Catena-X

Data requirements for recycling of ELVs

Whitepaper 1.0 (July 2024)

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1. STATUS QUO (INTRODUCTION & MOTIVATION)

The White Paper supports our vision for an open data ecosystem intended for the automotive industry that enables sustainable and commercially viable recycling processes, by facilitating communication and collaboration among all industry players and by leveraging standardized protocols and frameworks. We are committed to developing innovative solutions that ensure high-quality recyclate and promote a more circular economy, while exploiting the enabling ability and efficiency gains of real-life data exchange ("4th industrial revolution"). We believe that the intercompany exchange over the whole supply chain and usage of data will be a game changer in respect to all attempts of recycling of the last three decades.

Currently, the end-of-life (EoL) process for cars is neither transparently nor efficiently organized. The industry is highly fragmented, with over 1,000 dismantlers in Germany and more than 10 000 in the EU, of which only a small have an industrial-style operation beyond craftmanship. Many decommissioned cars are either exported or leave the EU, leaving an estimated 6 million out of 11 million cars sold annually in the EU available for dismantling (1). Traditionally, material recycling of metals is done but partly downcycled after shredding, while other materials such as glass, liquids, plastics, leather, and wood are mostly only thermally recovered after shredding. The regulatory, societal, and entrepreneurial need for change is obvious.

Catena X aims to change this situation by designing a seamless data flow and process set-up. The goal of the material recycling white paper is to draft a more transparent and well-organized EoL process for cars. By leveraging the power of data and technology, we believe that we can optimize the material recycling of metals and enable material recycling for other materials, namely plastics through standardization and the promotion of solutions with commercially sound use cases. Through our approach, we seek to promote the efficient use of resources by reducing the amount of thermally recovered materials. We believe that our efforts will drive positive change and lead to better business cases targeting material recycling.

Central to the Circular Economy (CE) is the shift from a linear cradle-to-grave system to a cradle-to-cradle system, following a life-cycle approach. This means considering the entire lifecycle of a product along the value chain, including raw material extraction, component supply, manufacturing, distribution and use, as well as end-of-life and waste management (2). There are various approaches to implementing a circular economy, the so-called R-strategies.

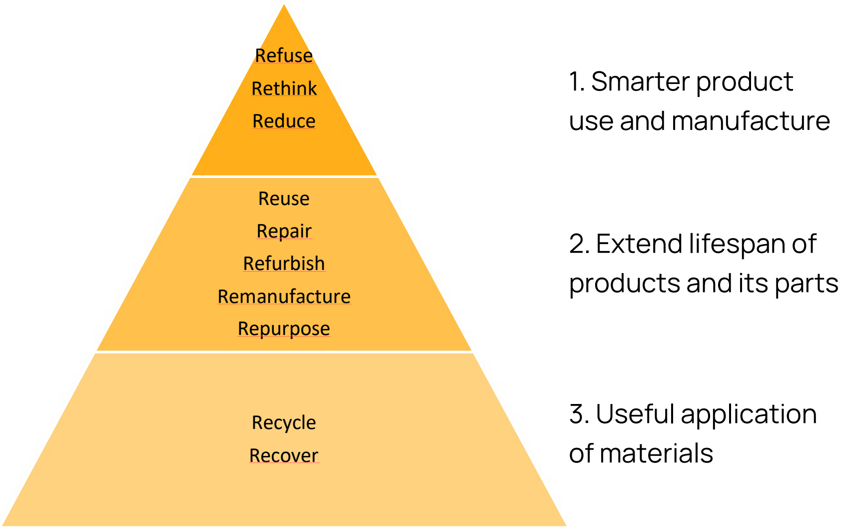

Figure 1 Comparison of R-strategies based on Pottering et al, 2017 (3)

Figure 1 shows R-strategies based on value retention. 'Remanufacturing' and 'reuse' are key strategies to extend component lifespan and reduce resource consumption. When end-of-life parts cannot be reused or remanufacture as the preferred R-Strategies, material recycling should be the approach to conserve resources. Efficient management of materials recycling is critical for reducing environmental impacts and supporting circular economy principles. Thermal recovery is not part of the whitepaper and suggested data model.

The recycling process involves depollution, dismantling, and shredding the entire vehicle or its components. Dismantling and sorting individual components before shredding can be advantageous, depending on material and quality requirements. Post-shredding, materials are sorted by type—metals, plastics, glass, rubber, etc.—and further separated into specific fractions. These materials undergo additional processing, such as mechanical, biological, solvent-based, and chemical recycling, to extract usable recyclate. The end of the recycling process is when recyclate is mixed with prime material and accounted for as secondary material content.

Facilities prioritize maximizing material recycling and optimizing resource allocation while ensuring compliance with safety and environmental standards. The commercial viability of material recycling depends on the availability of ELVs, legal and quality requirements, technological feasibility, and process maturity. Since some material recycling processes are still maturing, the commercial viability of current facilities versus future installations can vary widely, especially with ongoing industry developments and regulatory changes.

2. REGULATORY CONTEXT

The current and upcoming legal obligations and requirements could have a transformative effect on the automotive industry and are driving innovation and investments in the circularity context in the years to come.

The most prominent upcoming regulation within the European Union for the automotive industry represents the new proposal of the ELV regulation 2023/0284. This proposal aims to update and improve the ELV Directive (4). It will impact most major materials in the car to achieve circularity, resource efficiency and environmental protection. This proposal is aimed to be a regulation instead of a directive which makes it more stringent and legally binding.

The ELV regulation concerns circularity requirements on vehicle design and production related to reusability, recoverability and recyclability and covers the complete lifespan of a vehicle, from design to disposal.

The regulation enhances four key areas:

Firstly, it focuses on the use of recycled content, with mandatory requirements for the Post Consumer Recyclate (PCR) of polymer (25% PCR for new complete vehicles including 6.25% from ELV of the same vehicle type) and mandates efforts to establish future minimum levels for steel, potentially including aluminium, magnesium, and REE-based magnet alloys. This promotes the sustainable use of materials in vehicle production.

Another regulatory aspect is the requirement for information and labelling on parts, components, and materials. This improves material traceability and end-of-life (EoL) treatment, facilitating better material recycling processes.

Extended Producer Responsibility (EPR) is also a significant component. This policy shifts responsibility to producers, encouraging them to design vehicles with EoL in mind, manage the take-back of used vehicles, and oversee their recycling and final disposal. Such measures promote sustainable practices throughout the vehicle's lifecycle.

Furthermore, the regulation limits exports outside the EU. This ensures better EoL treatment of vehicles and supports domestic recycling and the recovery of valuable resources.

Additionally, the regulation includes updates such as incorporating trucks and other vehicles under the ELV directive, broadening its scope. It also merges the ELV Directive with the 3R Type-Approval Directive, streamlining regulations and improving compliance across the industry.

The ELV regulation is expected to be published in Q4 2024.

As part of this regulation, the Commission would be allowed to adopt delegated acts to set targets e.g. for recycled steel, critical raw materials, and aluminium, based on an assessment of their added-value and feasibility. These delegated acts are expected to further reinforce rules on extended producer responsibility.

From the dismantling perspective, the list of mandatory removal of parts before shredding has been significantly enlarged and updated. Dismantlers will need to remove these parts to be able to assess them for reuse, remanufacturing, or recycling before further processing.

Relevant for the current legal obligation there is on the one hand the Waste Framework Directive 2018/851 which sets out basic concepts and definitions relating to waste management. These include definitions of waste, recycling, and recovery. It emphasizes the prevention of waste and states that landfilling of waste should be the last option. The Directive also includes the concept of end-of-waste (EoW), which specifies when certain waste ceases to be waste and becomes a product or a secondary raw material.

In addition there is the EU Battery Regulation 2023/1542 which aims to minimize environmental impacts of batteries by promoting sustainability and circular economy. It covers the entire battery lifecycle, from raw material extraction to recycling. Key aspects include ethical sourcing of raw materials, CO2 footprint of battery production, reuse and recycling of batteries, and specific safety and labelling requirements.

And on the other hand the actual End-of-Life Vehicle Directive 2000/53/EG (ELV Directive) implements measures to prevent and limit waste from end-of-life vehicles (ELVs) and their components through reuse, recycling and recovery. It aims to improve the environmental performance of all economic actors in the life cycle of vehicles and sets clear targets for the reuse, recycling, and recovery of ELVs and their components. Overall, these three directives (Waste Framework

Directive, Battery Regulation and End-of-Life-Vehicle Directive) work together to promote the circular economy in the automotive sector and minimize the environmental impact of vehicles.

Apart from the ELV regulation, other initiatives for current and upcoming regulations, e.g. Green Claims Directive, ESPR…, need to be considered in the context of material recycling and are considered as part of the data requirements.

Catena-X aims to address the challenges of material recycling by structuring them along circular economy processes. We evaluate materials and material groups on a process level to determine their technical and commercial viability for effective material recycling. Through careful analysis, we identify key objectives and bottlenecks, and work towards developing a guiding framework.

Catena-X offers data standards to support solutions for these challenges. Our goal is to contribute to a sustainable and circular economy by optimizing material recycling and addressing the underlying processes.

3. STATE-OF-THE-ART (USE CASE EXAMPLES)

To address the highest recycling potential in respect to component weight, value and overall retrievable volume in the existing automotive fleet, the most promising components, which are easily dismantled and have a decent amount of material, were selected: large plastics parts, airbags, car seats, and aluminium hang-ons.

3.1. PLASTICS OVERVIEW

Plastics are a crucial component in the automotive industry due to their versatility, lightweight nature, and cost-effectiveness. The use of plastics in automotive manufacturing has significantly increased over the years, driven by the need for fuel efficiency and emission reductions. Plastics contribute to the overall reduction of vehicle weight, which improves fuel efficiency and reduces greenhouse gas emissions. An average car today contains approximately 197.85 kg of plastic, which constitutes about 15.9% of the total vehicle weight, as highlighted in the Kurea study. Roughly 15kg of these plastics are big, detachable parts.

The types of plastics used in vehicles vary, with polypropylene (PP), polyurethane (PUR), high-density polyethylene (HDPE), and polyamide (PA) being some of the most common. According to the Kurea study, the composition of plastics in an average car includes polypropylene (PP) at 25%, polyurethane (PUR) at 14%, high-density polyethylene (HDPE/PE-HD/MD) at 4%, and polyamide (PA) at 15%.

These plastics are utilized in various automotive components, such as bumpers, petrol tanks, and airbags, each serving distinct functions while contributing to the vehicle's overall performance and safety. The efficient recycling of these plastics is essential to meet environmental and economic demands, ensuring that valuable materials are recovered and reused, minimizing environmental impact. We focus on these specific components because they are relatively easy to dismantle, and therefore have low labour costs and time during recycling in comparison to other parts. Additionally, they represent a significant portion of the plastic used in vehicles, with bumpers alone accounting for 9.1 kg of plastic per car. Furthermore, the plastics in these components are often of consistent type and quality, simplifying the sorting and recycling process and improving the quality of the recycled material.

3.2. BUMPERS

Automotive bumpers, typically made from thermoplastic polymers like polypropylene (PP), polycarbonate (PC), and acrylonitrile butadiene styrene (ABS), are designed for impact resistance and durability. According to the Kurea paper, the combined weight of plastic in front and rear bumpers averages around 9.1 kg per car, which can vary widely. While front and rear bumpers generally use similar types of plastics, the front bumper may incorporate additional materials and structures to accommodate components like air intakes and sensors, reflecting its more complex design and higher impact requirements compared to the rear bumper. The recycling process for automotive bumpers involves several key steps:

Figure 2 Simplified process steps for recycling of bumpers.

Bumpers are collected from end-of-life vehicles (ELVs) at dismantling facilities and the decision is made, whether they are reused, refurbished or recycled. If the recycling decision is made, contaminants such as metal reinforcements, paint, and adhesives are removed by a decoater to ensure the quality of the recycled material. Separating bumpers from other plastic components and contaminants.

Two advanced sorting technologies are commonly used: X-ray based sorting and near-infrared (NIR) based sorting. X-ray based sorting uses X-ray transmission to measure the intensity of X-rays passing through the material, allowing for the separation of materials like PVC, elastomers, and metals. NIR based sorting illuminates the materials with halogen lamps, capturing the reflection spectrum in the NIR range to identify various plastic types.

Bumpers are shredded into smaller flakes, which increases the surface area and facilitates further cleaning and separation of other materials.

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The shredded and sorted plastic flakes undergo washing to remove residual contaminants, and the clean flakes are then melted and extruded into pellets. These recycled pellets can be used to manufacture new automotive parts, including bumpers, thus closing the recycling loop. The commercial viability of bumper material recycling is evident in niche markets, with companies such as Alba and Wipak actively involved. This activity is also observed internationally, contrasting with other automotive parts like seats, which are still in early-stage piloting.

Effective bumper recycling necessitates specific data inputs or optical part recognition processes. Car manufacturers providing detailed information on the materials comprising bumpers would streamline sorting and processing. Such data includes not only material composition but also details on the bumper's construction, such as structural design and integration of components. This information enhances the efficiency and effectiveness of the recycling process, ensuring that materials are properly sorted, cleaned, and reused in manufacturing new products.

3.3. PETROL TANKS

Petrol tanks in vehicles are primarily constructed from high-density polyethylene (HDPE), a robust and chemically resistant plastic material. This choice of material ensures that the tanks are lightweight yet durable, able to withstand the harsh conditions they are exposed to, such as fluctuating temperatures and exposure to fuel. Plastic tank systems decrease the vehicle's overall weight, as an average plastic tank weighs two-thirds less than an average steel tank.. The recycling process for petrol tanks involves several meticulous steps:

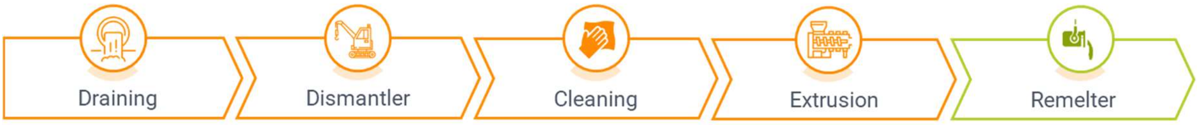

Figure 3 Current process steps for recycling of petrol tanks.

The collection of petrol tanks begins at dismantling facilities where petrol tanks are carefully removed from end-of-life vehicles (ELVs) to prevent contamination and ensure the safety of workers handling potentially hazardous materials. Once collected, the tanks undergo pre-treatment to remove any remaining fuel, vapours, and other contaminants. This often involves draining and rinsing the tanks.

The cleaned tanks are then shredded into smaller pieces to increase the surface area, making subsequent cleaning and processing more effective. The shredded plastic pieces undergo additional cleaning to remove any residual contaminants. After thorough cleaning, the plastic fragments are melted and extruded into pellets. These recycled pellets can be used to manufacture new petrol tanks, automotive components, and other plastic products, contributing to a circular economy and reducing the demand for virgin plastic materials.

Despite their high value, petrol tanks present challenges in recycling due to pollution concerns and the substantial effort required for dismantling. Efforts to standardize dismantling procedures, possibly through guidelines integrated into the Design for Recycling (DfR) principles or improved design strategies focused on recyclability enhancement, could mitigate these challenges in the future.

Accurate data on petrol tank construction, including the presence of inner liners for aromatic barrier purposes, is essential for optimizing the recycling process. Such data aids in determining the best methods for dismantling, cleaning, and processing, thereby improving overall efficiency and environmental outcomes.

3.4. AIRBAGS

Airbags, essential for vehicle safety, are primarily made from nylon, specifically polyamide 6.6 (PA 6.6), with a protective coating. Each vehicle's airbag system contains about 1-2 kg of this material. Investigating the recycling of airbags remains relevant due to the existing post-industrial recycling practices, which demonstrate a well-established infrastructure for waste recovery. This infrastructure can also be utilized for post-consumer recycling, as the end-of-life of airbags aligns closely with their beginning of life. Leveraging these existing systems can enhance the efficiency and viability of the recycling process. The post-consumer recycling process for airbags could have the following steps:

Figure 4 Current process steps for recycling of airbags.

Once the pyrotechnic is activated, hence neutralized, the airbags must be dismantled to separate the nylon fabric from other components like plastic housings and metal parts. The PA 6.6 fabric is highly valued for its strength and flexibility, making it suitable for various high-performance applications. The dismantled nylon fabric is then fed into a process involving cleaning and shredding resulting in smaller pieces, which increases the surface area for further processing. The clean nylon fragments are melted down and extruded into pellets.

These recycled pellets can be repurposed for manufacturing new airbags or other high-strength plastic products, such as technical components in the automotive and electronics industries. Plastic components of the airbag system, such as the housing, undergo a similar recycling process. They are shredded, cleaned, and melted to form pellets, which can be used to produce new automotive parts and various plastic products. Providing data on material composition, propellant types, and deactivation procedures would facilitate safer and more efficient recycling operations. Additionally, standardizing dismantling guidelines and improving design for recyclability could further streamline the process, making post-consumer recycling of airbags more commercially viable and environmentally beneficial.

3.5. CAR SEATS

The automotive seating market is systematically classified according to a range of seat types and materials extensively utilized within the automotive industry. Seat typologies encompass bucket seats, bench seats, split-bench seats, power seats, heated seats, ventilated seats, alongside specialized or nascent seat designs. Automotive seats comprise diverse material compositions, including plastics, metals, and textiles, integrated to ensure robustness, comfort, and aesthetic appeal. The seats are held by a seat frame, typically constructed from metallic alloys or durable polymers. A multi-layered padding system, incorporating various cushioning materials such as foam or cotton batting, is overlaid onto the frame to provide comfort and ergonomic support. The cover provides the seat with its visual and tactile characteristics, composed of specialized fabrics tailored for automotive applications.

The following deals with the recycling options for textile seat covers to represent a recycling path for textiles in automotive interiors. Given the annual production volume of seats expected to reach 712 million units by 2026 (5) globally within the automotive sector, this issue assumes significant proportions. The use case of car seats was selected because they are a significant contributor to shredder residue and are partly composed of mono-materials, which in theory, can be separated and are not fiber-enforced.

Figure 5 Current process steps for recycling of non-metallic parts of seats.

Textile seat covers, being integral components of automotive seats, are subjected to a complex construction process involving layers of padding materials and a textile cover affixed to a sturdy frame. The material composition of vehicle seats varies based on the type (bench or bucket style) and the connection to the vehicle. Seats with their own internal structure, bolted into the vehicle's frame, are primarily made of metal, with ferrous metal making up 65-75% of the total weight. In contrast, seats without their own structure and supported by the vehicle's frame are mainly composed of non-metal materials, with ferrous metal constituting only 20-25% of the total weight (6). The structure of composite materials for textile vehicle seat covers typically comprises three components that are bonded together by adhesive layers: Face materials such as woven, knitted, and crocheted fabrics, mainly made of polyester fibers, followed by a polyurethane foam layer and a knitted fabric made of polyester or polyamide as a cover. Attachment mechanisms, including hooks, clips, or adhesive agents, are employed to secure the textile cover to the seat frame, ensuring stability and resistance to displacement during usage. Seat cover fabrics are usually pre-treated with flame retardants and other chemicals. The disposal of automotive seats presents a persistent challenge due to their complex composition of diverse materials and adhesives. Although seats account for a very high proportion of the total mass of a car (15-20 kg), they are currently hardly ever made from recycled materials and are not recycled (7). An accessible database with the composition of the seats of the different brands and models does not exist at this point, hence detail knowledge on recyclability of the components, e.g. some additives might be not possible to reenter the process. Seats are mostly shredded and then thermally processed.

3.6. ALUMINIUM HANG-ONS

Aluminium is a key material in the automotive industry, particularly in the production of light-weight vehicles. The increasing use of aluminium in battery electric vehicles (BEVs) for range gain purposes has created high pressure on material recycling. Past use of this valuable material has been limited to high-spec and end-of-line vehicle brand and ranges, which are now coming back as ELVs. The average amount of aluminium used in European cars has increased by 18% from 174 kg in 2019 to 205 kg in 2022. This trend is set to continue, with the average aluminium content projected to increase from 205 kg in 2022 to 237 kg by 2026 (+15.6%) and 256 kg per vehicle by 2030 (+24.9%) (8). As their overall numbers and actual aluminium weight per vehicle is low in comparison to other materials such as steel, the efficient recycling of aluminium from ELVs is essential to meet the growing demand for this material and reduce the environmental impact of the automotive industry.

Wrought and cast aluminium are two forms of aluminium used in the automotive industry, each with distinct properties and applications. Wrought aluminium, also known as alloy aluminium, and produced through hot and cold working, is ideal for structural components due to its high strength-to-weight ratio. Common applications include body structures and panels, suspension components, and engine parts typically in the form of sheets, forged components, and extruded profiles. Cast aluminium, created by forcing molten aluminium into a mould, excels in precision and consistency, making it suitable for engine components, diverse component housing, casings, and transmission components. While wrought aluminium is often more expensive, its strength and ductility make it a popular choice for load-bearing applications, while cast aluminium's precision is essential for critical parts. The commonly applied methods to treat aluminium from ELVs are shredder operations, usually combined with some type of post-shredder treatment operations. Recycling results is a fraction which often has a high Al content but is also rich in impurities as it is a mix of different alloys. It can be applied in higher amounts in alloys which are more tolerant to impurities (e.g., casting alloys) but not in alloys where a high purity is required (e.g., wrought alloys). Hence improvements in the material collection through better data provision will result in higher wrought aluminium recovery rates.

Figure 6 Process steps for wrought aluminium recycling

Focusing on the valuable wrought aluminium, the current state-of-the-art post-shredder sorting technology can only commercially separate material to a certain degree of quality. To improve the quality of the material output, it must be re-run multiple times through the sorting equipment, which is commercially detrimental for the shredder operator, as other equipment potentially must be idle. The resulting fractions however can achieve qualities suitable for creating new wrought aluminium products with a Scrap Metal Content (SMC) of more than 30%.

Wrought aluminium is often seen as an intolerant material meaning that different series and even grades of aluminium are seldom compatible with each other. The high Si content inherited from cast parts is not admissible in wrought alloys, and the high main elements Zn and Cu content of 7xxx and 2xxx alloys respectively are not compatible with other sheet materials. Not only sorting of cast and wrought Al scrap is therefore of prime importance, but also the distinction of different wrought scrap Al series should in the future become economically viable (9).

To make sufficient high-quality material available for the market, alternative routes can be taken. Wrought aluminium components can be dismantled from the ELV prior to its shredding and collected separately. Dedicated shredder batch runs of this material can be followed by more efficient fine sorting and significantly increase the SMC of the targeted alloy. In both cases, the aluminium scraps are de-coated post-sorting at high temperatures to remove moisture and remaining organic impurities before testing and remelting with prime material. The current industry practice for most collected aluminium is to remelt it in a cast product, which presents a downcycling as a cast aluminium will never become a wrought alloy again given the chemical composition and currently known technologies.

Today, the main driver and consumer of aluminium castings is the automotive and light truck industry with around 2,2 Mt/y: it uses more than 85% of aluminium castings in Germany (10). Cast Aluminium in the automotive sector can theoretically be recycled again and again, saving up to 95% of energy for primary production which is extracted from its ore, bauxite, at temperatures exceeding

1,000 Celsius. This is the main reason that makes recycled cast aluminium cheaper than the primary material.

Typical applications for castings include engine blocks, cylinder heads and gearboxes. However, as vehicles shift to electric power, the need for engine blocks will slightly decrease. At the same time, plug-in hybrid and full battery electric vehicles use 25-27% more aluminium than the typical internal combustion engine car today. Like wrought components, large cast components (<10kg) are often dismantled from the car prior to shredding process. Those are typically ICE engines or wheels which often are dismantled before the shredding process and are directly sold either for reuse or to aluminium recyclers without further pre-treatment. (7)

4. CHALLENGES

The realisation of ambitious material recycling targets is facing a multitude of challenges on different levels such as commercial viability, operational process integration, regulatory requirements, ELV material availability and data access and management. Every such challenge could result in widely different outcomes and performances of the recycling effort. As the material recycling is initially linked to components made out of recoverable materials, which are then retrieved via subsequent processes, e.g. shredding, sorting… , the next chapter focuses on component level, which need to be dismantled and treated separately in comparison to a full car shredder approach.

4.1 MATERIAL RECYCLING CHALLENGES ON COMPONENT LEVEL

4.1.1 Use Case: Plastics (Bumpers, Petrol Tanks, Airbags)

Recycling automotive plastics, such as bumpers, petrol tanks, and airbags, presents several challenges that complicate the process. Even though these components are often designed to be mono material for easier recycling, they can still contain various attachments, coatings or protective layers that complicate the separation and recycling process. This is particularly significant for bumpers, especially front bumpers, which may include additional materials and structures such as sensors, air intakes, and reinforcements. This complexity not only increases the cost of recycling but also demands high levels of technological expertise to ensure accurate material recycling.

The dismantling process for automotive components, such as airbags, can be labor-intensive. For example, airbags, despite being relatively small and easy to access, still require careful handling. Assuming an efficient dismantling time of approximately 15 seconds per airbag, a typical car with four airbags would require about one minute of labor per vehicle. Newer and future cars, which often contain more airbags, will increase labor time proportionally. At a labor rate of €50-60 per hour per dismantler, the labor cost for removing airbags is relatively low. However, the material value of the airbag fabric (the "balloon" portion), which is made from high-quality polyamide 6.6 (PA 6.6), must be considered. The value of this material is significant, but often it does not completely offset the labor costs involved in the dismantling process, making it challenging to achieve a cost-effective recycling operation.

Transporting automotive plastics, especially bulky items like petrol tanks, poses significant logistical challenges due to their size, residual contents, and safety regulations, increasing transportation costs and complexity. Additionally, many automotive components, while made from a single type of plastic to facilitate recycling, include elements like metal reinforcements, paint, or adhesives that must be meticulously removed, adding steps and costs to the recycling process. Material degradation from exposure to heat, UV radiation, and mechanical stresses during the vehicle's lifecycle further complicates achieving high-quality recycled materials, as maintaining consistent quality is crucial for manufacturing new components. These multifaceted challenges, including transport logistics, safety measures, regulatory compliance, design complexity, and material quality control, underscore the importance of continuous innovation and industry collaboration to enhance recycling efficiency, reduce costs, and promote sustainable practices in automotive plastic recycling.

4.1.2 Use Case: Car Seats

Effective recycling requires separating the multi-layered seat cover materials during end-of-life processing, increasing dismantling time and potentially reducing cost-effectiveness without suitable separation technologies.

While the steel frameworks supporting the seats undergo successful recycling processes, the complex task of isolating the soft materials poses considerable difficulty. Post-shredding separation is an option, but post shredder plastics is much harder to distinguish and separate than metals due to their similar physical properties (11).

The reintroduction of composite materials made of PES and PU into the manufacturing cycle is scarcely feasible due to their non-homogeneous composition and inseparable bonding (12). At the moment, PUR is downgraded during recycling and is not eligible for the same applications in seat foams. Multilayer materials like PET-PUR present challenges in layer separation, as highlighted in a recent study by de Mello Soares et al. (2022), which categorizes recycling technologies into high-performance, chemical, and downcycling methods. Modern car seats also contain a lot of electronics, for example for seat heating and cooling and for seat adjustment. This must be removed to enable pure sorting and recycling. Another challenge poses the contamination of plastics, especially of textiles, which are mainly finished with flame retardants.

Even though separation and recycling processes for PUR foam seem complicated and time-consuming, a study highlights that seats are good candidates for recycling due to favorable cost deltas. The efficient cost difference between dismantling and 80% recycling (16,11€) and no dismantling (37,64€) result in a cost advantage of 21,53€ for recycling (13). However, this is influenced by the lack of a structured market for PUR recycling and uncertain dismantling efforts as well as recycling process costs and emissions. Additionally, seat disassembly costs could be higher than estimated due to the complexity and variability in materials. Hence such cost advantages would need to be assessed further in real-life scenarios over a range of brands and models.

Understanding the material composition and interfaces is essential to differentiate disassembly and dismantling operations for vehicle seats due to practical issues involved in both processes.

It currently lacks economic viability for dismantlers to separate low-cost material from end-of-life vehicles (14). Many dismantlers lack resources to determine the best disassembly methods, and the industry lacks standard procedures due to varied vehicle designs and lack of regulations. Establishing general guidelines can lead to a more efficient vehicle recycling industry.

Facilitating the dismantling and recycling of car seats requires a multifaceted approach involving design improvements, optimization of fastening elements, advancements in recycling technologies, promotion of circular economy practices, automation and digitization, and training and awareness.

A critical aspect of this approach is designing car seats for easy disassembly and recycling. This can be achieved by creating modular components, using fewer material types, and clear labeling. Optimizing fastening elements with simple systems like removable screws, bolts, and snap connections can speed up disassembly. Reducing adhesive use also aids in separating materials. Advances in recycling technologies, such as automated mechanical separation and chemical recycling for polymers, are essential. Automation and digitization, using robots and tracking with RFID chips or QR codes, can enhance efficiency. Training professionals in these techniques is also vital for success.

Concluding for seats, it needs to be noted that unless significant progress is made in data availability on material composition in the seats, the way seats are composed of mixed materials and bonded together and no strong market signal is established, that seat will most likely not be commercially dismantled ahead of shredding. Post-shredding recycling will also highly depend on advances in technology, which is not commercially available at this point, therefore seat non-metal material recycling will remain thermal recovery for the foreseeable future.

4.1.3 Use Case: Wrought Aluminium Hang-ons

Apart from the data availability discussion outlined in the next chapter, the complexity of recycling ELV wrought aluminium revolves around the commercial viability of running very expensive material detection and sorting equipment post shredder or to make the manual effort of dismantling hang-ons, such as doors or hoods, and stripping them of all additional components, e.g. plastic covers, sound systems, windows, window lifting system, cables,.. . Furthermore, in case of pre-shredder dismantling of components, logistics cost can become a relevant factor if the dismantled and clean parts cannot be compacted at collection site. The loose collection of hoods, doors and other large hang-ons can easily result in inefficient material distribution and can be a safety concern if not shipped in containers or large skips.
Given the high energy saving of up to 95% for recycled aluminium versus prime material, such efforts could be commercially viable and therefore depend next to labour and machine cost as well on external parameters such as energy cost for the remelting of the metal.

4.2. DATA ACCESS AND USAGE

To enhance the quality and recycling rate of the materials embedded in the components, the dismantler as the first stakeholder in the value chain needs to know for each vehicle, which parts can be economically removed from the ELV and sold to respective buyers. There is no sufficiently detailed database in the market that has detailed material information about all the brands and cars at the component level; except for the IMDS database, which has shared ownership of the information at the automotive supplier level and is therefore, at the time of writing, not able to provide the information to the recycling industry. Therefore, for the material recycling case, the dismantlers must either base their dismantling operations on their own assessment, such as a simple magnet test for aluminium components, or on specifications given by recycler industry customers. These specifications are generally not comprehensive for all models and are relatively vague, as even the recyclers do not have a good data foundation at the specific vehicle level, which reflects where exactly their materials have been used in the past.

An additional complexity, especially with plastics, is the change in legislation, which has become stricter in recent years in terms of legal limits of use of certain chemical components. This means that some components of an old ELV, which would seem suitable for recycling, are not, given their use of additives at the time of construction, which would not be legal under stricter current legislation. This shows the difficulty of the recycling industry to achieve meaningful SCM levels, as there are not only commercial and technical challenges but also significant uncertainty about the input materials that can be obtained from the ELVs. However, it is expected that the industry will make efforts to establish more data knowledge on the actual recyclability of the materials at the component level of the vehicle.

Furthermore, the level of information currently exchanged between the recycling industry stakeholders is unstructured and high level given the diverse nature of the underlying material fractions after sorting. As specific ELV shredder campaigns are not common as industry standard, the resulting material mixes can have a wide range of origins, such as construction, white goods, industrial scrap, ELV, etc. and there is limited tracking of which input components went into the largely continuous processes of shredding and sorting. As more accurate data is needed to meet certain industry and legal requirements, such as product carbon footprint or ELV origin, as described in the next chapter, the overall ELV recycling industry must further digitize its processes and communication. The starting point for this endeavour is quite different from company to company, as the recycling industry consists of a very heterogeneous landscape ranging from small family dismantlers with a few employees to large international corporations.

Concluding, an improved data availability of the material composition of ELVs and their components in combination with a standardized data exchange has the potential to significantly reduce the efforts and costs of material detection and collection and while making more components and materials available for high value preservation recycling.

4.3. VERIFICATION AND VALIDATION OF DATA

The verification and validation of data play a crucial role in the Catena-X network. It ensures the reliability and accuracy of the data, which increases the trust of the participants in the information circulating in the network.

The ISO/IEC 17029, a standard that sets out general principles and requirements for the conduct of validation and verification activities, plays an important role here. It emphasizes the need for an independent third party to ensure the integrity of the data.

The use of the ISO/IEC 17029 in the Catena-X network ensures that the information, data and statements provided are accurate and robust. This not only increases the trust of the participants, but also improves the value of the information shared in the network.

By confirming the reliability and accuracy of the data, it can be used more effectively to make informed decisions and optimize processes. Therefore, the role of an independent third party working according to ISO/IEC 17029 is essential in the Catena-X network.

5. INFORMATIONAL REQUIREMENTS

The diverse processes and decisions carried out across the supply chain and value chain, starting at a dismantling company, and ending with the recyclate, facilitate various business needs, which are influenced by economic, environmental, technical, and legislative factors. Business needs are defined as informational demands within an organization to address business challenges, improve operations, or achieve strategic objectives. Such business needs hold data requirements and, specific parameters.

In the following, the data requirements per business need are identified and listed, but this outline is considered a working agenda for the material recycling expert group to be further detailed and expanded in further updates. The key target remains to develop standards based on the data requirements and their implementation within the Catena-x network.

The need to exchange data via Catena-X is generally between companies in the supply chain network whenever material is transferred between entities and process steps. As an example, four generic data transfer options have been highlighted for a non-iron metal material for illustration purposes in 7. For each of these data (and material) transfers different type of information needs to be communicated to the receiving party due to the nature of the material at every particular step in the value chain.

Figure 7 Process steps for non-iron metal recycling with data handover steps.

The key difference between data requirements can be attributed to the state of the material at each highlighted step in this example:

1. Post dismantling: Material is part of a component, which has been manually cleaned to specification, but still has fractions of unwanted material attached to it, e.g. glue, rubber, small plastic pins, plastic coating… and is likely to be mechanically compacted for logistic purposes.
2. Post shredder: Material has been shredded into small scrap metal pieces of a few centimetres in length, which individually have higher purity levels, but are loosely mixed with a large variety of unwanted material.
3. Post Sorting: Material has been ideally sorted to high purity level in different alloy classes, but remains contaminated with impurities such as moisture, colours or glue.
4. Decoating: Material is at secondary material quality and sufficiently purified to be reused in the production process as secondary material.

As recycling processes can differ significantly depending on the material in question, the number of handover points and involved companies can swing also dramatically. For simplicity reasons for this version of the white paper, the focus has been on the final hand-over of the last recycling step (in this example step 4) to the recyclate re-user. The working group will subsequently enrich the data set to other steps in the value chain and other materials as future work.

5.1. FULFILLMENT OF ECONOMIC BUSINESS NEEDS (FINAL HANDOVER)

The key economic data exchanges focus on commercial data which has been specified as:

Data attribute	Description of attribute
Price per Ton (PPT)	The cost per ton of recyclate, including any discounts or surcharges.
Currency	The currency in which the transaction will be settled.
Offer Terms	Date until which the offer remains valid.
Payment Terms	The schedule and method of payment, including the duration of credit, interest rates, and any penalties for late payment.
Commodity Risk Compensation	The risk compensation method associated with fluctuations in the market value of the recyclate, which may impact the seller's pricing, e.g. price is floating on LME market price with mark-up.
Minimum Quantity	The minimum amount of recyclate in tons the seller is willing to supply in a single transaction.
Maximum Quantity	The maximum amount of recyclate in tons the seller can supply in a single transaction.
Handling and Storage Costs	Any additional costs associated with handling, storage, and processing the recyclate.
Freight Costs	The cost of transportation, which may be included in the price per ton or negotiated separately.

5.2. FULFILLMENT OF ENVIRONMENTAL BUSINESS NEEDS (FINAL HANDOVER)

Increasing legislative, customer and ESG related investor pressures require a seamless tracking and reporting of environmental data points:

Data attribute	Description of attribute

Environmental Compliance	The seller's adherence to environmental standards and compliance with regulatory requirements, i.e. naming the adhered to standards.
Hazardous Waste Certificates	In case of recyclate classification as hazardous waste, the relevant information needs to be provided.
Location Origin	Classification whether a material is EU or non-EU originated.
Product Carbon Footprint	The PCF measurement of the total greenhouse gas emissions associated with a product's lifecycle.
Certificate / Evidence of Material	Document or evidence verifying the origin, quality, or compliance of a material on batch level, incl. Certificates of Decommissioning for ELV.
Type of recycling technology	Specification of the technology used to create the recyclate, e.g. mechanical, physical or chemical recycling.

5.3. FULFILLMENT OF TECHNICAL BUSINESS NEEDS (FINAL HANDOVER)

The technical information encompasses logistics, quality, and usability aspects, which are an extension of the material accounting data model (), whose specifics are mentioned here on a high level:

Data attribute	Description of attribute
Material Classification Reference Standard	Identification code or reference number for a specific industry or regulatory standard, e.g. DIN EN ISO 1043-1 (which standardized abbreviations for plastics and code letters for the structure of these abbreviations, as well as code letters to identify special properties of plastics).
Material Classification Standardized Entity	Standardized name or identifier for a material, e.g. EN 13920 (Al scrap).
Material Classification Standardized Value	Standardized value assigned to a material's name for consistency and clarity, e.g. PP-TD 10.
Author ID	Business Partner Number of data provider in Catena X.

Date of Transaction	Specific date or timestamp associated with an event or transaction.
Batch ID Information	Batch identifier, if applicable, which specifies the batch in which the material was recovered, which could be multiple batches depending on sold lot sizes, e.g. 3432123, 3432124.
Material Net Weight	Handover of sorted material having a quality needed for manufacturing. Net-weight = usable atoms according to transport documentation.
Material Specification Physical Characterization	Detailed description of the physical characteristics and format of the material, e.g. loose scrap metal chips ‹ 20mm; potential use of EN standards, such as BS EN 13920-2 (18).
Material Specification Chemical Characterization	Description of the chemical composition and properties of the material, e.g. LiOH, CU; potential use of EN standards, such as BS EN 13920-2.
Chemical Composition	Starting with the most prevalent material, average % of volume, range of measurement uncertainty, measurement method, e.g. Al, 95%, +/-2%, LIPS Analysis.
Physical Composition	Starting with the most prevalent material, average % of volume, range of measurement uncertainty, measurement method, e.g. Al, 95%, +/-2%, LIPS Analysis.
Material Property Flag	Flag for the material either to be of primary or secondary origin.
Secondary Material Classification	% of material being either post-or pre-consumer with a further differentiation of being either automotive or non-automotive, e.g. 40% pre-consumer out of which 75% is automotive origin.
Delivery Terms	The terms of delivery, such as FOB (free on board) or CIF (cost, insurance, and freight), which determine who bears the cost of transportation.
Lead Time	The time between ordering and receiving the recyclate.
Density	The density of the material, which allows for transport and storage planning.

Transport Method	Terminology in respect to transport method, such as palletized, bulk bags, loose in skips, bulk transport or baled as the most prominent examples.
Location	Depending on logistic agreement, i.e. which party organizes logistics, either the pick-up or the drop-off location needs to be shared.
Gross Weight of Material	Total weight which needs to be moved including transport material, e.g. metal skip, Big Bag, pallets.

6. CONCLUSION & OUTLOOK

Material recycling is complex, and its success depends on a wide range of parameters such as data availability and verifiability, commercial viability, technical maturity and many more. Dependent on the material to be recovered and the desired quality output to be obtained, different processes need be followed, which have been demonstrated in a range of examples of component level. While material recycling from some components, for example seats, have been demonstrated to be commercially unviable now, partly due to the lack of data, many others have proven to be worth exploring further. To facilitate this process an overview of material data points has been worked out and listed.

We clearly believe that standardized communication within the Catena-X network will act as a game changer for the digital enablement towards the necessary transformation of the ELV recycling industry. Harmonized communication amongst stakeholders vertically and horizontally in the value chain will bring stakeholders together, increase flexibility and interoperability while bringing the industry together.

Going forward, the working group aims to release a data model for the specified information needs complementing the data standard of material accounting. Furthermore, more data handover steps will be covered to seamlessly accompany all process steps of the material flow from the dismantler to the Tier n user of the secondary material.

Additionally, more materials will to be covered in further versions of the whitepaper to ensure that the data model will support all real-life possibilities.

APPENDIX

1. Figures

2. References

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3. Further Reading Material and Regulations

Collection of further interesting reading material (apart from cited sources):

- ELVD Evaluation-Final report Aug2020-rev1.pdf (europa.eu)
- EU Strategy for sustainable and circular textiles

List of relevant regulations to be considered:

- End-of-Life Vehicle Directive (ELVD) – precursor to the new End-of-Life Vehicle Regulation
- New Eco Design For Sustainable Products Regulation (ESPR) + delegated acts)
- Critical Raw Materials Regulations
- New Critical Raw Materials Act (Proposal Stage)
- Persistent Organic Pollutants (POP) Regulation
- Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) Regulation
- Classification, Labelling and Packaging of substances and mixtures, amending and repealing (CLP) Regulation
- European List of Waste (LoW)
- Waste Framework Directive (WFD)
- New Waste Framework Directive (Proposal stage)
- Green Claims Directive

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