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Contents

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Acronyms and Abbreviations

AVO	Arteevo Technologies
ADL	Almas Partecipazioni Industriali
BUL	Brunel University London
CF	Carbon Fibre
CFRP	Carbon Fibre-Reinforced Polymer
DeFi	Decentralised Finance
DLT	Distributed Ledger Technology
EoL	End-of-Life
FAIR	Findability, Accessibility, Interoperability, and Reusability
FHV	Vorarlberg University of Applied Sciences
GF	Glass Fibre
GFRP	Glass Fibre-Reinforced Polymer
NFT	Non-Fungible Token
OBDI	Ontology Based Data Integration
PoH	Proof of History
PoS	Proof of Stake
PoW	Proof of Work
SOA	Service Oriented Architecture
SW	Semantic Web
TPC	Thermoplastic Composite
TPS	Transition per Second
TSC	Thermoset Composite
TVS	Technovative Solutions
UCAM	University of Cambridge
UNITN	Universita di Trento
ZOREN	Zorlu Enerji

Executive Summary

JIDEP is a digital space where industrial data is available for sharing and connecting manufacturers from different sectors into a collaborative, mutually beneficial knowledge and data-sharing relationship.

1. Objectives

The work described in this report contributes to the following WP1 objectives:

- Review of the cutting-edge technologies for enabling JIDEP
- Review of existing Distributed Ledger Technology (DLT), architectures and their applications
- Review of semantic modelling and ontology engineering technologies
- Review of up-to-date FAIR principles and compliance evaluation framework
- Review of material characterisation

2. Related Technologies

2.1 Distributed Ledger Technology

The preliminary conceptual centralised/decentralised hybrid architecture of JIDEP is shown in Figure 1. For traceability, immutability, auditability, trustless operation and non-repudiation, data will be stored off-chain and cryptographically anchored on a blockchain (the terms blockchain and DLT are used interchangeably in this document).

User access to the data (including user-transparent use of blockchain for the above purposes) will be performed via a centralised access gateway. The access gateway will provide user experience and presentation services such as dashboards.

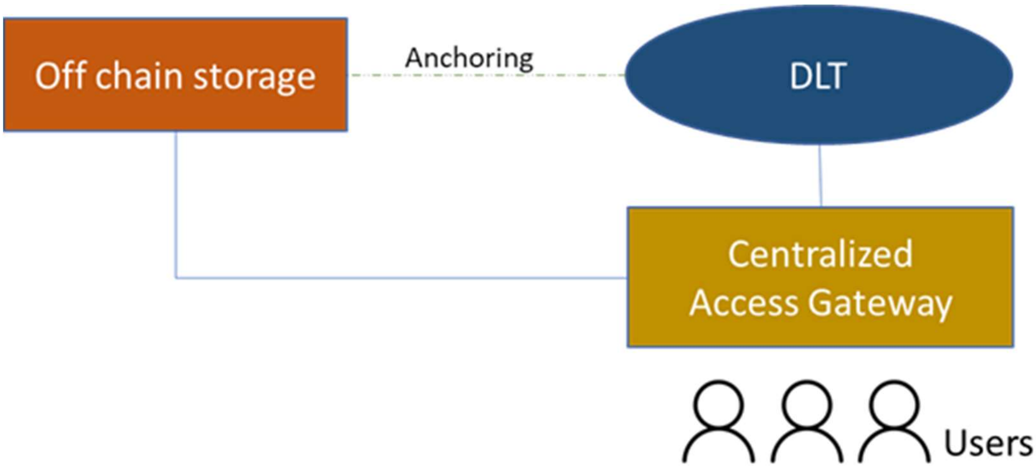

Figure 1: Preliminary JIDEP centralised/decentralised hybrid architecture

To survey the state of the art of the blockchain technologies applicable to the above architectural paradigm, we introduce another set of preferences: the blockchain is preferred to be public and permissionless.

Public – because public blockchains provide immediately available, highly reliable, sustainable infrastructure, and thus are excellent value for money to be spent by the project on research and development (no need to reinvent what has already been invented and is working and maintained by thousands of blockchain miners). ***Permissionless*** – because such blockchain imposes no governance requirements on JIDEP, such as cumbersome blockchain membership registration – anybody can freely join a permissionless blockchain.

Moreover, using a public and rather than private blockchain will minimise the development resources of JIDEP, as the project will not need to spent resources on development and maintenance of blockchain nodes, and developer resources for such blockchains are readily available. Another key preference of JIDEP is the ability of the blockchain to serve as a high-performance smart contract platform, and the associated developer support. Taken together, the above preferences may practically limit the scope of the present survey to three leading smart contract platforms: Ethereum [8], Polygon [33], and Solana [38].

Ethereum is the oldest, original smart contract platform established in 2013. It is also the largest, with the strongest developer support. However, its use is very costly in terms of gas (smart contract transaction fees), moreover, it is overcrowded and therefore slow. It is a classic, monolithic Layer 1 blockchain. A major improvement in Ethereum's speed is, however, expected in September 2022 due to "The Merge" [9] – an upgrade of Ethereum from the slow and energy-hungry Proof-of-Work (PoW) consensus protocol, to the faster and more efficient Proof of Stake (PoS) protocol [6].

Polygon (also known as *MATIC)* is a relatively new player that attempts to fix the inefficiencies of Ethereum by moving the smart contract and transaction load to other ("side") chains, using Ethereum only for low-frequency bulk anchoring of transactions on the side chains (the so-called Layer 2 blockchain approach.

Polygon is fully architecture- language- and software-compatible with Ethereum, allowing building a fast private Ethereum sidechain using the full power of the widely available Ethereum developer resources, with transaction blocks accumulated on the sidechain and anchored on the main Ethereum net only once in a while (a classic sidechain approach). This would, however, require building a private, permissioned sidechain.

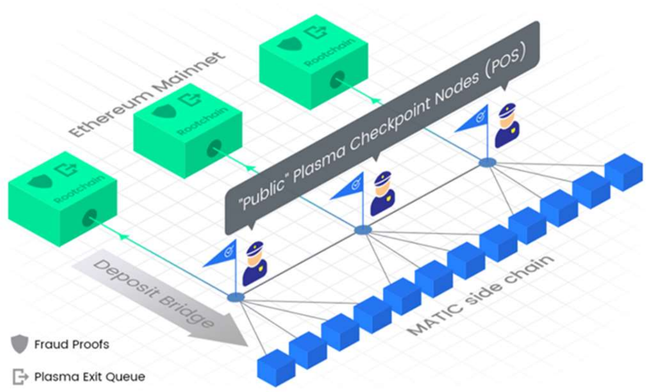

Figure 2 Polygon - Ethereum compatible Layer 2 multi-chain architecture.

Solana is a young but high-profile, head-on competitor of Ethereum. It uses a classic Layer 1 blockchain architecture and an extremely efficient combination of Proof-of-Stake (PoS)/Proof-of-History (PoH) consensus protocol. The PoH allows cryptographic verification of timestamps of transactions, voting and as a matter of fact of anything that occurs on the blockchain. This allows a very high transaction rate (up to 65,000 TPS theoretically).

Moreover, Solana's PoH protocol can be very efficiently performed by parallelising transaction verification on GPUs with thousands of cores. Another major advantage of Solana in terms of speed is that it is a stateless blockchain – it stores state in user accounts rather than in the blockchain memory, and its smart contracts are code- (i.e. read-) only. Unlike Ethereum and Polygon, Solana is not Ethereum-compatible and thus cannot make use of the huge Ethereum libraries and developer resources. However, it uses the mid-to-high level C, C++ and Rust as its scripted languages, compiled to WebAssembly, which are popular with developers.

Table 1 provides a comparison of main features of the three blockchains. Parameters important to JIDEP include also transaction/gas costs. Note that while a significant overlap exists in typical killer applications, Solana excels in non-fungible token (NFT) applications, while Polygon excels in Game Finance/Play2Earn (GameFi) and Decentralised Finance (DeFi) applications.

The findings of this survey will be balanced against the originally stated preferences in determining the DLT platform to be used by JIDEP, to be reported in Deliverable D1.3.

Table 1: Comparison of Ethereum, Solana and Polygon blockchains

Blockchain name	Ethereum	Solana	Polygon
Token symbol	ETH	SOL	MATIC
Market cap (04.09.2022)	$190 B	$11 B	$7.6 B
Architecture	Layer 1 stateful blockchain	Layer 1 stateless blockchain	Layer 2 multichain
Year of foundation	2013	2017	2017
Killer apps	NFT, DeFi	NFT	GameFi, DeFi,
Ethereum VM compatible	Yes	No	Yes
Actual transaction rate	~15 TPS	~3000TPS	Depends on the selected Layer 2 scaling
Main scripting language	Solidity	Rust, C, C++ (->Wasm)	Solidity, Golan, Vyper
Consensus protocol	PoW -> PoS	PoS + PoH	Pluggable
Gas cost per transaction	$0.0001 ~ > $.0003	~ $0.0001	~ $0.0001

2.2 Architectures

The architecture of a platform is the structural representation of the platform that describes the organisation of the system components, different components' functions, and their interactions [3] [44].

Before starting the development of a platform, a system architect needs to choose a suitable architecture pattern that will provide the following quality attributes [36]:

- **Overall Agility:** Ability to respond quickly to a constantly changing environment.
- **Ease of deployment:** Ability to deploy quickly toward a continuous integration and delivery (CI/CD) pipeline.
- **Testability:** Ability to test efficiently.
- **Performance:** Ability to perform well.
- **Scalability:** Ability to scale easily.
- **Ease of development:** Technological freedom, easy to develop, maintain and refactor.

This section aims to survey the characteristics, strengths, and weaknesses of several state-of-the-art architecture patterns suitable for platform development. Later this analysis will give enough information to choose the one architecture pattern that meets JIDEP platform requirements, to be reported in deliverable D1.3. The survey is limited to three popular architectural patterns: Layered / N-tier, Service-Oriented and Microservices.

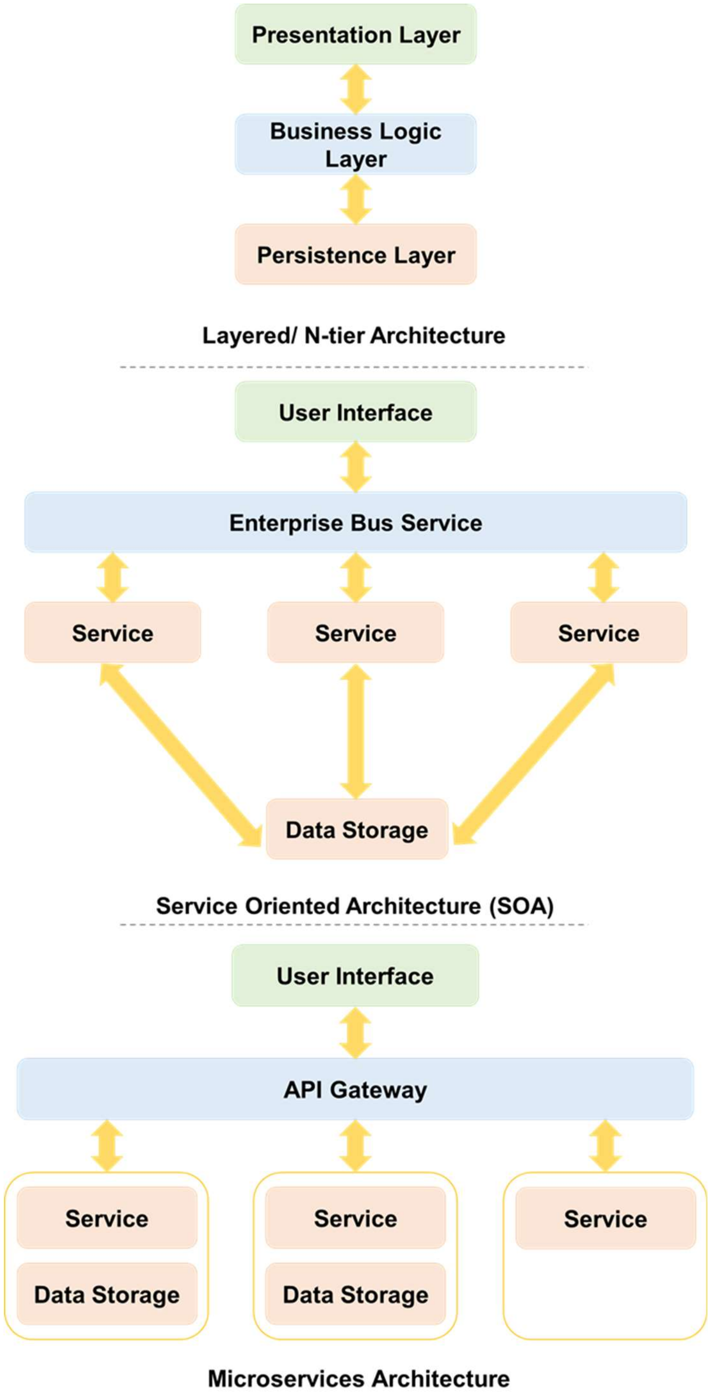

Figure 3: Three popular application or platform architecture patterns

Layered / N-tier architecture separates processes into different layers or tiers depending on their scope. Each layer consists of a group of software components, while tiers commonly refer to the hardware where the layer lives. Often a layered architecture consists of three distinct layers: presentation, business, and persistence. The presentation layer represents the user interface and translates the data resulting from the business layer. The business layer integrates the core functionalities of the platform and connects the persistence layer to get raw data, elaborates it, and returns the results to the presentation layer. Finally, the presentation layer usually stores data in a database. This pattern is a solid general-purpose pattern when application developers are unsure what architectural design best suits them. However, there are a couple of quality attributes to consider from an architectural standpoint when choosing this pattern. For example, the layered design tends to lend itself to monolithic applications, even if the presentation and business layers are separated. As a result, it poses some potential issues regarding deployment, robustness and reliability, performance, and scalability. At the same time, this may not be an issue for some applications [36].

Service Oriented Architecture (SOA) pattern separates processes into different services to solve the monolithic nature of an application. A service is a self-contained unit that carries out a complete, discrete business function and can be accessed remotely [35]. By reusing the services through a common communication mechanism called an enterprise service bus (ESB), SOA prevents developers from performing integration from scratch. Instead, ESB performs the integration between a centralized component and backend services and then makes them available as service interfaces. The service interfaces provide loose coupling, meaning services can be called without knowing how the integration is implemented. This pattern's loose coupling and reusing services can save development time. However, this pattern's ESB and shared data storage nature can become a single point of failure for the whole application.

The Microservices pattern is the evolution of SOA architecture. At first glance, these two architectures look similar. However, these two approaches have critical differences in architecture, component sharing, data governance, communication, and other elements. These differences determine which situation each method is best used for and how it impacts the overall business. For instance, microservices structure an application as a series of distinct, single-purpose services, while SOA is a group of modular services that "talk" together to support applications and their deployment [41].

Furthermore, the microservices pattern allows services to use different programming languages and data storage technologies. Finally, each service can use its communication protocol. However, microservices use lightweight messaging protocols like HTTP/REST (Representational State Transfers) and JMS (Java Messaging Service) to keep things simple. In contrast, the technology stack in SOA is limited, and services share the data storage. In addition, each service must share a common communication mechanism called an enterprise service bus (ESB). As a result, SOAs are more open to heterogeneous messaging protocols such as SOAP (Simple Object Access Protocol), AMQP (Advanced Messaging Queuing Protocol), and MSMQ (Microsoft Messaging Queuing).

A vital benefit of microservices patterns is the separate deployment of services due to their decoupling nature. Services can be developed, updated, deployed, and scaled independently to meet the demand for specific functions. As a result, deployment is straightforward and less time-consuming in the microservices than in the SOA.

Another critical benefit of the microservices pattern is its distributed nature. It means that components can be decoupled and accessed through a lightweight communication mechanism. Furthermore, this distributed nature of the design allows for its high scalability properties [21].

Table 2 summarises the pattern-analysis scoring for each architecture pattern described in this survey. Red cells represent low scores, yellow cells represent medium scores, and green cells represent high scores. This summary will help an architect determine which pattern might be best for the JIDEP platform, to be reported in deliverable D1.3. For example, suppose a platform architectural concern is the ease of deployment, testing, development, changes, and scalability. In that case, the microservices pattern is probably a good architecture pattern choice. Similarly, suppose a platform chooses the layered architecture pattern for ease of development. Still, deployment, performance, and scalability might be risk areas for that platform

Table 2: Architecture pattern analysis summary

	Layered / N-tier	Service-Oriented	Microservices
Overall Agility	The monolithic nature of the pattern makes changes difficult for large platform	Relies on sharing resources makes changes less flexible	Relies on bounded context for coupling makes changes more flexible
Ease of deployment	Minor change requires redeployment of the entire platform	Deployment is a time-consuming process and less flexible than the microservices pattern	Deployment is straightforward and less time-consuming
Testability	The presentation component can be mocked to isolate testing	Services are usually small size; Therefore, it is easier to debug and test the independent services.	Isolation of business functionality into independent services makes testing easy.
Performance	Not friendly for the high-performant platform	Distributed nature of the pattern might make it slow. However, performance can be improved by scaling.	Distributed nature of the pattern might make it slow. However, performance can be improved by scaling.
Scalability	Difficult to scale	Less scalable than the microservices pattern	Highly scalable than the SOA pattern
Ease of development	Easy to develop	The reusability of services makes it much easier and faster, however, less technological freedom	Smaller and isolated scope of service components make development easy and lots of technological freedom available.

2.3 FAIR

2.3.1 FAIR Principles

The FAIR principles are a set of technology-agnostic guidelines to make digital assets Findable, Accessible, Interoperable, and Reusable [49]. Due to the urgent need for data reusability, stakeholders from academia and industry to funding bodies and scientific publishers designed the FAIR Data Principles [49]. These measurable principles can be guidelines for data owners intending to allow machines to find and use the data automatically. [49] is the first scientific publication on the FAIR Data Principles where it is described how owners can prepare data to be FAIR principle compliant.

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 crucial for automatic discovery of datasets and services. Hence, for Findability:

1. Data, metadata or both are allocated a universally unique identifier that is also persistent
2. Data are narrated with a rich set of metadata
3. Metadata must describe the identifier of the associated data
4. Data, metadata or both are uploaded to searchable indexed storage or registry

Once the required data is discovered by the user, they require to know how the data can be accessed, possibly including authentication and authorisation. Hence, for Accessibility:

1. Data, metadata or both are retrievable via their identifier created with a standardised internet protocol. This principle covers two crucial aspects of the protocol:
    1. This must be an open, free and universally implementable protocol, e.g., HTTP
    2. This must support an authentication and authorisation procedure, where required.
2. Metadata is always accessible after the first entry of data to the searchable storage, regardless of the availability of data at a later stage.

The data commonly need to be integrated with other data. Additionally, the data need to interoperate with applications or workflows for analysis, storage, and processing. Hence, for Interoperability:

1. Data, metadata or both are described using a formal knowledge representations language.
2. Data, metadata or both use vocabularies designed, developed and published by following FAIR principles.
3. Data, metadata or both include contextual information through specialised references to other data or metadata resources.

The ultimate goal of FARI is to optimise the reuse of data. To accomplish this, metadata and data should be well-described so that they can be replicated and/or combined in different settings. Hence, for Reusability:

1. Data, metadata or both are described with a large number of relevant properties populated with an accurate value
    1. Data, metadata or both are accessible with a clearly defined and accessible license created for data usage
    2. Data, metadata or both are described with detailed provenance
    3. Data, metadata or both meet domain-specific standards used in the community.

There have been many implementation initiatives since the proposal of the FAIR Data Principles. Among FAIR data repositories, Harvard Dataverse has accumulated more than 60,000 datasets open to researchers from all subject areas [49]. Harvard Dataverse uses the Dataverse [7] open-source data repository software and is the largest among all Dataverse instances. Another example of FAIR Data implementation is FAIRDOM, which is built with the integration of SEEK [50] and openBIS [4] platforms to support a FAIR data and model management facility for the Systems Biology domain [49].
Achieving interoperability in implementing FAIR is non-trivial and relies on the convergence of solutions and standards used in research communities [13]. A coalition was formed in 2019 to create the Convergence Matrix consisting of communities of Practice and FAIR-supported Digital Resources [40].

Table 3: Summary of the FAIR principles [11].

	FAIR Principle	Recommendation
Findability	F1	Data, metadata or both are allocated a universally unique identifier that is also persistent
	F2	Data are narrated with a rich set of metadata
	F3	Metadata must describe the identifier of the associated data
	F4	Data, metadata or both are uploaded to searchable indexed storage or registry
Accessibility	A1	Data, metadata or both are retrievable via their identifier created with a standardised internet protocol. This principle covers two crucial aspects of the 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	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	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

2.3.2 FAIR Compliance and Metrics

Since the publication of FAIR principles, different stakeholders have been looking for a transparent evaluation approach to objectively determine the findability, accessibility, interoperability and reusability of a published resource, e.g., a dataset and a workflow. To achieve transparency and machine-enabled verifiability, a working group, the FAIR Metrics group, was formed that proposed the development of metrics to check compliance with FAIR principles and derived one exemplar metric for each FAIR principle [54]. An evaluator software was developed to assess whether a resource passes tests defined for relevant FAIR Metric subsets created or selected by a community [55]. FAIR Maturity Indicators were defined to address, for example, the issues of insufficient awareness of data publishing practices, overly simple responses and validation associated with FAIR Metrics and a framework for the evaluation of FAIR compliance was proposed to automatically identify the set of indicators in a resource [56].

2.4 Semantic Modelling and Ontology Engineering Technologies

A data representation structure that enables the description and management of data and their semantics or meaning is called a semantic model or semantic structure. The process of creating a semantic structure is called semantic modelling [34]. Ontologies are core technologies used on the Semantic Web to define and describe semantic models [10]. Knowledge Engineering approaches such as CommonKADS and MIKE apply ontologies to capture domain knowledge in developing knowledge-based systems and activate inference in such systems [[37]9].

The European Materials Modelling Ontology (EMMO) is an ontology developed for describing materials, including material models and characteristics, physical and chemical properties and engineering aspects covering components, systems and processes [12]. The Materials and Molecules Basic Ontology (MAMBO) focuses on the representation of nanomaterials, molecular materials, organic and polymeric materials and their different properties [31]. Materials transformation and product life cycle description are crucial aspects of JIDEP alongside materials modelling and representation. [43] applied an ontological approach for modelling and describing the transformation of materials from raw materials extraction and processing to the assembly of all components to create a product. [28] created a suite of Product Life Cycle (PLC) ontologies to use in combination with the Basic Formal Ontology (BFO) for representing the product life cycle phases from design to end of life.

OntoCommons, a Horizon 2020 project titled Ontology Data Documentation for Industry Commons, will develop a Top Reference Ontology (TRO) by integrating a Meta-Ontology (MO) with a set of Top-Level Ontologies (TLOs), including Basic Formal Ontology (BFO), DOLCE and EMMO, selected by the project consortium [60]. In OntoCommons, Middle-Level Ontologies (MLOs) will be developed by extending concepts for a discipline of interest, e.g., materials science and manufacturing, Domain Level Ontologies (DLOs) will be defined for describing a specific domain of interest, e.g., composite materials and Application-Level Ontologies (ALOs) will be created to describe the data about a specific application, e.g., a device manufactured using composite materials. The Industrial Ontology Foundry (IOF) provides a collaboration framework for developing and managing industrial ontologies [61]. The IOF classified ontologies into Upper Level, Mid-Level, Domain Upper Level and Domain-Specific Level. BFO has been selected as the candidate for Upper-Level ontology in the IFO. Smart Appliances Reference Ontology (SAREF) consists of concepts such as commodity (e.g., electricity and gas), device (e.g., sensor and washing machine), duration description and units of measure [62]. We also analysed and understood the relationship between JIDEP and LinkedDesign, FALCON, SatisFactory BOOST 4.0, etc.

Ontology Engineering Technologies enable the design and development of ontologies. Protégé [57] is the widely used ontology engineering tool developed by the Stanford Centre for Biomedical Informatics Research at the Stanford University School of Medicine. It supports the creation, edition, querying and reasoning of an ontology. TopBraid Composer is a technology developed at TopQuadrant, allowing users to define, edit and query ontologies. OWL API [59] provides programmable creation, access, query and management of ontologies.

2.5 Ontology Based Data Integration

The lifecycle of production systems (e.g., manufacturing and power plants) usually consist contributions by engineers from various disciplines that collaborate in multi-disciplinary engineering environments (MDEE). The stakeholders involved in a production system, utilise various engineering software tools, datasets, and terminologies, with limited overlap. Hence, collaboration amongst the stakeholders necessitates synchronising and exchanging data produced by software tools specific to their disciplines.

Ontologies are a major resource for data integration with Semantic Web (SW) technologies. Ontologies capture implicit knowledge across heterogeneous data sources and create semantic interoperability between them. This is known as ontology-based data integration (ODBI). In search of alternatives to software tools such a Microsoft Excel and hard-coded data transformers for the purpose of conducting data integration, researchers have explored several alternatives. Many of these alternatives are based on SW technologies.

OBDI techniques involve the representation of the semantic knowledge (in the form of ontologies) of each heterogeneous data source involved towards integrating them. Mainstream OBDI solutions are mainly of two types:

Data virtualisation:

- Provide a unique virtualisation of the data sources, without extraction and transformation of their data
- Four approaches: Single Global Ontology, Multiple Local Ontologies, Hybrid, Global-As-View
- Not user friendly due to mandatory requirement of knowledge representation expertise
- More focused on the data sources than the user's requirements

Data Materialisation:

- Extract, Transform, and Load (ETL) procedures used to extract data to be integrated from the respective data sources
- Materialisation works directly on data extracted from the sources, building a single, unified representation of the data (i.e. KG)
- It therefore reduces the amount of work in building ontologies (and mapping which are not required anymore)
- Have to deal with the heterogeneity of the data extracted from different data sources at different levels, e.g., concepts, language, knowledge, data.

3. Material Characterisation Post Recycling

3.1 Composite Materials

Composite materials are formed by combining two or more materials with different properties, without dissolving or blending them into each other. They are known for their durability, high strength, excellent quality, low maintenance and low weight, and are widely used in the automotive, construction, transportation, aerospace and renewable energy industries. In addition, the use of composites with very different structures instead of traditional materials in engineering applications is increasing. As with commonly used materials, the recycling and disposal of composite materials is an issue that needs to be addressed and studied with increasing importance. Due to technological and economic constraints in previous years, commercial recycling processes for used composite materials were very limited. However, R&D activities, studies in this field are increasing day by day.

Composites are usually classified by the type of material used for the matrix. The four primary categories of composites are polymer matrix composites (PMCs), metal matrix composites (MMCs), ceramic matrix composites (CMCs), and carbon matrix composites (CAMCs). In regards to the reinforcement types composite materials can be classified into particulate, fibre-reinforced, and structural composites [51]. Figure 4 shows the classification of the composite materials based on matrix and reinforcement.

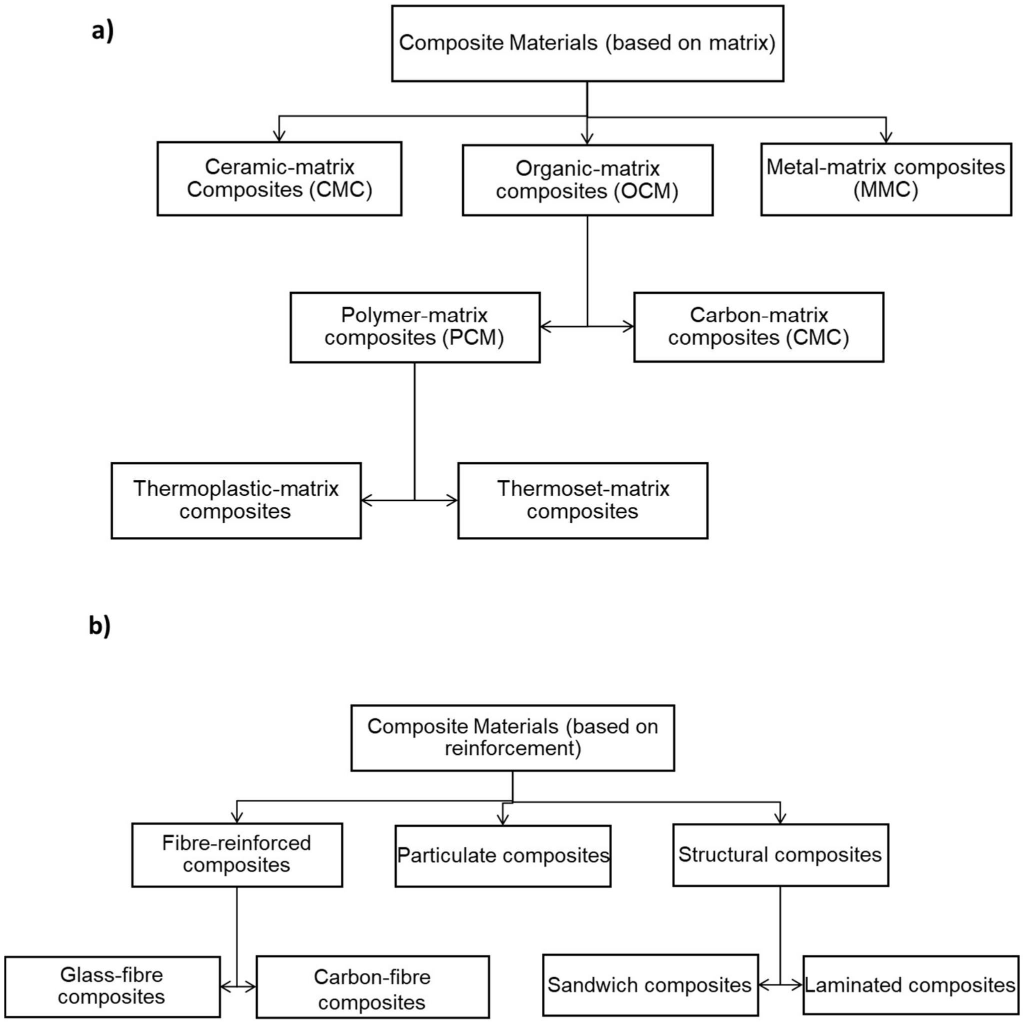

Figure 4: Classification of composite materials. (a) based on matrix materials and (b) based on reinforcement materials. Reproduced from [51].

3.2 Recycling of Composite Materials

Recently, significant events took place that added immensely to the sociotechnical pressure for developing sustainable composite recycling solutions, namely (1) a ban on composite landfilling in Germany in 2009, (2) the first major wave of composite wind turbines reaching their End-of-Life (EoL) and being decommissioned in 2019-2020, (3) the acceleration of aircraft decommissioning due to the COVID-19 pandemic, and (4) the increase of composites in mass production cars, due to the development of high volume technologies based on thermoplastic composites. Such sociotechnical pressure will only grow in the upcoming decade of 2020s as other countries are to follow Germany by limiting and banning landfill options, and by ever-growing number of expired composites EoL waste. Hence, the recycling of fibre-reinforced composite materials will play a major role in the future, particularly for the wind energy, but also for automotive, aerospace, construction, and marine [19].

In subsection 3.2.1, different types of composites materials that are of an interest to JIDEP project have been reviewed. In subsection 3.2.2 most common techniques for the materials of interest have been reviewed.

3.2.1 Recycling of Different Types of Composites

It is worth to review the recycling of different types of composites before review of the techniques themselves. In regards to recycling of composite materials, a distinction should be made between thermoplastic and thermoset composites. Different techniques are required for different types of composites.

3.2.1.1 Polymer Matrix Composites

As mentioned earlier in this section, composites can be categorised by a matrix or reinforcement type (i.e. OMC, CMC, MMC, and PMC). In this sub-section, the review has been completed on the recycling state-of-the-art of PMCs.

3.2.1.1.1 Thermoplastic Composites

The thermoplastic composite (TPC) is fully recyclable and can be repurposed and reused via cost-effective recycling methods such as re-melting and re-molding [24]. TPCs generally do not have a cross-linking structure and their polymer chains are able to slide across each other when heated. TPCs are recycled grinding finished parts into small particles. The particles can consequently be fed into an injection molding machine together with virgin TPC materials [19].

3.2.1.1.2 Thermoset Composites

In contrast to TPCs, thermoset composites (TSCs) cannot be re-melted or re-shaped due to its cross-linked molecular structure. Hence, for TSCs, the reinforcing fibres are separated from the resin and filler part. The separated fibres can be reused as reinforcing material in other applications; the resin and filler part are used again as filler in many other applications [17] Currently, epoxy resins are the predominant thermoset plastic used in performance carbon fibre composites [19].

3.2.1.2 Reinforcement

Composite materials can also be classified by reinforcement type, being subdivided into (1) Particle-Reinforced Composites and (2) Fibre-Reinforced Composites. In this report, only the fibre-reinforced composites have been reviewed. The two most common reinforcement material types are GFs and CFs. Hence, the recycling techniques mentioned in section 3.2.2 are only considered for these reinforcements.

The nature of composites generated by industry is known to be approximately 1/3 thermoplastics and 2/3 thermosets. Despite the advances, strong growth, and many innovations in other segments of the FRP/composites market, GFRP still remains the dominant material in the composites market with market share of over 90% as of 2020 [19].

3.2.1.2.1 Glass Fibre

The most commonly used GF, E-glass (E for electrical), has good strength, stiffness, electrical and weathering properties. In some cases, C-glass (C for chemical) is preferred, having better resistance to corrosion than E-glass, but lower strength. Finally, S-glass (S for strength) is more expensive than E-glass, but has a higher strength, Young's modulus and temperature resistance [42].

One of the major challenges facing TSCs industry is the recovery and reuse of GFs from manufacturing waste and EoL composites in cost-effective, sustainable, environmentally friendly means [42]. The reuse of these materials could result in a significant reduction in the environmental impact of the GF and composites industry where replacement of 50% of current GF products by recycled GF products would equate to a global reduction in CO_2 production of 2 million tonnes per annum from reduced melting energy requirements of the GF and GFRP industry. This would be in line with the growing societal and environmental pressure to reduce landfill disposal, increase the reuse of valuable raw materials and reduce CO_2 release to atmosphere [42].

Number of recent studies in the area of wind energy have been focused on the development of sustainable methods for the recycling and reuse of rotor blades. To overcome this challenge scientists have resorted to chemical and pyrolysis techniques to recover GF from EoL turbine blades [16]. Despite the high mechanical properties of the recycled fibres, these techniques may not be the most promising means in terms of commercialisation due to the use of hazardous chemicals and/or excessive cost [30]. According to [30], mechanical grinding is the only recycling technique, which has found its way to industrial application. In comparison to chemical and thermal techniques, this technique offers a simpler and economically feasible scheme for the recycling composites, in particular, GFR materials [27].

3.2.1.2.2 Carbon Fibre

CFs are extremely popular in industry due to their high tensile strength, low densities, good thermal and electrical conductivities, and high thermal and chemical stabilities [45].

Similar to GFs, there have been several studies on various types of recycling methods for CFs and CFRP materials. Some of these techniques are more commercially mature than others. Nonetheless, industrial applications using recycled CF are still not widespread, partly because of a lack of confidence in performance of recycled CFs, which are considered as of lower quality than virgin CFs. The most commonly used technique for recycling CFs is pyrolysis.

3.2.2 Recycling Techniques

There are various techniques that can be employed for recycling of composite materials, and they each of their advantages and disadvantages. Figure 5 shows the EoL scenarios of carbon/glass fibre-reinforced composites.

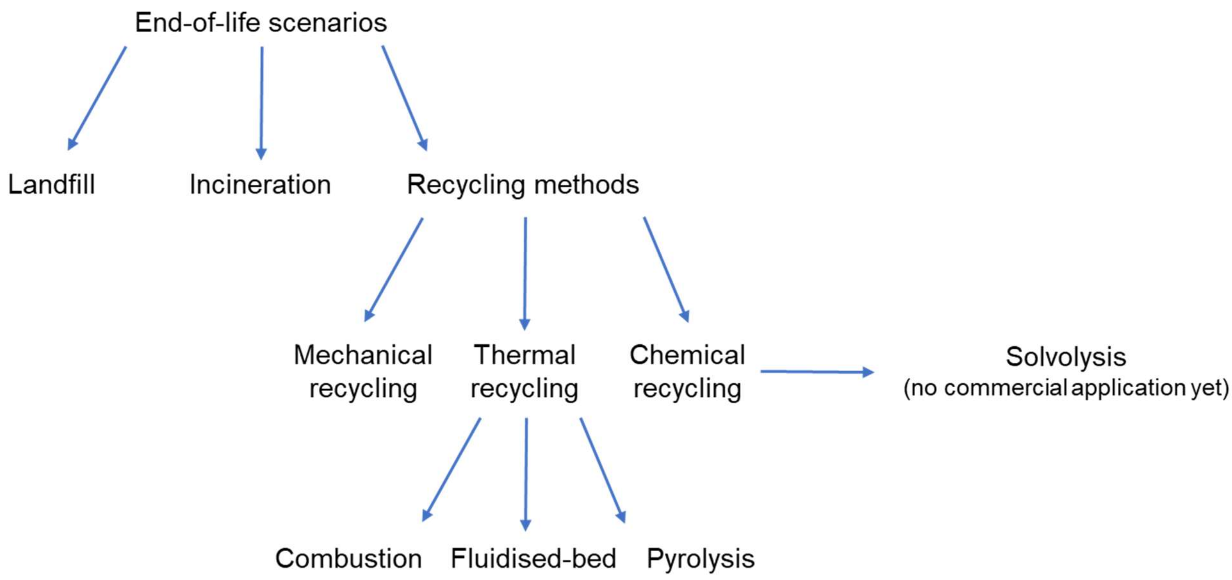

Figure 5: EoL scenarios of carbon fibre/glass fibre-reinforced composites. Reproduced from [19].

3.2.3 Mechanical Recycling

This technique has been investigated for both GFR and CFR composites, however, the most extensive research has been done on GF [32]. In general, mechanical recycling represents as a technique for shredding composite waste into smaller pieces also known as recyclates. In mechanical recycling, the process starts with cutting and shredding the scrap or discarded composites into smaller pieces. Subsequently, the

3.2.4 Thermal Recycling

The main objective of thermal recycling process is to separate the fibres from the matrix. This objective can be achieved via (a) pyrolysis, (b) fluidised bed pyrolysis, and (c) microwave pyrolysis process.

The most studied thermal process is **pyrolysis** performed in absence or in presence of oxygen, and more recently in the presence of steam [27]. The matrix degradation produces an oil, gases, and solid products (fibres, eventually fillers and char). The fibres are contaminated by this char and require post-treatment in a furnace at 450°C at least to burn it, for instance GFR composite (see Figure 6). The post treatment also leads to a higher degradation of the fibres. Pyrolysis has been more developed to recycle CFR matrices and has reached commercially exploited industrial scale.

GFs suffer from the high temperatures and their mechanical properties are decreased by at least 50%, especially as the minimal process temperature is 450°C. CFs are less sensitive to temperature but they can be contaminated by a char-like substance remaining from the degradation of the resin, which prevents a good bond with a new resin. At 1300°C this substance is completely eliminated and the fibres are perfectly clean with highly activated surface, however, their strength is significantly reduced.

A number of studies have reported the mechanical property values measured after pyrolysis. The studies reported that the tensile strength can be reduced by up to 85%, but can also be unaffected by the treatment. The treatment conditions hence play a major role on the resulting fibre properties. A lower reduction in strength was observed when fibres were reclaimed from a composite than when they were heated in air on their own (not embedded in a resin) [27]. Above 600°C the tensile strength of the recycled CF was reduced by over 30%. The fibres also seem to have a different sensitivity to pyrolysis conditions depending on their type.

In conclusion, a pyrolysis temperature in the range of 500-550°C appears then to be the high limit of the process in order to maintain acceptable strength for CFs; whereas GFs retain less than 50% of their mechanical properties at the minimal temperature of 400°C.

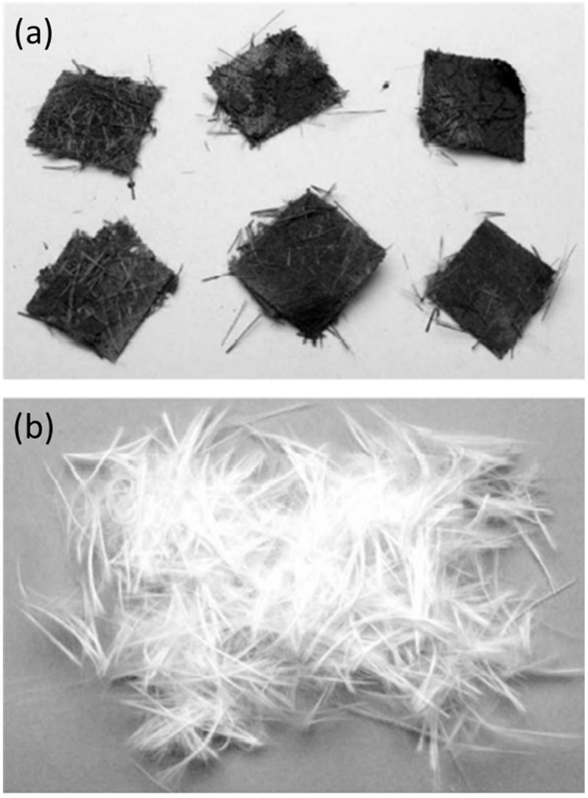

Figure 6: (a) Solid pyrolysis residues, (b) recovered fibre after separation. Image taken: [20]

Fluidised-bed process has been applied to recycling of GFR and CFR composites. This pyrolysis-based process uses a bed, of silica sand for example, fluidised by hot air so conditions are oxidant. This enables a rapid hearting of the materials and release the fibres by attrition of the resin [27]. Similar to standard pyrolysis, a small amount of oxygen is required to minimise char formation. In another study [32], a rotating sieve separator was implemented in the process to separate fibres from fillers of recycled GFR composites. The organic fraction of the resin was further degraded in a secondary combustion chamber at about 1000°C. Producing a clean flue gas (for energy recovery). At 450°C GF tensile strength was reduced by 50% while at 550°C the reduction achieved 80%/ CFs show a lower strength degradation of about 25% when processed at 550°C. Analysis of their surface showed that oxygen content resulted in a small reduction, indicating that the fibres have a good potential for bonding to a polymer matrix. The benefit of this process is that it can treat mixed and contaminated materials, with painted surfaces or foam cores in composites of sandwich construction or metal inserts. Hence, this process is particularly suitable for EoL waste, nonetheless, it has not largely been applied to reclaim fibres, especially CFs. Furthermore, the fluidised bed process does not allow recovery of products from the resin apart from gases, whereas pyrolysis can enable the recovery of oil containing potential valuable products. In addition to the high temperature, attrition by the fluidised sand might also damage the fibres.

3.2.5 Chemical Recycling

Chemical recycling is a process that polymers are chemically converted to monomers to partially depolymerised to oligomers through a chemical reaction. The polymer matrix present in the waste composite is broken down by dissolving it in any chemical solution in chemical recycling process including, e.g. acids, bases, and solvents [19].

3.3 Properties of Recycled CFs

When a technology was reported by several sources, a median number was calculated. Another factor to consider is that the lengths of the recycled fibres can vary. The highest tensile strength values are obtained from fibres produced by chemical recycling and the lowest values by mechanical recycling. The fibres that have been made using pyrolysis have values that lie in between. Furthermore, the recycled fibres may have different amounts of resin residues. It can be concluded that the fibres are not as clean and homogeneous as virgin fibres. Therefore, post-processing is necessary [19].

Table 4: Recycled CF retained tensile strength compared to virgin CF, based on [22]. *) Significant fibre damage has been stated, but no data has been found. This data is estimated by the authors; (**) No fibre strength has been found directly from the literature. Estimated to be the same ratio as the strength of a rotorcraft door hinge made with recycled CF compared to a virgin hinge

EoL Options	Retained Tensile Strength of Recycled Fibre Compared to Virgin Fibre, %	Reference
Mechanical	~50(*)	[25]
Fluidised-bed	~75	[20, 29, 52]
Pyrolysis	36-93; typically, ~80 or less	[26]
Microwave Assisted Pyrolysis	~80	[52]
Chemical	90-98; typically, ~95 or less	[14,26, 29, 53]
High Voltage Fragmentation	~83 (**)	[47]

Table 5: Comparison of CF mechanical properties before and after the chemical recycling of carbon fibre/epoxy resin composites under the mild condition as described by [14].

Property	Virgin CF	Recycled CF
Tensile Strength, GPa	4.07 ± 0.73	3.89 ± 0.75
Elastic Modulus, GPa	179.27 ± 12.5	173.79 ± 15
Strain-at-Break %	2.36 ± 0.45	2.28 ± 0.45

3.4 Properties of Recycled GFs

Although mechanical recycling is a cost-effective process, the mechanical performance of the fibres has greatly been ruined. Moreover only 70–75% strength retention in reclaimed fibres is reported when using the pyrolysis and fluidised bed processes. Nowadays enormous advances in chemical and electrochemical recycling methods have been made to minimise the damage to the fibres during recycling processes and to keep consistency of the fibre architecture. In Table , the different values for retained tensile strength of recycled fibre compared to virgin fibre for recycled GF are shown. When a technology was reported by several sources, a median number was calculated [22]. The highest tensile strength values are obtained from fibres produced by High Voltage Fragmentation and the lowest values by the pyrolysis and the Fluidised-bed processes. The fibres that have been produced using the mechanical method have values that lie in between.

Table 6: Recycled GF retained tensile strength compared to virgin GF: (**) No reference found, estimated to be the same as conventional pyrolysis as the processing conditions are similar. Reproduced from [22].

EoL Options	Retained Tensile Strength of Recycled Fibre Compared to Virgin Fibre, %	Reference
Mechanical	~78	[25]
Fluidised-bed	~50	[20, 29, 52]
Pyrolysis	~52	[26]
Microwave Assisted Pyrolysis	~52(**)	[20]
Chemical	~58	[29]
High Voltage Fragmentation	~88	[47]

3.5 Use Case 1 – Wind Turbine Blades

In wind energy industry, composites are used in blades, due to their high specific strength. It was reported by Global Wind Energy Council (GWEC), that there are more than a third of a million utility scale wind turbines installed around the world, most of which are designed for service life of 20-25 years. Turbines from the first major wave of wind power in 1990s are reaching their life expectancy nowadays and in the decade of 2020s [23]. As pressure is increased to have greener and more sustainable products, the recycling of wind turbine blades has increasingly attracted the interest of wind turbine blade manufacturers and owners. However, recycling of the blades remains a challenge. The difficulties related to the process are mainly due to the structure of the blade and the composite materials used in the blades (shown in Figure 7).

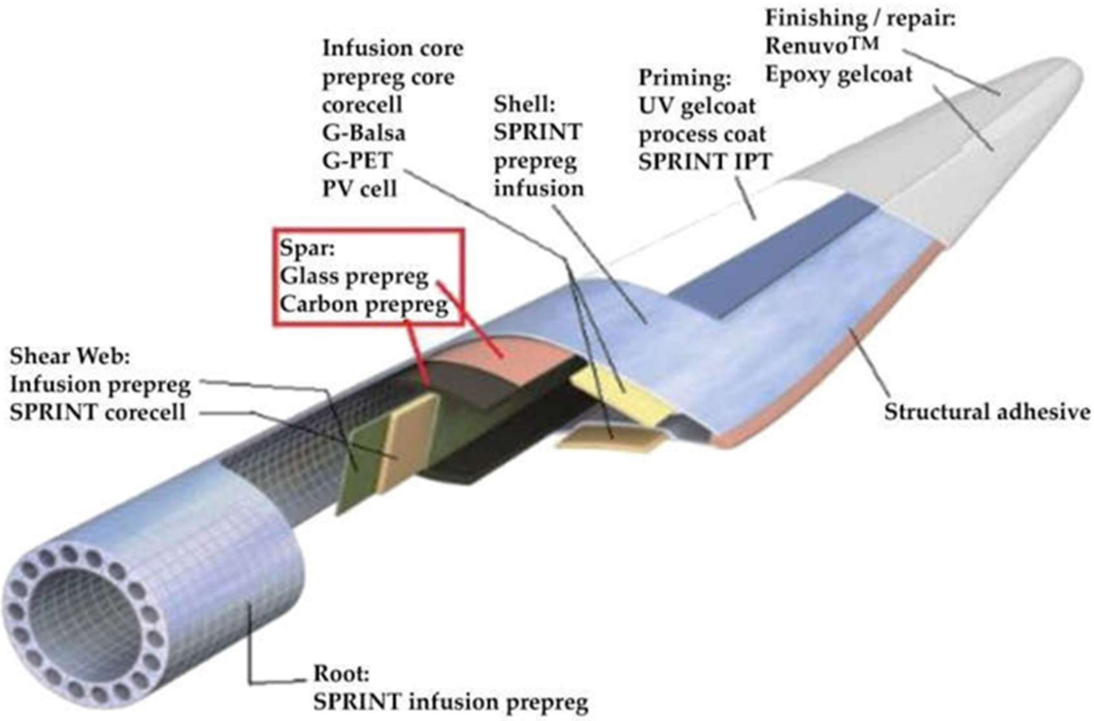

Figure 7: Materials used in the different parts of a wind turbine's blade. Image taken: [11].

Within the scope of the JIDEP project, the section obtained from the wind turbine will go through the recycling process. The materials used during the construction of the turbine blade vary according to the design and technical characteristics of each blade. Studies will be carried out on the properties of the raw material obtained from the recycles turbine blade. Determining what portions of carbon fibre, glass fibre, and resin used in the construction of the turbine are recycled is an important step in the project.

3.6 Use Case 2 – Automotive Chassis

There is high demand in automotive industry for composite materials as a consequence of highest performance achievable with lightweight. Recent developments in mobility have paved the way for an electric propulsion and autonomous guide technologies. These vehicles required to be lightweight in order to reach longer ranges between recharging (electric cars), hence, leading to a new driver for high volume production technologies of composites and their EoL disposal definition. One of the objectives in automotive industry is to have fuel-efficient cars. Application of carbon fibre reinforced polymers (CFRP) in car parts reduces the weight of the cars by 30%, in comparison to a standard car, leading to a more fuel-efficient vehicle and therefore, contributes to decrease of greenhouse emissions [2]. Thus, the demand for high volume of carbon fibre parts has led to high percentages (20-40%) of the raw materials going to waste [37]. In the automotive industry, EU legislation required 85% of a vehicle to be recyclable [2]. CF waste can be recovered and converted to new products using less than 10% of the energy required to produce the original CF, fulfilling legislative and sustainability targets [2].

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