meaning the value must be a string, such as a product name like "Eco-friendly Chair."

These properties are used across various classes within the ontology to capture relevant and detailed information. For instance, in the case of materials, data properties like `materialType` or `quantity` provide descriptions of the material's composition and the amount used. In the manufacturing process, data properties such as `manufacturingDetail` or `factoryLocation` capture specific production information, allowing detailed documentation of how and where products are created. Similarly, for environmental impact, data properties like `carbonFootprint` or `resourceConsumption` offer measurable values that describe the ecological footprint of a product, providing critical insights into sustainability efforts. Each data property is defined by its domain and range, ensuring consistency in how data is represented and understood. The domain specifies the class being described (such as `Product`, `Material`, or `ManufacturingProcess`), while the range constrains the type of data that can be assigned (such as `xsd:string` for text, `xsd:decimal` for numeric values, or a predefined unit for measurements). This structured approach enables the ontology to manage a wide variety of data while maintaining clarity and precision in its descriptions.

Table 4: List of Data Properties with Description

Data Property	Domain	Range	Description
productName	Product	xsd	The name of the product.
modelNumber	Product	xsd	The model number of the product.

serialNumber	Product	xsd	The serial number of the product.
batchNumber	Product	xsd	The batch number of the product.
traceabilityCode	Product	xsd	The code used for tracing the product through the supply chain.
batchTraceability	Product	xsd	Traceability information for the product batch.
isCostEffective	Product	xsd	Indicates if the product is cost-effective.
materialType	Material	xsd	The type of the material used in the product.
quantity	Material	qudt	Quantity of the material used, aligned with appropriate units.
source	Material	xsd	The source or origin of the material.
certification	Material	xsd	Certifications associated with the material, e.g., wood certifications.
manufacturingDetail	Manufacturing Process	xsd	Details about the manufacturing process.
factoryLocation	Manufacturing Process	schema	Location of the factory where the product was manufactured.
productionMethod	Manufacturing Process	xsd	Method used in the production of the product.
recycledMaterialPercentage	Manufacturing Process	xsd	Percentage of recycled material used in the product.
supplyChainTraceability	Manufacturing Process	xsd	Details about the supply chain and its traceability.
productPerformance	Manufacturing Process	xsd	Information about the product's performance.
carbonFootprint	Environmental Impact	qudt	The carbon footprint of the product.
resourceConsumption	Environmental Impact	qudt	The amount of resources consumed by the product.
waterUsage	Environmental Impact	qudt	The amount of water used during the product's lifecycle.
wasteProduction	Environmental Impact	qudt	The amount of waste produced by the product.
labourSafetyInfo	Environmental Impact	xsd	Information about labor safety and related practices.
safetyStandards	SafetyCompliance	xsd	Safety standards applicable to the product.
complianceCertifications	SafetyCompliance	xsd	Certifications and compliance information for the product.
environmentalRegulations	SafetyCompliance	xsd	Environmental regulations relevant to the product.
packagingMaterial	Packaging	xsd	Material used for packaging the product.
productSize	Packaging	xsd	Size dimensions of the product.

productWeight	Packaging	qudt	Weight of the product.
transportationMethod	Packaging	xsd	Method used for transporting the product.
transportationDistance	Packaging	qudt	Distance the product is transported.
usageManual	UsageInstruction	xsd	The usage manual for the product.
productCareInstructions	UsageInstruction	xsd	Instructions on how to care for the product.
repairInstructions	MaintenanceInstruction	xsd	Instructions on how to repair the product.
storageInstructions	MaintenanceInstruction	xsd	Instructions on how to store the product.
recyclingInstructions	Recycling	xsd	Instructions on how to recycle the product.
safeDisposalInstructions	EndOfLifeStage	xsd	Instructions on how to safely dispose of the product.
byproducts	Recycling	xsd	Byproducts of the product that can be recycled or reused.
recyclingPartners	Recycling	xsd	Partners involved in recycling the product.
warrantyPeriod	WarrantyService	xsd	Details about the warranty period of the product.
serviceCenters	WarrantyService	xsd	Information about service centers for the product.

4.5. Object Properties

Object properties in the ontology define relationships between different classes, establishing connections that model how entities interact. Unlike data properties, which link classes to literal values, object properties connect instances of one class to instances of another. These relationships are essential for representing complex interactions, such as product lifecycles, materials, and processes. Each object property has a domain and a range, which specify the classes involved. For example, `hasLifecycleStage` links a `Product` to its `LifecycleStage`, while the inverse property, `isLifecycleStageOf`, connects the lifecycle stage back to the product. Similarly, `hasMaterial` links a product to its materials, and `isMaterialOf` links materials to the products they are used in. These relationships enable tracking material flow and lifecycle stages in a product's lifecycle.

Object properties also capture the processes involved in different stages. For instance, `hasProcess` links a `LifecycleStage` to a `Process`, such as manufacturing or recycling. Additionally, object properties like `isManufacturedBy` associate a product with the organization responsible for its production, highlighting stakeholder roles within the lifecycle. These relational links reflect real-world interactions, making the ontology more robust and interoperable. By defining domains and ranges for each object property, the ontology ensures consistency in how relationships are represented, supporting applications like DSMs and lifecycle management. In this way, object properties are critical for capturing the complex relationships needed to manage product data effectively across various systems and stakeholders.

Table 5: List of Object Properties with Description

Object Property	Domain	Range	Description
hasLifecycleStage	Product	LifecycleStage	Links a product to a stage in its lifecycle.
isLifecycleStageOf	LifecycleStage	Product	Indicates that a lifecycle stage is associated with a product (inverse of hasLifecycleStage).
hasProcess	LifecycleStage	Process	Associates a lifecycle stage with a process.
isProcessOf	Process	LifecycleStage	Indicates the lifecycle stage a process is part of (inverse of hasProcess).
isProducedBy	Product	ManufacturingProcess	Indicates the manufacturing process that produced the product.
producesProduct	ManufacturingProcess	Product	Indicates that a manufacturing process produces a product (inverse of isProducedBy).
isManufacturedBy	Product	Partner	Links a product to the partner that manufactured it.
manufacturesProduct	Partner	Product	Indicates that a partner manufactures a product (inverse of isManufacturedBy)

hasMaterial	Product	Material	Links a product to the materials used in its production.
isMaterialOf	Material	Product	Indicates that a material is used in a product (inverse of hasMaterial).
hasDocumentation	Product	Documentation	Links a product to its documentation.
isDocumentationFor	Documentation	Product	Indicates that the documentation is for a product (inverse of hasDocumentation).

5. DATA FLOWS FOR DATA SHARING MODELS

Understanding data flows is crucial for implementing effective data-sharing strategies, particularly in collaborative environments where multiple stakeholders need to access, exchange, and utilize shared data. This section will examine the mechanisms behind data flows in centralized, decentralized, federated, and peer-to-peer models, as well as their implications for security, efficiency, and scalability. Through this analysis, we aim to provide insights into optimizing data flows for improved interoperability and collaboration in digital ecosystems.

5.1. DATA FLOWS IN PLC STAGES

5.1.1. Resource Phase

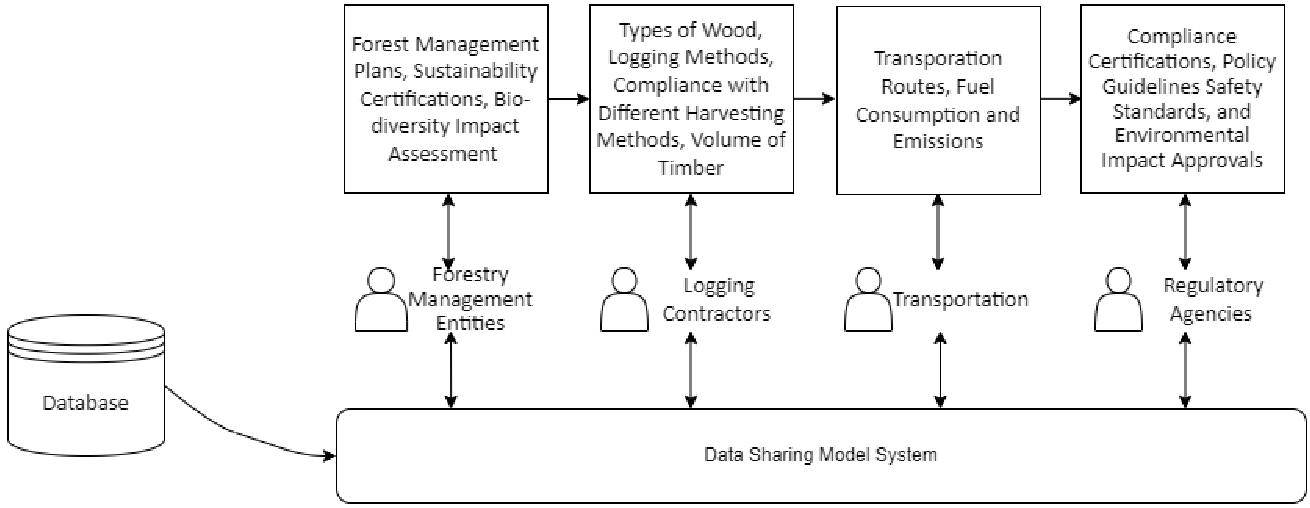

Figure 11: Data Flow in Resource Phase

At this stage of the product life cycle, forest resources data and data on forestry practices in timber production, such as certification and biodiversity impacts, are collected and recorded through a data-sharing model. This stage ensures transparency and traceability from the forest to the mill, enabling stakeholders to track the origin, composition, and environmental impact of wood-based materials. Information on material sourcing, sustainability certifications, and the manufacturing process is gathered from key stakeholders, including forest managers, logging companies, transportation services, and regulators. The data flow includes traceability of wood material, certification adherence, and environmental impact data, such as carbon footprint and resource consumption. This system supports better decision-making, resource efficiency, and compliance with industry standards. At this point, partnerships and actors involved in the logistics and manufacturing processes are crucial. These include tracking the movement of materials, their transformation through various stages, and ensuring their alignment with regulatory and sustainability frameworks. The Wood 2 Wood (W2W) project relies on this interconnected network to maintain the integrity and sustainability of products throughout their lifecycle stages, from resource extraction to production and distribution.

Here are example queries, each of the stakeholder can process with the given ontology:

Query for Forestry Management Entities:

To retrieve data about forestry management organizations responsible for forest resources and sustainability practices:

```
SELECT ?organization ?role
WHERE {
  ?organization rdf:type :Organization .
  ?organization :isInvolvedIn ?stage .
  ?stage rdf:type :ResourceStage .
  ?organization :role "forest management" }
```

Query for Logging Contractors:

To get details on the organizations or individuals involved in the logging process:

```
SELECT ?contractor ?process
WHERE {
 ?contractor rdf:type :Partner .
 ?contractor :isInvolvedIn ?process .
 ?process rdf:type :LogisticsProcess .
 ?process :isProcessOf ?stage .
 ?stage rdf:type :ResourceStage .}
```

Query for Transportation Companies:

To gather information on transportation companies involved in moving materials from the forest to the mill:

```
SELECT ?transportationCompany ?method ?distance
WHERE {
 ?transportationCompany rdf:type :Partner .
 ?transportationCompany :isInvolvedIn ?process .
 ?process rdf:type :LogisticsProcess .
 ?process :transportationMethod ?method .
 ?process :transportationDistance ?distance .}
```

Query for Regulatory Agencies:

To collect details on agencies responsible for overseeing and ensuring regulatory compliance in the forestry sector:

```
SELECT ?agency ?complianceType
WHERE {
 ?agency rdf:type :Organization .
 ?agency :isInvolvedIn ?process .
 ?process rdf:type :RegulatoryCompliance .
 ?process :hasComplianceType ?complianceType .}
```

5.1.2. Production Phase

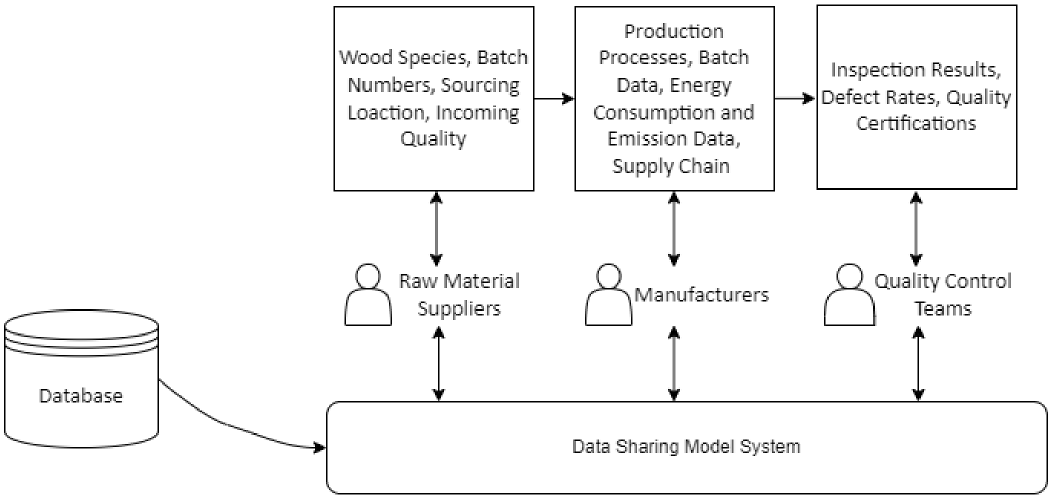

Figure 12: Data Flow in Production Phase

Raw wood is converted into wood products at this stage. The DSM facilitates the tracking and exchange of critical information, including the type of wood materials, sourcing locations, batch numbers, and incoming material quality. This ensures that material usage, energy consumption, emissions, waste generation, and inspection results are continuously monitored. Manufacturers contribute by sharing detailed information on production processes, batch data, and the energy consumed. They are also required to provide emissions and waste data, ensuring compliance with both environmental and legal guidelines. This data is crucial in assessing the environmental footprint of manufacturing operations and aligning with sustainability goals. The quality control teams focus on verifying the end product's compliance with established quality standards. Through inspections, they capture defect rates and certification information, which are recorded within the data-sharing model. This ensures that all products meet regulatory and industry-specific certifications, providing transparency across the supply chain.

Query for Raw Material Suppliers:

This query retrieves details of wood materials, their sourcing location, and batch quality for raw material suppliers:

```
SELECT ?material ?sourcingLocation ?batchNumber ?incomingQuality
WHERE {
 ?material a :WoodMaterial ;
      :source ?sourcingLocation ;
      :batchNumber ?batchNumber ;
      :certification ?incomingQuality .}
```

Query for Manufacturers:

This query retrieves the data related to the manufacturing process, including batch details, energy consumption, and emission data:

```
SELECT ?productionMethod ?batchNumber ?energyConsumption ?emissions
WHERE {
 ?process a :ManufacturingProcess ;
        :productionMethod ?productionMethod ;
        :batchNumber ?batchNumber ;
        :supplyChainTraceability ?energyConsumption ;
        :recycledMaterialPercentage ?emissions .}
```

Query for Quality Control Teams:

This query retrieves information on inspection results, defect rates, and certifications from the quality control teams:

```
SELECT ?inspectionResults ?defectRates ?certification
WHERE {
 ?inspection a :Inspection ;
        :inspectionResults ?inspectionResults ;
        :defectRates ?defectRates ;
        :certification ?certification .}
```

5.1.3. Distribution Phase

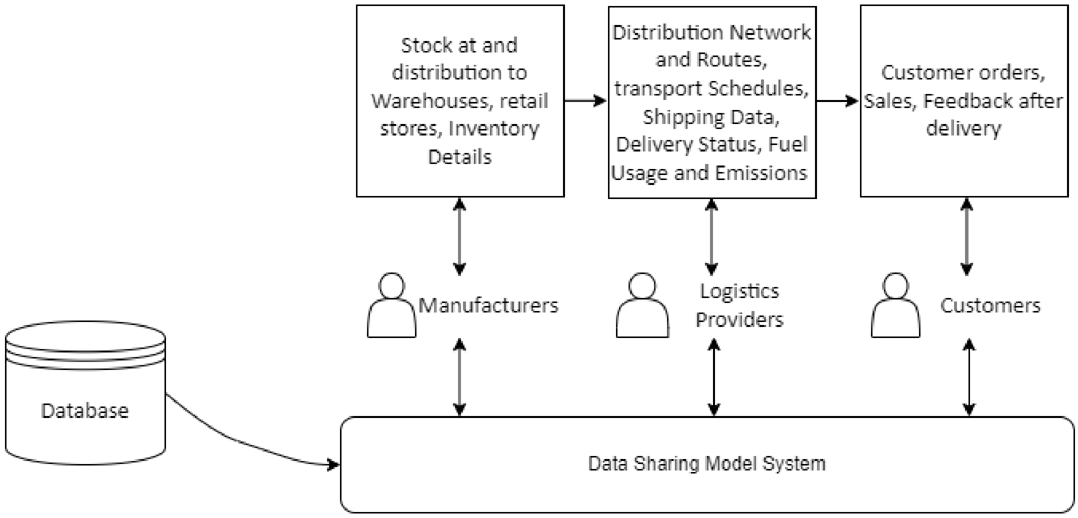

Figure 13: Data Flow in Distribution Phase

Finished products are transported from production sites to distribution centers and retailers before reaching customers. The data-sharing model records detailed logistics data, including transportation routes, fuel consumption, emissions, inventory data, and customer feedback. This comprehensive approach enables all stakeholders—manufacturers, logistics providers, and customers—to access up-to-date information, facilitating real-time decision-making. Manufacturers can track stock levels and inventory details across the distribution network, while logistics providers monitor routes, transport schedules, shipping data, and fuel usage to optimize efficiency. Customers can see real-time updates about their orders and provide feedback post-delivery. This transparent data-sharing model is crucial for optimizing logistics operations, calculating carbon footprints, and ensuring sustainability. Additionally, the model supports regulatory compliance, safety, and lifecycle management of products.

Query for Manufacturer:

This query identifies the stock levels of a wood-based product across various warehouses, showing the inventory details and location.

```
SELECT ?product ?inventoryLevel ?warehouseLocation
WHERE {
 ?product rdf:type :Product .
 ?product :hasMaterial :WoodMaterial .  Assuming it's a wood material-based product
 ?product :productName "Product X" .  Replace "Product X" with the specific product
name
 ?warehouse rdf:type :PhysicalEntity .
 ?warehouse :hasInventory ?inventoryLevel .
```

Query for Logistics Provider:

This query gathers the transportation details including the routes, fuel consumption, and emissions data for logistics providers.

```
SELECT ?route ?fuelConsumption ?emission
WHERE {
 ?logistics rdf:type :LogisticsProcess .
 ?logistics :hasLifecycleStage :Distribution .
 ?logistics :hasProcess ?route .
 ?logistics :fuelUsage ?fuelConsumption .
 ?logistics :emissionData ?emission .}
```

Query for Customer:

This query checks the delivery status of a customer's order and retrieves any feedback provided after the delivery.

```
SELECT ?order ?deliveryStatus ?feedback
WHERE {
 ?customer rdf:type :Actor .
 ?order rdf:type :PhysicalProduct .
 ?order :hasCustomer ?customer .
 ?order :deliveryStatus ?deliveryStatus .
 ?order :customerFeedback ?feedback .
```

5.1.4. Use and Maintenance Phase

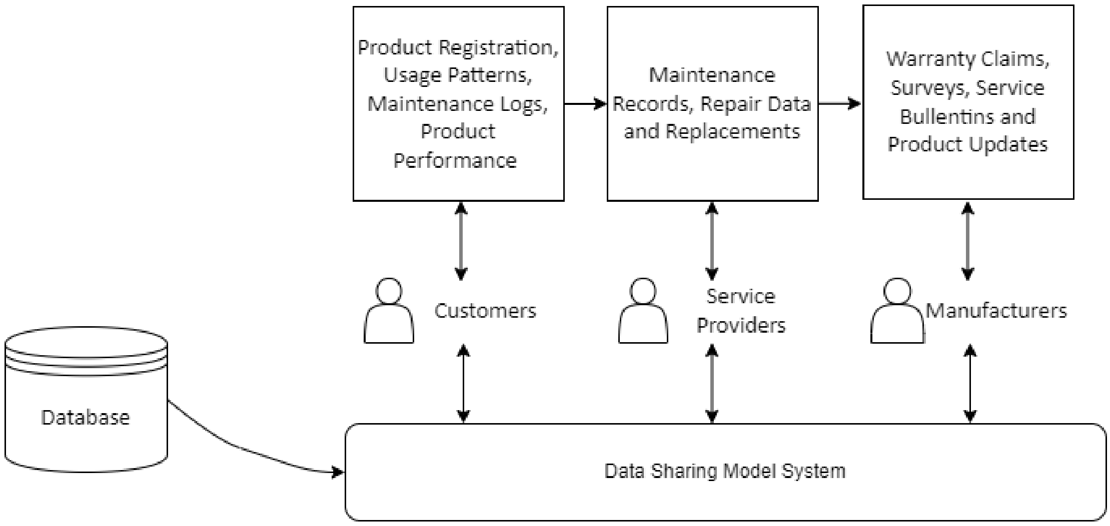

Figure 14: Data Flow in Use and Maintenance Phase

In this phase, companies or consumers use and maintain wood products. Usage trends, maintenance logs, repair and replacement data, and product performance are monitored as part of the DSM. With the aim of improving sustainability through design and material selection, this data generated and recorded by consumers, service providers, and manufacturers is used to evaluate the longevity and durability of products. This collaborative data sharing allows companies to design more durable products, create proactive maintenance strategies, and implement circular economy principles by enhancing the recyclability of materials and components. For instance, customers can contribute by tracking and sharing product registration data, usage patterns, and maintenance logs. This information helps identify common issues and optimize product performance throughout its lifecycle. Service providers, on the other hand, play a crucial role in documenting repair data, maintenance records, and replacement actions, all of which contribute to the continuous improvement of product designs and maintenance efficiency. Finally, manufacturers leverage warranty claims, service bulletins, surveys, and product updates to enhance both the quality and sustainability of the materials used, ensuring longer product lifespans and reducing waste.

Customer Query:

This query retrieves all physical products, along with their usage and maintenance instructions, product names, and performance data that a customer might contribute.

```
SELECT ?Product ?UsageInstruction ?MaintenanceInstruction ?productName
?productPerformance

WHERE {

 ?Product rdf:type :PhysicalProduct .

 ?Product :hasDocumentation ?UsageInstruction, ?MaintenanceInstruction .

 ?UsageInstruction rdf:type :UsageInstruction .

 ?MaintenanceInstruction rdf:type :MaintenanceInstruction .

 ?Product :productName ?productName .

 ?Product :productPerformance ?productPerformance .}
```

Service Provider Query:

This query focuses on service providers by fetching product-related maintenance instructions, repair instructions, and maintenance logs.

```
SELECT ?Product ?MaintenanceInstruction ?repairInstructions ?MaintenanceLog
WHERE {
 ?Product rdf:type :PhysicalProduct .
 ?Product :hasDocumentation ?MaintenanceInstruction .
 ?MaintenanceInstruction rdf:type :MaintenanceInstruction .
 ?MaintenanceInstruction :repairInstructions ?repairInstructions .
 ?Product :hasLifecycleStage ?UseStage .
 ?UseStage :hasProcess ?MaintenanceLog .
 ?MaintenanceLog rdf:type :Process .}
```

Manufacturer Query:

This query is designed for manufacturers, retrieving warranty details, service center information, and production details such as factory location and product performance.

```
SELECT ?Product ?WarrantyService ?warrantyPeriod ?serviceCenters ?factoryLocation
?productPerformance

WHERE {

 ?Product rdf:type :PhysicalProduct .

 ?Product :hasDocumentation ?WarrantyService .

 ?WarrantyService rdf:type :WarrantyService .

 ?WarrantyService :warrantyPeriod ?warrantyPeriod .

 ?WarrantyService :serviceCenters ?serviceCenters .

 ?Product :isProducedBy ?ManufacturingProcess .

 ?ManufacturingProcess :factoryLocation ?factoryLocation .

 ?Product :productPerformance ?productPerformance .}
```

5.1.5. *End of life phase*

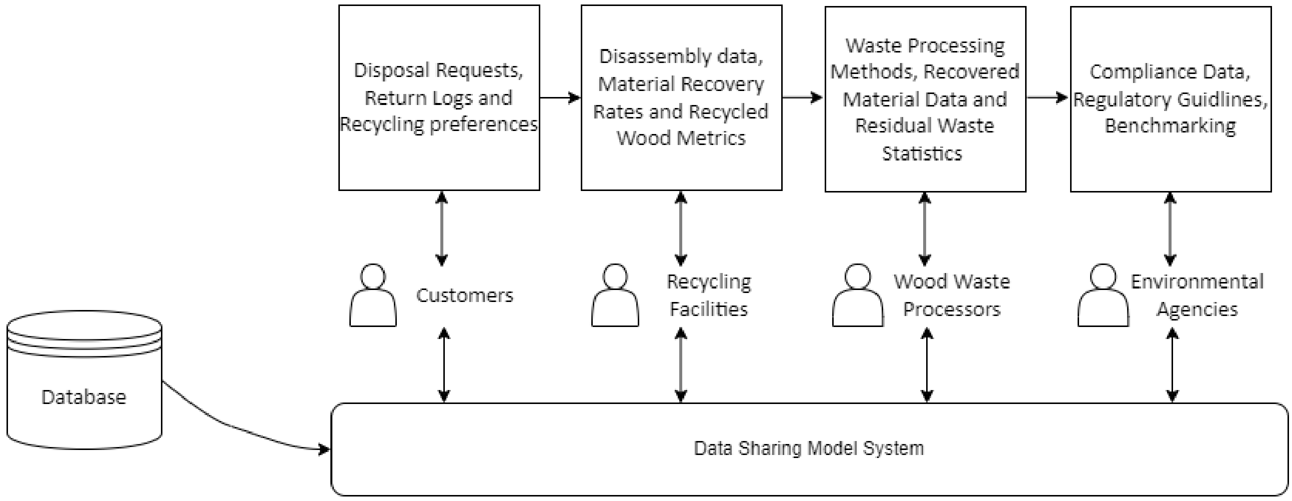

Figure 15: Data Flow in End-of-life phase

Wood products, when they reach the end of their lifecycle, are either recycled, reused, or disposed of based on established guidelines. The DSM system collects, integrates, and shares essential information such as disposal requests, material recovery data, recycling rates, and compliance data from multiple stakeholders. Customers provide data related to disposal preferences and return logs, while recycling facilities contribute disassembly data and material recovery rates. Wood waste processors share data on recovered materials and waste processing techniques, and environmental agencies ensure compliance by contributing regulatory guidelines. The circular economy benefits from this integrated model by enabling better tracking and monitoring of material flow, enhancing the recycling process, and providing a transparent system that stakeholders can use for benchmarking and accountability.

Customers Query:

This query retrieves disposal requests, return logs, and recycling preferences provided by the customers from the ontology.

```
SELECT ?disposalRequest ?returnLog ?recyclingPreference
  WHERE {
   ?customer a :Actor ;
         :provides ?disposalRequest ;
         :provides ?returnLog ;
         :hasPreference ?recyclingPreference .}
```

Recycling Facilities Query:

This query fetches disassembly data, material recovery rates, and recycled wood metrics from recycling facilities.

```
  SELECT ?disassemblyData ?materialRecoveryRate ?recycledWoodMetric
  WHERE {
   ?facility a :RecyclingProcess ;
         :provides ?disassemblyData ;
         :provides ?materialRecoveryRate ;
         :provides ?recycledWoodMetric . }
```

Wood Waste Processors Query

This query retrieves waste processing methods, recovered material data, and residual waste statistics contributed by wood waste processors.

```
SELECT ?wasteProcessingMethod ?recoveredMaterialData ?residualWasteStatistics
  WHERE {
   ?processor a :ManufacturingProcess ;
          :provides ?wasteProcessingMethod ;
          :provides ?recoveredMaterialData ;
          :provides ?residualWasteStatistics .}
```

Environmental Agencies Query:

This query collects compliance data, regulatory guidelines, and benchmarking information shared by environmental agencies.

```
SELECT ?complianceData ?regulatoryGuideline ?benchmarking
WHERE {
 ?agency a :RegulatoryCompliance ;
      :provides ?complianceData ;
      :provides ?regulatoryGuideline ;
      :provides ?benchmarking . }
```

5.2. User stories

User Stories provide a detailed yet concise description of the requirements from the perspective of different actors involved in the W2W project. These stories capture the needs, expectations, and interactions of each stakeholder with the system, offering a clear understanding of how the DSM will be utilized to achieve goals related to circular economy, material recovery, and regulatory compliance. By focusing on the specific tasks and objectives of customers, recycling facilities, wood waste processors, and environmental agencies, the user stories guide the development process, ensuring the system addresses real-world needs in a streamlined, user-centered way. This section outlines these interactions to create a foundation for functionality and system design.

5.2.1. Issuing a New Wood Product in the Data-Sharing Model

This user story addresses the need for manufacturers, product designers, and relevant stakeholders to issue a new wood product in an existing data-sharing model (DSM) to comply with industry regulations, ensure data consistency, and enhance supply chain transparency. The process aligns with the Wood 2 Wood (W2W) ontology to ensure adherence to FAIR data principles.

Assumptions:

- The Unique Product Identifier (UPI), represented by the ontology properties `:serialNumber` and `:modelNumber`, assigned to the new wood product (`:PhysicalProduct` and specifically `:WoodMaterial`), must be registered within the existing DSM.
- The DSM accommodates new product entries with various levels of data granularity (e.g., product type, batch, item level), consistent with the ontology's class hierarchy (`:Product`, `:PhysicalProduct`, `:Material`).
- All relevant stakeholders (`:Manufacturers`, `:ProductDesigners`, `:MaterialScientists`, `:RegulatoryAgencies`), categorized under `:Actor` and `:Organization` classes, have the

necessary permissions and credentials to access, modify, or view the DSM as per their roles, respecting access control mechanisms.

User Story:

As a Manufacturer (`:Partner`), I want to issue a new wood product (`:PhysicalProduct`) in the existing data-sharing model to ensure compliance with regulations and facilitate transparent data exchange across the supply chain, in accordance with the W2W ontology.

Steps:

1. Data Retrieval and Preparation:

The manufacturer's IT system sends a request to the central data registry to retrieve the required data fields and formats for integrating a new product into the existing DSM, utilizing the ontology's schema definitions and adhering to the `:adheresToFAIRPrinciple` properties.

Assumption:

- The required data fields and integration formats are dynamically retrieved via an API or web service based on the product category, ensuring interoperability (`I1`, `I2`, `I3`).

2. Product Data Collection and Assessment:

The manufacturer, in collaboration with Product Designers and Material Scientists (`:Actor` subclasses), gathers and prepares all necessary product data to be included in the DSM, such as:

- Product Specifications:
    - `:productName` (e.g., "Eco-Friendly Wooden Chair")
    - `:modelNumber` (e.g., "EFC-1234")
    - `:productSize` and `:productWeight` (captured using `qudt:QuantityValue`)
- Sustainability Certifications:
    - `:certification` linked to `:WoodMaterial` (e.g., FSC Certification)
- Safety Information:
    - `:safetyStandards` and `:complianceCertifications` under `:SafetyCompliance`
- Batch-Level Details:
    - `:batchNumber`, `:batchTraceability`

Remark: Data is sourced from internal systems (ERP, PLM) and external databases (certification bodies, suppliers), ensuring data properties adhere to FAIR principles (`F1`, `F2`, `F3`, `F4`).

3. Data Model Integration:

The manufacturer's IT system updates the DSM by adding a new entry for the product, ensuring that the product data is formatted according to the established data model's schema, consistent with ontology classes (`:Product`, `:Material`, `:Process`) and data properties.

4. Unique Product Identifier Registration:

The new product's UPI, corresponding to `:serialNumber` and `:traceabilityCode`, is registered within the DSM, linking it to all relevant data points (e.g., `:batchNumber`, production date, `:certification`).

5. Data Carrier Encoding and Attachment:

The manufacturer encodes the product identifier and necessary data onto a physical or digital data carrier (e.g., QR code, RFID tag), represented as `:traceabilityCode`, attached to the product packaging or labeling (`:Packaging`).

Remark: The data carrier is formatted according to industry standards to ensure compatibility across various stakeholder systems, aligning with FAIR interoperability principles (`I1`, `I2`, `I3`).

6. Product Launch and Data Access Configuration:

The manufacturer releases the new product to the market, ensuring that the updated DSM is accessible to all relevant parties (retailers, logistics providers, consumers), respecting access permissions defined in the ontology.

Alignment with the W2W Ontology and FAIR Principles:

This user story leverages the W2W ontology to define and structure product data, ensuring compliance with FAIR data principles:

Findability (`F1`-`F4`):

- Assigns globally unique identifiers (`:serialNumber`, `:traceabilityCode`), Describes data with rich metadata (`:productName`, `:materialType`), Metadata includes identifiers of the data they describe, Registers data in a searchable resource (central data registry).

Accessibility (`A1`-`A2`):

- Data retrievable via standardized protocols (APIs, web services), Protocols are open and universally implementable (`A1_1`), Supports authentication and authorization where necessary (`A1_2`), Metadata remains accessible even if the data is no longer available.

Interoperability (`I1`-`I3`):

- Uses formal, shared, and broadly applicable languages for knowledge representation (ontology classes and properties), Employs vocabularies that follow FAIR principles, Includes qualified references to other data (e.g., linking `:Product` to `:Material`, `:Process`).

Reusability (`R1`-`R1_3`):

- Richly describes data with accurate and relevant attributes, Associates data with clear usage licenses (`R1_1`), Includes detailed provenance information (`R1_2`), Meets domain-relevant community standards (`R1_3`).

5.2.2. Reading Open or Restricted Data from the Data-Sharing Model

This user story addresses the requirement that stakeholders such as consumers, product designers, and other relevant actors should have access to open data, and authorized access to restricted data within the DSM. The process aligns with the W2W ontology to ensure adherence to FAIR data principles.

Assumptions:

- The user starts a DSM-capable app or uses a standard QR-enabled camera on their mobile phone to access the data. The data carrier is represented by the ontology property `:traceabilityCode` attached to a `:Product`.
- The app or camera is capable of retrieving data without needing vendor-specific software, ensuring interoperability (`I1`, `I2`, `I3`).
- For restricted data, appropriate credentials must be provided by the user to access the information within the DSM, aligning with accessibility principles (`A1`, `A1_2`).

User Story:

As a Consumer (an instance of `:Actor`), I want to retrieve product data from a data carrier physically on the product (represented by `:traceabilityCode` on a `:PhysicalProduct`) so I can make informed purchasing decisions and understand the product's sustainability and compliance information.

Steps:

1. Scanning the Data Carrier:

The consumer uses a scanning device (e.g., mobile phone camera or DSM-capable app) to read the data carrier (e.g., QR code, represented by `:traceabilityCode`) attached to the product (`:Product`).

2. Requesting Data from the Resolution Service:

The app uses the URI obtained from the data carrier (`:traceabilityCode`) to request all available links from the resolution service component. This service component may be managed by the product manufacturer (`:Partner`) or a third-party service provider.

Assumption:

- The resolution service dynamically resolves the URI to relevant data sources or webpages that provide detailed product information, supporting the findability principles (`F3`, `F4`).

3. Receiving Data Links and Categories:

The resolution service responds back to the app with either a direct webpage, a link to a webpage, or a list of links and their associated types, detailing available data categories. These categories correspond to ontology classes such as `:EnvironmentalImpact`, `:ManufacturingProcess`, and `:ComplianceInformation`.

Remark: Links may represent categories such as sustainability information (`:EnvironmentalImpact`), manufacturing details (`:ManufacturingProcess`), product certifications (`:SafetyCompliance`), etc.

4. Accessing Open or Restricted Data:

If the product is identified through a unique identifier at the item level (`:serialNumber`, `:batchNumber`), and the user is authorized, the app shows all available data related to the product, including lifecycle data (`:LifecycleStage`) and downstream activities (e.g., repair and refurbishment records under `:MaintenanceInstruction`).

5. Authorization and Data Retrieval:

The data sources receiving the request determine the appropriate access level based on the querying party's credentials. The app then receives machine-readable data from multiple data sources identified by the links, both open and restricted, as permitted.

Assumption:

- User credentials and permissions are verified before allowing access to restricted or sensitive data, complying with accessibility principles (`A1_2`).

6. Presenting the Data to the User:

The DSM-capable app or web browser processes the received data and presents it in a user-friendly format, highlighting key product details and any additional information requested by the user.

Remark: The app may provide interactive features to explore product sustainability (`:EnvironmentalImpact`), compliance (`:SafetyCompliance`), and other relevant data in an intuitive manner, enhancing reusability (`R1`, `R1_1`, `R1_2`, `R1_3`).

Alignment with the W2W Ontology and FAIR Principles:

Findability (`F1`–`F4`):

- Globally Unique Identifiers (`F1`): The data carrier (`:traceabilityCode`) provides a globally unique identifier for the product (`:serialNumber`, `:modelNumber`), Rich Metadata (`F2`): Data is described with rich metadata properties such as `:productName`, `:materialType`, `:certification`, and `:safetyStandards`. Metadata Includes Identifiers (`F3`): Metadata clearly includes the identifiers of the data they describe, linking elements like `:Product` to its `:Material` and `:Process`. Indexed in Searchable Resources (`F4`): Data is registered or indexed in a searchable resource (the resolution service), making it findable.

Accessibility (`A1`–`A2`):

- Retrievable by Identifier (`A1`): Data is retrievable by its identifier using standardized communication protocols (e.g., HTTPS). Open Protocols (`A1_1`): The protocols used are open, free, and universally implementable. Authentication and Authorization (`A1_2`): For restricted data, authentication and authorization procedures are in place, ensuring secure access. Persistent Metadata (`A2`): Metadata remains accessible even if the data is no longer available, maintaining a level of transparency.

Interoperability (`I1`–`I3`):

- Formal Language (`I1`): Uses formal, accessible, shared, and broadly applicable languages for knowledge representation (e.g., OWL, RDF). FAIR Vocabularies (`I2`): Employs vocabularies that follow FAIR principles, as defined in the W2W ontology. Qualified References (`I3`): Includes qualified references to other data, such as linking `:Product` to `:Material`, `:ManufacturingProcess`, and `:EnvironmentalImpact`.

Reusability (`R1`–`R1_3`):

- Rich Descriptions (`R1`): Data is richly described with a plurality of accurate and relevant attributes, facilitating reuse. Accessible Usage License (`R1_1`): Data is released with a clear and accessible data usage license. Detailed Provenance (`R1_2`): Data is associated with detailed provenance information, enhancing trust and reusability. Community Standards (`R1_3`): Data meets domain-relevant community standards, aligning with industry practices and regulations.

5.2.3. Writing Data in the Data-Sharing Model

This user story addresses the requirements that stakeholders such as manufacturers, service providers, and relevant actors should be able to write data into the DSM to document updates, repairs, or modifications while ensuring data consistency and regulatory compliance. The process aligns with the W2W ontology to ensure adherence to FAIR data principles.

Assumptions:

- A business agreement exists between the service provider (e.g., repair shop, represented as `:Organization` and `:Partner` in the ontology) and the responsible entity (e.g., manufacturer, also a `:Partner`) to allow for data entry into the DSM.
- The product already has an item-level unique product identifier registered in the DSM, represented by properties such as `:serialNumber` and `:traceabilityCode` associated with a `:PhysicalProduct`.
- If the service provider is different from the original entity, appropriate credentials are needed to write into the DSM, ensuring compliance with access control policies (`A1_2`).

User Story:

As a Service Provider (an instance of `:Organization` and `:Actor`), I want to update the item-level data in the DSM so I can document the repair actions and maintenance performed on a product (`:PhysicalProduct`), ensuring data consistency and regulatory compliance, in accordance with the W2W ontology.

Steps:

1. Adding Repair Information:
The service provider's IT system adds information about the repair actions or replacements to the instance-level data about the product in the existing DSM. This involves creating or updating instances of `:MaintenanceInstruction` and related data properties.

Assumption: The repair data includes details such as:

- Nature of the Repair:
  - Captured under `:repairInstructions` (e.g., "Replaced damaged wooden leg").

- Components Replaced:
  - Linked via `:hasMaterial` to new instances of `:Material` (e.g., `:WoodMaterial` with updated `:materialType` and `:quantity`).

- Repair Date:
  - Recorded using properties like `prov:startedAtTime` and `prov:endedAtTime`.

- Technician Responsible:
  - Associated with an instance of `:Actor` (e.g., the technician), possibly using a property like `:performedBy`.

2. Data Validation and Consistency Checks:
The data entry process involves validation checks to ensure consistency with the existing data model, leveraging the ontology's constraints and data property ranges.

Remark: These checks ensure that all data entered aligns with predefined standards and does not conflict with existing data, adhering to FAIR principles (`F2`, `F3`, `R1_3`).

3. Linking Repair Data to the Product Identifier:
The service provider's system registers the updated data against the unique product identifier (`:serialNumber`, `:traceabilityCode`) in the DSM.

Remark: The product identifier ensures traceability and links to all relevant data points, such as previous repairs, maintenance schedules (`:MaintenanceInstruction`), and certifications (`:ComplianceInformation`).

4. Notifying Relevant Stakeholders:
The service provider's system notifies the product manufacturer (`:Partner`) and other relevant stakeholders (e.g., Quality Control Teams, instances of `:Actor`) about the updated repair information to ensure they are aware of the product's current status.

Assumption:
- Notifications may be sent via email, system alerts, or integration with other enterprise systems (e.g., ERP), supporting interoperability (`I1`, `I2`).

5. Archiving and Version Control:
The DSM implements version control to archive previous data entries and maintain a record of all changes made to the product's data, utilizing ontology properties that capture provenance (`prov:wasRevisionOf`, `prov:generatedAtTime`).

6. Access Controls and Permissions:
Appropriate access controls are set to ensure that only authorized users can modify or view sensitive repair information, enforcing role-based access defined within the DSM.

Assumption:

- Role-based access policies are already defined within the DSM, ensuring compliance with accessibility principles (`A1_2`).

Alignment with the W2W Ontology and FAIR Principles:

Findability (`F1`–`F4`):

- Globally Unique Identifiers (`F1`): The product's unique identifiers (`:serialNumber`, `:traceabilityCode`) facilitate data retrieval. Rich Metadata (`F2`): Detailed repair information is captured using ontology properties, enriching the metadata. Metadata Includes Identifiers (`F3`): Metadata entries include references to the product identifiers they describe. Indexed in Searchable Resources (`F4`): Updated data is registered in the DSM, a searchable resource.

Accessibility (`A1`–`A2`):

- Retrievable by Identifier (`A1`): Data is retrievable using standardized protocols via the DSM. Authentication and Authorization (`A1_2`): Access to modify data requires appropriate credentials, ensuring data security. Persistent Metadata (`A2`): Metadata remains accessible even if specific data becomes unavailable.

Interoperability (`I1`–`I3`):

- Formal Language (`I1`): The W2W ontology provides a formal language for knowledge representation. FAIR Vocabularies (`I2`): The ontology follows FAIR principles. Qualified References (`I3`): Data entries include qualified references to other data, such as linking repair actions to products.

Reusability (`R1`–`R1_3`):

- Rich Descriptions (`R1`): Repair data is richly described with relevant attributes. Detailed Provenance (`R1_2`): Version control and archiving provide provenance information. Community Standards (`R1_3`): Data entries meet industry and domain standards.

5.3. Survey on Data Availability

In an increasingly data-driven world, transparency and traceability of product information, manufacturing practices, and environmental impacts are becoming critical to both industry stakeholders and consumers. This chapter presents an analysis of a survey conducted to assess the availability of data related to product traceability, manufacturing certifications, and sustainability practices across various organizations. The objective of the survey was to identify the current state of data availability and highlight areas where improvements are needed for more sustainable and transparent industrial practices.

The survey, conducted as part of Task 4.4 by TUB (Authors of Deliverable 4.4), aimed to develop an ontology providing a comprehensive overview of data availability and transfer across Product Life Cycles (PLCs). This effort was critical for advancing the development of the DSM, grounded in the FAIR principles [1]. The survey remained open until September 20, 2024, and by the deadline, 20 companies had participated. However, not all respondents completed every question in the survey. The survey contains a total of 56 questions.

Survey Link: https://umfragen.tu-berlin.de/index.php/632987?lang=en

5.3.1. Methodology

The survey was distributed to organizations involved in manufacturing to assess their ability to track and provide data related to:

- Environmental and social impacts
- Carbon footprint and waste production
- Resource consumption and water usage
- Product traceability, certifications, and compliance

Respondents were asked to indicate whether they had access to these types of environmental data. The survey's goal was to identify gaps in environmental data availability and suggest actionable strategies for improvement.

5.3.2. Results: Current State of Environmental Data Availability

The survey responses reveal significant challenges in the availability of environmental data among the participating organizations. The findings suggest that many organizations lack the tools or systems necessary to collect, track, and report on key sustainability metrics.

- **Environmental & Social Impact Data**: Most organizations (83%) reported that they do not have data available related to the environmental and social impacts of their products or operations. This indicates that few organizations are monitoring the full lifecycle impacts of their products.
- **Carbon Footprint & Waste Data**: Similarly, 83% of respondents were unable to provide data on their carbon footprint or waste production. Only one respondent indicated partial availability of this data.
- **Resource Consumption & Water Usage Data**: All respondents (100%) reported that they do not have data on resource consumption or water usage, highlighting a major gap in sustainability monitoring and reporting.

5.3.3. Insights from the Results

The lack of available data in these areas points to several key challenges:

1. **Inadequate Systems**: Many organizations do not have the infrastructure or processes to effectively monitor environmental metrics.
2. **Supply Chain Complexity**: The globalized nature of manufacturing makes it difficult to track environmental data across all stages of the supply chain.
3. **Low Priority for Environmental Data**: Organizations may not view environmental data tracking as a priority, particularly if it is not required by regulation or demanded by consumers.

5.3.4. Discussion: Improving Environmental Data Tracking

Given the current gaps in data availability, there are several strategies that organizations can adopt to improve their environmental data tracking and reporting.

I. Adopting Digital and Automated Systems

IoT Solutions and Real-Time Monitoring: Implementing IoT sensors and real-time monitoring software allows organizations to automatically capture environmental metrics such as energy consumption, water usage, and emissions. These technologies provide accurate, real-time data without the need for manual reporting.

Environmental Management Software (EMS): EMS platforms can integrate environmental data across multiple domains, providing a centralized system for tracking carbon footprints, waste production, and resource usage. This makes it easier to generate reports and track performance over time.

II. Establishing Standardized Reporting Frameworks

Global Reporting Standards: Adopting frameworks such as the **Global Reporting Initiative (GRI)**, **Carbon Disclosure Project (CDP)**, or **ISO 14001** can help organizations align their data tracking with global best practices. These standards ensure that data is collected in a consistent manner, making it easier to compare across industries and regions.

Uniform Data Collection Protocols: Creating standardized data collection processes across departments and supply chains ensures that organizations track environmental metrics consistently. This can involve defining clear categories for reporting, such as separating scope 1, 2, and 3 emissions in carbon footprint reporting.

III. Collaboration Across the Supply Chain

Supplier Engagement: Organizations should work closely with their suppliers to ensure that environmental data is being tracked at every stage of the supply chain. This can involve encouraging suppliers to implement their own sustainability tracking systems or conducting joint sustainability audits.

Supply Chain Transparency: By increasing transparency in the supply chain, organizations can better assess their environmental impacts and ensure that sustainable practices are being followed at every stage of production.

IV. LCA Tools

Integrating Environmental Data into LCA Tools: LCA tools help organizations assess the environmental impact of products from production to disposal. Integrating real-time environmental data into these tools allows for more accurate assessments and can help organizations identify opportunities for reducing their environmental footprint.

Product-Level Tracking: Linking environmental data to specific products can provide detailed insights into the sustainability of individual items. This granular level of data allows for targeted improvements in product design and manufacturing processes.

V. Regulatory Compliance and Government Incentives

Regulatory Alignment: Ensuring that environmental data tracking aligns with local, national, and international regulations is critical for compliance. Organizations should regularly review their data collection processes to ensure they meet the latest regulatory requirements, such as the EU's Green Deal or the U.S. Clean Air Act.

Leveraging Incentives: Many governments provide financial incentives for companies that invest in sustainability practices. These incentives can offset the costs of implementing advanced data tracking systems, making it more feasible for organizations to adopt these tools.

VI. Data Transparency and Public Disclosure

Public Reporting: Publishing sustainability reports and disclosing environmental data can improve accountability and transparency. Publicly reported data builds trust with consumers and stakeholders, while also putting pressure on organizations to improve their sustainability practices.

Third-Party Verification: Engaging third-party auditors to verify environmental data ensures its accuracy and credibility. Verified data can enhance the organization's reputation and provide reassurance to investors and consumers that the company is genuinely committed to sustainability.

5.3.5. Survey summary

The findings from this survey reveal that many organizations currently lack the infrastructure and processes necessary to effectively track environmental data. This chapter has outlined several strategies to address these challenges, including adopting digital tools, collaborating with suppliers, and aligning with global standards. By improving their data collection and reporting practices, organizations can not only meet regulatory demands but also contribute to broader sustainability goals.

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Achieving comprehensive environmental data tracking will require concerted efforts from both individual organizations and industry-wide initiatives. By investing in the necessary tools, expertise, and frameworks, companies can play a critical role in the global transition toward more sustainable industrial practices.

6. CONCLUSION

The W2W project exemplifies a forward-thinking approach to sustainable resource management, specifically addressing the challenges posed by the current linear "take-make-use-dispose" wood consumption model. By transforming discarded wood from construction, demolition (C&D) waste, and furniture into valuable secondary resources, W2W provides a compelling pathway towards a circular economy. The project's focus on reducing environmental degradation caused by deforestation, excessive waste generation, and increased carbon emissions aligns with global sustainability goals and the EU's Circular Economy Action Plan.

This deliverable, cantered on the creation of a DSM based on FAIR digital principles, plays a pivotal role in the project's success. The development of DPPs ensures the seamless flow of accurate, standardized information across the wood material lifecycle, from raw material sourcing to end-of-life recycling. By fostering data transparency and traceability, these passports enable stakeholders—including manufacturers, recyclers, suppliers, regulators, and consumers—to make informed decisions that enhance resource efficiency, reduce waste, and promote sustainability.

The implementation of ontologies within the DSM further strengthens the system's ability to manage complex data structures and relationships, ensuring interoperability across platforms and stakeholders. By establishing clear standards for data categorization and communication, the W2W project facilitates collaboration among diverse industry players, thereby improving material recovery rates and extending the lifespan of wood products. These innovations not only support compliance with evolving regulatory frameworks but also promote environmentally responsible practices in wood-based industries.

Additionally, the W2W project tackles the technical and operational challenges associated with recycling contaminated or composite wood products, such as those found in laminated flooring and furniture. Through the introduction of advanced sorting and dissolving technologies, the project enables the recovery of high-value components, such as cellulose and lignin, even from mixed or polluted wood materials. This significantly enhances the viability of wood upcycling processes and minimizes the need for landfilling or incineration, which contribute to greenhouse gas emissions and pollution.

The project's emphasis on digital tools, such as real-time lifecycle assessments (LCAs) and dynamic data-sharing mechanisms, ensures that stakeholders can continuously monitor and optimize their processes. These digital solutions provide valuable insights into the environmental impacts of wood product recycling, enabling ongoing improvements and promoting the adoption of circular economy principles. By aligning economic incentives with sustainability goals, W2W supports the shift towards a regenerative industrial model where materials are continuously reused rather than disposed of.

In conclusion, the deliverable 4.4 demonstrates the transformative potential of circular economy frameworks in the wood industry. Through the combination of cutting-edge digital tools, innovative upcycling technologies, and robust data-sharing models, W2W sets a precedent for sustainable wood resource management. The integration of FAIR principles into the DSM and the creation of DSMs not only facilitate better material flows but also lay the groundwork for a more transparent and resilient industry. By reducing environmental impacts, enhancing material efficiency, and fostering collaboration across the supply chain, W2W is poised to make a lasting contribution to both the wood sector and global sustainability efforts.

Looking ahead, the ongoing development and refinement of these technologies and models will play a critical role in ensuring that the wood industry can meet the increasing demands of the future without compromising the health of the planet. The outcomes of deliverable 4.4, if widely adopted, could serve as a blueprint for other industries seeking to integrate circular economy practices, ultimately contributing to a more sustainable and resource-efficient world.

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