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Disassembling the Problem

A Frame Creation-Based Strategy for Human-Centered Automation in ELV Recycling

LINDA MARIA SESEKE

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Abstract

End-of-life vehicle recycling faces systemic obstacles: fragmented dismantling practices, economic pressures, and regulatory misalignments undermine circular material flows. Automation is often reduced to task substitution, yet its potential lies in serving as a coordination platform that integrates human expertise, technology, and institutional frameworks. This thesis applies Dorst's Frame Creation methodology, combining literature analysis with 27 expert interviews across dismantlers, recyclers, OEMs, suppliers, and regulators. The study identifies eight recurring themes—ranging from market barriers to information gaps—summarized in the overarching construct of "systemic coordination failure." Building on this diagnosis, the thesis develops strategic frames that reconceptualize automation as boundary infrastructure. Rather than replacing labor, robotic systems and human integration are positioned to align economic drivers, embodied work practices, and regulatory demands. The results demonstrate that scalable and sustainable vehicle disassembly requires automation embedded in broader coordination architectures, linking information, incentives, and human capabilities.

Keywords

Vehicle Disassembly, Automation Strategy, Human-Robot Collaboration, Recycling, Circular Economy, Automotive Industry, End-of-Life Vehicles, Disassembly

Sammanfattning

Återvinning av uttjänta fordon möter systemiska hinder: fragmenterade demonteringspraktiker, ekonomiska påfrestningar och regulatoriska missanpassningar undergräver cirkulära materialflöden. Automatisering reduceras ofta till uppgiftsersättning, men dess verkliga potential ligger i att fungera som en samordningsplattform som integrerar mänsklig expertis, teknik och institutionella ramverk. Denna avhandling tillämpar Dorsts Frame Creation-metodik och kombinerar litteraturanalys med 27 expertintervjuer med aktörer från demontering, återvinning, OEM:er, leverantörer och myndigheter. Studien identifierar åtta återkommande teman – från marknadshinder till informationsluckor – vilka sammanfattas i det övergripande begreppet ”systemiskt samordningsmisslyckande”. Utifrån denna diagnos utvecklar avhandlingen strategiska ramar som omtolkar automatisering som gränsinfrastruktur. I stället för att ersätta arbete positioneras robotsystem och mänsklig integration som medel för att samordna ekonomiska drivkrafter, kroppsligt förankrade arbetspraktiker och regulatoriska krav. Resultaten visar att skalbar och hållbar fordonsdemontering kräver automatisering som är inbäddad i bredare samordningsarkitekturer, där information, incitament och mänskliga förmågor kopplas samman.

Nyckelord

Fordonssdemontage, Automatiseringsstrategi, Människa-robot-samverkan, Återvinning, Cirkulär ekonomi, Fordonsindustri, End-of-Life-fordon (ELV), Demontering

Master Thesis

Disassembling the Problem

A Frame Creation-Based Strategy for Human-Centred Automation in ELV Recycling

Linda Maria Seseke

Thursday, October 9, 2025

“No sympathy for the devil; keep that in mind.
Buy the ticket, take the ride…
and if it occasionally gets a little heavier than what you had in mind, well…
maybe chalk it up to forced consciousness expansion:
Tune in, freak out, get beaten”

Hunter S. Thompson's, Fear and Loathing in Las Vegas.

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Then there are the constants from the years before all this began – the ones who witnessed every reinvention and tolerated every detour. Luise and Marlene, whose phone calls (and screenshots) have carried me through every stage of life since Würzburg, know the full story by heart. Jack Jack, my longest academic companion, whose postcards and dry humour made even the dullest days less dull. And finally, Julian, Lukas, Nam, Simon, Thilo, and Timo – for saying less but being there; for an endless list of eventful nights, half-philosophical and half-nonsensical conversations, dumb jokes, and good company; and for having a beer for everything and nothing.

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Disclaimer

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List of Abbreviations Used

- 3TG – Tin, Tantalum, Tungsten, and Gold (conflict minerals)
- ACP – Adaptive Coordination Platform
- ASR – Automotive Shredder Residue
- ATF – Authorized Treatment Facility
- BEV – Battery Electric Vehicle
- CE – Circular Economy
- ECU – Electronic Control Unit
- ELV – End-of-Life Vehicle
- ELV Directive – Directive 2000/53/EC on End-of-Life Vehicles
- EoL – End-of-Life
- ERP – Enterprise Resource Planning
- EV(s) – Electric Vehicle(s)
- GDP – Domestic Gross Product
- HRC – Human–Robot Collaboration
- OEM – Original Equipment Manufacturer
- PCB – Polychlorinated biphenyl
- PVC – Polyvinyl Chloride
- WEEE – Waste Electrical and Electronic Equipment

Note: A separate glossary has not been included. All abbreviations and technical terms are either introduced in the main text or clarified through footnotes to ensure contextual precision and avoid redundancy.

1 A System Under Pressure

The automotive end-of-life system in Europe is facing intensifying pressures from multiple directions. On the one hand, the number of battery electric vehicles (BEVs) reaching end-of-life (EoL) is steadily increasing [1]. On the other, these vehicles are becoming more complex to dismantle and recycle [2-6]. Lightweight composite materials, embedded electronics, and high-voltage batteries not only raise the environmental and economic stakes, but they also introduce major technical and organisational challenges. The irony is clear: the more valuable the materials inside vehicles become, the harder and costlier they are to recover.

Meanwhile, critical raw material access is becoming a geopolitical risk [7, 8]. The European Union's reliance on fragile supply chains and export-heavy economies undermines long-term strategic resilience. Yet a significant portion of end-of-life vehicles (ELVs) simply vanish from official treatment paths, especially through unregulated exports and informal reuse markets [9, 10]. Even when vehicles do enter the system, current processes are still largely geared toward basic metal recovery [11, 12], while high-value materials like rare earths, precious metals, and intact electronics are routinely lost along the way [13-15]. This problem is not new, but it is intensifying. Currently, manual dismantling—where recovery of high-purity fractions should ideally begin—remains the dominant approach [16, 17]. It is labour-intensive, inconsistent, and increasingly uneconomical in the face of rising wage costs in Europe. More critically, it is under-industrialised: most dismantling operations lack the infrastructure, automation, and digital capabilities needed to address the growing demand of recycling as well as the rising complexity of ELVs [13, 18].

At the same time, regulation is moving forward. A proposed revision [19] of the EU ELV Directive 2000/53/EC[1] [20] introduces ambitious new requirements: mandatory recycling quotas for plastics, traceability through digital product passports[2], disassembly guidance, and extended producer responsibility mechanisms[3]. Achieving these targets through outdated manual dismantling processes is, however, increasingly unrealistic. The message is clear: Europe expects more, both from its ELV recycling system and from the automotive industry in terms of scale, transparency, and technological maturity [21].

Therefore, the pressure to scale—to industrialise—is no longer optional. It is systemic. Meeting current and future political sustainable demands requires more than incremental improvements in machinery or sorting efficiency. It calls for coordinated action across industry actors, digital integration, and infrastructure tailored to the diverse and evolving nature of modern vehicles. It is time to address areas that have long been deprioritised.

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[1] From 2000. The directive was the first to set recovery and recycling targets for ELV materials, bans hazardous substances in new vehicles, and requires vehicle manufacturers to take back their vehicles at the EoL.

[2] Structured digital records that contain detailed information about a product's materials, components, origin, repairability, and recyclability. They are designed to improve transparency and traceability across the product's lifecycle.

[3] Policy tools which include responsibilities for collection, recycling, reuse, and safe disposal. It aims to shift the burden of waste management from public authorities to producers, incentivizing them to design more sustainable and easily recyclable products.

This comes at a moment when European car manufacturers are already navigating significant pressure, ranging from the challenges of electrification and evolving market expectations to structural adjustments such as factory closures and workforce reductions [22]. It is a demanding period for the industry. Yet, as in previous times of transformation, these pressures can also serve as catalysts. The question is not only how to adapt but also how to shape the path forward.

But where to start? Academic and industrial literature point toward a familiar direction: automation, digitalisation, and intelligent process design [23]. Just as Industry 4.0 reshaped the production [24, 25], a similar transformation is now planned to take place in reverse logistics. Robotic disassembly is increasingly seen as a key enabler for reconciling ecological responsibility with economic feasibility. The goal is clear: to maximise reuse and recyclability while minimising manual labour and operational variability [26, 27]. But is this a truly good goal?

To begin with, disassembly is not simply "assembly in reverse". While modern assembly processes grapple with increasing personalisation [28], they still benefit from standardisation and controlled environments. Disassembly, in contrast, typically lacks access to sufficient digital product documentation [29] such as CAD models[4], bills of materials, or even reliable service histories. It must cope with product variation, wear, corrosion, hidden damage, and undocumented repairs [30], collectively summarised under the challenge of uncertainty. While recent advances in AI and robotics offer promising tools to address these issues [31], major limitations remain. Robotic systems continue to struggle with the unpredictability and low-volume diversity typical of disassembly contexts.

At present, there are not even clear concepts as to what forms of robotic assistance are technically and economically viable. The question is whether and where automation can realistically provide value in the first place. Economic pressures place narrow boundaries around what kind of investment in automation is feasible. Systemic questions of scale, standardisation, and information flow therefore remain unresolved, leaving many proposals at the level of technical prototypes rather than industrial practice.

Against this backdrop, the debate on Human–Robot Collaboration (HRC) has gained traction. HRC systems seek to combine human contextual awareness and adaptability with robotic endurance and precision [32, 33]. But the way these systems are designed matters. Too often, humans are treated as reactive substitutes, brought in to compensate for what automation cannot (yet) handle. Rather than designing systems that thoughtfully integrate both human and machine strengths from the outset, many solutions default to full automation and then "patch in" people when problems arise. This reactive design approach is not only inefficient but also risks

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[4] Computer-Aided Design models are detailed digital representations of physical objects used in engineering and manufacturing. These 2D or 3D models provide precise information about a product’s geometry, structure, and components. Essential for design, simulation, and production planning.

sidelining human capabilities, assigning them unstructured or frustrating roles. This dynamic is not new and has been discussed in manufacturing literature [34-37].

As new disassembly systems are developed, there is an opportunity—and a responsibility—to think differently and design with a forward-looking, human-centric perspective from the outset. Waiting to consider the human factor until after the technical systems are in place leads to reactive design, retrofitting, and ultimately inefficiency. This shift in thinking aligns with the transition from Industry 4.0 to Industry 5.0 [34, 37-49]. While the former emphasised efficiency and automation, Industry 5.0 introduces a more holistic paradigm. As Yu et al. [23] and Khan et al. [50] argue, future ELV systems must integrate values such as resilience, inclusiveness, ethical responsibility, and purposeful human–robot collaboration by design, not by necessity. This means actively designing for human involvement through hybrid workspaces, intelligent task allocation, and meaningful roles that go beyond the limitations of current automation. But designing such systems is anything but trivial.

There are multiple methodological pathways to approach the challenge of allocating tasks in dismantling. A classical ergonomic approach begins by identifying the set of tasks involved and subsequently deciding which are more suitable for human workers and which for robotic systems [41]. Alternatively, virtual process simulations can be employed to model different configurations and compare them across criteria such as cost, ergonomics, and throughput (cf. [51]). These methods are valuable and have their place, particularly once concrete systems or pilot lines exist to be tested and optimised.

The difficulty, however, is that no fully automated vehicle dismantling system exists to date, nor is there a standardised process for such a system to follow, as each ELV constitutes a unique case. While dismantling facilities operate with structured routines and recognisable patterns, the variability across vehicles, components, and conditions continues to resist complete standardisation. Under these circumstances, the central challenge is not merely to determine which actor—human or machine—performs which task. Rather, it is to confront the broader trade-offs, anticipate possible future scenarios, and deliberately design for evolving roles and values within dismantling systems. This leads to the central research question of this thesis:

RQ1: *How can automated dismantling systems for battery electric end-of-life vehicles be designed to address technical complexity while enabling human-centred and economically viable strategies for recycling and material recovery?*

This question cannot be answered by prescribing best practices, because the field is still far from having the granularity required to define them. Nor can it be resolved by simply dividing tasks between humans and machines, since the technological, economic, and social conditions of dismantling remain unsettled. The challenge is about asking: *how can we move forward at all?* How can design paths be designed that are not only technically robust and economically sound but also socially responsible?

That is why I take a position through which I embrace dismantling as a truly complex problem in the sense of Dorst [52], characterised by uncertainty, competing rationalities, and evolving conditions. Rather than applying a linear method, the approach here is grounded in design abduction: a form of reasoning that begins not with known solutions, but with open questions and emerging observations. This abductive logic supports the creation of new perspectives, rather than just optimising existing ones. By emphasising framing, co-evolution, and iterative experimentation, this thesis aims to produce both theoretical insight and practical guidance—contributing to a shift from reactive patchwork to proactive system design in ELV dismantling, aligned with the broader transition from Industry 4.0 to Industry 5.0.

The remainder of this thesis is structured as follows. Chapter 2 develops the theoretical foundation, outlining the ELV recycling process, its systemic challenges, and the state of research on automation and human–robot collaboration. Chapter 3 presents the methodological rationale, detailing the abductive research design, frame creation approach, and expert interview strategy. Chapter 4 reports the thematic analysis, organising empirical insights into key systemic barriers and synthesising them into the concept of coordination failure. Building on this, Chapter 5 develops new frames and future scenarios for dismantling, with a particular focus on automation as part of an adaptive coordination platform. Finally, Chapter 6 discusses the implications of these findings for industry, policy, and research before concluding with reflections on the contribution of this work.

2 System Context and Theoretical Foundations

To understand the just-described problem deeply, I need to take a step back. To do this, this chapter explores the broader context that shapes the development of dismantling automation. It begins by examining the upstream dynamics of sustainable car manufacturing: material intensity, electrification trends, and the regulatory push toward circularity. Together, they define both the urgency and the complexity of improving ELV recycling. I then shift focus to the downstream end-of-life phase, tracing the current structure of ELV treatment in Europe. This includes a detailed examination of the key process steps as well as the critical blind spots that persist in recovery practices.

Note on Terminology and Accessibility

This thesis brings together a wide range of stakeholders and disciplines, including (but not limited to) recycling, robotics, manufacturing, design, economics, and policy. Because of this broad scope, terminology from various fields is used throughout. While terms may be familiar to domain experts, they may not be clear to all readers. In the spirit of inclusivity and interdisciplinary collaboration, all potentially unfamiliar or field-specific terms are briefly explained in footnotes.

2.1 Sustainable Car Manufacturing

The future of sustainable car manufacturing is both one of the major challenges and one of the key opportunities currently facing the mobility sector. Before diving deeper into this topic, it is worth briefly noting how the focus of this thesis is framed. Since this work is the result of a collaboration between a Swedish and a Dutch university, alongside a German automotive manufacturer, the overall perspective is European. As highlighted in a bibliometric analysis by Yu et al. [23], much of the research on ELV management and recycling is strongly influenced by region-specific regulatory and infrastructural contexts. While international examples exist [4, 53-57], the emphasis here remains on the European context. This regional focus is a natural limitation of the thesis.

Let’s start with a simple—albeit uncomfortable—truth: cars and sustainability are not inherently compatible. Modern societies are deeply dependent on individual mobility, but this reliance comes at a significant environmental cost. As Pritchard [58] points out, while car ownership has long symbolised freedom and autonomy, the growing reliance on private vehicles is fundamentally unsustainable.

A key issue lies in the immense resource demands of vehicle production. For example, a conventional vehicle typically contains carbon steel, cast iron, aluminium, copper, magnesium, glass, polymers, rubber, platinum, and composite materials[5] [59]. The automotive industry is responsible for a significant share of material consumption in the European Union: about 17% of all steel, 10% of all plastics, and around 40% of total aluminium use [60]. With over 1.6 billion vehicles on the road in January 2025 [61], the cumulative impact of material extraction and production has only grown. Yet, discussions around sustainable mobility continue to

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[5] Common examples include carbon fibre-reinforced plastics.

focus predominantly on tailpipe emissions[6], often neglecting the substantial upstream effects of vehicle manufacturing. These include biodiversity loss, water and soil pollution, and the depletion of finite natural resources [62]. To put this into perspective: the automotive sector is responsible for nearly 5% of all global industrial waste [63].

However, according to Tywuschik [64], the automotive industry showed limited commitment to environmental protection until the late 1980s, when regulatory pressure and public concern began driving attention to the full vehicle lifecycle. But despite this rising awareness, car ownership continues to grow. Dargay et al. [65] project that global vehicle stock will exceed 2 billion by 2030, with particularly rapid growth in China and other emerging markets.

In response, in 2000 the European Union introduced the ELV Directive 2000/53/EC [20], aimed at reducing environmental impacts by promoting the reuse, recycling, and recovery of vehicle components and marking a milestone in integrating environmental accountability into automotive production. The directive operationalised this ambition through binding quantitative targets, the restriction of hazardous substances, and the prohibition of the use of lead, mercury, cadmium, and hexavalent chromium above set concentration values in new vehicles. Beyond material goals, the Directive further introduced the principle of extended producer responsibility, obliging manufacturers to ensure that vehicles can be taken back at no cost to the last holder and to provide dismantling information to treatment facilities. Authorised Treatment Facilities were required to obtain permits, remove fluids and hazardous components in standardised depollution steps, and comply with technical operating conditions. Member States were tasked with monitoring compliance and reporting performance to the European Commission.

2.1.1 Material Complexity and Electrification

Faced with growing public and regulatory scrutiny, especially regarding tailpipe emissions, automakers have significantly invested in technologies aimed at improving vehicle consumption efficiency. By the early 2000s, vehicles had evolved substantially from their mid-20th-century predecessors, integrating new materials and advanced systems specifically designed to reduce emissions and enhance fuel efficiency. Iron has largely been replaced by aluminium alloys[7] in components such as cylinder heads, gearbox cases, body-in-white structures[8], and wheels [3, 66, 67]. These innovations offer clear environmental benefits: reducing vehicle weight can decrease fuel consumption. Specifically, a 100 kg weight reduction leads to approximately 0.2 litres per 100 km lower fuel consumption and a 10 g/km reduction[9] in CO_2 emissions [68]. According to Sakai et al. [4], the

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[6] Gases released from a vehicle's tailpipe, the final part of the exhaust system. These include pollutants such as CO_2, nitrogen oxides, hydrocarbons, and particulate matter.

[7] Aluminium is not typically used in its pure form for most applications due to its softness. It's almost always combined with other materials (copper, magnesium, silicon, or zinc).

[8] Vehicle's main structural frame, typically made of welded metal panels. Before painting and before installation of components like the engine, interior, or electronics.

[9] Reduction per vehicle is roughly equivalent to the annual carbon absorption of about 2% of a football field's worth of forest.

copper content per vehicle is expected to triple by 2030, and the demand for rare earths is projected to rise sixfold. In parallel with the growing use of metals and critical materials, lighter alternatives are also being explored wherever possible. Plastics now dominate vehicle interiors [69, 70], offering design flexibility and further weight savings.

One of the automotive industry's most profound transformations has been the shift toward electrification, driven notably by the Dieselgate scandal[10] of 2015 [71]. Various forms of electric vehicles (EVs) have since emerged, besides BEVs, also hybrids, plug-in hybrids, and fuel cell vehicles. BEVs, powered exclusively by electric motors, represent the largest segment and are thus the primary focus here due to their central role in future economic and technological developments. In 2023 alone, 2.4 million new EV registrations accounted for 22.7% of total car sales in Europe. Countries like Norway (85%), Sweden (39%), and Iceland (50%) lead this shift [72]. Further regulatory support includes the EU's binding commitment to halt the sale of new internal combustion engine vehicles by 2035 [73] and infrastructure enhancements, notably extensive charging [74].

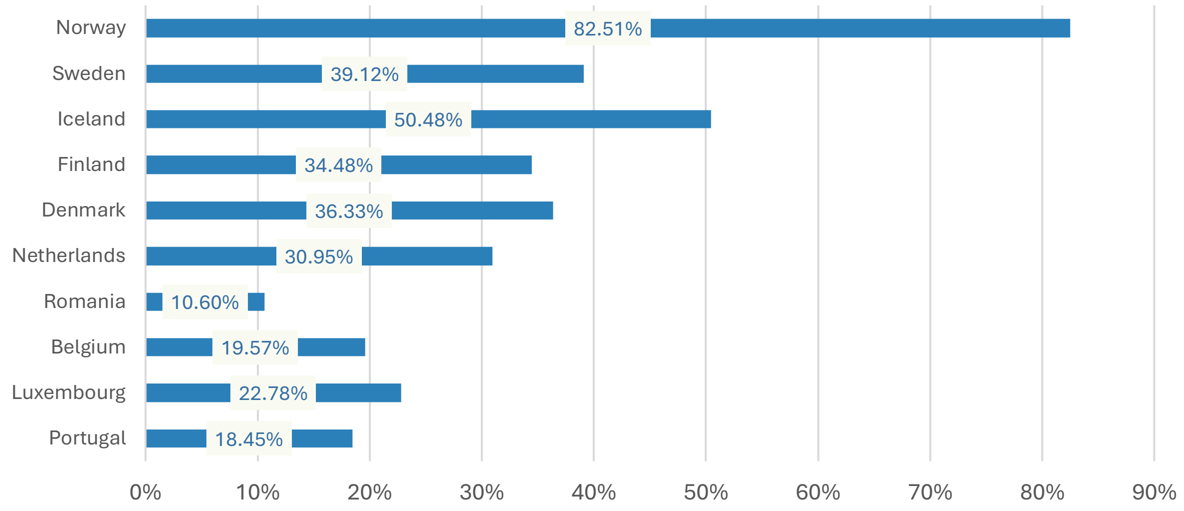

Figure 1. Percentage of newly registered battery electric cars by country. Only the top ten countries are displayed. Data is from the European Environment Agency [73]

But the question remains whether electrification alone is sufficient to ensure sustainable mobility. The short answer: not yet. While BEVs eliminate tailpipe emissions and improve energy efficiency, they introduce new environmental and geopolitical challenges. Excluding the discussion of the effects of the electricity mix[11] here [75], extracting critical battery materials—such as cobalt, lithium, and nickel—can severely harm ecosystems

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[10] Emissions fraud in which Volkswagen and other car manufacturers were found to have installed software in diesel vehicles that manipulated emissions tests. These "defeat devices" made cars appear cleaner during testing, while in real-world driving they emitted significantly higher levels of nitrogen oxides.

[11] Combination of energy sources used to generate electricity in a specific region or country. This can include fossil fuels, nuclear power, and renewable sources.

and communities, prompting regulations like EU Regulation 2023/1542 [76], which mandates carbon footprint disclosures and recycling content minimums for batteries [77]. Moreover, BEVs incorporate significantly more electronic and electrical components [15], including ECUs[12], microprocessors, and printed circuit boards, all requiring rare earth elements and precious metals [2, 10]. A typical modern vehicle contains between 15 and 48 electrical units, many challenging to disassemble and recycle efficiently [6]. This trend makes today's cars sound like a chemistry lab. According to Ortego et al. [2], a single passenger car may contain nearly 50 different metals and raw materials. These include 3TG[13], the "conflict minerals", as defined by U.S. law (Dodd–Frank Act, Section 1502) [78], and indium, niobium, neodymium and dysprosium. Other strategically important materials—like nickel, lithium, cobalt, terbium, antimony, bismuth and silver—are vital. Volkswagen currently identifies 18 priority raw materials as critical [79].

The geopolitical implications of critical raw materials further complicate this scenario. China dominates global rare earth production, accounting for approximately 98% of the EU's rare earth imports [7]. Furthermore, essential materials like cobalt, graphite, and lithium often originate from regions with poor governance and widespread corruption[14] which raises concerns about environmental justice, human rights, and supply chain security [8].

In conclusion, while BEVs significantly outperform internal combustion vehicles on several environmental metrics, substantial limitations remain regarding their weight, resource intensity, infrastructure requirements, and recyclability [5]. Electrification, thus, represents a critical step but not a complete solution. Achieving truly sustainable mobility demands a systemic transformation across the entire vehicle lifecycle, from responsible resource extraction and sustainable vehicle design to circular EoL strategies. Which leads us to the pressing question: What happens to a car when it reaches the end of its road? That, indeed, is the focus of the following sections, but before diving into ELV treatment processes, it is helpful to revisit the broader context of sustainability.

2.1.2 Framing Sustainability in ELV Management

Glavič and Lukman [80] offer a useful taxonomy of sustainability-related terms. Building on this, Lieder and Rashid [81] introduce the concept of the circular economy, which serves as a central theoretical lens in this research. As this discourse can be conceptually fuzzy, anchoring these definitions is crucial to ensure clarity throughout the analysis.

Recycling as a Foundational Recovery Strategy. *Recycling* is often the first strategy that comes to mind when discussing sustainability, and for good reason. It represents a foundational principle aimed at reducing the use

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[12] Electronic Control Unit.

[13] Tantalum, tin, tungsten and gold.

[14] Democratic Republic of Congo (cobalt), China (graphite), and parts of South America including Bolivia, Argentina, and Chile (lithium).

of hazardous substances, conserving natural resources, and minimising overall energy consumption [80]. In the context of ELVs, recycling refers to the process through which materials such as steel, aluminium, and plastics are recovered from vehicles and reintegrated into new production cycles (Figure 2). This understanding builds on the definition provided by the EU Waste Framework Directive [82], which emphasises that recycling does not entail preserving intact components but rather extracting raw materials that have been separated from their original structures.

At the same time, closely related terms exist: *recovery* and *regeneration*. As outlined by Glavič and Lukman [80], regeneration refers to restoring a material to its original form for reuse, often without altering its intrinsic properties. Recovery, by contrast, is a broader concept that includes various processes aimed at extracting value from waste, including combustion[15], pyrolysis[16], and anaerobic digestion[17]. In this hierarchy, recycling is classified as a subset of recovery rather than regeneration, mainly because it typically involves extensive transformation and can be energy-intensive. This is where one of the core challenges emerges: although recycling aims to retain material value, it often results in downcycling[18] [2, 85].

However, not all materials lend themselves equally well to recycling. Copper, for example, is particularly well-suited due to its ability—provided it remains sufficiently pure—to be recycled indefinitely without significant loss of quality [86]. This makes it especially valuable, given also its critical role in automotive wiring and electronics. Plastics, on the other hand, are far more challenging: they often consist of complex multi-layered composites or blends, may be contaminated with residues or coatings, and are frequently downcycled or incinerated[19] rather than truly recycled [87]. This poses a growing problem, particularly as plastics now dominate vehicle interiors [68].

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[15] Burning of materials in the presence of oxygen, converting them into heat, CO_2, water vapor, and ash.

[16] Breaking down of organic materials in the absence of oxygen, producing a mix of solid (char), liquid (oil), and gaseous products [83].

[17] Biological process in which microorganisms break down organic matter (such as food or agricultural waste) in the absence of oxygen, producing biogas (mainly methane and CO_2) and nutrient-rich digestate [84].

[18] Degradation of material quality during processing. The result is contamination and reduced purity, limiting the usability of the recycled output in high-performance applications.

[19] Burning waste materials at high temperatures in specially designed facilities to reduce their volume and sometimes recover energy (as in waste-to-energy plants). While incineration can divert waste from landfills, it typically leads to the complete destruction of material value and may generate air pollutants such as dioxins, heavy metals, and greenhouse gases.

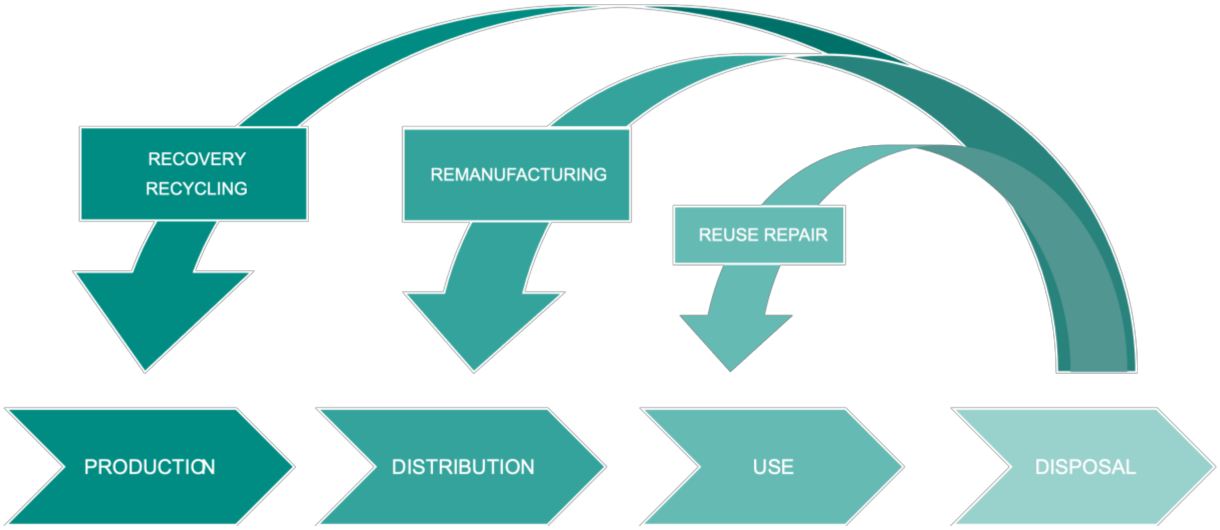

Figure 2. Circular Economy Concepts.

Reuse, Repair, and Remanufacturing. *Reuse* entails utilising discarded products or materials again without modifying their structure. *Repair* refers to interventions that extend the functional life of a product, delaying the need for replacement and reducing overall material throughput [80]. Within this family of approaches, *remanufacturing* holds a particularly important place. It involves the substantial rebuilding of products to restore them to a usable or near-new condition [85] (Figure 2). By this, remanufacturing prioritises the preservation of the product's integrity. For example, rather than melting down a damaged car door, a remanufacturing approach might involve repainting it, replacing fasteners, and reselling it. While recycling rather leads to downcycling, remanufacturing upcycles products to restore or surpass their original specifications, which adds value from an economical and an environmental perspective [85].

This leads to the question: are some strategies inherently better than others? According to Rose et al. [88], there is indeed a hierarchy of EoL strategies. Reuse, repair, and remanufacturing are generally more sustainable than recycling, which in turn is vastly preferable to disposal—the least favourable option. Although remanufacturing has a long-standing presence in the automotive sector [81], this thesis centres on recycling as the primary strategy, not because it is the most desirable, but because it is currently the most institutionalised and widely adopted approach, as highlighted by Ranta et al. [89]. Regulatory incentives[20], established business practices, and supply chain configurations strongly favour recycling, while reuse and repair continue to face cultural and systemic barriers. Nevertheless, referencing these related approaches is important for contextualising current practices and for informing the interpretation of the study's subsequent sections.

The Circular Economy as a Transformative Industrial Strategy. To effectively react to the current situation in the automotive industry and to implement the aforementioned sustainability strategies in industrial practice, the

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[20] Tax benefits, emissions credits, subsidies.

Circular Economy (CE) offers both a guiding framework and a strategic ambition, particularly relevant for companies like Volkswagen. As Lieder and Rashid [81] emphasise, industries face increasing pressure from resource scarcity, regulatory complexity, and volatile geopolitical supply chains. In this context, CE is more than a sustainability trend; it is a transformative strategy to strengthen resilience, resource independence, and long-term competitiveness.

At its core, the CE concept aims to establish closed-loop systems in which materials are continually cycled at high quality, waste is minimised, and environmental impact is reduced, without stifling innovation or profitability. The concept has evolved into incorporating business models that extend product life and shift away from ownership-based consumption. This shift is increasingly important in the mobility sector, where Mobility-as-a-Service is disrupting traditional ownership models. Consumers are moving toward shared, service-orientated usage patterns, which in turn demand vehicle designs that prioritise durability, reparability, and component reusability [26]. These changes create strategic opportunities for OEMs[21] to retain ownership over components and materials, enabling high-quality recycling and effective closed-loop production systems.

Crucially, as Lieder and Rashid [81] point out, CE implementation must align with economic incentives to gain industrial traction. Environmental benefits alone are not sufficient; circular practices must be profitable or at least strategically valuable. This alignment between economic and ecological objectives is also a central driver of this project, which explores how dismantling processes can be designed to be not only more sustainable but also industrially scalable and economically viable.

2.1.3 Europe’s ELVs: Deregistered, Then What?

After navigating the often-vague terrain of sustainability definitions, it is now time to examine what occurs when vehicles reach the end of their life in Europe. The focus on Europe is intentional: along with Japan, the region is one of the world’s largest producers of cars and also ELVs [4, 26, 90]. According to the European Environment Agency, a vehicle is considered an “ELV” when it qualifies as “waste” under Article 1(a) of Directive 75/442/EEC. Waste, in this legal context, refers to “*any substance or object that the holder disposes of, or is required to dispose of, according to national regulations*” [91]. In simpler terms, the vehicle is no longer usable, effectively "dead".

Each year, approximately 10 million vehicles are deregistered within the European Union [92], while around 6 million are officially disposed of through designated EoL treatment processes [1]. Vehicles reach this stage for a variety of reasons, including collisions, economic total losses, or increasingly stringent safety and emissions regulations. But the road does not end there. In fact, it often gets much bumpier.

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[21] Original Equipment Manufacturer. In the automotive industry, an OEM refers to car manufacturers such as Volkswagen, BMW, or Toyota, who produce vehicles and original spare parts.

If one takes a closer look at the presented data, a troubling gap becomes apparent. Theoretically, each deregistered vehicle should follow one of two legal pathways [90]: either it is processed by a certified recycling facility, or it is exported for further use. According to multiple sources, between 4 and 5 million vehicles each year in the European Union fall outside of these formal channels, classified as "missing". These "vehicles of unknown whereabouts" are deregistered but neither recycled nor exported nor traceably processed, effectively disappearing into informal or unregulated markets [90, 92]. Today, the deliberate detour most often leads south. The export without proper documentation of ageing, heavily polluting vehicles[22] to developing countries has serious environmental and public health consequences [93, 94]. This behaviour is not merely a statistical irregularity; it constitutes a systemic blind spot within the EU's circular economy framework. The European Commission has acknowledged the issue, proposing an export ban on ELVs [21]. However, the sheer persistence of this problem highlights how far Europe still is from treating ELV recycling as an industrial priority rather than a peripheral obligation.

2.2 Understanding the ELV Recycling Process

ELVs, together with Waste Electrical and Electronic Equipment (WEEE), constitute one of the largest sources of secondary raw materials in Europe's transition toward a CE [95]. When managed efficiently, ELVs are not simply waste but valuable reservoirs of secondary raw material. Recognising this potential, the European Union has enforced ambitious recycling and recovery targets through the ELV Directive [20]. Since 2015, the Directive mandates that 95% of a vehicle's weight must be reused or recovered, with a minimum of 85% being reused or recycled. The remaining 10% can consist of lower-priority recovery processes, such as energy recovery via incineration. Although incineration with heat capture is considered a form of recovery under the Directive, it ranks the lowest in the EU's waste hierarchy due to its limited contribution to true circularity.

2.2.1 From Deregistration to Residue

On paper, these targets appear ambitious; nevertheless, they are being achieved. In 2022, approximately 4.7 million ELVs were processed within the European Union. According to Eurostat [1], 94.4% of this volume was reused or recovered, and 89.1% was reused or recycled. How is this possible? Although the ELV recycling process follows a broadly similar structure worldwide, its practical implementation depends on national policy frameworks, infrastructure maturity, and market dynamics [4, 90]. In the EU, the ELV Directive has succeeded in somewhat standardizing this process across member states, establishing a five-step treatment path: formal *deregistration* and collection, *depollution* and *dismantling*, *shredding*, *post-shredder treatment*, and final material recovery or *disposal*. The steps are explained followingly and are sown in Figure 3.

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[22] Older diesel or petrol vehicles without modern emissions control technologies or with poor fuel efficiency. It also refers to vehicles that leak pollutants (oil, coolant, or brake fluids) into the environment due to degraded components.

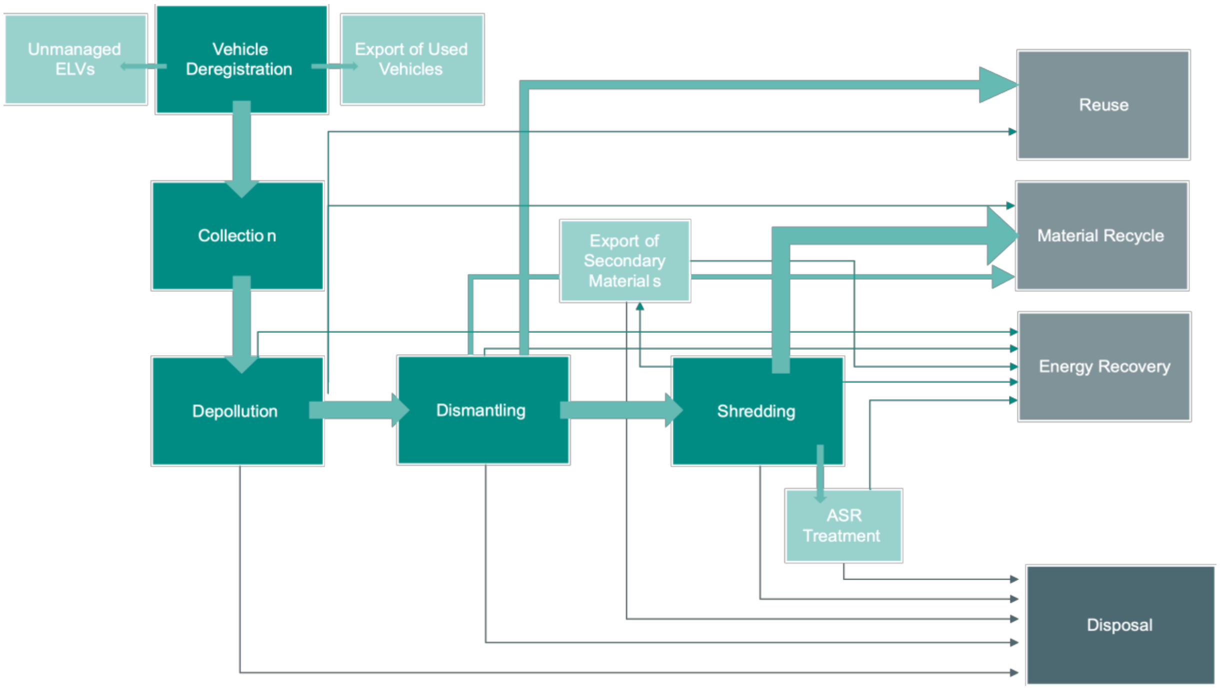

Figure 3. Overview of the ELV recycling steps.

Depollution and Dismantling. The journey begins with the formal deregistration of a vehicle, during which owners must deliver ELVs to authorised collection points—often car dealerships or repair garages—that collaborate with Authorised Treatment Facilities[23] (ATFs). Once accepted, these facilities issue a Certificate of Destruction[24], marking the vehicle's official exit from circulation [90]. Manufacturers are legally required to take back vehicles at no cost to the last owner, involving organisation between OEMs, dismantlers, recyclers, and public authorities in a multi-stakeholder enforcement effort; in addition, consumers must be informed about the recycling performance of new cars [2, 96]. While system-level improvements are often discussed in theory, practice tells a different story. In April 2025, the European Commission fined 15 major car manufacturers and the European Automobile Manufacturers' Association a total of €458 million for participating in a cartel that deliberately undermined the ELV recycling process. Over a span of 15 years, these companies coordinated efforts to avoid paying dismantlers for vehicle treatment and collectively withheld information about the recyclability of their products and the use of recycled materials in new vehicles [97].

Next comes depollution, where hazardous components are removed to prevent environmental damage and protect downstream processing; after all, no one wants an exploding airbag further down the line. Alongside airbags, this includes batteries, fuel tanks, oils, refrigerants, tyres, and electronic components [2, 4, 13]. The

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[23] Officially licensed sites where ELVs are legally processed in accordance with environmental regulations. These facilities operate under the ELV Directive and must meet strict requirements regarding material handling, component recovery, and record-keeping.

[24] Serves both as a legal proof of deregistration and as an environmental safeguard, ensuring that the vehicle will not be resold or reused improperly.

importance of this step is amplified in modern vehicles—especially BEVs—which firstly have a huge battery, which constitutes a dangerous good, and secondly, as discussed, contain more complex materials such as rare-earth magnets, lithium-based cells, and printed circuit boards [98]. Studies show that effective depollution significantly reduces environmental impact [50, 99, 100]. Yet in practice, depollution is often only partial. While economically valuable or hazardous, items like starter batteries and airbags are typically removed; others—such as hydraulic oils, brake fluids, or embedded electronics—may be left in place because of time and cost pressure [54, 101]. Depolluted materials typically account for just 3% of the vehicle's mass, with tyres alone making up about that share, and their disposal, often via landfilling, remains problematic [14].

Following depollution, the dismantling phase focuses on recovering reusable or high-value parts such as engines, catalytic converters[25], suspensions[26], electronics, and bumpers[27] [2, 13]. For the remanufacturing sector, dismantling is especially important. In 2014, starter batteries made up over 80% of reused components [90]. Electronics are often tested and sold as guaranteed second-hand parts via OEM or third-party networks [102]. Even beyond resale, dismantling plays a critical role in maximizing resource recovery before the car enters the shredder. The more that's removed up front, the less contamination downstream, and the higher the material quality of what's left. As Ferrão and Amaral [103] found, removing just 14% of a vehicle's mass—especially plastic components—can boost recycling rates above 80%, even for vehicles with lower steel content. Studies underline that pre-shredder separation is the only viable route to producing clean polymer fractions [14, 54, 102]. The challenge? These operations are only profitable if dismantlers have a steady, free supply of ELVs and if scrap prices are favourable [103].

Shredding and the ASR Dilemma. What now remains of the vehicle—commonly referred to as "hulk"—is sent to industrial shredders. This is a pivotal stage in ELV processing, marking the shift from manual, component-level handling to high-throughput bulk material fragmentation [2, 13]. Shredders crush and grind the vehicle together with other things like washing machines into small fragments, which are then mechanically separated into three main streams: ferrous metals (typically 65–75% of total mass), non-ferrous metals such as aluminium and copper (about 5–10%), and everything else; a heterogeneous mix collectively known as Automotive Shredder Residue (ASR) [4, 13, 14]. The recovered ferrous and non-ferrous metal mixes like Zorba[28] are typically sent to smelters and reintroduced into production cycles as secondary raw materials. The residual ASR, comprising approximately 20–25% of the vehicle's original mass, presents one of the most challenging

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[25] Emission control devices in the exhaust systems of internal combustion engine vehicles. It contains precious metals like platinum, palladium, and rhodium to catalyse chemical reactions that convert harmful exhaust gases—such as CO, NO_x, and unburned hydrocarbons—into less harmful substances like CO_2, N_2, and water vapor.

[26] Mechanical systems that connect the wheels to the chassis and manage the vehicle's ride quality. Relevant for recycling mainly for remanufacturing to be resold.

[27] Front or rear protective covering, designed to absorb minor impacts and reduce damage. Typically consist of a combination of plastic covers, energy-absorbing foam, and metal reinforcement bars. Relevant for large part plastic recycling.

[28] It generally includes aluminium, copper, zinc, brass, and stainless steel. The term is widely used in the scrap and recycling industry to denote a valuable yet heterogeneous material stream that often requires further refining [104].

issues in ELV recycling [13, 14]. ASR is a complex, often contaminated mixture of rubber, plastics, foams, textiles, glass, dirt, fibres, residual metals, and hazardous substances such as lead, zinc, mercury, PCBs[29], PVC[30], and chlorinated organics [12, 14]. It is typically classified as hazardous waste and poses both environmental and regulatory concerns. Despite its risks, ASR is still largely landfilled in the EU due to its heterogeneity, toxicity, and the technical difficulties of recovery [14, 90]. Automobiles are often presented as closed-loop products, but the reality of ASR undermines this narrative [15]. In contrast, Japan has implemented stricter regulations and more advanced treatment strategies, reducing ASR landfill rates to as little as 1–2% of total ELV mass [4].

To address the ASR challenge, three main strategies have emerged [103]. The first relies on improving *post-shredder technologies*, which aim to extract value from ASR after fragmentation. It employs advanced sorting technologies, including eddy current separators[31], air classifiers[32], magnetic separation, and density-based systems [2, 11]. However, technologies struggle with ASR's complexity, and substances like PVC pose serious problems; during thermal processing, they release corrosive and toxic emissions, damaging equipment and necessitating expensive flue gas treatment[33] [14]. Second, given ASR's high calorific value (15–30 MJ/kg), energy recovery has been proposed through methods like co-incineration[34], pyrolysis, and gasification[35], which can reduce ASR volume by up to 90% [14, 15]. Yet, emissions from flame retardants[36] and chlorinated plastics require advanced control, and residuals still often end up in landfills [12]. Moreover, the EU currently lacks commercial-scale, cost-effective thermal treatment facilities for ASR [15]. The third approach is *intensive dismantling*, which seeks to remove more plastics, electronics, and glass before shredding. This, however, remains labour-intensive and often economically unfeasible, especially in regions with rising labour costs and weak markets for recycled materials, such as Europe [4].

2.2.2 Research on Challenges and Trends

The described ELV recycling process is now well established as a multi-stage industrial system that, on paper, consistently meets the EU Directive's recovery and recycling targets. However, at a policy level, D'Adamo et al. [96] show that performance metrics across EU countries can be misleading due to the international flow of used

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[29] Polychlorinated Biphenyls. Group of synthetic organic chemicals that were historically used as additives in industrial materials like plastics, sealants, and insulation. Banned in many countries due to their toxicity and persistence [105].

[30] Polyvinyl Chloride. Common polymer used in wiring insulation, interior trims, and underbody coatings. While durable and versatile, PVC contains additives that can release toxic substances during incineration or improper recycling [106].

[31] To separate non-ferrous metals from mixed waste streams. using a rapidly rotating magnetic rotor to create "eddy currents" in conductive metals, which generates opposing magnetic fields that repel these metals away from the rest of the material.

[32] Use of a stream of air to separate light materials (foams, fibres, plastics) from heavier ones (glass, rubber, or metals) based on their aerodynamic properties (weight, shape, and density).

[33] Scrubbers, filters, and catalytic converters used to clean the exhaust gases (flue gases) released from industrial processes.

[34] Burning materials as a fuel substitute in industrial processes typically in cement kilns or power plants to recover energy.

[35] Conversion of carbon-rich materials into a synthetic gas by applying heat with a limited amount of oxygen or steam.

[36] Chemical substances added to slow the spread of fire or prevent ignition. Commonly used in wiring insulation, seats, dashboards, and electronic casings. They have raised concerns due to their persistence, bioaccumulation, and toxicity when released during improper disposal or thermal treatment [107, 108].

vehicles. Countries that appear to meet the targets may simply import ELVs from elsewhere. Arpino et al. [109] confirm that nations with GDP[37] per capita below €35,000 show better performance when regulation and infrastructure are strong. Conversely, in higher-GDP countries, frequent fleet renewal and exports distort actual recovery rates, highlighting the need for transparent, context-specific policy frameworks.

Recent events further underscore this point. In June 2025, the Catalan Waste Authority sanctioned several major OEMs for intentionally violating Spain's ELV recycling regulations. Over multiple years, these manufacturers failed to provide verifiable data on the traceability and treatment of ELVs, submitted only theoretical data points, and neglected to document disposal costs [110]. The case further exposes the systematic gaps in the enforcement of extended producer responsibility, even within established European markets, and raises broader questions about industry transparency and compliance practices.

Another crucial aspect is economic viability, and for this, material matters. Steel continues to anchor the economic viability of ELV recycling, accounting for up to 70% of a vehicle's mass and benefiting from established secondary markets and high environmental returns [11, 12, 111]. Aluminium, while lower in volume, contributes significantly to circularity due to its high recyclability and energy savings during reprocessing [9]. Copper also holds strong value, but only when it can be recovered in high purity [86]. The purity challenge is also directly related to the subject of hot shortness[38]. In contrast, plastics pose entirely different economic and technical challenges: their low market value, material diversity, and contamination issues often make them unprofitable to recycle [112]. Yet, as ASR treatment costs rise and raw material markets become more volatile, the economic model underpinning ELV recycling is becoming increasingly fragile [4]. Until today ELV recyclers remain tied to fluctuating scrap prices, while OEM participation is limited by cost pressures and weak enforcement of extended producer responsibility [11]. In unregulated or under-regulated regions, including the U.S. and parts of the Global South, traceability and investment in treatment infrastructure remain persistent bottlenecks [4].

Further, the ELV system's performance across stages remains uneven. Schmid et al. [113] highlight that depollution contributes less than 4% to recovery, dismantling between 5 and 10%, and the majority—67–70%—is achieved during shredding and post-shredder treatment. This imbalance has triggered growing interest in technological optimisation, as well as calls for system-level improvements targeting materials, processes, and policy. However, the academic treatment of the ELV system remains fragmented. Karagoz et al. [63], in their review of 232 ELV-related studies, found that most contributions focus on isolated challenges, often overlooking real-world industry dynamics, social behaviour, and systemic uncertainty.

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[37] Gross Domestic Product. Standard economic indicator that measures the total monetary value of all goods and services produced within a country's borders over a specific time period.

[38] Copper contamination in steel can degrade recyclate quality. Even in small amounts it can cause that steel becomes brittle and prone to cracking during hot working processes like rolling or forging. This occurs because copper does not alloy well with iron at high temperatures and instead segregates at grain boundaries, weakening the structure.

As outlined, technological advancements in the automotive sector are radically transforming EoL dynamics. However, comprehensive strategies for managing the increasing complexity of ELVs, particularly due to electrification and intelligent vehicle systems, remain largely underdeveloped [13]. Traditional shredding systems, originally optimised for the separation of ferrous metals and basic alloys[39], are proving increasingly inadequate in the face of modern, multi-material vehicle assemblies. These include advanced polymers, thermoset composites[40], embedded electronics, and sensor networks [14, 109]. As a result, the valuable and strategic materials are often lost in the process, either through downcycling or by becoming embedded in ASR [115, 116].

This issue is particularly critical in the case of automotive electronics. Despite containing high-value and hazardous substances such as gold or lead, these components are not classified as WEEE. This regulatory gap is striking, especially considering that many of these parts are functionally identical to those found in consumer electronics [98]. Many of these electronics also contain copper-rich wiring, which increases the risk of hot shortness when not properly separated. Ergo, without mandatory pre-shredding removal, such components contaminate the ASR stream and result in significant material losses. From a thermodynamic rarity[41] perspective, they represent nearly 27% of the system's total rarity-weighted value [2].

While for a long time overshadowed by downstream recovery technologies, dismantling is increasingly recognised as the stage where circularity can either begin—or fail. As researchers emphasise, ASR is not merely the result of inefficient post-shredder separation; it is also a consequence of insufficient or imprecise pre-shredding interventions, especially when valuable components such as electronics, plastics, and batteries are left intact [14, 15, 98].

Despite its centrality, dismantling remains under-represented in ELV research and policy. Tarrar et al. [17] identified persistent gaps between academic focus areas and the needs of practitioners, especially regarding battery and plastic handling, cognitive operator support, and systemic integration with emerging ownership models (e.g., leasing, car-sharing). In unregulated markets, dismantlers face a recurring dilemma: whether to continue operations or withdraw when scrap prices drop below profitability. This uncertainty—referred to as the *"dismantler's dilemma"*—disrupts material flows and creates volatility across downstream recycling and remanufacturing processes [11].

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[39] Aluminium, zinc, or magnesium.

[40] Materials made by reinforcing a thermosetting resin (such as epoxy, polyester, or phenolic) with fibres like glass, carbon, or aramid. Once cured, thermosets form a rigid, cross-linked structure that cannot be remelted or reshaped. These composites are valued for their strength, durability, and lightweight properties, but are difficult to recycle, as they do not soften with heat like thermoplastics [114].

[41] Intrinsic energy and material cost of extracting and refining a chemical element from the Earth's crust. It considers how dispersed or chemically bound an element is in nature, and how much energy is required to isolate it in a usable form. Elements with high thermodynamic rarity—such as rare earths, platinum, or cobalt—are not necessarily scarce in terms of quantity, but are difficult and resource-intensive to obtain, making their efficient use and recovery critical for sustainable technologies [2].

Dismantling's current limitations are well-documented: it remains tool-limited and lacks standardisation [17, 102]. Despite this, manual dismantling continues to dominate globally. It is labour-intensive, reliant on operator skill, and yields variable outcomes depending on tooling and technique. In most facilities, workers still rely on basic tools like screwdrivers, cutters, and ropes [16], which makes the process slow, inconsistent, and difficult to scale.

Yet dismantling offers economic advantages that downstream processes like shredding alone cannot replicate. Even when labour costs are higher, manual dismantling enables higher recovery yields, especially for delicate or mixed-material components that would be lost or degraded in shredding. Studies [2, 50, 96, 109] highlight that effective dismantling not only reduces landfill waste but also improves remanufacturing profitability and supports EU circular economy objectives. This is particularly evident in electronics recovery. Rosa and Terzi [13] compared two long-term strategies: a shredder-led model, where vehicles are minimally pre-treated and sent directly to shredding, and a dismantler-led model, where valuable parts and materials are removed before shredding. Over time, the dismantler-led approach yielded significantly better outcomes—€15 billion in cumulative profits, outperforming the shredder-led model by €2.5 billion—and aligned more closely with EU policy targets. However, this model also places greater demands on dismantlers, who must take on higher upfront investment, process complexity, and responsibility for material tracking and quality.

Nowhere is this more urgent than in battery recycling. The new EU Battery Regulation 2023/1542 [76] marks a turning point for dismantler obligations. Yet, a big part of literature continues to focus predominantly on post-dismantling processes—shredding, pyrometallurgy[42], or hydrometallurgy[43]—while overlooking the dismantler’s role at the entry point of this chain. Critical gaps remain in defining safe, efficient battery removal protocols and in integrating dismantlers as key actors within circular battery flows [18, 118]. Recent studies suggest that disassembling EV batteries to the cell level[44], although not yet industrially mainstream, can significantly improve recyclate purity and reduce downstream treatment complexity [18]. Yet the question remains: how far should dismantling go? While deeper disassembly allows better separation and higher-quality outputs, it also drives up costs. According to Choux et al. [18], the economic viability of such strategies is highly sensitive to material composition, throughput volume, and system design.

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[42] Use of high temperatures to melt or chemically reduce metal-containing materials. Common in smelting processes, it is effective for bulk recovery but is energy-intensive and can generate toxic emissions if not properly controlled [117].

[43] Use of aqueous chemical solutions (acids or leaching agents) to dissolve metals for later recovery through precipitation, solvent extraction, or electro-winning. It operates at lower temperatures than pyrometallurgy and allows for more selective recovery of metals but can involve hazardous chemicals and complex waste streams [117].

[44] An EV battery is typically structured in three hierarchical levels: pack, module, cell. The pack is the complete unit installed, containing all necessary enclosures, wiring, and thermal management systems. Inside the pack are several modules, which are intermediate building blocks that group together multiple battery cells for easier handling and safety. The cell is the smallest functional unit, where electrochemical energy is stored and discharged. Cells come in various formats (cylindrical, prismatic, pouch) and contain the critical active materials [119].

Projecting this challenge onto the whole vehicle, this is further intensified by evolving policy dynamics. In July 2023, the European Commission proposed a major revision of the ELV Directive [120], raising expectations for dismantling and material recovery. The revised directive aims to recover an additional 5.4 million tonnes of materials annually. Key measures include a requirement that at least 25% of the plastics used in new vehicles be recycled—with one-quarter sourced from ELVs—alongside mandatory standardised dismantling guidelines from OEMs and improved transparency and traceability throughout the recovery chain [120].

To summarise, real progress depends on more than new machines or better sorters. OEMs, dismantlers, regulators, and tech providers must work in sync. As Arpino et al. [109] argue, leveraging OEM dealer networks to capture and route ELVs efficiently could be one major boost. But without technical solutions for the disassembly bottleneck, even this coordination will fall short. This is where the literature begins to converge on a way forward. Robotic disassembly is emerging as a promising response to both economic and ecological demands [18].

2.3 Automation in Disassembly

As the integration of automation into disassembly processes becomes increasingly indispensable in modern EoL treatment strategies, it is essential to differentiate between traditional *dismantling* and *disassembly*. The former typically refers to a fast, often destructive process optimised for speed and cost-efficiency, primarily aimed at material recovery. The latter, in contrast, denotes a more systematic, reversible, and technically informed approach [26, 27]. Disassembly seeks to maximise the recovery of reusable and recyclable components while reducing manual labour and enhancing operational consistency. This thesis primarily concentrates on disassembly for *recycling* purposes, while also drawing on insights from *remanufacturing* research due to their conceptual overlap and shared technical challenges [121].

It is worth reiterating the fact that disassembly is not simply the inverse of assembly. While assembly systems grapple with pressures such as customisation, reconfiguration, and scaling demands [34, 122], they typically operate under highly standardised conditions with full access to digital product data. Disassembly, by contrast, confronts its core obstacle: uncertainty. Unlike assembly lines working with known products, disassembly facilities often process a wide variety of product types, generations, and unknown conditions. EoL items may exhibit corrosion, wear, prior repairs, or structural damage [123]. Additionally, permanent joining techniques—such as welds or adhesives—and unstructured working environments pose further complications [29]. Many products are still designed only with assembly, and not disassembly, in mind, which amplifies these barriers [30]. The absence of embedded product identifiers like RFID tags[45] or digital product passports further limits automated systems' ability to identify and assess components in advance [124]. These challenges are not confined to the automotive sector but are widespread across other industries where EoL treatment is relevant,

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[45] Radio-Frequency Identification tags. Small electronic devices used to store and wirelessly transmit data using radio waves

such as electronics (e.g., smartphones and laptops with glued components) [125], household appliances (e.g., washing machines with mixed-material casings) [126], and even wind turbines or aircraft [127].

Nonetheless, the disassembly field has not remained stagnant. It has actively responded to the momentum of Industry 4.0, a paradigm defined by the convergence of technologies such as the Internet of Things, cloud computing, data analytics, and cyber-physical systems [24]. Smart manufacturing stands at the core of this transformation, promising new capabilities for real-time data gathering, system integration, and process adaptation [24]. These developments are now increasingly reflected in disassembly automation.

2.3.1 Focus Areas in Automated ELV Disassembly

A review of the literature reveals that research on automation in ELV disassembly is heavily concentrated on EVs [30, 51, 77, 128-144], with particular emphasis on high-value, high-risk components such as lithium-ion batteries [119, 130, 139, 145, 146], electric motors [51, 128, 129, 147], and ECUs [95, 148-150]. Among these, EV battery systems dominate the discourse due to their strategic material relevance, complex structure, and safety-critical nature[46] [151]. Battery disassembly automation aims to minimise human risk exposure and reduce processing costs by leveraging technologies such as robotic manipulators[47], machine vision[48], and AI-driven control systems [77, 130].

The urgency surrounding battery recycling is further underscored by macroeconomic and environmental projections. For instance, the local recycling of lithium-ion batteries is expected to eliminate the need for up to twelve new lithium mines by 2040, potentially reducing sector-related CO_2 emissions by as much as 20% [152]. This prioritisation of batteries and electronics reflects not only their environmental and strategic value but also the relatively high level of technological readiness in these domains. A portion of the literature draws on prior research in WEEE disassembly [31, 153], which has historically been more conducive to automation, probably due to the smaller scale and uniformity of WEEE products. In contrast, ELVs are structurally complex, dimensionally large, and highly variable, factors that most likely have constrained experimental work and technological uptake in this field. At this point, it is clearly emphasised that there is currently no known study that presents a comprehensive, fully automated ELV dismantling system, pointing to a significant research gap.

Within the domain of ELV automation, the literature identifies several recurring technology clusters. A foundational component is the use of robotic systems—primarily industrial robotic arms from manufacturers such as KUKA [51, 154, 155], FANUC [145], and Universal Robots [147]—equipped with purpose-built end-

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[46] EV battery systems store and manage large amounts of electrical energy, often under high voltage. If damaged, improperly handled, or subjected to faulty conditions, they can pose thermal runaway (one cell overheating triggers neighbouring cells to heat up and fail in a chain reaction difficult to stop), fire, or explosion.

[47] Mechanical “arms” to perform tasks such as grasping, moving, rotating, or assembling objects. They typically consist of multiple joints and actuators that mimic the movements of a human arm and can be programmed or sensor-guided.

[48] Use of cameras, sensors, and image-processing algorithms to enable machines to "see" and interpret visual information for e.g. object recognition, quality inspection, position detection, or guiding robotic manipulators.

effectors like electric screwdrivers, cutters, or grippers for tasks involving engines, gearboxes, or battery modules.

Beyond hardware, sensor technologies and perception systems play a vital role. These include machine vision for object recognition and localisation [132, 156, 157], force and torque sensors[49] for safe interaction [158, 159], and inertial measurement units[50] [160]. Meanwhile, AI-driven software components are increasingly applied to support adaptive task planning, anomaly detection, and failure recovery [123]. Emerging tools such as digital twins[51] and augmented reality systems add further capabilities, facilitating remote supervision, interactive training, and real-time decision support in complex disassembly environments [119, 143]. For the purposes of this thesis, which focuses specifically on collaborative robotic disassembly, only studies explicitly involving human–robot interaction were selected for detailed analysis.

Despite this technological progress, many limitations remain. Specific sub-tasks—such as wire harness[52] removal or the detachment of connectors[53]—are still difficult to automate reliably [77] and limited integration with digital product data or traceability tools continues to constrain the responsiveness and intelligence of automated systems. A more fundamental constraint lies in the products themselves. Unlike modular consumer goods, vehicles are not designed with disassembly in mind. In many cases, they are explicitly designed *not* to be taken apart. Mechanical joints are optimized for strength and durability rather than separability. Even as automotive lifespans are becoming shorter [161], design-for-disassembly principles remain the exception rather than the rule. In some cases, the resistance to disassembly is not an oversight; it is an intentional outcome, driven by safety, durability, or cost considerations.

Given the limits of current automation, full robotic disassembly of ELVs remains an aspirational goal rather than an immediate reality. The unpredictable, variable, and often undocumented conditions of EoL products make it exceptionally difficult to design closed-loop, fully automated systems that can operate without human oversight or intervention. Human–Robot Collaboration offers a pragmatic alternative, but this is easier said than done.

2.3.2 The Role of Human–Robot Collaboration

Industrial robots have traditionally been built for speed, strength, and precision; designed to operate in isolated zones, performing repetitive tasks with minimal human interference. For decades, the dominant logic in

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[49] Devices that measure mechanical load and rotational force enabling machines to detect how much pressure they are applying, allowing for controlled movements, delicate handling, and real-time feedback.

[50] Measures a device's motion and orientation used for navigation, stabilisation, and motion control, using accelerometers, gyroscopes, and sometimes magnetometers.

[51] Virtual representations of physical systems, such as machines, components, or entire production lines. They are dynamically linked to their real-world counterparts via sensors and data streams, enabling real-time monitoring, simulation, and predictive analysis.

[52] Bundled electrical wiring systems that connect and power various components. Wire harnesses are routed throughout the vehicle body and often secured with clips, fasteners, or adhesives. Their removal is challenging and labour-intensive due to their complex routing, fragility, and integration with multiple electronic systems.

[53] Electrical plugs and sockets that link vehicle components. They are often small, tightly fitted, and secured with clips, locks, or seals to ensure durability. Automated detachment is challenging because it requires precise force and positioning.

automation emphasised performance above all, with interaction limited to safety-focused protocols aimed at preventing human injury [162, 163]. However, contemporary systems increasingly prioritise collaboration over isolation. This shift has been driven by growing demand for flexibility, customisation, and the ability to handle complex or unpredictable tasks, areas where human adaptability complements robotic precision.

Collaborative robots—commonly referred to as *cobots*—are designed to share workspaces with humans and respond to their cues [164]. The forms of interaction between humans and robots vary widely. In some configurations, robots remain physically separated, activated by human input but operating independently [162]. In more integrated scenarios, humans and robots work side by side, sharing tasks and sometimes even physical contact, which Weber and Stowasser [165] classify as true collaboration. Such proximity raises critical design challenges. Collaborative work environments require sophisticated control systems, adaptive speed regulation, and robust safety mechanisms [166].

But beyond technical safeguards, the quality of collaboration hinges on psychological factors. Working alongside an autonomous or semi-autonomous system can be cognitively and emotionally demanding. Workers may struggle with uncertainty, particularly if the system behaves in unpredictable ways or lacks transparency. Intuitive interfaces, clear feedback, and predictable behaviour are essential to establish user confidence [167]. Yet those aspects are not only shaped by the robot's performance; they are also deeply affected by the surrounding environment. Industrial settings often include external stressors such as noise, time pressure, surveillance, and managerial oversight, all of which influence how users perceive and engage with robotic systems [168]. Many workers are introduced to collaborative systems with minimal training, which can increase cognitive load, cause frustration, or even provoke fear and resistance [169, 170]. Designing for successful collaboration must therefore take these human factors into account. The physical and social presence of robots also shapes user interaction [171-174]. Despite this, much of the current trust research still relies on anthropomorphic[54] design principles. These frameworks, while useful, risk limiting innovation and generalisability. Critics have increasingly pointed out the shortcomings, arguing that they often fail to address the deeper, contextual dynamics of collaborative interaction [175, 176].

Ultimately, the goal of robots should not be to replace human labour but to support it, taking over repetitive or physically strenuous tasks so that human workers can focus on higher-order decision-making and complex problem-solving [170]. For this division of labour to be effective, systems must be designed not only for function but also for *trustworthiness*. This includes behavioural transparency, responsive adaptation, and environmental support conditions such as low stress and high situational awareness [131, 177, 178]. The ideal configuration? A collaborative setup in which humans and robots truly complement one another, each performing the roles they are best suited for. It is within this design space that I situate my investigation: exploring HRC not as a

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[54] Attribution of human-like characteristics, form, or behaviour to non-human entities. An anthropomorphic robot is one that resembles the human body or mimics human actions, e.g., with arms, hands, or facial features.

stopgap for automation, but as a strategically viable, human-centred approach to tackling complex disassembly processes. This hybrid approach is particularly valuable in disassembly tasks, where component conditions and joint types vary unpredictably [121]. This necessitates investment in technologies that can enhance interaction quality, such as skill acquisition interfaces, adaptive control, and shared workspaces [30, 121, 179].

2.3.3 State-of-the-Art of HRC in Disassembly Systems

The integration of HRC in disassembly systems is usually described as combining human flexibility and decision-making with robotic precision, repeatability, and strength, named human-robot collaborative disassembly [30, 33, 48, 180-182], where robots undertake repetitive or hazardous tasks, while humans perform complex decision-based operations. These systems often operate under semi-autonomous or asynchronous parallel frameworks to balance safety, flexibility, and efficiency [151]. Some systems use shared workspaces [159] with real-time co-presence. A wide range of interaction mechanisms is employed, including machine learning methodologies [183] and advanced control strategies like skill-based programming[55] [155], sensor-integrated systems, augmented reality, and virtual reality for planning and training [34], and impedance control[56] [186] for physical safety.

Disassembly Strategies. The literature reveals a wide range of disassembly strategies developed to address the complexity of ELV products. These strategies are broadly categorised along two key dimensions: complete vs. partial disassembly [187] and destructive vs. non-destructive disassembly [30]. Most studies adopt partial disassembly, e.g., [132, 140, 158, 159], targeting high-value or high-risk components such as battery modules, electric motors, or fasteners. Complete disassembly is less common and usually confined to controlled environments or remanufacturing contexts, typically focusing on specific subsystems [51, 188]. Some hybrid approaches dynamically shift between full and partial disassembly depending on component condition and recovery objectives [189]. There is a strong emphasis on non-destructive disassembly [30, 145, 160] [180] [190], particularly for components intended for reuse or second-life applications. However, this approach is often constrained by product designs that prioritise assembly efficiency, using permanent joining methods. These methods hinder non-destructive separation and frequently necessitate destructive disassembly, which limits component recovery potential [30, 77]. Occasionally, semi-destructive methods are employed for components with snap-fits or sealed joints, where clean separation is not feasible [124].

Process Structure. Disassembly can follow a sequential or parallel approach. Sequential disassembly—where components are removed in a predefined, step-by-step order—remains the dominant methodology, especially

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[55] Approach to robot programming where complex tasks are built from a library of modular, reusable “skills”—each representing a basic capability such as grasping. Rather than writing low-level code, users (including non-experts) can combine and sequence these predefined skills to create more advanced workflows [184].

[56] Robotic control strategy that regulates the dynamic relationship between force and motion, allowing a robot to respond flexibly and compliantly when interacting with its environment. Instead of strictly following a position, the robot behaves like a virtual spring-damper system, adapting its movement based on external forces (e.g., from a human or object) [185].

for structured assemblies like EV battery packs (e.g., pack → module → cell) [134, 145, 190]. Parallel disassembly, involving concurrent tasks, is used to enhance efficiency, particularly in systems utilising multi-agent robots or distributed workstations [159, 187, 191, 192]. Hybrid models combining both approaches are gaining interest, especially in HRC and adaptive workstation designs [144, 193-195].

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According to Jacob et al. [179], a structured disassembly process generally includes the following stages:

1. **Product Acquisition and Condition Assessment**
   Evaluates degradation and informs disassembly decisions.

2. **Product Representation and Classification**
   Uses disassembly matrices[57], AND/OR graphs[58], or vision systems to map component structures.

3. **Disassembly Sequence Planning**
   Optimises task order for efficiency, safety, and environmental performance.

4. **Task Allocation**
   Distributes tasks between humans and robots based on skill, complexity, and ergonomics.

5. **Adaptation to Variability**
   Employs flexible strategies to manage diverse configurations and component conditions.

While the first two stages are foundational for object recognition and classification, HRC research primarily focuses on sequence planning, task allocation, and adaptation. In this context, sequence planning remains a research priority [196]. Several algorithmic approaches are used to optimise disassembly paths. These include evolutionary algorithms[59] like block-based genetic algorithms[60] [197] and swarm-based methods[61] like the Bees Algorithm [181, 198, 199]. Regarding task allocation, techniques such as particle swarm optimisation and hybrid Q-learning[62] have been applied to optimise task sequencing, motion planning, and real-time distribution of work [180]. Fuzzy logic[63] [182] and graph theory are also used to improve sequence optimisation and quality [200]. As Hjorth and Chrysostomou [30] note, disassembly requires more sophisticated modelling and optimisation strategies than assembly.

While the technical literature offers a wide array of planning strategies, algorithmic methods, and performance metrics, these contributions largely remain fragmented and domain-specific. Standardised approaches to collaborative disassembly—especially those balancing technical feasibility with human-in-the-loop complexity—are still rare. Nonetheless, reported benefits across studies suggest significant potential: modular and repeatable tasks have shown cycle time reductions[64] of up to 70% [30, 132, 159], while precision handling

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[57] Structured representation that maps the relationships between components and the actions needed to remove them, helping identify feasible sequences and dependencies.

[58] Visual modelling tool used to represent alternative paths or decision branches in a disassembly process—indicating which parts must be removed together (AND) or can be removed independently (OR).

[59] Optimization methods inspired by natural selection processes, used to iteratively improve solutions.

[60] A type of evolutionary algorithm that mimics biological evolution through selection, crossover, and mutation of candidate solutions.

[61] Group of optimization algorithms inspired by the collective behaviour of decentralized, self-organizing systems in nature—such as flocks of birds, schools of fish, or colonies of ants and bees.

[62] A reinforcement learning approach where the system learns optimal actions by interacting with its environment, often combined with other methods for improved adaptability.

[63] A decision-making approach that allows reasoning with degrees of uncertainty, rather than binary true/false logic.

[64] Time it takes to complete one full operational cycle of a task. In manufacturing and recycling, reducing cycle time improves throughput and cost-effectiveness. In most cases, the main reason why parts are not removed is because it would simply be too expensive. Faster cycle times enable the economic viability of robotic systems compared to manual labour.

[136] by robotic systems contributes to improved recovery rates and reduced component damage [119]. Ergonomic advantages for human workers are also cited [201, 202], particularly in shared workspaces designed to minimise strain. Moreover, the integration of real-time adaptation into disassembly sequence planning has demonstrated notable gains in both energy efficiency and cost-effectiveness [51, 194]. What emerges, then, is a shared recognition of viewing disassembly not as a linear technical sequence but as a collaborative process shaped by both material and human factors, a view that guides the direction of this project.

2.4 Challenges and Gaps in Disassembly Automation Research

Despite increasing interest in recent years, research into disassembly automation continues to leave several critical questions unanswered. To begin with, there is surprisingly little engagement with the environmental implications of automated ELV treatment—an ironic omission, given the field's frequent association with sustainability. The logistics required to scale or restructure disassembly systems can carry significant ecological consequences, particularly when automation alters transport flows, facility requirements, or recovery priorities. Yet these systemic effects remain largely absent from current assessments [63].

A second issue concerns the limited scope of most automation research. As one can see, the overwhelming majority of studies focus on high-value, high-risk components—especially lithium-ion batteries and electronic control units—while neglecting the broader material composition of ELVs. Components such as tyres, engines, glass, plastics, and fluids are often left unaddressed, despite their centrality to recovery efficiency and material purity. What is still missing is a genuinely full-vehicle perspective, one that reflects how disassembly actually unfolds in practice. Such a shift could reduce dependence on downstream shredding, enable more intelligent material separation, and create more viable deployment scenarios for robotics and AI beyond isolated modules.

A related blind spot is the lack of insight into real-world implementation. While HRC has become a popular topic in academic contexts, there is still little documentation of how these systems are—or could be—used at industrial-scale ELV dismantling. The few existing case studies tend to focus on already modularised components and rarely provide detail on actual operator practices, integration constraints, or deployment outcomes. To be more precise, there is a wealth of research analysing isolated, small-scale tasks—such as specific steps in battery dismantling or material separation—but little attention is paid to how such research transitions into actual systems. Questions around how to begin implementation, how to adapt to heterogeneous input conditions, and how to orchestrate the shift from today's manual-dominated operations to a more automated, hybrid setup are largely left unaddressed. The link to operational reality and the analysis of such a system in its entirety—accounting for uncertainty, logistical realities, and evolving roles of human workers—is still missing from the academic discourse. In short, it remains unclear how automation in disassembly even begins to scale in most contexts.

Another recurring challenge is how uncertainty is handled. Although variability in product conditions is widely acknowledged in theory, it is often operationalised in highly simplified terms, usually to serve the needs of a tightly scoped experiment or optimisation model. While this is understandable from a research perspective, such simplifications make it difficult to translate technical findings into usable strategies for real-world environments. Many studies present promising robotic demonstrations or algorithmic frameworks but stop short of addressing how these systems could adapt to damaged components, undocumented configurations, or inconsistent material states.

Even when HRC is proposed as a solution to flexibility and safety challenges, its implementation often lacks depth. Real-world factors—such as user training, safety validation, and day-to-day integration into human workflows—are frequently sidelined. Many collaborative systems operate more in name than in function, featuring spatial proximity without shared decision-making or meaningful interaction [30, 121]. Robust strategies for actual cooperation under dynamic conditions are still underdeveloped. Beyond this, disassembly continues to be treated as a stand-alone technical operation, rather than as part of a broader circularity strategy. There is limited attention to upstream design constraints or downstream reuse pathways, and even less to the organisational and logistical systems that must support them. Workforce capabilities, cross-facility coordination, and data integration are often treated as externalities, despite being key to determining whether automation adds value or friction [203].

Social acceptance and human-centred design remain another underexplored frontier. Very few studies systematically include the workers who are expected to interact with these systems. The emphasis continues to rest on technical feasibility, not on what is actually acceptable, meaningful, or beneficial from a human perspective [37, 121]. Ethical considerations—such as preserving operator autonomy, minimizing stress, or building trust into the interaction—are often reduced to compliance checklists, than treated as design priorities. As Di Pasquale et al. [41] argue, frameworks that support socially robust, user-informed HRC are still largely missing. Finally, an emerging concern involves power dynamics. As robotic systems gain more autonomy in task planning and execution, there is a growing risk that human roles will become subordinated to machine constraints. Instead of collaboration, the system risks drifting toward quiet automation dominance where humans are simply expected to accommodate robotic behaviour. In the context of Industry 5.0, where cooperation and human agency[65] are supposed to be foundational, this raises uncomfortable questions about control, decision authority, and the distribution of cognitive and physical work [37].

Together, these challenges suggest a deeper misalignment between the current research focus in disassembly automation and the practical, systemic needs of sustainable ELV management. What is missing is not just more

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[65] Capacity of individuals to make choices, take actions, and influence outcomes within a given system or context. Maintaining human agency means ensuring that people retain control, decision-making power, and the ability to intervene or adapt processes rather than becoming passive operators or merely following machine-led workflows.

technical refinement but a shift in research framing: one that integrates the full vehicle, embraces real-world collaboration, and elevates human and ethical considerations to the same level as engineering metrics.

It is precisely against this backdrop that my research is situated. Rather than asking only *what* can be automated, my focus lies on *how* automation can be meaningfully embedded within the dismantling system—technically, economically, and socially. This requires reframing the research problem from a purely technical optimisation exercise to a broader exploration of systemic conditions, organisational dynamics, and human-centred strategies. From this perspective, the guiding research question is:

RQ1: *How can automated dismantling systems for battery electric end-of-life vehicles be designed to address technical complexity while enabling human-centred and economically viable strategies for recycling and material recovery?*

The next chapter outlines the methodological strategy I adopted to explore this question.

3 Research Method

I followed a dual-track research design inspired by Tarrar et al. [17] and based on the concept of Frame Creation [204]. I combined qualitative, field-orientated research, centred on semi-structured expert interviews, with analytical literature research, used to identify transferable concepts and models from adjacent academic fields. Together, these two tracks enabled an iterative process of problem exploration and reframing, culminating in the development of a new strategic frame for automation in ELV dismantling. The rationale behind this design was to surface systemic challenges from within the field and explore how existing knowledge from adjacent disciplines might offer alternative entry points or solution patterns.

Note:

An earlier version of the research plan proposed a more technical route, focusing on detailed process mapping, data modelling, and simulation in cooperation with Volkswagen's internal R&D[66] units. However, due to confidentiality restrictions, limited access to live system data, and the timing of ongoing development cycles, this approach proved unfeasible. In response, the research design was strategically adapted to ensure analytical depth and practical relevance while preserving methodological openness.

3.1 Methodological Rationale

At present, much of the academic and industrial discourse on ELV dismantling points toward the question of *what* should or could be automated. However, as the previous chapter has shown, this question is anything but straightforward. Karagoz et al. [63] offer a comprehensive overview of how ELV-related research has been structured so far. Most studies fall into four major categories: literature reviews, recycling and production planning, network design, and regulatory analysis. In terms of methodology, there is a clear preference for tools drawn from operations research and systems optimisation, ranging from artificial neural networks and genetic algorithms to AHP[67], DEMATEL[68], and material flow models[69]. These methods are undoubtedly effective when applied to well-defined, stable, and primarily technical problems. But—as I described it here—ELV recycling breaks that mould.

For this, I draw on the conceptualisation of "truly complex" problems, characterised as being open, complex, dynamic, and networked [204]. As discussed in practice, dismantling processes are marked by high variability and uncertainty. Further, stakeholders operate within very different frames of reference. Accordingly, Karagoz et al. [63] highlight that issues such as social acceptance, uncertainty, risk sensitivity, and the realities of

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[66] Research and Development.

[67] Analytic Hierarchy Process. Structured decision-making method that breaks down complex problems into a hierarchy of criteria and alternatives, allowing users to assign weights and compare options based on pairwise comparisons [205].

[68] Decision-Making Trial and Evaluation Laboratory. Method used to visualize and analyse cause-effect relationships among complex factors, often applied to identify key drivers and feedback loops in system-level problems [206].

[69] Analytical tools that track the movement and transformation of materials through a system, often used in recycling and resource management to assess input-output balances, losses, and recovery potentials [57].

industry practice remain significantly under-represented in current ELV research. This is not a coincidence. As Dorst [204] explains, most conventional problem-solving methods were developed for what he calls a “miniworld”: a stable, hierarchical system in which problems can be isolated, broken into subproblems, and solved analytically. But ELV dismantling is not a miniworld; in fact, it can rather be described as a huge ecosystem. But what to do when conventional strategies no longer help to move forward? As Dorst [207] writes: *“In a truly complex situation, there is no solution—the way to achieve progress is to create high-quality interventions to bring the whole system forward into a more desired state.”* This insight fundamentally reshapes how one can approach automation in dismantling. Rather than seeking an optimised endpoint—or treating dismantling simply as a technical problem to be solved—it requires us to adopt a more integrated, exploratory perspective. In order to start somewhere, one should look again at the problem itself, as Dorst [204] suggests that the core of such “hard” problems is often a paradox: not a contradiction in logic, but a collision of multiple, valid perspectives that cannot be resolved through compromise or optimisation alone. In real-world dismantling, these paradoxes are made even more difficult by the clash of what Bucciarelli [208] calls *object worlds*—the different institutional and disciplinary rationalities that shape how stakeholders interpret and act within the system.

3.2 Frame Creation Process Model

Frame Creation introduces a structured process that supports the development of new frames: new ways of seeing and structuring a situation. A frame links three interdependent components: (1) a desired value or outcome, (2) a pattern of relationships that define the system’s logic, and a (3) set of possible elements or interventions that may operate within that system [204]. The process to achieve this unfolds through nine iterative stages [52, 204], starting with the exploration of a problem’s historical evolution and moving through the identification of paradoxes, contextual mapping, frame development, future projections, and finally the formulation of integration strategies:

1. **Archaeology** – Tracing the history and evolution of the problem framing.
2. **Paradox** – Identifying conflicting goals, constraints, and assumptions.
3. **Context** – Mapping immediate stakeholders and their practices.
4. **Field** – Exploring the broader societal, regulatory, and technological landscape.
5. **Themes** – Uncovering deeper patterns and value tensions across the system.
6. **Frames** – Reframing the problem by clustering themes into new logics.
7. **Futures** – Projecting possible directions for solution development.
8. **Transformation** – Outlining the shifts required to support these futures.
9. **Integration** – Synthesising insights into actionable opportunities.

Each stage builds on the previous one, yet the process remains non-linear, allowing for loops, returns, and revisions. Early stages deliberately widen the scope of analysis: first to the immediate context and problem owner, then outward to other stakeholders, and eventually to the broader societal field. This outward expansion opens the space for new perspectives about possible actors and futures. From this widened horizon, the process then *zooms in* again, concentrating around recurring themes that emerge as meaningful universals. These themes connect the abstract exploration of values and logic with the concrete task of reframing the problem and identifying actionable interventions. In this sense, Frame Creation can be visualised not only as a linear sequence but also as two movements of expansion and concentration that meet at the point where new frames emerge (see Figure 4). A key early move is the suspension of judgement [204]. Though often counterintuitive, this step is crucial to prevent premature conclusions that limit potential. At its core lies the assumption that problem definitions are not neutral. They are shaped by mental models, organisational cultures, and institutional constraints and must therefore be questioned as part of the design effort. That is why the process invites engagement with paradoxes, competing logic, and diverse perspectives before settling on any interpretation.

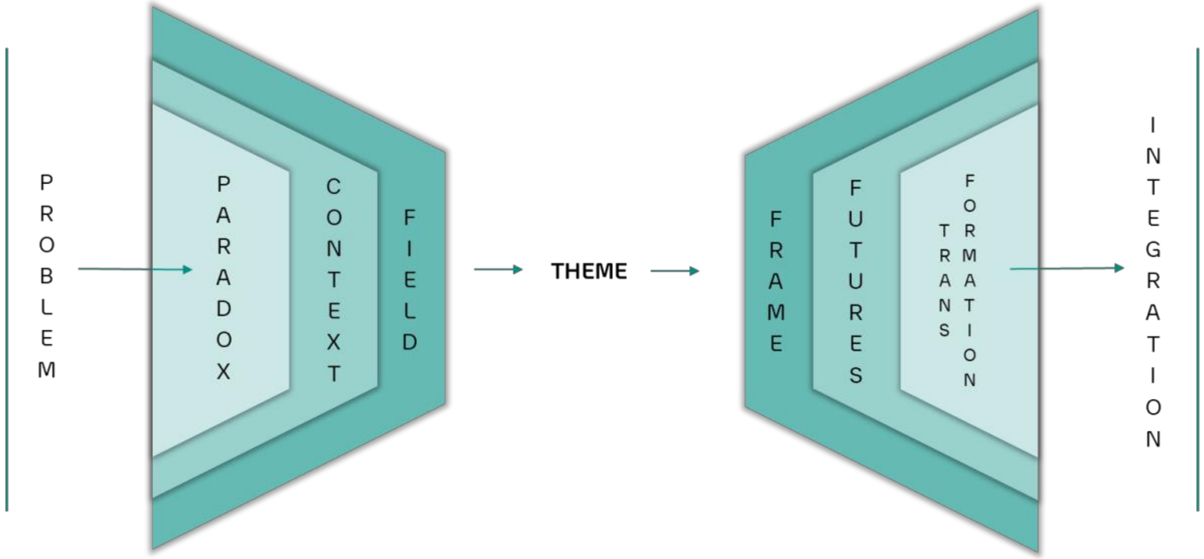

Figure 4. Stages of Frame Creation: Expanding and Concentrating.

In comparison to the summarised methods by Karagoz et al. [63], the Frame Creation model stands out as an unconventional approach within the domains of automation, production systems, and recycling. Precisely because of this, it shows promise in contexts where conventional engineering logic reaches its limits. According to Dorst [204, 209], engineering methods typically rely most commonly on abductive reasoning: a defined problem (“what”) is matched with a suitable solution path (“how”), based on established technologies, processes, and principles. This approach is powerful and remarkably versatile, and engineering remains an outstanding way of tackling problems, especially when both the problem and its context are well understood

[52, 204]. However, Dorst maintains that when both the nature of the problem and the boundaries of the context are ambiguous—as I argue here is the case for ELV recycling—traditional methods begin to falter. In response to this, Dorst [204] proposes an alternative logic: design abduction. In design abduction, *neither* the problem *nor* the solution is known from the outset. Instead, both must be actively constructed through exploration and inquiry. This process acknowledges the framing of the problem itself as a core design activity and as one that influences not only what solutions are imagined but also what kinds of outcomes are perceived as meaningful or even possible.

The attentive reader will have noticed that the first two stages of the Frame Creation process—Archaeology and Paradox—have already been addressed in substance, if not by name, in the previous chapter. Building on this foundation, in the remainder of this project I will focus on the stages of Context, Field, Themes, Frames, and Futures. While full-scale implementation, handover, and evaluation fall outside the formal scope, their intent is reflected in the concluding sections. To operationalise this approach, I followed the typical phases of a Frame Creation project [204]: data collection resembled the introductory literature review as well as the Context and Field stages, for which I conducted stakeholder interviews, mapped practices, and gathered contextual insights. The resulting qualitative material was then analysed to surface emerging themes, which then informed the development of novel frames. These frames were subsequently used to generate a possible future. The evaluation of this future informed the concluding chapter, where the broader implications of the findings are reflected upon and strategic recommendations are proposed.

3.3 Context and Field: Stakeholder Interviews

The process began with preparing and conducting context-rich conversations, deliberately chosen over rigid methodological frameworks. I decided to prioritise direct dialogue with stakeholders across the value chain, particularly with those often under-represented in strategic and technological discourse, yet whose perspectives are crucial for grounded system innovation. In the context of dismantling and recycling, technical concepts are frequently developed without engaging the people who operate within the realities of the existing system (cf. [17]). The intention behind this step was to deepen the understanding of current practices by surfacing the values, constraints, routines, and tensions that shape stakeholder behaviour and perspectives. I further examined whether the problem space outlined above—drawn from academic and industrial literature—resonates with the lived experiences of those directly involved. But mainly this step served to identify sources of systemic complexity and to map converging or diverging visions for the future as expressed by actors across the value chain.

3.3.1 Interview Strategy and Stakeholder Mapping.

I began with identifying and defining a diverse group of stakeholders representing a broad spectrum of roles within and around the ELV recycling system in Germany. The decision to focus on Germany was deliberate. As noted earlier, ELV recycling practices vary significantly across Europe and globally. To maintain contextual consistency and comparability across responses—while also ensuring accessibility given my current location—I concentrated on the German context. This choice naturally limits the international generalisability of the findings, but it strengthens the depth and coherence of system-level insights within one representative national setting.

For the stakeholder selection, I followed a concentric mapping strategy, distinguishing between an inner circle of actors directly involved and an outer circle of adjacent experts with the potential to reframe the situation through alternative perspectives. This two-pronged approach was chosen to enable a balanced perspective, capturing both hands-on operational realities and broader systemic logics. The search for suitable interview partners was guided by targeted online research into relevant actors and their involvement in public projects. Many were identified through media coverage, industry publications, and prior visibility in the field. I reached out to each potential participant via email, outlining the purpose of the study and inviting them to take part. In some cases, follow-up reminders were necessary to secure participation. Figure 5 shows an overview of the distribution and grouping of the selected stakeholders.

Primary System Actors. Here I settled on individuals from multiple Authorised Treatment Facilities (ATFs) and sector associations, as well as corporate stakeholders from Volkswagen. At ATF sites—such as RETEK, Volkswagen Group Services, and within Volkswagen itself—the selected stakeholders were those directly involved in the dismantling process. They can represent, in its most tangible form, the lived experience of dismantling. The set comprised both dismantling managers and hands-on workers. Managers, who organise and execute dismantling under real-world conditions, could potentially highlight tensions between profitability, regulatory requirements, and the practicalities of day-to-day operations. Because of reasons discussed, conversations with hands-on dismantlers were seen as important, and additionally, these workers can share embodied knowledge of shop-floor practices and adaptive problem-solving in dismantling work.

Representatives of Germany's key industry associations, bvse[70] and BDSV[71] were included to ensure a sector-level perspective. As umbrella organisations for hundreds of recyclers and dismantlers, they can provide insight into how automation is positioned within the broader landscape of policy development, compliance frameworks, and material flow logistics. Their perspectives could potentially illuminate how national policy ambition connects—or fails to connect—with operational realities and how structural conditions may influence the feasibility of technological change in mid-sized dismantling and recycling companies.

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[70] Bundesverband Sekundärrohstoffe und Entsorgung e.V. (Federal Association for Secondary Raw Materials and Waste Disposal

[71] Bundesvereinigung Deutscher Stahlrecycling- und Entsorgungsunternehmen e.V. (Federal Association of German Steel Recycling and Waste Management Companies)

Given that this research was embedded within Volkswagen Group Innovation, it was essential to include perspectives from across the company, particularly those operating at the intersection of sustainability, production, and strategic development. Participants from the Group's sustainability and circular economy teams could contribute insight into lifecycle strategy, compliance demands, and organisational considerations when implementing dismantling automation. From the research and innovation side, system-level reflections could clarify how production logic, material recovery, and long-term transformation goals intersect. Individuals from planning and engineering teams—responsible for vehicle architecture and assembly automation—were included for their ability to explain how current design and manufacturing processes shape disassembly feasibility and what parameters future automation concepts would need to accommodate.

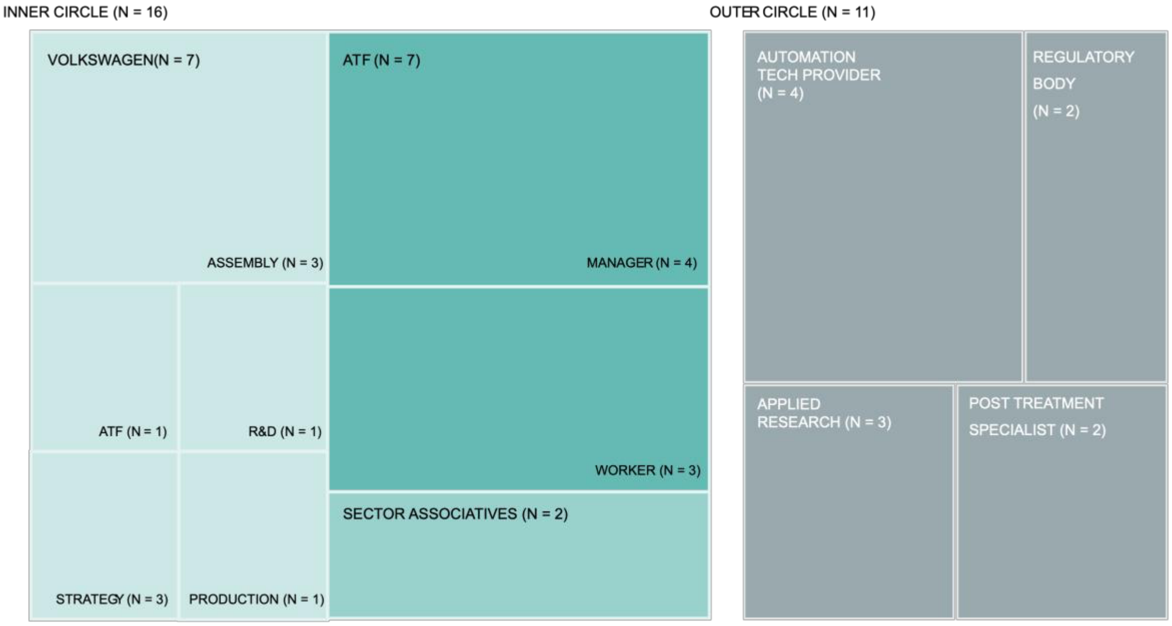

Figure 5. Overview of the defined stakeholder groups.

Outer Circle Stakeholders. The outer circle was defined to comprise actors operating adjacent to or in structural relation with the dismantling process. They were included to provide critical outside-in perspectives that could help reframe system boundaries and transformation pathways. This group covered recyclers and post-treatment specialists, automation enablers from industry and applied research, and regulatory authorities involved in oversight, standardisation, and policy enforcement.

FIT Umwelttechnik, a service provider specialising in the disassembly and analysis of prototype and series vehicles, was included for its ability to contribute experience in evaluating recyclability, material compatibility, and disassembly feasibility for OEMs. Such expertise could support the early identification of automation potential through teardown analysis. For recyclers and post-treatment specialists, representatives from ALBA Metall Nord and ThyssenKrupp Steel were interviewed. These actors sit downstream of dismantling but are directly affected by its outputs. Their perspectives could potentially shed light on how upstream disassembly choices—particularly in relation to part separation and material purity—affect the efficiency, profitability, and sustainability of downstream processing.

A second set of outer-circle actors comprised automation technology providers (EKS Intec and Zimmer Systems) and applied research institutions (Fraunhofer IWU, TU Braunschweig). These organisations could contribute insight into the technical frontier of dismantling automation. EKS Intec was included for its expertise in digital process simulation and modular process modelling; Zimmer Systems for its experience with robotic hardware such as end-effectors and grippers. Applied research actors were selected for their technical contributions to process planning, reversible joining, human-robot collaboration, and disassembly simulation, as well as their role connecting automation development with broader innovation goals through national and EU-funded projects such as SARESA (cf. [210]).

Finally, regulatory perspectives were gathered from the German Environment Agency UBA[72] and the Federal State Trade Supervisory Office[73]. These institutions could help clarify how policy targets, legal frameworks, and enforcement practices shape the scope for automation in ELV dismantling. The UBA was included for its role in aligning disassembly practice with national and EU-level circularity and recovery goals, while the State Trade Supervisory Office could provide insight into local enforcement, permitting, and operational oversight.

3.3.2 Interview Design and Execution

Between June 24 and July 25, 2025, I conducted interviews with 27 experts across the vehicle dismantling and recycling ecosystem. The planned stakeholder coverage was achieved.

In the analysis, raw interview transcripts were segmented into *quotations*—that is, text passages that capture a discrete idea, observation, or statement relevant to the research questions. Each quotation was then assigned one or several *codes*, which are analytic labels representing a conceptual category or theme. Codes thus function as the basic units of interpretation, while quotations constitute the empirical evidence on which the thematic analysis is built. Table 1 provides an overview of the sample, broken down by group, participant's organisational role, and the volume of coded data (codes and quotations) contributed by each subgroup.

However, it should be mentioned that several strategically relevant actors declined to participate. In many cases, their refusal reflected internal development conflicts, affiliations with competing automation projects, or concerns about Volkswagen's involvement. While unfortunate, these absences are telling; they underscore the political sensitivity and commercial entanglements that characterise the field.

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[72] Umweltbundesamt

[73] Staatliches Gewerbeaufsichtsamt Hildesheim

Table 1. Details of interview participants and their contribution.

Stakeholder Group		Job Description	Codes	Quotations
Inner Circle (N = 17)	Volkswagen (N = 8)	Assembly (N = 3)	7	10
		ATF (N = 1)	31	39
		R&D (N = 1)	10	8
		Production (N = 1)	10	8
		Strategy (N = 1)	26	29
	ATF (N = 7)	Manager (N = 4)	46	52
		Worker (N = 3)	16	20
		Sector Associative (N = 2)	35	36
Outer Circle (N = 10)		Automaton Tech Provider (N = 4)	19	20
		Regulatory Body (N = 2)	30	30
		Applied Research (N = 2)	39	65
		Post-Treatment Specialists (N = 2)	18	20

The interviews followed a semi-structured format, designed to balance consistency across participants with the flexibility to respond to domain-specific insights and emerging topics. Further, they were crafted to support contextual understanding but also speculative thinking. Core topics included systemic constraints, operational bottlenecks in everyday practice, tensions around values and responsibilities, and perspectives on automation and human–robot collaboration. The complete interview guide can be found in appendix B.

Each interview lasted between 45 and 75 minutes and was held in either German or English, depending on the participant's preference. With one exception, all interviews were conducted in German. Participation was entirely voluntary and uncompensated. For hands-on roles such as treatment facility staff and dismantlers, I conducted all sessions on-site to enable contextual immersion and gain direct exposure to operational environments. While most conversations were conducted one-on-one, dismantling workers were interviewed in a small group to support open conversation in a familiar setting. Depending on availability, interviews took place either online or in person. Before each interview, participants were informed that their organisations would be named in the thesis, but that all statements would be anonymised and detached from their contextual identifiers.

With informed consent, interviews were audio-recorded and manually transcribed. Audio files were permanently deleted following transcription.

The study received ethical approval from the Computer & Information Sciences Ethics Committee of the University of Twente. All interview procedures adhered to applicable data protection guidelines. Participants were informed of their right to decline questions or withdraw from the interview at any time prior to thesis submission. Data was treated confidentially and anonymised for analysis and publication. Participants are referenced in generalised terms, and no personal information is disclosed in this thesis or related documentation.

4 Thematic Analysis

This section presents the full thematic analysis, moving from the analytical procedure to the results and their synthesis, as presented in Figure 6. It begins with the coding logic used to structure and interrogate the interview data (1 + 2). The reader is then guided through the full empirical analysis. It opens with a brief validation of the dataset against the literature, ensuring consistency with the theoretical framework established earlier. The core analytical work presents the eight aggregated themes with their evidence (3). Finally, the section culminates in the conceptual synthesis, mapping the interconnections between themes and distilling them into a single higher-order construct (4). This synthesis is the analytical bridge to the next chapter, forming the foundation for reframing the problem space and developing strategic implications.

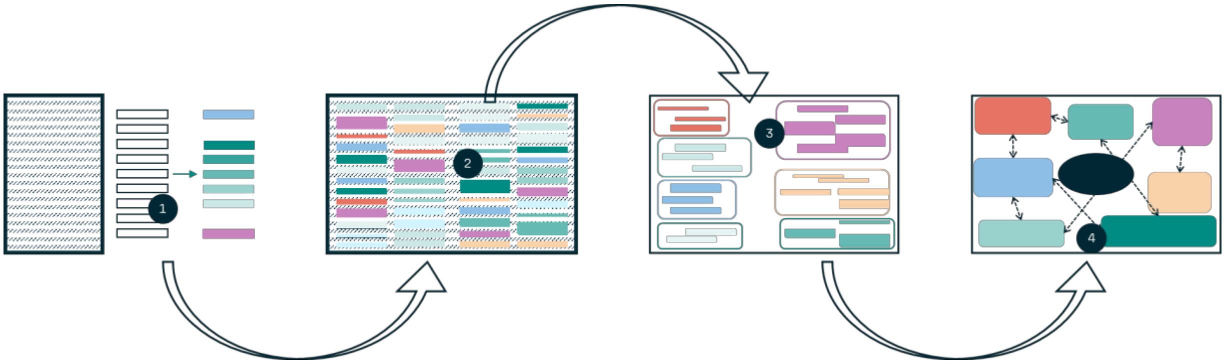

Figure 6. Theme analysis process

4.1 Coding Logic and Analytical Procedure

The analytical process began with data familiarisation during the transcription phase. For this, I manually tagged passages that reflected contradictions, assumptions, perspectives, institutional logics, or obstacles. For anonymisation, all names and company affiliations were removed during this step, and each participant was assigned a unique random identifier (P01–PN), which is used consistently throughout the analysis. In addition, transcripts were tagged with stakeholder group identifiers to enable reviewing coverage of themes by specific stakeholder groups later on. Tagged passages were recorded in a spreadsheet; Table 2 shows an excerpt, illustrating how it was used to structure the initial analysis.

Table 2. Excerpt from the interview documentation spreadsheet.

ID	Group	Category	Passage
P03	Inner Circle, Volkswagen, Strategy	Systemic Contradictions	Vision of reuse vs. lack of access to products *“Actually, we want to keep all our vehicles in circulation, but they no longer belong to us after they are sold.”*

P12	Outer Circle, Post-Treatment Specialist	Assumption	Scrap = neutrally usable, but in practice, composition leads to restrictions *“Depending on the production concept, there are clear limits to how much scrap can be dumped in.”*
P20	Outer Circle, Regulatory Body	Technical Obstacle	Difficulties in separating materials *“Complex composite materials and painted plastic parts are technically challenging.”*
P21	Inner Circle, Sector Associative	Perspectives	Emphasis on material, logistical, and economic bottlenecks beyond political wishful thinking.

Based on this familiarisation, I developed an initial coding scheme for the thematic analysis, structured around a three-part logic encompassing emerging themes, theory resonance, and visions. The initial thematic categories included responsibility, market logic, information flows, automation narratives, embodied knowledge, and design conflicts. The anonymised transcripts were then uploaded into ATLAS.ti Web, with the scheme serving as a reference guide. I conducted line-by-line coding, randomising the interview order to reduce anchoring effects and applying a combination of open and axial coding to capture both predefined and emergent codes. Interim findings informed adjustments to the direction and focus of later interviews. Where overlapping or contradictory meanings arose, I revisited and refined code definitions to maintain conceptual clarity and analytical consistency. After coding all transcripts, I systematically reviewed the quotations, reassessed code assignments, and consolidated them into a refined, hierarchical coding system which is presented in Appendix A.

4.2 Empirical Themes

I consolidated the findings into eight empirical themes that were repeatedly raised during the interviews presented in Figure 7. Each theme combines several codes, with the aim of maximising internal homogeneity and external heterogeneity. While many of these themes are interconnected and at times mutually reinforcing, the objective was to capture the full range of perspectives in a coherent and differentiated structure. As illustrated by the distribution of coded quotations (Figure 7), automation dominates stakeholder attention, economic considerations remain central in a market-driven system, and early design decisions emerged as a recurring point of leverage.

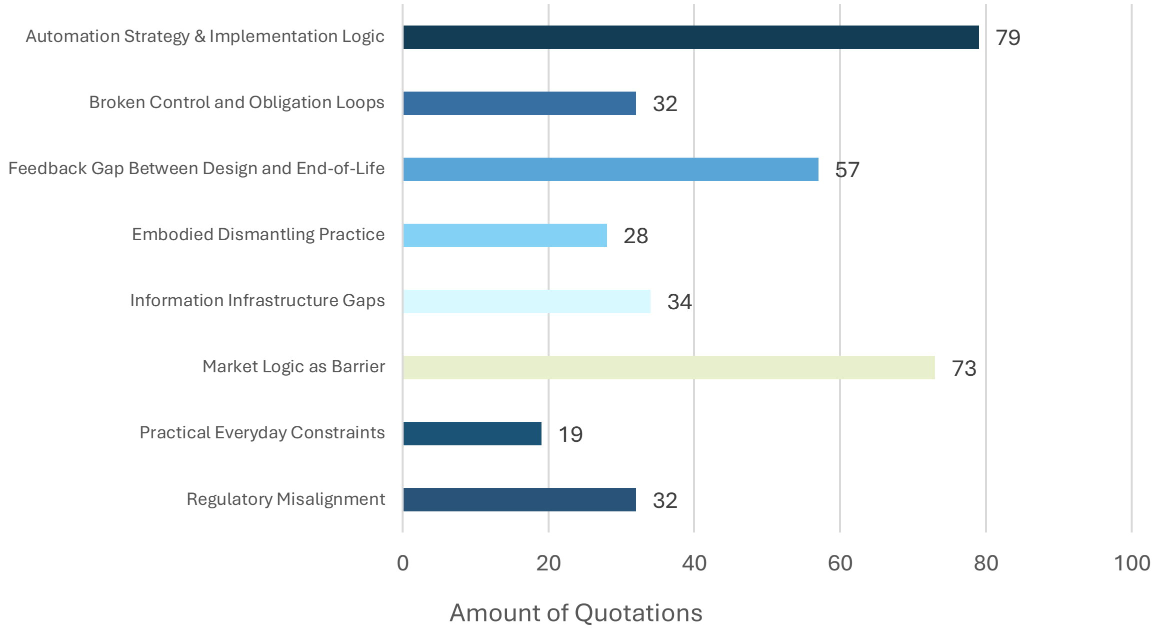

Figure 7. Distribution of coded quotations across the eight themes.

The overall resonance was consistent and specific, sufficient to treat the corpus as theoretically grounded. The interviews confirmed that dismantling is not just a downstream afterthought but a decisive stage in the recycling chain. As one participant stated, *“For true decarbonisation, we need high-quality recovery, and this is particularly successful through targeted, pre-shredding dismantling. Why should components be mixed together in an uncontrolled manner, only to have to separate them again in an energy-intensive process later on?”* (P20); mirroring core arguments in the literature on the benefits of early-stage separation [14, 15, 98]. Participants independently described systemic gaps identified in previous studies, including vehicles exiting the regulated loop [90, 92]. *“Many [ELVs] leave Germany as ‘used cars’ and therefore do not appear in the official recycling statistics […] We would have the capacity to process significantly more material”* (P02). The field accounts also reinforced established findings on heterogeneity and its impact on planning and automation [28-30, 34, 123]: *“A key issue […] is the high degree of heterogeneity […] different years, conditions, maintenance histories”* (P03) and *“unlike production, there is no standardization […] heights, weights, connections, everything varies”* (P03). P17 shorthand captures it: *“In assembly, you have four vehicle types; in dismantling, you have 400.”*

Interviewees explicitly rejected the “run the line backwards” assumption [34, 122]: *“Not every vehicle is in perfect condition […] Many have been involved in accidents, are deformed or damaged. This often makes access to individual components difficult or impossible”* (P02). And further accounts described complexity from vehicle individualization: *“Every vehicle returns in a different condition […] Often, the original components are no longer installed”* (P03). Automation was positioned as conditional rather than universal: *“If at all, then only* *with AI support and lots of cameras […] The work is too complex to be automated in a standardized way"* (P10). Time inflation and access constraints aligned with documented design trends [15, 122]: *"There is simply much more technology installed",* (P06); *"Today, you sometimes have to remove the entire engine to even get to the catalytic converter. […] In the past, vehicles might have had two airbags, but today there are 8, 12 or even 16"* (P05), and *"even with standard parts such as a 12V lead battery, it is now hidden somewhere in the water tank or under the driver's seat"* (P04).

The distribution of coded quotations presented in Figure 8 reveals the breadth of engagement across the thematic landscape. While all groups appear within multiple themes, the intensity of their presence varies. Workers, applied research experts, ATF managers, and sector associative contribute most frequently, while members of production and assembly teams appear more selectively. Some themes show concentrated ownership: Automation Strategy and Implementation Logic is driven by workers, managers, and providers of automation technology; Feedback Gap Between Design and End-of-Life is dominated by applied research experts; and Embodied Dismantling Practice reflects predominantly worker perspectives. Others, such as Information Infrastructure Gaps and Regulatory Misalignment, are more evenly populated, pointing to challenges that cut across roles and institutional boundaries. Followingly the themes are presented.

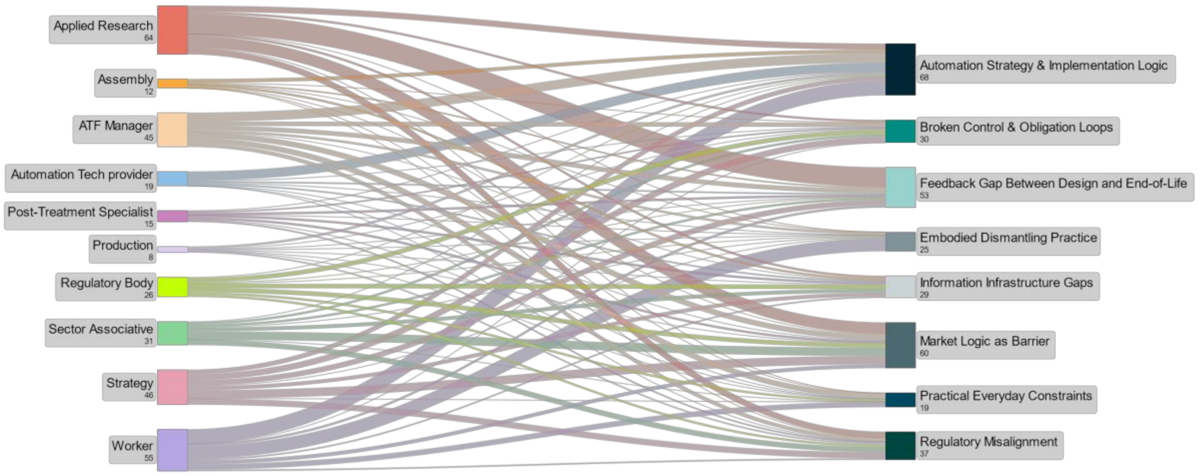

Figure 8. Flows of coded quotations from stakeholder groups to thematic categories.

4.2.1 Market Logic as Barrier

This theme was constructed through 73 coded quotations, grouped into 11 codes across two major clusters: (1) *Economic Incompatibility of Circularity* (45 quotes), including categories like profit over circularity, labour vs. material value, and cost-driven material choices (2) *Market Failure and Volatility* (28 quotes), including categories such as missing markets, price instability, and insufficient demand incentives. The theme appeared consistently across groups. It describes a core contradiction between ecological ambitions and prevailing cost-efficiency logics.

A fundamental barrier that was described is that recycling and reuse are rarely profitable under current market conditions. While circularity is recognised as an ecological imperative, it is structurally outcompeted by the economic logic of production, as P01 described it bluntly: *“Production is carried out to make profit, not because it is needed.”* For example, the same part of a vehicle could be made of different materials *“On the exterior mirror, the painted cover is sometimes made of ABS*[74] *and sometimes of ASA*[75]*, even though it is the same component. The inner carrier is often made of PP*[76] *with a high glass fibre content”* (P01). These material differences arise depending on the supplier’s cost advantage, resulting in unpredictable material mixes that undermine recycling, which creates a downstream burden (*“Why is a cent saved in production often worth more than $100 that has to be spent later on recycling?”* P01). From a systems perspective, dismantling and recycling are cost centres and not value drivers. As P12 explains: *“There is an overarching conflict between ecology and economic efficiency. Of course, we all aim to reduce the carbon footprint of our products. But this must also remain affordable.”* As long as sustainability lacks a clear return on investment, it will be seen as a luxury rather than a priority.

Recyclers operate under similarly constrained logic. The viability of material recovery hinges on value density, purity, and stable resale potential. P03 emphasised, “*If certain materials, such as plastics, are not valuable, they are simply not dismantled.*” The cost of separation outweighs the resale value, leading to incineration or landfilling, even when technical recycling options exist (*“Technologically, much is already possible with sufficient capital. However, the structures, particularly the plant technology and infrastructure, are still lacking. Economic scalability in Europe has also not yet been achieved.”* P14). The challenge becomes even more acute when a part is not only difficult to sell but has no market at all. For many components—textiles, plastic trims, bonded tanks, or older electronics—there is simply no buyer, even if the part is intact. As P02 explained, *"no one wants them […] there is no market, for example, for old tanks or complex bonded parts, so removing them makes no business sense.”* T02). This logic extends even to technically recyclable materials like glass. P15 noted that although *“automotive glass is recyclable, it’s typically shredded and landfilled, because no buyer exists and disposal is cheaper than separation”*. OEMs, meanwhile, continue to focus on new part sales; reusing components may even threaten their profit models. As P06 remarked, *“in a total loss, insurance pays for a new car, and the OEM sells it twice.”*

Participants confirmed the dismantler's dilemma discussed in [11] which shows how volatile raw material prices undermine planning security. As P05 explained: *“Rhodium, one of the three precious metals used in catalytic*

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[74] Acrylonitrile Butadiene Styrene is a common thermoplastic polymer known for its strength, impact resistance, and ease of processing.
[75] Acrylonitrile Styrene Acrylate is a thermoplastic like ABS but with superior weather and UV resistance.
[76] Polypropylene is a lightweight, semi-crystalline thermoplastic.

converters, alongside platinum and palladium, was trading at around €20,000 to €25,000 per kilo before the coronavirus pandemic [then] the price rose to €800,000 and then fell back to €40,000. It is currently around €160,000." In such conditions, even precious metals pose a strategic dilemma: to recover, to store, or to scrap (*"A key question is: Do I want to recycle the vehicle for raw materials or use it for spare parts? A classic example is the catalytic converter. Do I sell it directly as a valuable raw material, i.e., "a bird in the hand," or do I store it as a spare part and hope for a higher selling price?"* P05)? That said, short-term spikes can change behaviour. P10 explained that rising copper prices currently justify the effort of extracting and separating cables, but only because the market signal is strong enough to offset labour costs. The same participant emphasised, *"We could get even more out of it, but at some point, the time required would no longer be acceptable."* Circularity, in this framing, is reactive rather than strategic.

This volatility creates hesitation not only among recyclers but also among OEMs. Even when technically capable of redesigning vehicles for recovery, manufacturers often resist change without a clear economic trigger. As P20 noted: *"Sustainability is often not seen as a business case, but as an additional expense with no return on investment."* This reinforces a cycle in which recyclability remains outside of core production logic even in high-potential domains like battery recovery, which is explained by P21: *"[There is] no reuse of spare parts from batteries, these are usually passed on directly (e.g., to take-back systems). Unlike traditional vehicle parts which are stored for 2–3 years and then sold, no one wants batteries lying around in their yard."* P03 illustrates how the system is primarily controlled by margin logic: *"From today's perspective, pure material revenues from recycling do not support the business model, at least not at the current repurchase prices. If, for example, we purchase a vehicle for €2,000, the recycling revenues alone do not cover the processing costs. That is why the focus is currently clearly on used replacement parts. Components such as doors or engines, for which there is still a market, especially for conventional vehicles, form the economic basis of the model."* Material recovery, especially for degraded or low-value fractions, simply doesn't pay.

This pressure within the system causes recycling tasks and teams to be perceived as a financial burden, as P01 put it: *"Like a 'ball and chain.' We incur costs, uncover weaknesses, and demand changes. This is unpopular internally, […] Our work […] often makes products more expensive and complex. Direct recycling within the production chain is accepted because it is efficient. But as soon as downstream recycling processes are involved, it is quickly seen as a burden."* P10 explains a similar perception regarding the dismantling of old, damaged vehicles that are not suitable for spare parts: *"With cars like these, we sometimes spend four days just dismantling and then just disposing them. By comparison, the same work takes about two days on a new vehicle, where screws can be easily removed by hand. Everything that is unscrewed must be sorted, separated, and disposed of correctly, which takes an enormous amount of time and brings in very little money. The scrap price per ton is often all you can get."*

P20 counters this perception: *"It is often criticised that recycling and closed-loop recycling cost money—but no one questions that oil and other pollutants must be removed from ELVs, even if this also involves costs. […] we are at the point where resource conservation and CO_2 reduction are also legitimate reasons […] even if it costs money. And this is urgently needed: we cannot always just ask ourselves whether something 'pays off' in the short term."* Circularity may not yet be a business case, but it is becoming a societal one, as these economic logics do not operate in a vacuum. They are entangled with regulatory structures that, instead of steering the system toward circular outcomes, frequently amplify existing inefficiencies.

4.2.2 Regulatory Misalignment as a Systemic Obstacle

This theme is based on 32 coded quotations grouped into seven categories:

1. Regulatory Micromanagement (7 quotations)
2. Lack of Execution and Quota Gaming (6 quotations)
3. Liability Uncertainty (6 quotations)
4. Regulation Mismatch (5 quotations)
5. Over-Complex Rules (4 quotations)
6. Compliance Costs without Return (3 quotations)
7. Policy Volatility (1 quotation)

This theme captures my observation of a recurring contradiction in the interview material: the tension between regulatory ambition and systemic feasibility in ELV recycling. Across the accounts I gathered, regulation did not consistently appear as a driver of circularity. Instead, it was often described as generating friction, uncertainty, and strategic ambiguity within the dismantling ecosystem. The misalignment identified here does not stem from a lack of rules but from the way multiple layers of regulation interact in practice, producing cumulative incoherence and—in many cases—a disconnect from operational realities.

The first fracture line participants described lies in regulatory complexity turning compliance into an ongoing, resource-intensive task. As P02 noted plainly: *"Legal regulations are constantly increasing and becoming more complex."* Even well-meaning provisions were said to overburden smaller actors: *"Requirements, for example, regarding process documentation, dismantling standardisation, and handling high-voltage batteries. These are leading to increasing pressure to invest and improve qualifications, especially for small businesses with low margins"* (P03). Beyond technical knowledge, dismantlers are often left guessing how, when, and to what extent specific directives apply. P22 illustrated the interpretive burden with the case of lead content: *"There is a list of components or materials that must be removed if they exceed certain limits […]. However, implementation is problematic: On the one hand, it is unclear whether these requirements apply to every single vehicle or are only examples. On the other hand, there is often a lack of transparency about how much lead is actually used. In practice, every part would have to be removed to check this, […] although there is an information provided by manufacturers that is supposed to provide whether removal is necessary, in practice the system is neither clear nor particularly user-friendly […]."*

From these accounts, a compliance paradox emerges: the more precise and protective the regulation becomes, the less operable it can be, particularly for actors without dedicated legal teams. Running in parallel, some legal standards shaped by design-stage decisions do not translate into meaningful recycling practice: *"[Now] prohibited substances may be contained if they were still permitted at the time the vehicle was placed on the market. However, this poses a problem in the recycling process, especially when recycled materials are used"* (P01). Others appear technically feasible yet lack downstream utility: *"The first draft stated, for example, that all dashboards had to be removed. However, this does not make sense, similar to […] glass. After removal, the components end up in containers and then back all together in the shredder and are incinerated. This is pointless if there is no downstream use"* (P04). In cases of OEM regulation conflicts, well-preserved vehicles are scrapped wholesale due to formal approval issues, as P16 explained: *"Despite being close to series production, all vehicles are currently being 'flattened,' i.e., completely scrapped, even those that would be suitable for spare parts recycling. The reason is that many vehicles have not passed the approval test and are not formally allowed on the market, which would constitute a violation of the regulations if they were to be sold anyway."* In such situations, legal formalism overrides material logic, resulting in unnecessary destruction and underutilised value.

Meanwhile, what participants described as regulatory micromanagement introduces detailed control mechanisms that paradoxically reduce flexibility, efficiency, and trust in local problem-solving: *"Under REACH alone, around 40 new substances are banned every year, [… resulting] in new candidate lists, restrictions, and changes to limit values. We have to update our databases twice a year, even for existing substances whose classifications may have changed. It is not enough to have correctly assessed methylene once; you have to constantly check whether anything has changed"* (P01). Such governance also extends into quotas and materials tracking, where prescriptive control can ignore material heterogeneity and market functioning (*"If it means that the scrap must come from vehicles, it becomes micromanagement."*, P02: *"In a converter with 200 tonnes of material, such recycling is hardly realistic."* P12).

A further layer of uncertainty was raised around liability, particularly concerning recycled materials and reused parts. Interviewees repeatedly expressed low confidence in verifying material safety and integrity: *"Many [of now illegal] substances remain in the recycled material […]. When I purchase new, I receive a certified, documented material for which the supplier guarantees that it does not contain any prohibited substances. With recycled materials, you don't know exactly what it contains, and some plastics can be 20 years old. If it is not clear what the material contains, it is only used for non-critical applications. Material analysis to check the contents is expensive [… but] no one wants to sign for a recycled material that has not been fully analysed"* (P01). Next to illegal substances, there are also questions about warranties for used parts sales: *"Who is liable for the quality of these parts? What happens in the event of invisible damage such as hairline cracks? Which parts may have been used in repairs and are not original parts?"* (P16).

All of this plays out under the weight of rising compliance costs that, according to participants, often outpace any economic return. Operators are expected to perform extensive documentation, validation, and process upgrades, yet this effort is rarely compensated (*"Legal and regulatory requirements are constantly increasing, but human and financial resources remain the same."* P02; "*Regulations lead to high control and implementation costs."* P01; *"This will be expensive, and the question arises: Who will pay for it? Probably the customer, because manufacturers will pass on the costs."* P10).

And yet, paradoxically, enforcement was often described as weak, opening the door for quota gaming, selective compliance, and systemic opacity. Several voices openly described this tension: *"A classic area of tension in dismantling operations is the conflict between quantity and regulatory requirements. You can either process a lot of vehicles and ignore certain legal requirements, to put it mildly, or you can sleep on it and think about how to combine the two."* P04 and P05 elaborated, P05: *"As long as there are quotas, there will be cheating."* P04: *"For two reasons: malice and ignorance. Many certification bodies or expert offices carry out superficial checks, and some quotas are based on unreliable volume estimates. One example: oil filters have different densities, which leads to widely varying calculations. If someone is at 69% when they should be at 75%, they know exactly which screw to turn. The figures are sent to state statistics offices, are not checked for plausibility, and the Federal Environment Agency then forwards them unfiltered to Brussels. This is absurd; laws are written, material flows are planned, and subsidy programmes are set up on this basis."* What emerges from these accounts is less a regulatory system steering toward circularity and more a form of compliance theatre where targets may be met on paper yet are practically diluted through downcycling and loopholes.

4.2.3 Feedback Gap Between Design and End-of-Life

The theme is based on 57 coded quotations grouped into nine categories:

1. Feedback gap between design and EoL (11 quotations)
2. Design for Recycling competence cap (10 quotations)
3. Function/safety vs. design for recycling (9 quotations)
4. Complex material composition (7 quotations)
5. Uncertainty about material composition (5 quotations)
6. Vehicle design as a lever (5 quotations)
7. Lack of foresight (4 quotations)
8. Limited recyclability (3 quotations)
9. Recycled materials are less performative (3 quotations)

It reflects my interpretation of the *"major problem that vehicle design does not take subsequent dismantling into account"* (P04). Across the material I collected, participants described a structural gap in feedback EoL practice back into the design process. The result is that many design choices are fixed years before a car reaches the dismantling hall (between 15 and 25 years), with little or no consideration for their downstream consequences. What emerges is less a shared design–recycling cycle and more two parallel worlds, separated by organisational structures, timelines, and priorities.

By the time a vehicle arrives for dismantling, its architecture is set. Adhesives that cannot be reversed, inaccessible fastening points, and multi-material composites are no longer negotiable; they are physical realities dismantlers must work around. The professionals making these design decisions often never set foot in an application facility (*"The designer is not willing to travel on business; he never sees how things work in the factory."* P17), and conversations between design and dismantling teams are rare, brief, and often filtered through multiple management layers. P24 summarised the missed opportunity: *"Only when the designer receives feedback—not just on whether something can be built, but also whether it can be dismantled—can future-proof solutions be designed*." These loops are too rare today. Some OEMs have reacted by closing this gap (*"the design department must obtain approval from the recycling department"* P01) or setting up *"booster teams [… that] work in parallel with regular development and analyse existing components for alternative design options […] whether there are more efficient or sustainable design options"* (P03). These exceptions should become the rule, according to P23, which argues for a necessary change in education and culture: *"Training institutions must follow suit; dismantling, circular design, and recycling principles belong in the curriculum."*

Even when a willingness to consider recyclability is present, the skill and knowledge required to integrate it early are often absent from the design role. Material compatibility, separation techniques, and alloy identification are specialised fields rarely embedded in core design training. P01 reflected: *"A design engineer must primarily work functionally; they need to know how stable a component is and whether it meets the requirements. Expecting them to also be materials scientists or legal and standards experts is asking too much of them."* This results in information gaps that propagate downstream, for example, in faulty entries in material databases: *"We were in regular contact with suppliers to understand why they had provided certain information. Often it was simply a lack of knowledge or missing instructions."* Hence P13 proposes to take *"a team from this [design] department and let them really get their hands dirty with a vehicle, [and try] to open a trunk like that. The gaps are so narrow that I could barely reach in with my small hands, and even then, only with a lot of effort."*

These disconnects are not purely a matter of oversight; they are also shaped by unavoidable trade-offs. Safety, structural integrity, and durability often require multi-material solutions that complicate recycling. Lightweighting demands [65, 66], crash performance, and heat resistance can all necessitate combinations of plastics, metals, or composites that resist clean separation. In such a hierarchy, recyclability becomes a negotiable attribute, while crash safety is not. P01 explained why POM[77] remains indispensable in certain friction applications, even if they complicate recycling: *"POM is ideal for friction contacts because it does not 'flow'. A combination of POM*

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[77] Polyoxymethylene, also known as acetal, is a high-stiffness, low-friction thermoplastic valued for its dimensional stability and wear resistance.

and PA66[78] *is often used in ball joints or gear wheels. Two PA66 components would wear out because PA66 'bites.'"* P01 further lists examples of design choices that balance both needs, e.g., dashboards made from fully compatible polyolefin systems (*"a PP carrier, PP foam on top of that, and EPDM*[79] *as the outer skin"*), but these remain exceptions as *"the standard is still PP carrier, PUR*[80] *foam, and PVC*[81] *top layer"*) because: *"PVC does have advantages […] it is naturally UV-resistant. EPDM is not. This means that it decomposes and discolors quite quickly"*, but *"if you can't separate them cleanly, the only option is disposal.*

In practice, these trade-offs often manifest in "function integration", where multiple functions are combined into a single part to, e.g., reduce weight, assembly time, and complexity. From a production standpoint, this is efficient. From a dismantling perspective, P01 summarised: *"Integrating different functions into a single component means that I also have to combine different materials, which makes separation and recycling extremely time-consuming."* The challenge extends beyond plastics (*"If a part is made of seven different plastics, the only option is to incinerate it. And even that's not a good working solution."* P21)—even in high-value assemblies like batteries, *"Aluminium housings are fine, and so is a little lithium. But what remains is a black mass from which cobalt, nickel, and manganese can only be extracted with enormous effort, often at very low percentages"* (P04).

These challenges are compounded by imperfect or absent knowledge about material composition in the dismantling stage. Dismantlers describe planning their work in the dark, unsure of exactly what is inside a component or whether markings are accurate, even though P01 points out that *"plastic parts weighing more than 100g and elastomers weighing more than 200g must be labelled in accordance with standards such as ISO 1043* [82]*and ISO 18064*[83]*. There are corresponding standards for almost all material groups that set clear requirements for material labelling in vehicles, from plastics and metals to cast and sheet metal components. However, this labelling requirement is not always implemented correctly."* The problem extends to metals: high-end exterior steel grades are particularly sensitive to contamination, and without precise scrap composition data, quality risks grow. As P12 explained, *"foreign materials such as copper, […] can cause problems even in small quantities in the melt—especially in high-quality outer skin products."* Even as policy pushes for higher recycled content, technology and process limitations keep certain loops closed only on paper: *"Electric arc furnaces*[84] *can process more scrap, but they cannot produce every grade, especially not high-strength steels,*

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[78] Polyamide 66 is a high-performance thermoplastic known for its strength, wear resistance, and thermal stability.

[79] Ethylene Propylene Diene Monomer is a synthetic rubber with weather, ozone, and heat resistance.

[80] Polyurethane. A class of polymers formed by the reaction of polyols with diisocyanates. Widely used due to their adjustable hardness, elasticity, and chemical resistance.

[81] Polyvinyl Chloride. A widely used thermoplastic with good chemical resistance and versatility.

[82] *Plastics — Symbols and abbreviated terms* (Parts 1–4). International Organization for Standardization, Geneva. Defines standardized abbreviations for polymers, fillers, and reinforcing materials.

[83] *Thermoplastic elastomers — Nomenclature and abbreviated terms.* International Organization for Standardization, Geneva. Establishes uniform terminology for thermoplastic elastomers.

[84] A steelmaking furnace that melts scrap or direct-reduced iron using electric arcs between graphite electrodes, widely used in secondary steel production due to its efficiency and ability to process recycled metal.

or outer skin grades. […] This is where scrap concepts quickly reach their limits. […] Better scrap quality could increase the proportion, but this depends heavily on the production process” (P12).

Recycled materials face further hurdles before they can re-enter high-value applications. Limitations in performance, appearance, or purity often make designers and manufacturers wary of using them in visible or safety-critical parts. P10’s blunt remark— *“Recycled material is always rubbish; primary material is primary material”—captures* a sentiment that, while overstated, reflects genuine market reluctance. P01 noted that recycled plastics *“absorb odours and emissions during their service life, e.g., smoke, exhaust gases, or plasticisers. These substances cannot be completely removed from open-pored materials. This makes it difficult or impossible to use recycled materials in sensitive areas of vehicles such as the interior without incurring significant processing costs.”*

Despite these constraints, participants repeatedly pointed back to *“vehicle design [as] the most important lever”* (P03), the single most powerful point of intervention. Small changes upstream—compatible material combinations (P01), standardised joining techniques (P11), early-stage disassembly testing (P24)—could ripple downstream into shorter dismantling times, higher yields, and better economic viability. And while some advocate for binding design guidelines, e.g., *“model-based system engineering, as used in aviation, to improve separability and data”* (P23), the gravitational pull of current practices remains strong. The shift, however, demands a long view, as P03 points out: *“Even if we were to focus more on “design for disassembly” […] in vehicle design today, this would only have an effect in future vehicle generations.”* At the root is a deeper cultural habit. As P01 reflected, *“sometimes it might make more sense to build something a little heavier, but with materials that are easier and safer to recycle in the end.”* Until such foresight becomes embedded in the design process, it seems that the feedback gap between creation and dismantling will remain one of the most enduring fractures in the circularity chain. The absence of structured feedback loops outlined here is compounded by fragmented information systems.

Information Infrastructure Gaps

This theme is based on 34 coded quotations grouped into five categories:

1. Fragmented and incomplete data (11 quotations)
2. Need for digital low-threshold tools (9 quotations)
3. No shared data culture (6 quotations)
4. Digitalization and system interoperability (5 quotations)
5. Dismantling data blind spots (3 quotations)

It reflects my interpretation of a structural absence repeatedly described by participants: the lack of a coherent, shared information infrastructure. Across the accounts I gathered, the problem appears not simply as a missing technical tool but as a deeper systemic condition where data is fragmented, tools are ill-suited to dismantling needs, and mutual transparency is rare. In an industry where efficient disassembly and high-quality material recovery depend on timely, detailed, and interpretable information, this absence becomes a bottleneck that shapes everything from operational decisions to the feasibility of automation.

At its root, several participants linked the problem to a missing conception of a shared data culture. P14 summarised this succinctly: *“The topic is often discussed, but true transparency is rarely practised. Throughout the entire chain, from vehicle recyclers to steel producers, there is a lack of open data flows and honest cooperation.”* P20 pointed to practical alternatives: “*Either you have an unknown mixture and use sensors to determine the material, or you have access to the product data from the outset. Systems such as IMDS*[85] *[…] or platforms such as Catena-X*[86] *[…] could help here—for example, by linking them to chassis numbers.”* For automated disassembly processes, however, not only are the compositions of the components relevant, but also how they were assembled, but without trust, shared incentives, or a collective understanding of why data exchange matters, even the most advanced systems cannot deliver their intended value. P24 captured the tension between potential and mindset: *“Ideally, I have suitable dismantling processes that can be derived from the original assembly processes. However, this quickly brings us to the issue of data protection—I could imagine that certain interests would stand in the way of this […] no one inside the company would support this at the moment, at least not with the current mindset.”* In this landscape, each actor manages their own silo of information, but cross-system transparency is structurally obstructed.

This cultural vacuum is mirrored in the technical layer as fragmented and incomplete data. P21 was blunt: *“2002 model is digitised? Bullshit. Digital vehicle data is hardly available or unusable for recyclers.”* Even where information exists, it is often partial, outdated, or incompatible across systems. P16 described how even in production environments, data gaps persist: *“Test setups [in production development] are often not properly documented, problems are solved ad hoc and not properly followed up afterwards.”* For dismantlers, such gaps mean working in uncertainty about material composition, joining methods, or safety-critical details. The impact ranges from increased disassembly time to compliance risks. As P10 admitted after a data crawling trial, *“We thought it was feasible, but I learnt the hard way that it doesn't work that way.”* P24 lists a critical structural reason*: “In vehicle assembly, so-called ‘marriages’ occur in which components such as the body and drive are joined together”,* ergo, manufacturing data models treat joined components as a single unit but dismantling requires reversing this logic: *“We have to make the individual parts visible again, map virtual separation processes, loosen screw connections and reverse material flows. Our existing systems are not fully designed for this, [it’s] ultimately a data problem: the necessary input data is missing or is not granular enough. This*

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[85] *International Material Data System*: A global reporting platform for automotive manufacturers and suppliers to collect, manage, and share detailed material composition data of vehicle components.

[86] An industry-wide, open data ecosystem for the automotive sector, designed to enable standardized, secure sharing of information across the supply chain.

means that we need completely different data sets than before to be able to map disassembly processes virtually."

Without such datasets, operators fall back on improvisation, trial-and-error, or assumptions, each introducing additional cost, delay, or safety risk. Even with access to manufacturer databases like "ElsaPro[87]" (P20), dismantling automation can be limited. *"Series are often structured differently than documented […] due to modifications, variants, and interim solutions,"* P10 explained. This reinforces the need for tools that can integrate real-world variations and feed practical instructions to those on the ground. As P11 put it: *"As humans, we often can't consider all perspectives at once […] A tool like this could help fill in those blind spots because it can integrate insights from across the entire lifecycle of the product."*

Participants stressed that such tools must be low-threshold to be effective in dismantling operations (for similar results, cf. [124]). Information delivery must be simple, intuitive, and adapted to workers who may have limited experience with complex IT systems. P22 illustrated the gap: *"Of course, manufacturers provide information, but not everyone in the companies can use it. Many employees have a relatively low level of education […]. They are very skilled with their hands but often have little experience dealing with administration or computer systems. Low-threshold information services that are truly practical are needed; otherwise, well-intentioned guidelines will fall flat."* Visual and intuitive systems like IDIS[88] were cited as promising: *"The system is based on visual recognition and facilitates material-specific sorting,"* P01 explained. But even these have limitations, as P20 noted: *"From my perspective […] the system doesn't seem very user-friendly."*

The visions for improvement are strikingly tangible. P13 imagined: *"You would take a tablet, scan the vehicle identification number, take a few pictures […] and you're done."* P20 envisioned augmented reality integration: *"A car recycler […] puts on the glasses and sees a display showing which tool to use, where the component is located, and exactly what the work step looks like. However, this would require a comprehensive database."* Both ideas underline a core contradiction: while digitalisation is widely hailed as a significant change for the sector, it remains inaccessible, incomplete, or irrelevant to many of the people expected to use it. Without cultural alignment, shared standards, and purpose-built datasets for dismantling, the promise of digital tools risks remaining just that: a promise.

4.2.4 Broken Control and Obligation Loops

The theme is built from 32 coded quotations, grouped into 4 sub-codes:

1. Structural fragmentation (6 quotations)

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[87] *Elektronisches Service-Informationssystem Professional (Electronic Service Information System Professional)*: Volkswagen Group's internal electronic service platform that provides workshop manuals, repair instructions, wiring diagrams, and maintenance information for vehicles.

[88] *International Dismantling Information System*: A standardized database developed by European, Japanese, and Korean automakers to provide licensed dismantlers with vehicle-specific information.

2. Actor-specific optimization (9 quotations)
3. Power asymmetry and EPR contradictions (9 quotations)
4. Systemic non-ownership (8 quotations)

It is meant to capture a fundamental systemic dysfunction: the absence of integrated control and a shared sense and image of responsibility throughout the ELV system. Despite formal responsibility frameworks, there is no operative feeling of ownership covering the full dismantling process. Instead, responsibility is passed along a chain that is itself fragmented, resulting in a system where no actor holds full accountability, technically, economically, or ecologically. Rather than revealing task-level problems, it surfaces contradictions between roles, incentives, and system logics.

The foundation of the problem lies in how structurally fragmented the dismantling ecosystem is. Information, power, and accountability are perceived as being unevenly distributed, often with no clear alignment possibilities*: "In many cases, the people involved in recycling aren't even part of the same company as the designers or developers. They may never interact. So even if someone wanted to incorporate feedback from recyclers, they simply wouldn't have the opportunity"* (P11). This disconnection is especially visible in the dismantling sector, which, in comparison to the OEMs and post-treatment facilities, is composed largely of small and medium-sized enterprises (cf. Figure 9) operating *"on narrow margins and have little scope for major investments. This makes it difficult to integrate new, long-term approaches into existing business models"* (P03).

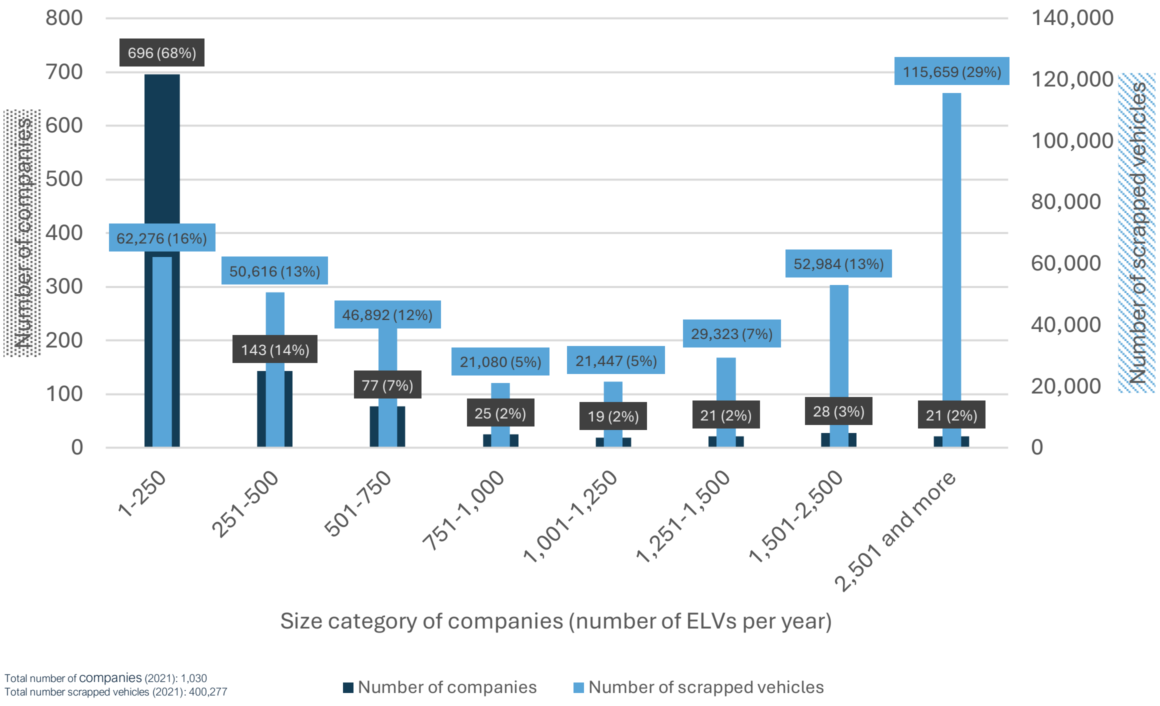


Figure 9. Size categories of ELV recyclers in Germany, 2021. Figure based on German Environment Agency (German Environment Agency 2024)

Due to this fragmentation and the widely varying size of the players, a power dynamic appears to be emerging: OEMs retain strategic leverage, while dismantlers remain operationally peripheral and economically exposed. The dynamic was captured pointedly in a conversation between P04 and P05, *P05: "We are at the end of the chain. OEMs say, 'If you want our old vehicles, take them, but for free. Please take on all responsibility, but don't expect a penny from us. And otherwise, leave us alone.'" P04: "We no longer want to be seen as the 'end of the chain', but as the beginning […] We don't want special status; we just want to operate on an equal footing.")* This imbalance extends to market control, with some OEMs actively limiting the reuse of parts. *"Components such as coloured wheel hubcaps are sometimes deliberately damaged at the factory. The aim is to completely control the aftermarket. Other OEMs are actively promoting secondary marketing and operating their own dismantling facilities. They sell directly to end customers via the dealer network or purely B2B, but with a clear intention to sell. And they have a clear advantage, of course, because in the end, it's all about price, especially when there is an oversupply"* (P04).

The asymmetry is especially problematic when dismantlers face no viable outlet for recovered parts or materials, transforming operational feasibility into financial burden. *"Perhaps we need to think more about extended producer responsibility, also in a financial sense. Car manufacturers would have to take responsibility if there is no market for certain components"* (P02). This tension feeds into the debate on extended producer responsibility. While some participants, like P02, argued for financial responsibility when no market exists for certain recovered parts, OEM interpretations of EPR often remain narrowly tied to design compliance rather than end-of-life economics. P03 described the conditionality of OEM engagement: *"This requires VW to make a strategic commitment to controlling the return flow of its vehicles in the future, either directly or through partners. Only then will the additional design costs be worthwhile."* The disconnect between stated sustainability ambitions and actual investment priorities becomes clear, as P20 recalled: *"I recently attended an industry event that focused on the use of recycled materials […]. There was a lot of talk about technical hurdles, such as additives, paints, and flame retardants in plastics. But in the end, the basic attitude was: 'It mustn't cost anything.' But if you want to change something, you have to be prepared to invest money."*

A second structural layer is actor-specific optimisation. Each stakeholder group operates within its own performance metrics, cost structures, and data visibility, making decisions that are rational in isolation but misaligned at the system level. For shredders, material recovery beyond high-value metals is uneconomical. P15 explained, "We *extract iron and non-ferrous metals. Anything beyond that is waste for us, which we send to thermal incineration and have to pay for. The exact composition is therefore of secondary importance to us."* For OEM development teams, design for recycling rarely becomes a binding criterion under the time and cost pressures of production projects. P03 described the difficulty of challenging entrenched requirements, because *"development processes are highly optimised, and quality standards are extremely high. Within the "sustainability bubble" […] there is openness and a willingness to change. But as soon as you get into the actual product projects, where decisions are made under high time and cost pressure, it is extremely difficult to push through alternative approaches."* Meanwhile, P21 criticised the use of adhesive joining techniques in battery housings: *"Manufacturers are 'gumming up' battery housings and using complex composite materials without considering how they will be dismantled later on. That is absolutely outrageous!"* The outcome is a structurally disconnected system in which each actor "does their job", but the whole fails to move towards greater circularity.

This is compounded by what I describe as systemic non-ownership: no single actor assumes responsibility for dismantling outcomes across the vehicle lifecycle. At the societal level, P13 linked this to consumer culture: *"We simply throw away vehicles, bicycles, whatever, without considering the resources that went into making them."* Institutionally, the same pattern appears in OEM logic, as P06 noted*: "Currently, OEMs are developing vehicles without considering disposal. We have entire yards full of batteries, and no one knew what to do with them.*" Once a vehicle is sold, responsibility is effectively severed—*"Our responsibility currently ends with the sale"* (P03). Several participants saw this as the root reason why systemic improvement stalls. P18 summarised it succinctly: *"Very bogged down because no one takes ownership."* Attempts to address dismantling holistically are often slowed by indecision or perfectionism. P27 warned: *"My concern is that we will wait too long to develop the 'perfect solution.' I very much hope that we will start pragmatically, implementing initial partial solutions and putting them into practice step by step. If we wait until we have found the global, maximum solution, nothing* *will happen in the end."* Taken together, these accounts describe a circularity chain in which influence and accountability are asymmetrically distributed, economic logic rewards narrow optimisation over collective performance, and responsibility for dismantling is structurally diffused. This combination entrenches the status quo: no single actor feels mandated—or incentivised—to bridge the gap.

4.2.5 Human Embodied Dismantling Practice

The theme is based on 28 coded quotations and grouped into seven categories:

1. Physical discomfort (7 quotations)
2. Worker-driven innovation (7 quotations)
3. Embodied knowledge and manual intuition (4 quotations)
4. Invisible work and recognition gap (4 quotations)
5. Tacit identification and condition judgement (3 quotations)
6. Emotional labour and personal routines (2 quotations)
7. Skills shortage (1 quotations)

This theme reflects dismantling as a form of work that is inseparable from the body, honed through repetition, and sustained by those who do it. Where the small, often invisible acts of adaptation keep the process moving despite strain. It is a form of labour that begins in physical exertion, matures into embodied knowledge, and is held together by routines, preferences, and mutual support. Yet, it remains structurally undervalued, its significance at risk of disappearing as skilled workers exit the trade.

The work is first experienced in the body. The physical strain is immediate and persistent: awkward lifts, constrained postures, and repetitive motion define the day long before any part reaches resale. P08 described stiff rotator cuffs from constant pulling: *"door sill trims are often very tight […] even with the clip puller, sometimes it doesn't help; you have to pull harder […] At some point, I probably twisted myself doing it. Now I'm in pain, but there's nothing I can do about it."* For P09, certain tasks carry a reputation: *"No one likes doing [underbody work …]; you have to loosen what feels like 8,000 screws for the trim, and your arms fall asleep from constantly holding the cordless drill overhead."* Tight engine bays require contortions, sometimes under hoods that cannot be removed; drainage work leaves workers *"wet […] with oil, brake fluid […] you loosen a screw, and it drips on you."* (P07). Small tools—like mini screwdrivers—are valued not for their price but for *"sparing fingers over hundreds of repetitive motions"* (P08). Here, physicality is not incidental; it is the medium through which dismantling happens.

Over years, these repeated motions turn into embodied knowledge: tacit, situation-specific know-how that allows a worker to act precisely in low-visibility, instruction-free situations. Removing an airbag, for example, involves pushing hidden springs behind the steering wheel: *"You have to imagine exactly what it looks like behind there because you can't see it. You need good spatial awareness […] feeling and luck; that sums it up pretty well"* (P09). Such skill is learnt over time and is model-specific; it exists outside manuals. P16 noted:

“Workers do not read instructions. They rely on their ‘trained eye’; sequences […] are based on practical experience, not on plans.” This practical intelligence often outpaces design assumptions, as P27 cautioned: *“The simpler a manual process looks today, the more difficult it often is to implement in fully automated systems.”* Condition assessment is another domain where tacit judgement plays a decisive role. P10 explained: *“Take a door […] the part number isn’t stamped anywhere […] we identify the component based on year of manufacture and model code […] If there is any uncertainty, we prefer not to remove any parts at all.”* These judgements weigh removal time, resale potential, and defect likelihood—often informed by knowledge that certain models are *“notoriously prone to defects”* (P10). The decision to act or not act is made in seconds, without formal criteria, but carries economic consequences for the entire operation.

Adaptation is constant. Workers adjust tools, sequences, and techniques to fit the realities of the job. Some modifications are elegantly simple: *“We bent a screwdriver from the tool kit so that it fits perfectly between the steering wheel and the airbag. The tool costs €1, but it's really valuable”* (P10); an angled screwdriver to reach *”the top of the dashboard; there are screws on the left and right that you can't reach with a normal screwdriver”* (P09); or a modified hand manipulator, originally for rims, now used to *“transport doors. It is handy and mobile and is now used regularly by our colleagues”* (P10). Process innovations—such as moving climate gas extraction earlier in the sequence or adjusting wheel removal to ease vehicle handling—often originate from the shop floor, not management. *“Such optimisations cost nothing but bring a lot of benefits,”* P10 observed. *“This kind of improvisation comes directly from the employees, not from above.”* Work is also sustained through personal routines and emotional labour. Teams negotiate preferences—working *“at the front”* or *“in the back”* of the vehicle—to finish together (P07–P08). Dislikes are handled with humour *(“I hate cables […] I’m afraid of electricity,”* P09), and mutual support is woven into the workflow. These habits are not trivial; they regulate pace and preserve morale.

Despite its importance, much of this labour remains invisible in formal value assessments. Marketable outputs—the parts sold—are measured, but the embodied skill, judgement, and coordination enabling them are not. P13 lamented, “Nobody *cares anymore whether what you do has any social value […] if it doesn’t look pretty or can’t be shared on Instagram, it’s not interesting.”* Essential supporting tasks, such as cleaning, photographing, and packaging parts for resale, are often excluded from productivity calculations, even though they demand spatial skill (*“pack a dismantled car sensibly into boxes”* P13) and organisation. As P14 pointed out, *“The devil is in the details: the processes before and after the actual dismantling are often overlooked.”* In automation discussions, these realities risk being abstracted away, as P22 warned, *“leaving critical but unquantified work out of the picture entirely.”*

Underlying all of this is a structural fragility: a shortage of skilled workers. P02 noted, *“Skilled workers are moving to other industries where they find better conditions and pay.”* Without intentional transfer, the embodied knowledge, tacit judgement, and adaptive creativity that underpin dismantling risk vanish. Losing these skills would mean a loss of efficiency, leaving a gap that neither police nor automation could easily fill.

4.2.6 Practical Everyday Constraints

The theme is based on 19 coded quotations and grouped into four categories:

1. Space and layout constraints (9 quotations)
2. Logistics and bundling constraints (5 quotations)
3. Packaging as bottleneck (3 quotations)
4. Documentation as process burden (2 quotations)

This theme is meant to capture the grounded, physical and procedural realities that shape dismantling work long before questions of automation or circularity enter the picture. These physical limits cascade into logistical, packaging, and administrative pressures that determine how fast, safe, and economically parts can be recovered.

It begins with space and layout. Physical access is the most current currency of dismantling, yet it is chronically scarce: *"We currently have too little space to use"* (P06). Lifting platforms restrict access *"either from below or from the side"* (P05), forcing workarounds and breaking sequences into smaller steps. At one site, the workflow requires pushing the vehicle back and forth: *"First, we push the vehicle forward to create space […] to handle things in the interior […] This way, the pillars are out of the way. Once the interior is completely empty, we push the vehicle back, lift it up, and then remove the wheels."* (P10). Sometimes the problem is the vehicle's own geometry: *"The catalytic converter is huge, and the space between the engine and the bulkhead is very tight. […] You can hardly reach the screws, and if you want to remove [it …], the axle is in the way at the bottom. And to get it out at all, you sometimes even have to destroy the water tank."* (P07). And then there is the issue of storage: *"If you dismantle vehicles really thoroughly, how many 'piles' can, or should you make? Do you store each aluminium alloy and each type of plastic separately? […] This raises not only the question of purity but also of available storage space."* (P20).

These spatial realities spill directly into logistics and bundling. Without sufficient volumes, certain recovery streams are not worth initiating. P20 recounted the case of control units: *"A recycler will gladly pay me for them. But only if I have four tonnes […] I'll be long retired by the time I've collected that many."* Condition on arrival can eliminate recovery options before they start: Pre-pressed bodies save transport costs, but *"this means that the body is already deformed […], making removal impossible"* (P15). Even routine compliance adds planning complexity; for example, arranging for the legal and economic handling of a leaking (*"incontinent"*) vehicle requires advanced coordination across transport, containment, and dismantling: Even compliant handling can be a logistical puzzle: *"Who transports it and how? As the person accepting the vehicle, I am responsible for* *ensuring that everything runs according to the rules. […] Just because a car is leaking doesn't mean it's not valuable. But it does require a clean, well-thought-out process”* (P13).

Once parts are removed, packaging can become a bottleneck that constrains the entire operation. P09, asked what they would remove from the process, replied without hesitation: *“Packing the boxes. Packing and wrapping”* (P09). In some teams, packaging occupies one worker full-time while the other continues dismantling (P08), breaking the rhythm of paired work. Heavy or awkward parts, like fully equipped doors, require careful handling: *“It will fly out of your hands if you don’t secure it properly” (P13),* and lifting aids are not always available. Packaging is also tied to presentation, with managers insisting that parts be wrapped, labelled, and photographed *“in the way you would like to receive them yourself at home”* (P13), adding time but ensuring market readiness. Finally, documentation introduces an administrative layer that is both compliance-driven and, for some workers, a source of friction. Regulations require serial number logging for certain parts, detailed labels, and photographic proof. P07 admitted, *“Paperwork just isn’t my thing,”* while P13 noted a more systemic skill gap: *“Documenting everything neatly, packing, labelling […] some have been with the company so long they simply don’t want to fill out forms anymore […] and hardly write anymore, certainly not by hand […] even letters are confused, a Z, a two, an R, a K […] it’s often illegible.”* This mismatch between administrative demands and workers’ writing or typing habits leads to errors, omissions, or delays.

Taken together, these accounts reveal dismantling as a *tightly coupled system* where floor space, storage configuration, part flow, packaging throughput, and documentation capacity interact in real time. They shape what can be recovered and how quickly, as much as—and sometimes more than—the design of the vehicle itself. Strategies for automation or circularity that ignore these embedded realities risk designing for an idealised workspace. In practice, it is these ground-level constraints that determine the boundary between what is theoretically recoverable and what actually leaves the hall in market-ready form.

4.2.7 Automation Strategy and Implementation Logic

The theme is based on 79 coded quotations and grouped into eight categories:

1. Task-specific automation
    a. Heavy and ergonomic (13 quotations)
    b. High-value components (3 quotations)
    c. Initial inspection and depollution (11 quotations)
    d. Universalizable and standardizable (10 quotations)
2. Flexible automation architecture (5 quotations)
3. High automation potential for material retrieval (9 quotations)
4. Manufacturer-specific automation (4 quotations)
5. Mobile, on-demand robotics (4 quotations)
6. Practicability and acceptance (2 quotations)
7. Precision handling and advanced tooling (8 quotations)

8. Undefined states, takt time, and site constraints (10 quotations)

This theme is meant to capture how stakeholders imagine and delimit automation in dismantling: not as a monolithic “full automation” vision, but as a set of tactical moves constrained by real-world conditions. Across the interviews, automation strategy emerged less as a question of can we build the technology? And more so, where will it actually work, under our constraints, and pay off? The clearest traction points found were in task-specific applications: relieving heavy and ergonomic loads, targeting universalisable components, or recovering high-value parts. These are all framed by the ground rules of dismantling—undefined vehicle states, takt time pressures, and site-specific limitations.

The context setting often starts here: dismantling lines do not operate in the clean predictability of production [30] and each site has its own layout, approvals, and throughput rhythm: *“Vehicles usually arrive in a very undefined state,”* as P27 argues, often in degraded condition or inaccessible; hence, *“It makes sense to create a defined starting point through manual preparatory work and then initiate automation steps from there […] Sure, the vision is that the car drives in and is dismantled fully automatically. But the effort required […] is enormous.”* Some stakeholders pointed out how small, seemingly simple tasks can become highly variable in practice.

Wheel locks are a frequent example: *“simple in theory, but in practice there is great variation and resistance”* (P18) and even visual inspection tasks can be problematic (*“how can I tell if a plastic clip is positioned correctly?”* P19). This variability interacts with takt-time economics: *“Automation is worthwhile from around 15,000 units and with cycle times of no more than 15 minutes”* (P18). Before investing in robotics, operators weigh basic feasibility factors like “*What property is available? Is the hall suitable? Is it located in a water protection area? What about fire safety and floor conditions?”* (P13) alongside business risks: *“If I purchase a robot that has to be amortised over months, but the real benefit is unclear, then that is economically questionable”* (P10). P13 stressed that *“before you even think about automation, you need to be clear about how big the whole thing is going to be. […] the scope of the approval depends on it: […] what kind of residues or waste will be produced? […] If you process 2,000 vehicles a year, what will be left at the end?”* Against this backdrop, the strongest arguments found in the interviews for automation were task-specific.

Against this backdrop, the most compelling automation arguments in the interviews targeted specific, well-defined, and ergonomically demanding tasks. Many dismantling jobs are dominated by weight, reach, and repetition, making them prime candidates for machine assistance. Participants repeatedly named large exterior panels, wheels, seats, batteries, and modules. Components are getting heavier (*“Vehicles are getting heavier and heavier, and so are their components. This puts a strain on employees”* P05, cf. Figure 10), and certain tasks create notable ergonomic burdens—*“especially […] 21- or 22-inch wheels”* that leave workers *“feeling it* *all over your body after stacking them up"* (P07), or seats whose "*removal has been very time-consuming up to now, especially because of airbag connections*" and mounting variability (P16).

Robots could help by *"placing heavy doors in transport crates, transporting parts over long distances"* (P10), or removing lids, hoods, bumpers, and underbody panels—anything *"accessible from the outside"* that can be worked *"from the outside in to create space"* (P01). Some see early opportunities where the task is already well-structured and the risks to humans are high, such as battery module handling: *"high risk to humans, clear task structure, suitable for robots […] the robot could also generate profits here"* (P10). Even hazardous steps like *"the removal of windows: sawing them out causes glass dust, therefore requires protective measures, and is dangerous, which is why automation would be ideal here"* (P16). Wheel removal was a recurring example of being characterised as heavy, repetitive, and standardised enough that *"machine assistance can already provide real relief and efficiency here, both ergonomically for the worker and economically"* (P03).

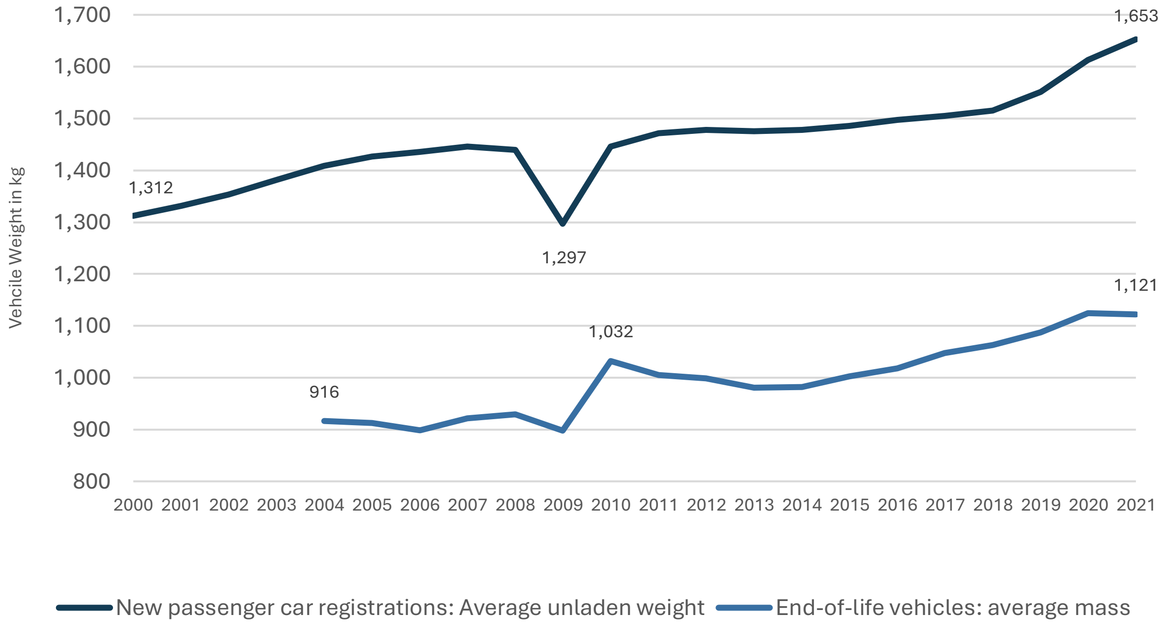


Figure 10. Average weight of old and new vehicles in Germany. Figure based on German Environment Agency (German Environment Agency 2024)

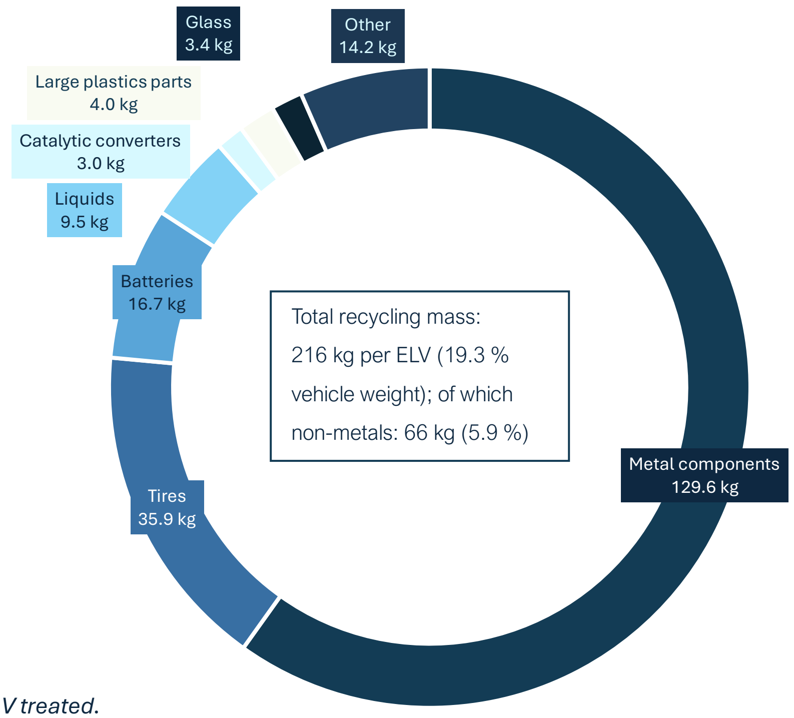
From a systems perspective, standardisation was viewed as the bridge between prototype automation and scalable deployment. Parts that are common across models have consistent geometry and predictable access points, creating automation footholds: *"Certain process steps should also be made more efficient with machine support, for example, for the 30 components that are common to most models"* (P03). The majority of participants mentioned wheels as a suitable automation starting point. P11 contrasted these with complex multilayered components: *"Tires usually include rubber, the metal rim, often aluminium, and steel screws or* *other parts. Their relatively simple composition makes them easier to handle compared to […] dashboards or interior trim."* P14 based their argument on repetition: *"There are many repetitive tasks, such as wheels."* and P16 sees *"potential where high removal rates can be achieved, for example with wheels: large, valuable parts such as 20-inch rims with good access to screws. Doors, flaps, and fenders are also relatively easy to access and currently physically demanding for workers."* Windscreens, while more variable, were also discussed in light of incoming regulatory requirements that every pane be removed separately (*"In the future, there will be no more exceptions; every pane must be removed separately"* P10). Where design variability is low, automation is easier. The guiding idea: if a part's material composition and attachment points can remain stable over time, it becomes a reusable automation module in the dismantling process.

Where mentioned variability or decentralisation make fixed automation impractical, some participants saw potential in mobile systems (*"Mobile robots would be ideal,"* P10) that *"could drive to the vehicle […] and start dismantling it straight away"* (P10), bringing the tool to the car, rather than the other way around. This model allows for targeted deployment on recurring but distributed tasks like door or wheel removal and could be more easily approved and adapted to current facilities. Stakeholders described use cases such as fully removing battery screw connections without the overhead strain of manual work. *"I think a system like this would be well accepted"* (P10). Even if slower than human work, *"a robot may take four times as long […] but it can work around the clock"* (P24). Future visions involved AMRs with collaborative arms, coupled to digital product passports that would *"not only provide the material data, but also […] the assembly sequence from which the disassembly steps can be derived"* (P25). The trade-off: speed and throughput give way to flexibility and cost-effectiveness for varied or remote processes, as *"the production or disassembly concept must then also be adapted accordingly. You don't just integrate an AMR into a classic industrial robot line—you redesign the entire line"* (P25).

Several interviewees argued for focusing automation on a narrow set of high-value targets first. Cable harness extraction was one example: *"It is almost impossible for a human to pull out a complete cable harness […] A robot arm with sufficient power could simply pull it out […] which would be an enormous help in raw material recycling"* (P05). Outer components with good access may be automated relatively soon, but *"internal parts with complex interconnections become much more challenging"* (P11). In this view, full-vehicle automation—once again—remains a distant goal; near-term gains will come from combining automation modules with manual work, targeting overlap between value recovery and ergonomic relief, and keeping usability central: *"It has to be user-oriented, not just technically possible"* (P11).

After discussing what tasks to target, this part shifted toward *how* automation could function as a system and under what conditions it would be worthwhile. Once the focus shifts from individual components to material flows, the equation changes. Bulk recovery offers scale, and with it, the possibility of justifying investment in specialised tooling and destructive methods. As one P01 put it, "Material *extraction requires a rough* *mechanical approach, e.g., hot cutters. But as soon as spare parts come into play, precise, non-destructive processes are needed, and we are still a long way from that today"* (P01). This distinction between raw material recycling and parts recovery runs through many interviews. In pure recycling, throughput is prioritized; aesthetics are irrelevant. *"No humans are needed there,"* P05 argued*, "but it's different when it comes to spare parts: every vehicle is different […] many of these tasks can only be solved with human experience."* However, in raw-material recovery, destructive removal of standardized items *"to obtain material fractions that are free of impurities"* could be used more strategically (P03). The appeal of *"total scrapping"* was bluntly expressed by P07: *"just photograph the chassis number, enter it in the list, and add my name. No packing boxes, no sorting, no small parts management, nothing. It's just less work."*

Several participants saw potential in hybrid models that combine human loosening with robotic extraction. As P10 put it: *"A robot […] recognizes certain components, such as electric motors or aluminum elements, and simply pulls them out […] Humans loosen the screws and robots take over the removal. After all, no robot can handle screwed-in bearings unless it destroys them."* P23 suggested prioritizing *"components with high mass, risk, or reuse value",* handled with hydraulic shears, grinders, and saws as readily as with wrenches. For P20, the material case is reinforced by the decarbonization argument, pointing out that current dismantling recovers only a fraction of valuable glass and plastics: *"only around 2–4 kg of the average 30–35 kg of glass in an ELV is actually dismantled. The ratio is similar for plastics: over 100 kg, only around 4 kg is removed. Bumpers, tanks and battery housings are potential areas for automation"* (see Figure 11). The challenge lies less in the tools themselves than in deciding where the cut-off point lies, when to unscrew, and when to cut.



Total recycling mass: 216 kg per ELV (19.3 % vehicle weight); of which non-metals: 66 kg (5.9 %)

Average weight of ELV in 2021: 1,121 kg.

Amount in kg per ELV treated.

End-of-life vehicles accepted and processed by dismantling companies in Germany in 2021: 396,773 units.

Figure 11. Recycling of dismantled materials from end-of-life vehicles in Germany 2021. Figure based on German Environment Agency (German Environment Agency 2024)

Automation could also intervene *before proper dismantling* as a gatekeeper. Preparatory processes like *"drying, fluid extraction, wheel removal, possibly scanning systems for vehicle identification"* (P02) not only improve safety but also create defined starting conditions for downstream automation. P03 imagined AI-supported intake systems that *"record the condition and reusability of components"* and route vehicles into different processing paths. P04 pictured conveyor-based halls where *"vehicles arrive, go through a car wash, then an automated visual inspection, […] and all-round image documentation. The vehicle then drives into a hall, is assigned to a stage, and is dismantled there manually, and the parts go directly to the warehouse […]. Fractions such as plastic, metal, and glass leave the building separately."* Automated vision systems could also assess if, *"for example, a car window is badly scratched. [then] it is not worth removing it at great expense; it can simply be destroyed"* (P25). Another possibility would be to assess whether a vehicle is original or modified and whether sorting by type is necessary at all (P25). The underlying logic is simple: the better the intake, the more predictable the dismantling (*"it can take photos and document the part number. The aim is to provide proof, check the series status, and prepare for sale"* P10). But the technological leap is significant, requiring systems that not only recognise components but also decide what to do with them.

For many high-value or ergonomically critical tasks, the limiting factor is neither motivation nor process design but the mechanical dexterity of the system. End-effectors must handle delicate connectors, recognise hidden fasteners, and adapt to small variations in geometry: *"Many components are elaborately screwed together […] A robot with a camera system has to recognize the screws in the wheel housing, under panels, behind bumpers. And then work cleanly"* (P01). The vision is for robots that can both *"pull out a plug and disconnect it in one step*" and handle the fragile pins without damage (P10). This requires adaptive control and responsive sensor feedback: *"a human intuitively knows whether a part is correctly positioned. A robot can only detect this with sensors and appropriate control systems"* (P26). This technical sophistication links directly to design decisions upstream. Where connectors, fasteners, and geometries are standardized, tooling can be both simpler and faster. Where they are not, precision handling becomes the bottleneck.

If variability is the constant, then flexibility must be the architectural response. Interviewees warn against locking into rigid, single-purpose systems. *"Don't think in terms of fixed models or standards,"* P03 advised, *"develop an open, adaptive logic."* P13 recommends parallel lines.

> "One line just for electric vehicles […], and a second one for combustion engines and mixed vehicles […]. I would only partially automate the combustion engine line, as there are more variants here. At the same time, you always need flexible work areas, e.g., lifting platforms for special work such as glass roof removal, because these are dirty processes that should not take place on a conveyor belt. Set it up more like a production line, with defined cycle times and a clear process structure […] You start with wheel removal, then doors, roof, underbody, depending on what you want to achieve. Important: You always need to be able to remove vehicles from the process, e.g., for special tasks or if a problem arises. The car can then be processed separately with a forklift or Stringo without disrupting the main process."

Such architectures would also allow phased adoption. In the early stages, many connections may still be manually loosened before automation takes over; over time, design convergence and digital product passports could shift that balance (*"It's an evolutionary process. We're already seeing that camera systems need 30 days of training just to pick up loose battery parts from pallets."* P25). The goal is not universal coverage from day one, but an infrastructure that can evolve.

A niche strategy, but one with potentially high returns, is to focus on single-OEM or even single-model dismantling (*"It would make sense for the future to focus initially on certain models […]. This would allow a stable inventory of parts to be built up […], which would be attractive and reliable for customers."* P03*)* because tailored lines can achieve efficiencies impossible in mixed-flow operations (*"I don't believe in a 'miracle plant' […] But I do think a manufacturer-specific dismantling line is realistic"* P24). Here, control over both the product and the data enables precise tooling, faster cycle times, and quality assurance for recovered parts, as P24 argues: *"Processes change. Think back to the early days of just-in-time production – no one would have believed back then that external suppliers would be working directly on the VW premises. Today, that's standard practice. In this respect, I can well imagine that at some point we will have robots with VW's own control system that are located on a recycling site but are operated completely autonomously within VW."* Some even imagine dismantling becoming an OEM-controlled process, either in-house or through specialist clusters with privileged data access (*"Whether vehicle manufacturers will eventually integrate dismantling into their own process chain. This would have clear advantages: lower repurchase costs for materials, more control over quality, fewer dependencies. I could imagine two models emerging in the future: Either the OEM will take over itself, or specialized clusters will emerge."* P27).

Finally, the sobering reminder: no matter how advanced the system is, it will fail if it doesn't fit into the working culture. Robots that slow down the process, manipulators that disrupt established storage workflows, or wearable aids that make workers feel constrained—these all end up *"standing unused in the corner"* (P10). Adoption hinges on speed, ergonomics, and user agency. If automation makes the job harder, it will be quietly sidelined, no matter how technically impressive it is.

4.3 Conceptual Synthesis: Coordination Failure

Having explored each theme individually, the next step is to examine their shared underlying logic and to consider what this means for intervention. To do this, I mapped their interconnections into a nomological network, following Dorst's [204] (see Figure 12). What emerges is what can be summarised as systemic coordination failure. This construct captures the persistent inability of the ELV dismantling system to act as a coherent whole, despite the formal presence of regulations, market mechanisms, and advanced technical capabilities. It is not the absence of rules, actors, or technology that defines the problem, but their chronic misalignment and inability to operate in synchrony.

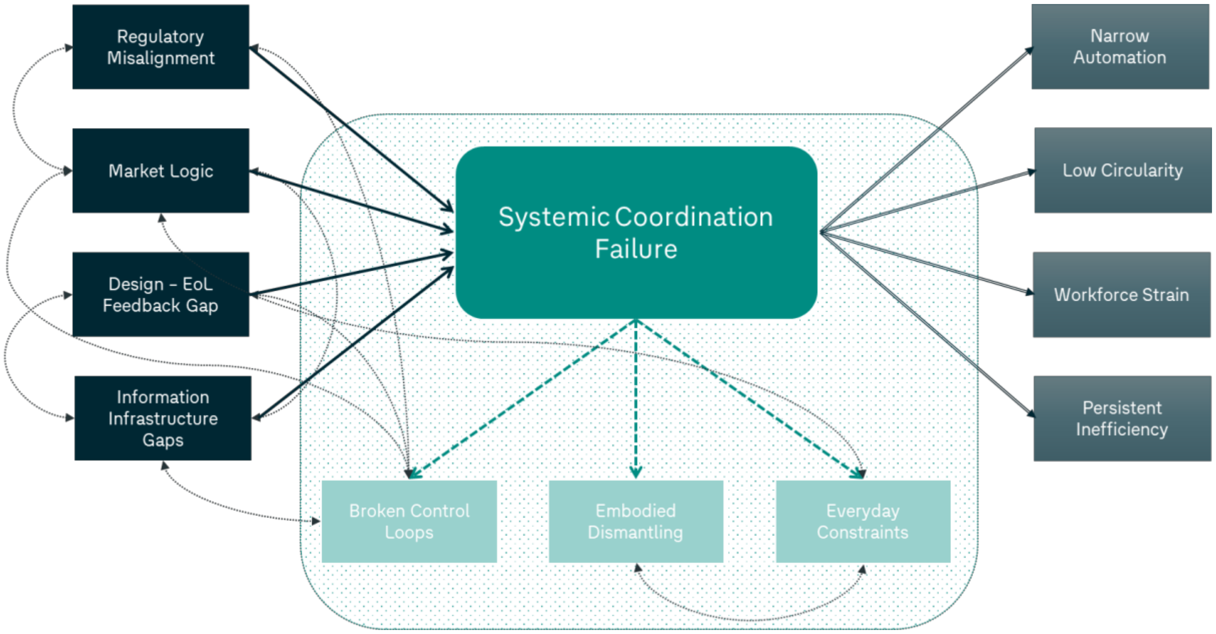


Figure 12. Nomological network of extracted themes.

Several structural antecedents feed directly into this failure. Regulatory misalignment layers ambitious requirements on top of one another without resolving contradictions or clarifying execution, producing compliance effort without coherent direction. Market logic as a barrier ensures that production-side economic drivers consistently outcompete ecological imperatives at the end of life, locking circularity efforts into marginality. The feedback gap between design and EoL entrenches material and joining choices for decades, with no systematic loop to challenge or improve them. Information infrastructure gaps prevent the formation of a shared situational picture across the system, forcing actors to decide in isolation from one another. These relationships form a closed loop of stagnation: regulation without coordination fails to create viable markets; missing data blocks feedback and learning; worker adaptation normalises structural constraints; and the diffusion of responsibility holds the whole cycle in place.

Operational dimensions make this breakdown tangible. Broken control and obligation loops mean no single actor feels—or is empowered to take—responsibility for the full process, whether technical, economic, or ecological. Human-embodied disassembly practice holds critical tacit expertise, yet this knowledge remains disconnected from upstream decision-making. On the dismantling floor, practical constraints—tight spaces, heavy parts, unpredictable vehicle conditions—set the outer limits of what is achievable, regardless of strategic ambition or regulatory demand. The consequences are predictable and self-reinforcing. Automation strategy and implementation logic narrow to site-specific, tactical fixes rather than coordinated transformation. High-value recovery opportunities are routinely lost. Skilled practitioners exit the workforce, taking with them irreplaceable experiential knowledge. Across technical, economic, and ecological dimensions, inefficiencies do not dissolve—they compound.

5 Frames and Futures

A frame is a deliberate way of seeing a problem and a complementary way of acting within it. As Dorst [204] argues, framing is the hinge between values and action: once a credible frame is proposed, concrete elements can be designed and tested against the intended outcome; until then, he writes, a frame remains a working hypothesis for how to move.

5.1 Grounding Coordination Failure in Prior Research

This section validates the central theme identified in the empirical analysis—systemic coordination failure—by situating it within established research. My interviews made clear that dismantling struggles are rarely isolated technical problems alone but reflect deeper breakdowns in how interdependent actors align. To give these insights conceptual weight, I linked them to academic literature across a variety of fields. This establishes the theoretical scaffolding for the frames developed in the following section. As shown in Figure 12, I placed systemic coordination failure at the centre and surrounded it with close terms and observed patterns of action. This visual served as the bridge: it mirrors the issues voiced in interviews against established mechanisms in research. The literature confirms what practitioners described: coordination failures appear across disciplines whenever interdependent actors struggle to align their actions.

5.1.1 Mechanisms of Systemic Coordination Failure

While coordination can be characterised as the attitudes, behaviours, and outcomes of the joint *determination* of common goals, cooperation refers to the attitude, behaviour, and outcome of the *implementation* of those goals [211]. In the case at hand, both poor cooperation and failed coordination are evident. Such breakdowns are not random but stem directly from the structural features that shape interaction. Holahan and Lubell [212], drawing on collective action theory, frame this as a dilemma: short-term individual gains often outweigh the long-term benefits of collaboration. They argue that solutions usually take the form of institutions that shift incentives, making cooperative outcomes advantageous to individuals.

Recurring dynamics echo across fields. Information asymmetry, for example, undermines supply chain coordination (cf. [213]). Ivanović et al. [214] show how modularity can solidify local optimisation islands that resist system-wide coherence under disruption. Their work highlights that it is often the small, everyday disturbances that generate the bulk of operational and financial losses. They argue that combining long-term decentralisation and loose coupling with short-term centralisation—breaking routines to temporarily restructure—is the most effective way to contain disruption.

Power asymmetries, affordances[89] embedded in artefacts, and path-dependent design decisions also reveal how complexity accumulates and persists into dismantling. Here too, the literature shows that rigid, sector-specific organisational structures hinder the cross-sector collaboration required for complex projects. In eco-city planning, this rigidity obstructs the integration of environmental concerns [215]. In high-stress contexts such as trauma care, the absence of explicit verbal communication during unexpected procedures produces conflicting actions, missed support, or unsafe improvisations [216]. Behavioural and cognitive factors amplify these structural problems: actors routinely underestimate the difficulty of coordination ("coordination neglect", Fehr [217], project past successes onto new contexts, and, under strategic uncertainty, expect low effort from others and scale back their own, producing collectively suboptimal outcomes [218].

High-risk environments make these mechanisms especially visible. Coordination is only restored—if at all—through communication-intensive workarounds and flexible role negotiation, which remain fragile under cumulative pressure [216, 219, 220]. Taken together, these insights confirm the central proposition: addressing systemic coordination failure—rather than optimising isolated tools—offers the most promising leverage for designing human-centred and economically viable automation in ELV dismantling.

5.1.2 Interventions and Strategies for Overcoming Coordination Failures

The literature does not stop at diagnosing failures. Across domains, researchers have converged on a repertoire of remedies that can be grouped into three families: improving information flows, restructuring organisational networks, and aligning incentives and governance. Each family addresses a different layer of the coordination problem, and together they map the conceptual ground on which new frames for ELV dismantling can be developed.

The most immediate interventions improve how information circulates among interdependent actors. Coordination improves when the flow is explicit, granular, and timely—through, e.g., shared dashboards, traceability, and clear signalling in time-critical settings [216]. Beyond tooling, cognitive artefacts[90] that visually render group processes can act as oblique aids to joint problem-solving and shared situational awareness [220]. At the systems layer, Gu et al. [221] show how integrating information systems with product-lifecycle management can support eco-design and cleaner production by making decision-relevant data available when and where it is needed, eliminating redundancy and strengthening cross-system interactions. Seidel et al. [222] complement this with design principles for information systems that actively scaffold organisational sensemaking via salient affordances and lightweight decision devices, for example, voting mechanisms that surface what matters the most, separate behavioural from infrastructural levers, and keep users engaged

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[89] Action possibilities that an object or environment offers to a user, based on both its physical properties and the user's capabilities. In design, affordances describe how users perceive and act upon functionalities

[90] Human-made objects that maintain, display, or operate upon information to serve a representational function. They extend or augment human cognitive abilities by helping individuals store, process, or share information (e.g., calculators, maps, or digital interfaces)

through open communication and feedback. The common thread is not “more data”, but legible data with purpose, embedded in workflows that people actually use.

Regarding embodied interaction contexts, the Coactive Design framework adds that coordination depends not only on information but also on how interdependence is structured between actors. Its central principle is that autonomy must be shaped by interdependence, requiring that agents make their state and intentions observable, their behaviour predictable, and their actions directable when circumstances change [223, 224]. Interdependence extends beyond “hard” dependencies, filling only capacity gaps, to “soft” or opportunistic interdependencies, where collaboration actively enhances efficiency, robustness, or safety. To make these interdependencies workable, Coactive Design defines three requirements: observability (agents must be able to perceive each other’s relevant state and actions), predictability (agents must be able to anticipate likely next steps), and directability (agents must be able to guide or be guided when circumstances change).

A second family of solutions reframes the organisation itself—re-networking rather than merely retuning. Yuan [225] underlines the importance of managing public sentiment and stakeholder expectations in major initiatives, arguing that understanding the affordances of large multi-actor projects can prevent social lock-in and, crucially, that engaging peripheral stakeholders early helps justify decisions and navigate complexity. Yin et al. [215] operationalise this idea through temporary multi-organisations as cross-sector instruments that break barriers and generate integrated environmental solutions for the case of complex urban projects. Their findings are pragmatic: political will and consistent sponsorship grant legitimacy and reduce conflict; interactive participation builds shared understanding; and capacity-building programmes—with early, broad involvement—improve the odds of mutual solutions and sustained inter-organisational coordination. Adjacent arrangements include potential clearing houses in extended producer responsibility that standardise exchanges and reduce bilateral bargaining costs [226], and techno-political frameworks in reverse logistics that deliberately bind policy to process design [227]. In the EoL tyre context, Castañeda-Rodríguez and Pérez [227] propose a multi-objective optimisation model that integrates suppliers and recyclers into a cohesive network and uses stakeholder selection and capacity investments as governance levers, thereby turning conflicts among objectives into structured coordination choices. In the background sits a long-standing insight: ad hoc meetings and informal messaging are what organisations reach for when things get hard, but they rarely scale; formalised mechanisms that mediate and stipulate coordination work reduce complexity to a manageable level [228].

A third set of remedies addresses incentives. Contracting schemes that share liability and rewards and that institute cooperative governance make coordination individually rational rather than aspirational; healthcare’s

Accountable Care Organisations[91] are an example [229]. Yet structure is not sufficient. Experienced managers signal specific effort levels, foreground mutual benefits, and avoid ornate plans that confuse rather than align [230].

Groups that, after failure, endogenously rebuild their own communication norms also coordinate more effectively—evidence that *how* people talk (timing, content, expectations) can matter as much as the formal scaffolding around them [217]. This links to social identity dynamics that can modulate these mechanisms. Actors coordinate more readily with in-group members; cross-group coordination improves when leadership cultivates a superordinate identity that reframes “us vs. them” into a broader “we” (Tajfel and Turner 2004). Identity work can therefore be a design lever: by shifting who counts as “we”, leaders shift expectations—and thus the reachable coordination equilibria.

Governance frameworks can stabilize coordination by clarifying roles and decision rights, specifying transparent accountability, and institutionalizing routines that lower the cognitive cost of aligning across boundaries (Feiock 2008). Because coordination failures span individuals, organizations, and institutions, multi-level governance is often necessary: arrangements that connect local practice, organizational policy, and regulatory oversight reduce the risk that improvements remain isolated pilots. Finally, hybrid cooperative models show how governance can travel across sectors. Studying tropical pine, Rolfe et al. [231] find that leadership, information sharing, trust, market forecasting, risk sharing, accountability, and targeted technical support constitute the package that sustains coordination as the best business model across horizontal and vertical chains—with horizontal coordination proving more critical than vertical integration for maintaining commitments as systems scale.

Taken together, these insights highlight two things: first, that coordination failures are deeply structural and recurrent across domains; and second, that remedies are available, but they rely on deliberate re-design of information flows, organisational networks, incentives, and governance. This dual recognition provides the theoretical grounding for the next step: the development of frames that reimagine how systemic coordination failure in ELV dismantling can be addressed in practice.

5.2 Frame Selection for ELV Dismantling Automation

The through-line across these studies is clear: make information legible and consequential, re-network organisations to match the problem’s topology, align incentives so coordination pays, and invest in the leadership and governance that keep these elements coherent over time. As described in the methodology, the identification of themes and frames first serves to expand the problem space before refocusing on the research

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[91] Health care organizations established primarily in the United States under the Affordable Care Act (2010). They are groups of doctors, hospitals, and other providers who voluntarily coordinate care for Medicare patients. The goal is to improve quality of care and reduce unnecessary costs by holding providers jointly accountable for patient outcomes.

question with an enriched understanding. Let us recall the central question: *How can automated disassembly systems for battery-electric end-of-life vehicles be designed in ways that address technical complexity while also enabling human-centred and economically viable strategies for recycling and material recovery?* From this perspective, it now becomes clear: the task cannot be understood as mere technologisation. Automation must instead be embedded into a systemic transformation, or, put differently, systemic transformation must be designed into automation.

The groundwork of this study shows that the question demands an approach beyond local cost–benefit evaluations of single tools. It requires attention to the interdependencies that shape outcomes across the entire ELV ecosystem. In practice, automation is often planned as a substitution of manual work to lower costs and improve cycle times. Yet this logic tends to deliver only incremental efficiency gains while neglecting regulatory linkages, work realities, feedback from design-for-recycling, and market dynamics, not to mention the basic conditions of raw material supply (here the ELVs) and product markets for the recovered outputs. Under such constraints, even successful pilot projects will most likely not scale easily, since they fail to address the deeper coordination costs and fractures in the system.

Only by placing coordination at the centre, I argue, can automation serve as a lever to realign technical capabilities, human roles, and economic incentives. If actors can be brought together through boundary-crossing projects (for example, temporary multi-organisations that break silos, cf. [215], new social identity dynamics may emerge that reshape mechanisms of alignment. Identity work can thus be a design lever: by redefining who counts as “we”. Political will and consistent sponsorship can secure legitimacy and reduce conflict, and capacity-building programmes with early, broad involvement improve the odds of shared solutions and sustained inter-organisational coordination. From this vantage, four design frames follow:

Frame 01: Automated disassembly as coordination infrastructure. Instead of seeing automation as task replacement, it can scaffold system-wide coordination by standardising and making information visible, for example, by implementing design principles using salient affordances and lightweight decision devices. For instance, intake condition assessments, transfer of product/joining data (e.g., digital product passports), feedback loops, traceability, and open interfaces for downstream steps can reduce planning uncertainty and duplication, enabling new resource mobilisation. This frame addresses the empirical themes of information gaps, responsibility diffusion, and the design–EoL feedback gap and picks up aspects from literature and policy.

***Frame 02:* Automation as Coordination Enabler for Manual Work**. If automation is approached not as substitution but as coordination support, it can remove systemic bottlenecks—documentation gaps, logistics, or split-second decisions between material recovery and spare parts—and allow workers to focus on higher-value recovery tasks. By embedding interdependence into design, automation shifts from substitution to coordination support, aligning human judgement with robotic precision to stabilise workflows under real-world variability. This frame addresses the empirical themes of logistics, embodied knowledge, and automation and implementation logic.

Frame 03: Automation as a platform for incentive alignment. Coordination becomes individually rational when better information directly translates into better economics: quality premiums for pure outputs, recovery/benefit-sharing contracts, neutral clearinghouses for data and flows, and shared KPIs across the chain. Such mechanisms stabilise material streams, lower sorting costs, and distribute value fairly—preconditions for scaling. This frame addresses the empirical theme of the market as a barrier.

Frame 04: Automation embedded in adaptive governance structures. Instead of hard-coding today's assumptions, modular procedures, adaptable standards, auditability, and scalable pilot sandboxes allow continuous adaptation to regulations, design changes, and market volatility. Clearly named integration roles, explicit decision rights, and multi-level governance ensure improvements persist rather than remain isolated pilots. Transparent accountability and institutionalised routines lower the cognitive costs of alignment across boundaries. Because coordination failures span individuals, organisations, and institutions, only multi-level governance can prevent improvements from evaporating. This frame addresses the empirical themes of broken control loops and regulatory misalignment.

5.3 Developing the Future of an Adaptive Coordination Platform

Once a proposed frame has been applied to the broadened problem space, it must undergo a process of coevolution [204]. Dorst [204] explains that the purpose of this stage is to test whether the frame can generate viable strategic directions for the specific problem field. What matters here is fruitfulness: does the frame open multiple potential pathways that can later be refined, and can these pathways be aligned with the interests of key stakeholders? The guiding question is whether the frame points to a future that different actors might consider worth pursuing.

I developed a future scenario based on the frames introduced and the visions articulated during the interviews. The intent is not to present a "best solution". Rather, the aim is to outline one possible direction that directly addresses the systemic coordination failure identified as the central barrier. Testing such a future in practice would remain the task of stakeholders and lies beyond the scope of this thesis. What this does achieve, however, is to prove whether an integrated vision can help dissolve existing tensions, create new alliances, and strategically anticipate the shift toward circular dismantling practices. The developed scenario directly builds on the interpretation of the selected frames and centres on an Adaptive Coordination Platform (ACP). The purpose of this scenario is to test whether a single configuration could simultaneously:

1. Coordinate fragmented actors across dismantling, recycling, and OEM networks.
2. Generate sustained demand for recycled grades that currently lack stable markets,
3. Adapt dynamically to changing conditions such as new vehicle architectures, shifting market logics, and evolving regulatory frameworks, and
4. Deliver tangible worker benefits by applying automation selectively to specific tasks rather than pursuing wholesale substitution.

5.3.1 Overview: Layered Architecture

The envisioned Adaptive Coordination Platform is conceived as an institutional “stack” that integrates three tightly coupled layers which are visually displayed in Figure 13: the material layer (what is physically done), the information layer (how decisions and traceability are generated), and the governance layer (how priorities, rules, and incentives are set and adapted). This architecture is designed to make dismantling predictable, investable, and learnable under real-world variability. Therefore, discussed aspects from the empirical themes as well as remedies identified in prior research [215, 222, 225-228] were included. The aim of this platform is precisely what Yin et al. [215] refer to: to connect stakeholders through a new, cross-company identity concept and thus fundamentally improve cross-group coordination structures.

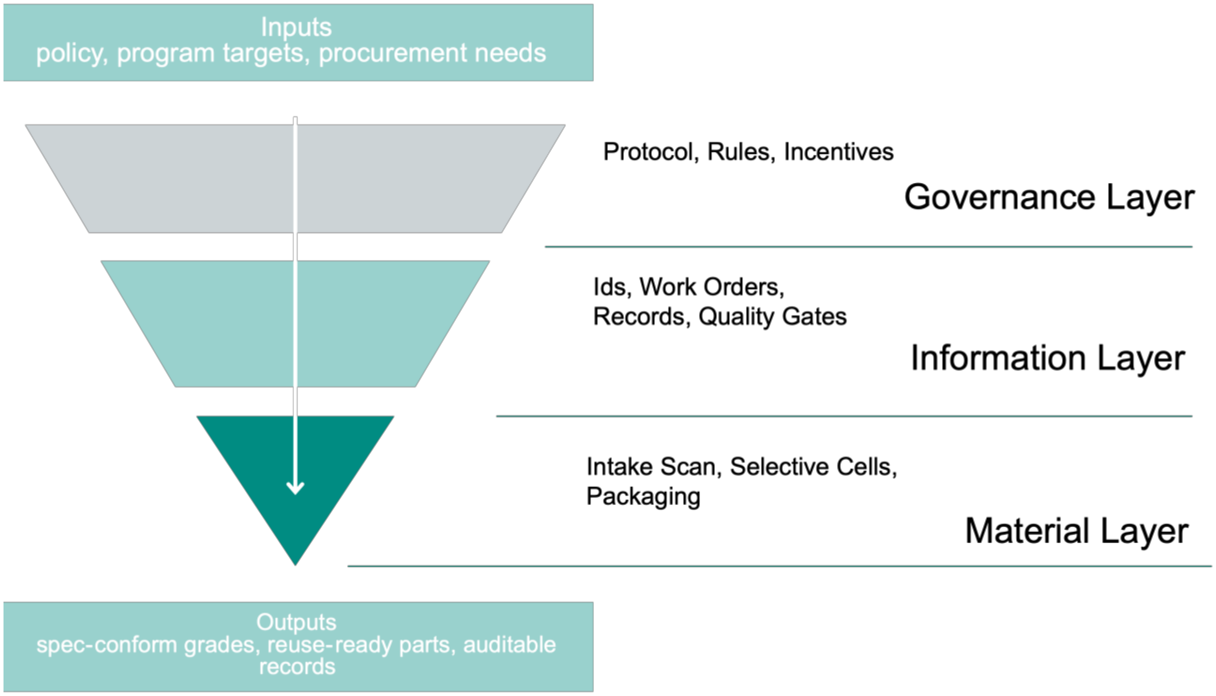

Figure 13. The envisioned adaptive coordination platform.

The Material Layer. This layer organises how each ELV enters the platform, is processed, and leaves as verified material grades or parts. Variability is treated as a baseline condition rather than an exception. As proposed in literature and interviews, automated cells carry out heavy, repetitive, or hazardous tasks such as high-voltage battery extraction, wheel and axle handling, adhesive separation, and wiring-loom withdrawal. Human operators supervise these cells, handle the inevitable edge cases created by model variation or wear, and validate quality, in line with Coactive Design principles that interdependence must shape autonomy through observability, predictability, and directability [223, 224]. Upstream, manufacturers define a limited set of standardized “recipes” for recycled materials, for example two to three polypropylene or polyamide blends. This will help to close the missing demand the interviews mentioned. Outputs leave the hub as specification-conforming material grades, such as copper harnesses at defined purity or clean aluminium housings. Independent laboratories sample each batch and issue certificates, which are linked to the digital record of origin, process parameters, and testing results, thereby establishing routines that institutionalise accountability and reduce the cognitive cost of cross-boundary alignment. To extend participation beyond large hubs, the platform issues targeted requests to smaller dismantling facilities, for instance, limited asks for wiring harnesses or bumpers in each month. These facilities receive simple identification codes and pack-and-pick kits, which avoid blanket “strip everything” mandates that are unrealistic for small operators. Such formalised coordination mechanisms scale far better than ad hoc messaging, which organisations typically resort to under stress but which rarely endure. To support downstream integration, clearing houses in extended producer responsibility can standardise exchanges and reduce bilateral bargaining costs [226], while techno-political frameworks in reverse logistics deliberately bind policy to process design [227]. In combination, these arrangements make dismantling predictable and investable, while ensuring that outputs meet both technical specifications and market requirements.

The Information Layer. This layer translates raw observations and market signals into executable plans and persistent records. Upon vehicle intake, a rapid scan and minimal digital product passport generate a work order that sequences targeted extraction steps, making life in the dismantling hall more efficient in line with aspects mentioned in the interviews. Selection is driven by live off-take contracts, programme targets for recycled content, and the relative carbon impact compared to alternatives. The result is a standardised plan that links process steps with grade specifications and safety constraints. Each graded output is then anchored to a digital record including provenance, processing steps, test results, and yields, which serves simultaneously as a contract basis, audit trail, and feedback loop to engineering and compliance. This fulfils the literature’s call for legible, purposeful information flows that scaffold coordination [216, 220-222]. Integrating information systems with product-lifecycle management ensures that decision-relevant data is available when and where it is needed, strengthening cross-system interactions and eliminating redundancy [221]. To maintain usability, data exposure follows a need-to-know logic: dismantlers see task lists, timing, and pay codes; recyclers and compounders receive batch specifications and forecasts; manufacturers monitor carbon balances, recovery performance, and design-for-environment insights; and programme management tracks financial outcomes and avoided emissions. Such graduated observability reflects Coactive Design requirements for effective interdependence management [223, 224]. Because information is captured as work happens, the platform can surface indicators such as recovery rates, damage patterns, and quality drift, and it can forecast supply to reduce negotiation overhead and enable earlier planning, which is needed from stakeholders to make their business more profitable and therefore more sustainable. Smart manufacturing technologies provide the technical backbone for this transformation, offering real-time data gathering, system integration, and adaptive process control—capabilities increasingly applied to disassembly automation [24]. The Information Layer thus operationalises the first family of remedies identified in prior research by making information flows both actionable and embedded in everyday routines.

The Governance Layer. The Governance Layer converts strategies and rules into executable logic and incentives while ensuring the platform adapts under changing conditions. Membership requires adherence to a shared protocol that defines minimum data, interface standards, safety and quality requirements, and dispute mechanisms. Operating on these "rails" enables predictable settlement and trusted interfaces while supplying the data necessary for system learning. At its core, the task selection engine optimises portfolios of recovery targets against profitability, carbon impact, and contractual commitments. Here, algorithmic approaches such as block-based genetic algorithms [197], swarm-based methods like the Bees Algorithm [181, 198, 199], Particle Swarm Optimisation, hybrid Q-learning, fuzzy logic [182], and graph theory support task sequencing, motion planning, and real-time distribution of work [180]. The integration of real-time adaptation into disassembly sequence planning has demonstrated notable gains in both energy efficiency and cost-effectiveness [193, 194]. New regulatory requirements—such as take-back obligations, recycled-content quotas, or testing standards—are encoded as machine-readable rules with version histories and effective dates. Work orders update immediately, anomalies escalate to human review, and feedback loops retrain recognition models or refine procedures. This practice reflects multi-level governance principles that link local action, organisational policy, and regulatory oversight [232]. Incentive alignment is achieved through contracting schemes that share liability and rewards (cf. [229]). Norms and identity also matter, as they can foster a superordinate identity that reframes "us vs. them" into a broader "we" [233]. A lightweight steering group with representatives from different stakeholder groups oversees disputes and protocol updates, with decisions recorded to maintain a single source of truth. Finally, hybrid cooperative models illustrate that horizontal coordination can be more decisive than vertical integration in sustaining commitments as systems scale. The Governance Layer therefore consolidates the third family of remedies by aligning incentives, institutionalising accountability, and providing the adaptive scaffolding needed so that improvements do not remain isolated pilots.

5.3.2 Human-Centred Operating Model and the Role of Automation

The ACP is not premised on replacing human labour but on redistributing effort in ways that enhance value, safety, and agency. Automation is introduced selectively, targeting those steps where it delivers clear ergonomic relief, economic payback, and consistency in recovery. Human operators remain central as supervisors, exception handlers, and quality specialists, ensuring that automation strengthens rather than weakens human roles. This reflects the Industry 5.0 vision of cooperation and human agency as foundational, countering the risk of “quiet automation dominance” where people are expected to merely accommodate machine constraints [37].

In this operating model, dismantling shifts from physically demanding, repetitive tasks to higher-value activities. Operators become system supervisors, component analysts, or rule configurators—roles that formalise tacit expertise into recognised contributions. Coactive Design principles [223, 224] provide the foundation: human and robotic agents must be mutually observable, predictable in behaviour, and directable when conditions change. Interfaces are designed to minimise cognitive load and maximise transparency, using augmented reality prompts, structured checklists, and intuitive feedback loops to make collaboration legible and trustworthy [167]. Workers retain decision authority in ambiguous situations, with the ability to approve or override system suggestions and turn local improvisations into codified rules. In this way, invisible knowledge becomes visible, credited, and integrated into the system’s learning.

Automation is deployed most effectively in heavy, hazardous, or standardised tasks: battery and module extraction, wheel and axle removal, glass cutting, adhesive separation, or recovery of copper harnesses and aluminium housings. These applications echo the focus of disassembly research, which often prioritises partial disassembly of high-value or high-risk components such as batteries, motors, or electronic units [132, 140, 158, 159]. More comprehensive approaches appear in controlled remanufacturing contexts [51, 188], while hybrid strategies dynamically combine partial and full disassembly depending on component condition and recovery objectives [189]. A strong emphasis is placed on non-destructive disassembly for reuse or second-life applications [30, 145, 160, 180, 190]. Where design standardisation exists—wheels, bumpers, windows—automation can scale; where variability persists, semi-automated or manual interventions remain more efficient.

From a process perspective, structured disassembly involves five recurring stages: acquisition and condition assessment, representation and classification, sequence planning, task allocation, and adaptation to variability. Each stage offers opportunities to distribute tasks between humans and machines according to skill, complexity, and ergonomics. Parallel disassembly, where multiple tasks are performed concurrently, has been shown to improve throughput in multi-agent robotic systems. Adaptation remains crucial, as ELV flows are inherently diverse. Flexible, modular cells—supported by mobile or collaborative robots—replace rigid lines, enabling facilities to handle both BEVs and ICE vehicles under shifting market and regulatory conditions.

Yet technical efficiency alone does not guarantee effective collaboration. Psychological and organisational factors shape the quality of human–robot interaction. Unpredictable system behaviour, limited transparency, or high cognitive load can erode trust and increase stress [167]. These effects are amplified by industrial stressors such as noise, time pressure, and managerial oversight. Minimal training and poor introduction to collaborative systems often exacerbate frustration or resistance [169, 170]. Addressing these risks requires not only intuitive interfaces but also attention to the work environment and training pathways that support professional progression from operator to supervisor or analyst. The resulting operating model is one of true complementarity: humans and robots perform the roles they are best suited for, each making the other more effective. In practice, this means automation removes physical strain while humans provide judgement, adaptability, and oversight. The ACP thereby creates dismantling work that is safer, more predictable, and more meaningful, while improving the quality and consistency of material recovery.

5.3.3 Economic Logic of Incentive Alignment

The ACP is designed to be profitable not by maximising volume alone, but by embedding demand creation, risk sharing, and reduced coordination costs into its operating model. Its central proposition is that circular recovery can only scale if incentives are aligned across dismantlers, recyclers, and manufacturers. By stabilising demand, de-risking investment, and lowering transaction frictions, the platform creates conditions where each actor benefits economically from participation.

At the heart of the system are long-term purchase commitments. Automakers and Tier-1 suppliers[92] enter rolling three- to five-year contracts for specific recycled grades. These contracts are structured with price-collar clauses: when market prices fall, recyclers are shielded from losses, and when prices rise, benefits are shared. This contractual stability enables recyclers to justify capital expenditure on higher-quality preprocessing equipment, which would otherwise be too risky. For dismantlers, profitability comes from targeted dismantling tasks. The platform issues clear work orders tied directly to contracted material streams. By matching tasks with active demand, recovery efforts remain both efficient and economically worthwhile.

The platform distributes risks that currently discourage investment. Performance warranties, underpinned by laboratory testing, guarantee recyclers and compounders that material specifications will be met. OEM-funded inventory buffers smooth seasonal scrap flows, protecting recyclers from supply shocks. Because recycled grades are pre-qualified and embedded into manufacturer systems—product lifecycle management databases, bills of materials, and engineering toolkits—they become the default option for designers. The engineer no longer must “fight” for recycled content: it is presented as a ready-to-use, low-risk choice. These mechanisms also enhance investment security. Transparent records of recovery rates, CO_2 savings, and compliance evidence reduce risk for financiers, who can now evaluate facilities and processes on auditable performance metrics. With stable contracts, warranties, and transparent data, investors and leasing companies can fund equipment with confidence.

The platform itself acts as a market infrastructure. Regional preprocessing hubs, co-owned by recyclers and Tier-1 suppliers, aggregate flows from small dismantlers, ensuring that even family-run facilities can participate

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[92] Companies that supply components, systems, or modules directly to an OEM. In the automotive industry, Tier-1 suppliers deliver critical, often highly engineered parts (e.g., seats, braking systems, electronics.

without managing the full complexity of quality assurance and logistics. Forward demand curves and batch quality assurance are managed through a closed-loop exchange, making flows predictable at scale. Because rules and contracts are encoded into the platform's governance logic, new business models can be introduced without wholesale redesign. For example, carbon-adjusted procurement or "materials-as-a-service" schemes can be layered on top of the existing rails. This adaptability ensures that the system remains profitable even as regulatory and market conditions evolve.

Profitability also emerges from reduced waste and overhead. Standardised work orders cut negotiation time, encoded protocols reduce compliance disputes, and reliable process execution decreases rework and rejection rates. Together, these reduce transaction costs across the chain—or, as Ivanović et al. [214] argue, the small, everyday disturbances—freeing up margins that are often lost in today's fragmented arrangements. The economic model also includes platform-level revenues. Members pay access and transaction fees to use the coordination rails, while additional revenue comes from data services—dashboards on recovery performance, CO_2 balances, and forward supply forecasts. These revenues finance the upkeep of the platform and the evolution of its governance logic.

Who pays and why:

- Automakers and Tier-1 suppliers pay for access to compliance dashboards, design feedback, and legal cover, and they commit to long-term offtake contracts that deliver reliable circularity claims.
- Recyclers pay price premiums for specification-grade feedstock, justified by lower sorting costs, stable quality, and higher equipment utilisation.
- Dismantlers and small treatment facilities pay modest fees for platform access, which are outweighed by faster payout, clearer work orders, and reduced negotiation risks.
- Platform operators capture access and data revenues, which fund the maintenance of the coordination rails and ensure continued alignment.

5.4 Transformation and Implementation

After the future scenario of an ACP has been elaborated, the purpose of this chapter is to determine which frames and directions can realistically be implemented—what needs to change in the concept itself and what needs to change in stakeholder practice. Frames that would require radical organisational shifts from actors with little incentive to move should be filtered out. To support this filtering, several possible implications were explored and critically assessed through expert feedback.

A dedicated focus group was convened with selected experts With selected experts who are currently working on this topic within Volkswagen. The background, motivation, and objectives of the study were explained, and the underlying theme of systemic coordination misalignment, together with the envisioned ACP future, was presented for discussion. On this basis, experts assessed which implementation paths appear realistic and which are less likely to materialise. The outcome is a transformation agenda that combines short-term, practical measures with long-term commitments to gradually adapt routines, roles, and interfaces. This dual horizon ensures that proposals remain both actionable and adaptable over time.

Because there is no single way to realise an ACP, several alternative implementation configurations were developed. All preserve the coordination layer—the shared protocol, quality assurance, and data services—while varying asset ownership and physical footprint. However, for all of them it is agreed on phased automation and on tailored objectives for automation; distinguish between bulk recycling and automation for spare-part recovery.

(1) Hub-and-Spoke. A regional hub operates the full layered architecture. Mobile micro-cells visit smaller ATFs to conduct intake and first separation on-site, shipping semi-processed modules back to the hub for grading and settlement.

(2) In-Plant Reverse Line. A compact reverse line within a manufacturer's remanufacturing or refurbishment site. It uses the ACP protocol to process returns and test design changes against end-of-life realities under controlled conditions. Because this configuration remains entirely under OEM control, data does not leave the company. Starting with a single brand or model concentrates inventory, accelerates return on investment, and simplifies quality assurance.

(3) "Dismantling API." A purely digital service (software and data interface) that allows independent ATFs to connect their own equipment to the ACP rails. Work orders, quality assurance, and certification are enabled without requiring adoption of the physical hub. Clear access rules govern which data can be viewed or modified by whom.

(4) Public–Private Guarantee. A minimum price floor for selected priority grades (such as copper harnesses or engineering plastics). This mechanism stabilises early volumes and unlocks private investment in the coordination infrastructure.

Planning on how to start, automation would first be applied to three high-impact steps: high-voltage battery removal, wheel and axle handling, and wiring harness extraction. Participants would include two ATFs of different sizes, one recycler or compounder with an active offtake agreement, one OEM engineering team, and one independent laboratory. The aim is to establish minimum data requirements and generate preliminary automated work orders. These can then be validated by dismantlers and fine-tuned for practical use.

The next stage scales to several thousand vehicles per year across the consortium. Key metrics include cycle times for automated steps and the introduction of quality mechanisms. Once decision logic achieves sufficient robustness, pre-qualified recycled grades can be embedded into product lifecycle management systems and fed back to OEMs. In this phase, the first price-collar contracts for critical materials are introduced, and recovery bonuses are negotiated and paid. Regular scorecards are published, reporting conformance, volumes, realised premiums (€), and avoided CO_2.

If the pilot hub proves effective, replication to three to five hubs follows. To ensure smooth scaling, a Dismantling API is launched, allowing equipped ATFs to plug in remotely. A versioned protocol and certification system are introduced. Over time, material streams expand to cover standardised “house recipes” for recycled plastics and polyamides. As data accumulates, the infrastructure can also support component reuse, if buyers and test procedures are defined.

The validity of the ACP concept rests on measurable signals. If specification-conform grades generate predictable premiums, offtake volumes grow, capital is unlocked through auditable data, disputes decline, and workers report greater agency while takt times are maintained, then the frame “automation as coordination infrastructure” is validated. Incentive alignment is functioning, and the adaptive governance layer is performing real work. If these signals do not emerge, the same instrumentation will reveal where the frame breaks down—whether in governance, incentive design, or human fit—without binding the system to a monolithic solution.

Embedding demand creation directly into procurement, design, and dismantling practices sets in motion a self-reinforcing cycle: guaranteed offtake → investment in recycling → higher-quality grades → easier engineering adoption → broader procurement pull. Over time, recycled plastics, copper, and aluminium gain path dependency like steel, becoming default inputs rather than exceptions.

This reasoning resonates with Andersson’s [111] findings in technological innovation systems research: the evolution of ELV iron recycling capabilities was driven by the interplay of demand-side pull, supply-side capability, and policy support. Strengthening capabilities for other materials, particularly scarce metals and plastics, may likewise depend on initiatives that foster continuous co-evolution. Given that ELV material configurations and market conditions will continue to shift, uncertainty should be treated as the norm rather than the exception. Long-term policy support is therefore essential—not only to enforce quotas but to orchestrate an adaptive evolution of the recycling ecosystem.

6 Discussion and Conclusion

This thesis examined how automated dismantling systems for battery-electric end-of-life vehicles can handle technical complexity while staying human-centred and economically viable. I treated dismantling as the pivotal junction between upstream design and downstream recovery in Germany's ELV system. Its systemic weight is clear: current practice is tool-limited, non-standardised, and variable [16, 17], yet selective dismantling creates value that shredding cannot—higher recovery yields, remanufacturing options, and better alignment with policy—even when labour costs are higher [2, 50, 109]. Over time, dismantler-led pathways outperform shredder-led baselines [13]. Still, viability hinges on material mix, throughput, and system design [18], which points to a development path that reduces uncertainty, shares information, and coordinates decisions.

Methodologically, I combined semi-structured expert interviews with analytical literature synthesis, built themes from practice and scholarship, and prototyped a future scenario to operationalise these insights. I use this foundation to answer the central question: how can automated dismantling systems be designed to address technical complexity while enabling human-centred and economically viable recycling and material recovery?

Two premises shaped the approach. Best-practice prescriptions are premature; the field lacks stable standards and shared operational baselines. And automation is not a simple human/robot split; technical, economic, organisational, and regulatory conditions co-evolve. I therefore adopted a dual-track abductive strategy inspired by Tarrar et al. [17] and structured by Dorst's Frame Creation [52, 204]—aiming for frames that are intentional, actionable, shareable, integrative, and context-specific. The stance aligns with Collingridge's "Intelligent Trial and Error": keep changes small, feedback fast, and architectures flexible so learning stays cheap and reversible under uncertainty [234]. In an environment shaped by accelerating AI, cloud infrastructures, and tightening regulation, such incremental, feedback-rich development is a pragmatic precondition for credible automation. The remainder of this chapter interprets the findings through that lens, draws out the strategic implications, and sets clear limits for transfer and next steps.

6.1 Interpretation of the Findings

The analysis revealed a recurring pattern of tensions that together block effective automation and high-quality recovery. Across dismantlers, recyclers, OEM representatives, and regulators, the picture was consistent: economic logics privilege production over recovery, regulation piles on without clarifying execution, design and end-of-life remain disconnected, and information infrastructures fail to generate a shared situational picture. Responsibility is diffused, tacit dismantling expertise is essential but uncaptured, workplace conditions impose hard limits, and automation projects remain tactical fixes rather than systemic transformations.

Taken together, these findings amount to what I describe as systemic coordination failure. The problem is not the absence of actors, rules, or technologies, but their chronic misalignment. Structural contradictions such as regulatory misfit, market dominance, and missing feedback reinforce operational bottlenecks like diffuse responsibility, unrecorded knowledge, and fragmented pilots. The effect is a self-stabilising loop of stagnation and within such a loop, adding more technology alone does not improve outcomes.

Placed against the literature, these results extend existing work. As Karagoz et al. [63] show, research on ELV dismantling remains dominated by optimisation methods that work well in stable, technical contexts but overlook the realities of an open, dynamic, and networked system. This explains persistent blind spots: limited treatment of social acceptance, fragmented coordination, and overemphasis on single components. Dorst [204] reminds us that such contexts are not shaped by solvable contradictions but by paradoxes—safety versus throughput, modularity versus cost, and compliance versus practicality.

The scenario developed in this thesis seeks to break that loop. It proposes shared identifiers and work-order schemas, versioned quality gates, systematic feedback to engineering, and a human-centred operating model that elevates embodied practice into the system design. This scenario is not offered as a definitive solution but as a structured orientation and a credible path for intelligent trial and error: incremental, feedback-rich development that lowers risk for workers, firms, and the environment. In this sense, the contribution of the thesis lies in widening the aperture. Instead of asking *what to automate*, the question becomes *how to align information, incentives, and responsibilities so automation can scale*. This reorientation foregrounds the often overlooked "cement" of the system—packaging, documentation, human–robot collaboration, and bench-level coordination—and translates them into testable mechanisms. It also points toward new research seams with relevance beyond ELVs, such as WEEE recycling, where similar conditions prevail.

Dorst's perspective on innovation provides the conceptual spine of this interpretation. Progress in complex systems is not about heroic breakthroughs or prescriptive best practices. It comes from reframing problems to reduce unnecessary risk, from redefining success to include learning and capability alongside financial return, and from resisting routine responses that solve the wrong problem with great efficiency. Innovation in this sense requires disciplined exploration, staged decision gates, and cumulative capability building [204].

Against this background, the findings allow me to answer the central research question. Automated dismantling systems for battery-electric vehicles can be designed to manage technical complexity, remain human-centred, and achieve economic viability **only when they are conceived as coordination infrastructures**. Their value lies less in replacing manual work directly and more in creating the data, rules, roles, and interfaces that allow actors across the value chain to work in synchrony. In this way, automation becomes not the end of the process but the platform through which technical capability, human expertise, and organisational alignment can co-evolve toward more circular and sustainable recovery.

6.2 Strategic Implications

For Volkswagen, the findings underscore that production-orientated automation logics—full automation, standardisation, and takt-time optimisation—do not transfer to end-of-life. Disassembly is not reversed assembly. Vehicles were never designed for deconstruction, and the incentives around recovery remain fundamentally misaligned with those of production. What emerges instead is the need for a coordination-first hybrid approach. Pilots should be anchored on a shared “rails” layer: minimal identifiers and work-order schemas, versioned quality gates, and auditable dispute protocols. By holding these elements constant across sites, learning can occur collectively rather than in isolation. Within such a model, human roles require redefinition. Operators become supervisors, quality analysts, and exception triage specialists, with human–robot collaboration deployed in areas where variability meets force and risk. Tacit knowledge must be made legible through ergonomic interfaces and systematic documentation. Data infrastructures need to elevate packaging, photo documentation, and condition metadata to first-class status, linking them to instruments like the Digital Product Passport and feeding them back into engineering and procurement. Collaboration models should be multi-party by design, bringing together dismantlers, recyclers, internal engineering, and independent validation labs around consistent cell specifications. Success must be measured not only in cycle times and costs but also in validated quality assurance, recyclate stability, exception-handling speed, worker safety, and supplier acceptance. Risk should be managed through staged decision gates, expanding only when milestones are met. This is Dorst’s [204] principle of disciplined exploration in practice: cumulative capability built through structured learning, not heroic leaps. At the product level, a gradual move toward modular design rules and traceability would expand dismantling options over time without requiring disruptive, all-at-once redesigns.

Policy, too, emerges as a critical field of implication. Interviews revealed rising compliance costs without proportional returns and a regulatory environment where enforcement remains uneven, enabling quota gaming and opacity. Regulatory instruments should be designed to support shared platforms for identifiers, documentation, and quality gates, ideally coupled with independent lab validation that anchors trust between OEMs, dismantlers, and recyclers. Governance must combine stable long-term signals—such as recyclate quotas and extended producer responsibility obligations—with room for experimentation through pilots and iterative scaling. This adaptive stance would allow smaller actors to participate meaningfully without being overburdened. Policy frameworks should also move beyond a narrow fixation on recovery rates toward metrics that capture material quality, reuse, and transparency—outcomes that actually stabilise secondary markets. To reduce transaction costs and raise baseline capabilities, targeted support for SMEs through training, digital toolkits, and packaging standards is essential. Finally, EU-level initiatives like the battery regulation and the digital product passport must be aligned with dismantling realities. Data that matters at the bench—fast access points, joining techniques, and hazards—needs to be included; otherwise, the promise of digital traceability risks remaining abstract.

For practitioners—dismantlers, recyclers, and technology providers—the implications are equally concrete. Standardised work packages that begin with photo-first intake, minimal work-order schemas, and packaging kits can stabilise quality and accelerate validation. Human–robot collaboration should be directed at heavy or awkward subassemblies and repetitive, high-strain tasks, supported by playbooks built from real-world exception handling. Quality and offtake arrangements should be co-developed with downstream users, ideally under memoranda of understanding that stabilise demand and justify selective dismantling steps. Tacit expertise—knowledge of tools, sequences, and interferences—should be systematically recorded and looped back into engineering, influencing design-for-disassembly decisions upstream. Technology vendors, meanwhile, must be encouraged to develop robust, field-serviceable end-effectors and vision systems that integrate seamlessly with the coordination rails.

The through-line across all three domains is clear: automation scales only when coordination scales. For Volkswagen, policy, and practitioners alike, the challenge is to build the connective tissue—shared identifiers, quality gates, feedback mechanisms, redefined roles—that allows automation to serve as a platform for synchronising diverse actors in the system. The scenario developed here makes this logic tangible by showing how IDs feed into gates, gates feed into feedback, and feedback feeds into new roles and responsibilities. Only by embedding automation in this way can the system move from tactical fixes to coordinated transformation.

6.3 Limitations

This thesis carries several methodological limitations that shape how the findings should be interpreted. First, it was conducted as an exploratory scoping study. The primary aim was to surface systemic tensions, grounded perspectives, and potential reframings of the problem, not to deliver prescriptive solutions. The reliance on expert interviews yielded practice-based insights into dismantling, automation, and regulation, but such material inevitably reflects subjective experiences, institutional positions, and selective viewpoints. Bias cannot be eliminated, though triangulation across industrial, technological, academic, and regulatory domains mitigated it.

Second, the adoption of Frame Creation as a methodological backbone shaped both the process and the outcome. The method excels at surfacing hidden assumptions and opening new entry points for innovation, yet it does not prescribe concrete technical or organisational solutions. The study therefore remained at the level of thematic synthesis and scenario development, rather than producing implementable designs. This is both a strength, in its systemic perspective, and a limitation, in its absence of ready-made answers. It also raises the question of organisational embedding. Frame Creation runs against the grain of established problem-solving logics in large firms, particularly at the middle-management level, where roles and responsibilities are tied to routines of efficiency and risk control. As Dorst [204] notes, senior leadership is often better positioned to work with open-ended, adaptive approaches. This structural tension between frame innovation and established routines limits the immediate uptake of the approaches proposed here.

Third, the situated character of the research constrains its transferability. The results are shaped by the case of Volkswagen, German regulatory structures, and the perspectives of dismantling and recycling stakeholders within this national setting. While many systemic challenges in ELV recycling are transnational, the findings cannot be assumed to apply wholesale elsewhere. Their value lies in showing how coordination failures manifest in practice and in offering a starting point for experimentation in other institutional contexts. Concentrating on Germany also ensured consistency and comparability across responses, while keeping the empirical work feasible within the time and resource limits of the study.

Fourth, the empirical base was necessarily limited. Twenty-seven expert interviews provided rich material, but the inclusion of more perspectives—particularly from policymakers, international actors, and other OEMs—would have added depth and balance. The validation process, which combined interview reflection with use-case mapping, prioritised depth over breadth. The resulting “golden rules” are therefore best understood as provocations: they are meant to spark dialogue, experimentation, and adaptation rather than define final prescriptions.

A further limitation lies in the structure of the industry itself. ELV treatment remains fragmented and dominated by small, family-owned businesses with limited capacity for large-scale transformation. These firms rely heavily on tacit knowledge, improvisation, and experience-based decision-making. Introducing industrialised automation into such contexts risks alienating precisely those actors most essential for material recovery. It also creates a structural contradiction: manufacturers demand standardised, high-throughput recyclate streams, yet expect them to be delivered by under-resourced operators. Rather than treating this as a barrier, I have framed it as a form of “distributed craftsmanship”—a knowledge system in its own right that requires engagement rather than erasure.

Beyond the empirical scope, several system-level effects remain underexplored. Scaling selective dismantling and new automation approaches will inevitably reshape logistics, transport flows, and facility requirements, with ecological consequences that remain largely absent from existing assessments. Similarly, disassembly continues to be treated in much of the literature as a stand-alone technical operation, rather than as part of a broader circularity strategy. Upstream design constraints, downstream reuse pathways, workforce capabilities, cross-facility coordination, and data integration are often relegated to the margins, even though they determine whether automation adds value or friction. These gaps frame avenues for future research but also highlight the contextual limits of the present work.

Finally, the open-ended nature of design reasoning must be acknowledged as both a limitation and a strength. Outcomes can shift when new frames are adopted, allowing designers to move beyond initial paradoxes and rethink goals altogether [204]. This flexibility enables innovation, but it also means that the results of a Frame Creation process are never final. The scenario and "golden rules" proposed here should therefore be seen as contributions to an ongoing process of exploration, not as an endpoint.

In sum, the findings are bounded by method, case, and scope. They do not claim universal validity, but they provide a structured orientation grounded in practice. The argument remains: automation scales when coordination scales. The task ahead is disciplined experimentation—testing identifiers, work-order schemas, and quality gates; measuring learning and risk reduction alongside cost; and iterating with upstream design and downstream offtake.

6.4 Conclusion

This thesis asked how automated dismantling systems for battery-electric end-of-life vehicles can be designed to manage technical complexity while remaining human-centred and economically viable. I approached this as a systems problem and developing a future scenario that makes these insights operational. The findings show that dismantling is both indispensable and constrained. Further, scaling automation is currently mainly blocked not by a lack of technology but by systemic coordination failure: economic drivers favour production over recovery, regulations pile up without clarifying execution, design choices lock in downstream difficulty, and fragmented information infrastructures prevent alignment. Responsibility is diffused, tacit expertise remains uncaptured, and automation efforts stall as tactical fixes.

From this analysis, the thesis makes three main contributions. Conceptually, it reframes automation from machine substitution to coordination infrastructure: a platform of data, rules, and roles that synchronises actors across the system. Empirically, it consolidates dispersed knowledge into a coded evidence base that explains where automation works, why it fails, and which constraints matter most—from variability and takt-time pressures to packaging and documentation bottlenecks. Practically, it translates frames into a scenario with concrete mechanisms: shared identifiers and work-order schemas, versioned quality gates, feedback channels to engineering, and redefined operator roles. Together, these elements specify how automation can begin to scale under real-world uncertainty. The broader methodological contribution lies in applying Frame Creation to an industrial recycling problem. It demonstrates how reframing reduces unnecessary risk, how success must be redefined to include learning and capability alongside immediate returns, and how disciplined exploration with decision gates can build cumulative capacity.

The answer to the research question is therefore clear: automated dismantling becomes viable only when designed as a coordination infrastructure. Its role is not to replace human labour but to connect actors, stabilise flows, and turn tacit expertise into shared capability. In this sense, automation is not the end of the process but the platform through which technical capacity, human knowledge, and organisational incentives co-evolve toward circularity.

If such a path is pursued, ELV recycling can move from aspiration to normal practice. By starting with targeted pilots that integrate robots, protocols, and quality assurance; wiring recycled grades into engineering and procurement; and growing the coalition that maintains the rails as conditions change, the automotive industry can shift from shredding value by default to recovering it on purpose.

7 Publication bibliography

[1] Eurostat. 2024. End-of-life vehicle statistics (November 2024). Retrieved 12/05/2025 from https://ec.europa.eu/eurostat/statistics-explained/index.php?title=End-of-life_vehicle_statistics

[2] Abel Ortego, Alicia Valero, Antonio Valero, and Marta Iglesias. 2018. Downcycling in automobile recycling process: A thermodynamic assessment. *Resources, Conservation and Recycling* 136 https://doi.org/10.1016/j.resconrec.2018.04.006

[3] Hiroki Hatayama, Ichiro Daigo, Yasunari Matsuno, and Yoshihiro Adachi. 2012. Evolution of aluminum recycling initiated by the introduction of next-generation vehicles and scrap sorting technology. *Resources, Conservation and Recycling* 66 https://doi.org/10.1016/j.resconrec.2012.06.006

[4] Shin-ichi Sakai, Hideto Yoshida, Jiro Hiratsuka, Carlo Vandecasteele, Regina Kohlmeyer, Vera Susanne Rotter, Fabrizio Passarini, Alessandro Santini, Maria Peeler, Jinhui Li, Gil-Jong Oh, Ngo Kim Chi, Lawin Bastian, Stephen Moore, Natsuko Kajiwara, Hidetaka Takigami, Takaaki Itai, Shin Takahashi, Shinsuke Tanabe, Keijiro Tomoda, Takashi Hirakawa, Yasuhiro Hirai, Misuzu Asari, and Junya Yano. 2014. An international comparative study of end-of-life vehicle (ELV) recycling systems. *Journal of Material Cycles and Waste Management* 16, 1, https://doi.org/10.1007/s10163-013-0173-2

[5] Idiano D'Adamo, and Paolo Rosa. 2019. A Structured Literature Review on Obsolete Electric Vehicles Management Practices. *Sustainability* 11, 23, https://doi.org/10.3390/su11236876

[6] Jie Li, Michael Barwood, and Shahin Rahimifard. 2018. Robotic disassembly for increased recovery of strategically important materials from electrical vehicles. *Robotics and Computer-Integrated Manufacturing* 50 https://doi.org/10.1016/j.rcim.2017.09.013

[7] Inga Carry, Nadine Godehardt, and Melanie Müller 2023. *The Future of European-Chinese Raw Material Supply Chains. Three scenarios for 2030 and their implications: SWP Comment*. German Institute for International and Security Affairs, City.

[8] Arne Nygaard. 2023. The Geopolitical Risk and Strategic Uncertainty of Green Growth after the Ukraine Invasion: How the Circular Economy Can Decrease the Market Power of and Resource Dependency on Critical Minerals. *Circular Economy and Sustainability* 3, 2, https://doi.org/10.1007/s43615-022-00181-x

[9] Md. Aynul Bari, Warren B. Kindzierski, Masoud Jahandar Lashaki, and Zaher Hashisho. 2011. Automotive Wastes. *Water Environment Research* 83, 10, https://doi.org/10.2175/106143011x13075599869650

[10] Lisa Tostado. 2021. End-Of-Life Vehicles: Final Destination Retrieved 16/04/2025 from https://eu.boell.org/en/end-of-life-vehicles-final-destination

[11] T. V. Krishna Mohan, and R. K. Amit. 2020. Dismantlers’ dilemma in end-of-life vehicle recycling markets: A system dynamics model. *Annals of Operations Research* 290, 1, https://doi.org/10.1007/s10479-018-2930-z

[12] Isabel Vermeulen, Jo van Caneghem, Chantal Block, Jan Baeyens, and Carlo H.A. Vandecasteele. 2011. Automotive shredder residue (ASR): Reviewing its production from end-of-life vehicles (ELVs) and its recycling, energy or chemicals’ valorisation. *Journal of Hazardous Materials* 190, 1, https://doi.org/10.1016/j.jhazmat.2011.02.088

[13] Paolo Rosa, and Sergio Terzi. 2018. Improving end of life vehicle’s management practices: An economic assessment through system dynamics. *Journal of Cleaner Production* 184 https://doi.org/10.1016/j.jclepro.2018.02.264

[14] Raffaello Cossu, and Tiziana Lai. 2015. Automotive shredder residue (ASR) management: An overview. *Waste Management* 45 https://doi.org/10.1016/j.wasman.2015.07.042

[15] Ala Khodier, Karl Williams, and Neil Dallison. 2018. Challenges around automotive shredder residue production and disposal. *Waste Management* 73 https://doi.org/10.1016/j.wasman.2017.05.008

[16] Jin Tian, and Ming Chen. 2016. Assessing the economics of processing end-of-life vehicles through manual dismantling. *Waste Management* 56 https://doi.org/10.1016/j.wasman.2016.07.046

[17] Malin Tarrar, Mélanie Despeisse, and Björn Johansson. 2021. Driving vehicle dismantling forward - A combined literature and empirical study. *Journal of Cleaner Production* 295 https://doi.org/10.1016/j.jclepro.2021.126410

[18] Martin Choux, Simon Waldemar Pripp, Frode Kvalnes, and Magnus Hellström. 2024. To shred or to disassemble – A techno-economic assessment of automated disassembly vs. shredding in lithium-ion battery module recycling. *Resources, Conservation and Recycling* 203 https://doi.org/10.1016/j.resconrec.2024.107430

[19] 2023. *Proposal for a Regulation of the European Parliament and of the Council on circularity requirements for vehicle design and on the management of end-of-life vehicles, amending Regulations (EU) 2018/858 and (EU) 2019/1020, and repealing Directive 2000/53/EC (COM(2023) 451 final)*. City.

[20] 2000. *Directive 2000/53/EC of the European Parliament and of the Council of 18 September 2000 on end-of life vehicles*. European Parliament and Council City.

[21] European Commission. 2025. Circular economy action plan Retrieved 12/05/2025 from https://environment.ec.europa.eu/strategy/circular-economy-action-plan_en

[22] Guillaume Ragonnaud. 2024. The crisis facing the EU's automotive industry Retrieved 24/07/2025 from https://www.europarl.europa.eu/RegData/etudes/ATAG/2024/762419/EPRS_ATA(2024)762419_EN.pdf

[23] Zhang Yu, Syed A. Khan, Hafiz M. Zia-ul-haq, Muhammad Tanveer, Muhammad J. Sajid, and Shehzad Ahmed. 2022. A Bibliometric Analysis of End-of-Life Vehicles Related Research: Exploring a Path to Environmental Sustainability. *Sustainability* 14, 14, https://doi.org/10.3390/su14148484

[24] Alejandro Germán Frank, Lucas Santos Dalenogare, and Néstor Fabián Ayala. 2019. Industry 4.0 technologies: Implementation patterns in manufacturing companies. *International Journal of Production Economics* 210 https://doi.org/10.1016/j.ijpe.2019.01.004

[25] Heiner Lasi, Peter Fettke, Hans-Georg Kemper, Thomas Feld, and Michael Hoffmann. 2014. Industry 4.0. *Business & Information Systems Engineering* 6, 4, https://doi.org/10.1007/s12599-014-0334-4

[26] Vi Kie Soo, Matthew Doolan, Paul Compston, Joost Duflou, Jef R. Peeters, and Yasushi Umeda. 2021. The influence of end-of-life regulation on vehicle material circularity: A comparison of Europe, Japan, Australia and the US. *Resources, Conservation and Recycling* 168 https://doi.org/10.1016/j.resconrec.2020.105294

[27] Joost Duflou, Guenther Seliger, Sami Kara, Yasushi Umeda, Aldo Roberto Ometto, and Barbara Willems. 2008. Efficiency and feasibility of product disassembly: A case-based study. *CIRP Annals* 57, 2, https://doi.org/10.1016/j.cirp.2008.09.009

[28] Yi Wang, Hai-Shu Ma, Jing-Hui Yang, and Ke-Sheng Wang. 2017. Industry 4.0: A way from mass customization to mass personalization production. *Advances in Manufacturing* 5, 4, https://doi.org/10.1007/s40436-017-0204-7

[29] Yuanjun Laili, Yongjing Wang, Yilin Fang, and Duc Truong Pham. 2022. *Robotic Disassembly for Remanufacturing* Optimisation of Robotic Disassembly for Remanufacturing, Springer International Publishing, Cham. https://doi.org/10.1007/978-3-030-81799-2_2

[30] Sebastian Hjorth, and Dimitrios Chrysostomou. 2022. Human–robot collaboration in industrial environments: A literature review on non-destructive disassembly. *Robotics and Computer-Integrated Manufacturing* 73 https://doi.org/10.1016/j.rcim.2021.102208

[31] Patrick Bründl, Albert Scheck, Huong Giang Nguyen, and Jörg Franke. 2024. Towards a circular economy for electrical products: A systematic literature review and research agenda for automated recycling. *Robotics and Computer-Integrated Manufacturing* 87 https://doi.org/10.1016/j.rcim.2023.102693

[32] Abdelfetah Hentout, Mustapha Aouache, Abderraouf Maoudj, and Isma Akli. 2019. Human–robot interaction in industrial collaborative robotics: A literature review of the decade 2008–2017. *Advanced Robotics* 33, 15-16, https://doi.org/10.1080/01691864.2019.1636714

[33] Quan Liu, Zhihao Liu, Wenjun Xu, Quan Tang, Zude Zhou, and Duc Truong Pham. 2019. Human-robot collaboration in disassembly for sustainable manufacturing. *International Journal of Production Research* 57, 12, https://doi.org/10.1080/00207543.2019.1578906

[34] Mandeep Dhanda, Benedict Alexander Rogers, Stephanie Hall, Elies Dekoninck, and Vimal Dhokia. 2025. Reviewing human-robot collaboration in manufacturing: Opportunities and challenges in the context of industry 5.0. *Robotics and Computer-Integrated Manufacturing* 93 https://doi.org/10.1016/j.rcim.2024.102937

[35] S. J. Baltrusch, F. Krause, A. W. de Vries, W. van Dijk, and M. P. and de Looze 2022. What about the human in human robot collaboration? *Ergonomics* 65, 5, https://doi.org/10.1080/00140139.2021.1984585

[36] Yuqian Lu, Hao Zheng, Saahil Chand, Wanqing Xia, Zengkun Liu, Xun Xu, Lihui Wang, Zhaojun Qin, and Jinsong Bao. 2022. Outlook on human-centric manufacturing towards Industry 5.0. *Journal of Manufacturing Systems* 62 https://doi.org/10.1016/j.jmsy.2022.02.001

[37] Tiziana C. Callari, Riccardo Vecellio Segate, Ella-Mae Hubbard, Angela Daly, and Niels Lohse. 2024. An ethical framework for human-robot collaboration for the future people-centric manufacturing: A collaborative endeavour with European subject-matter experts in ethics. *Technology in Society* 78 https://doi.org/10.1016/j.techsoc.2024.102680

[38] Enrique Coronado, Takuya Kiyokawa, Gustavo A. Garcia Ricardez, Ixchel G. Ramirez-Alpizar, Gentiane Venture, and Natsuki Yamanobe. 2022. Evaluating quality in human-robot interaction: A systematic search and classification of performance and human-centered factors, measures and metrics towards an industry 5.0. *Journal of Manufacturing Systems* 63 https://doi.org/10.1016/j.jmsy.2022.04.007

[39] Kadir Alpaslan Demir, Gözde Döven, and Bülent Sezen. 2019. Industry 5.0 and Human-Robot Co-working. *Procedia Computer Science* 158 https://doi.org/10.1016/j.procs.2019.09.104

[40] Navin K. Dev, Ravi Shankar, and Fahham Hasan Qaiser. 2020. Industry 4.0 and circular economy: Operational excellence for sustainable reverse supply chain performance. *Resources, Conservation and Recycling* 153 https://doi.org/10.1016/j.resconrec.2019.104583

[41] Valentina Di Pasquale, Paola Farina, Marcello Fera, Salvatore Gerbino, Salvatore Miranda, and Marta Rinaldi. 2024. Human Robot-Interaction: A conceptual framework for task performance analysis. *IFAC-PapersOnLine* 58, 19, https://doi.org/10.1016/j.ifacol.2024.09.096

[42] P. Johri, J. N. Singh, A. Sharma, and D. Rastogi 2021. *Sustainability of Coexistence of Humans and Machines: An Evolution of Industry 5.0 from Industry 4.0*. City.

[43] Praveen Kumar Reddy Maddikunta, Quoc-Viet Pham, Prabadevi B, N. Deepa, Kapal Dev, Thippa Reddy Gadekallu, Rukhsana Ruby, and Madhusanka Liyanage. 2022. Industry 5.0: A survey on enabling technologies and potential applications. *Journal of Industrial Information Integration* 26 https://doi.org/10.1016/j.jii.2021.100257

[44] Yevhen Palazhchenko, Vira Shendryk, Vitalii Ivanov, and Michal Hatala. 2024. *Industry 5.0: Aspects of Collaboration Technologies* Flexible Automation and Intelligent Manufacturing: Establishing Bridges for More Sustainable Manufacturing Systems, Springer Nature Switzerland, Cham. https://doi.org/10.1007/978-3-031-38165-2_71

[45] Francisco J. G. Silva, Luís Pinto Ferreira, José Carlos Sá, Maria Teresa Pereira, and Carla M. A. Pinto (Eds.). 2024. *Flexible Automation and Intelligent Manufacturing: Establishing Bridges for More Sustainable Manufacturing Systems* Lecture Notes in Mechanical Engineering, Springer Nature Switzerland, Cham. https://doi.org/10.1007/978-3-031-38165-2

[46] Attila Tóth, László Nagy, Roderick Kennedy, Belej Bohuš, János Abonyi, and Tamás Ruppert. 2023. The human-centric Industry 5.0 collaboration architecture. *MethodsX* 11 https://doi.org/10.1016/j.mex.2023.102260

[47] Xun Xu, Yuqian Lu, Birgit Vogel-Heuser, and Lihui Wang. 2021. Industry 4.0 and Industry 5.0—Inception, conception and perception. *Journal of Manufacturing Systems* 61 https://doi.org/10.1016/j.jmsy.2021.10.006

[48] Gang Yuan, Xiaojun Liu, Xiaoli Qiu, Pai Zheng, Duc Truong Pham, and Ming Su. 2025. Human-robot collaborative disassembly in Industry 5.0: A systematic literature review and future research agenda. *Journal of Manufacturing Systems* 79 https://doi.org/10.1016/j.jmsy.2025.01.009

[49] Xuesong Zhang, Amir M. Fathollahi-Fard, Guangdong Tian, Zaher Mundher Yaseen, Duc Truong Pham, Qiang Zhao, and Jianzhao Wu. 2024. Human-Robot Collaboration in Mixed-Flow Assembly Line Balancing under Uncertainty: An Efficient Discrete Bees Algorithm. *Journal of Industrial Information Integration* 41 https://doi.org/10.1016/j.jii.2024.100676
[50] Syed A. Khan, Danish I. Godil, George Thomas, Muhammad Tanveer, Hafiz M. Zia-ul-haq, and Haider Mahmood. 2021. The Decision-Making Analysis on End-of-Life Vehicle Recycling and Remanufacturing under Extended Producer Responsibility Policy. *Sustainability* 13, 20, https://doi.org/10.3390/su132011215
[51] Jun Huang, Sheng Yin, Muyao Tan, Quan Liu, Ruiya Li, and Duc Truong Pham. 2024. Task Allocation and Sequence Planning for Human–Robot Collaborative Disassembly of End-of-Life Products Using the Bees Algorithm. *Biomimetics* 9, 11, https://doi.org/10.3390/biomimetics9110688
[52] Kees Dorst. 2015. Frame Creation and Design in the Expanded Field. *She Ji: The Journal of Design, Economics, and Innovation* 1, 1, https://doi.org/10.1016/j.sheji.2015.07.003
[53] Muhammad Syafiq Sulaiman, Dzuraidah Abd Wahab, Zambri Harun, Hawa Hishamuddin, Nor Kamaliana Khamis, and Mohd Radzi Abu Mansor. 2023. Preliminary study on End-of-Life Vehicles recycling rate for Malaysia. *Energy Reports* 9 https://doi.org/10.1016/j.egyr.2023.05.250
[54] Lorenzo Berzi, Massimo Delogu, Alessandro Giorgetti, and Marco Pierini. 2013. On-field investigation and process modelling of End-of-Life Vehicles treatment in the context of Italian craft-type Authorized Treatment Facilities. *Waste Management* 33, 4, https://doi.org/10.1016/j.wasman.2012.12.004
[55] Zambri Harun, Altaf H. Molla, Mohd R. Mansor, and Rozmi Ismail. 2022. Development, Critical Evaluation, and Proposed Framework: End-of-Life Vehicle Recycling in India. *Sustainability* 14, 22, https://doi.org/10.3390/su142215441
[56] Altaf Hossain Molla, Hilal Shams, Zambri Harun, Ahmad Nizam Che Kasim, Manoj Kumar Nallapaneni, and Mohd Nizam Ab Rahman. 2023. Evaluation of end-of-life vehicle recycling system in India in responding to the sustainability paradigm: An explorative study. *Scientific Reports* 13, 1, https://doi.org/10.1038/s41598-023-30964-7
[57] Alessandro Santini, Luciano Morselli, Fabrizio Passarini, Ivano Vassura, Salvatore Di Carlo, and Francesco Bonino. 2011. End-of-Life Vehicles management: Italian material and energy recovery efficiency. *Waste Management* 31, 3, https://doi.org/10.1016/j.wasman.2010.09.015
[58] James Pritchard. 2022. MaaS to pull us out of a car-centric orbit: Principles for sustainable Mobility-as-a-Service in the context of unsustainable car dependency. *Case Studies on Transport Policy* 10, 3, https://doi.org/10.1016/j.cstp.2022.08.004
[59] Michael F. Ashby. 2013. *Materials and the environment: Eco-informed material choice*. (2nd ed. ed.). Butterworth-Heinemann, Waltham, Mass.
[60] Transport and Environment. 2024. End-of-life vehicles Regulation: A T&E position paper Retrieved 12/05/2025 from https://www.transportenvironment.org/uploads/files/2024_10_TE_position_paper_End-of-life_vehicles_Regulation.pdf
[61] Automotive Market Research. 2025. How Many Cars Are There In The World in 2025? Retrieved 13/06/2025 from https://hedgescompany.com/blog/2021/06/how-many-cars-are-there-in-the-world/
[62] Mohsen Moghimi Dehkordi, Zahra Pournuroz Nodeh, Kamran Soleimani Dehkordi, Hossein salmanvandi, Reza Rasouli Khorjestan, and Mohammad Ghaffarzadeh. 2024. Soil, air, and water pollution from mining and industrial activities: Sources of pollution, environmental impacts, and prevention and control methods. *Results in Engineering* 23 https://doi.org/10.1016/j.rineng.2024.102729
[63] Selman Karagoz, Nezir Aydin, and Vladimir Simic. 2020. End-of-life vehicle management: A comprehensive review. *Journal of Material Cycles and Waste Management* 22, 2, https://doi.org/10.1007/s10163-019-00945-y
[64] Simon Tywuschik. 2016. Eine vergleichende Analyse des betrieblichen Umweltschutzes in der deutschen Chemie- und Automobilindustrie zwischen 1960 und 2005. *Zeitschrift für Unternehmensgeschichte / Journal of Business History* 61, 2,

[65] Joyce Dargay, Dermot Gately, and Martin Sommer. 2007. Vehicle Ownership and Income Growth, Worldwide: 1960-2030. *The Energy Journal* 28, 4, https://doi.org/10.5547/ISSN0195-6574-EJ-Vol28-No4-7

[66] Amund N. Løvik, Roja Modaresi, and Daniel B. Müller. 2014. Long-Term Strategies for Increased Recycling of Automotive Aluminum and Its Alloying Elements. *Environmental Science & Technology* 48, 8, https://doi.org/10.1021/es405604g

[67] A. van Schaik, M. A. Reuter, U.M.J. Boin, and W. L. Dalmijn. 2002. Dynamic modelling and optimisation of the resource cycle of passenger vehicles. *Minerals Engineering* 15, 11, Supplement 1, https://doi.org/10.1016/s0892-6875(02)00080-8

[68] Plastics Europe. 2025. Why are plastics critical for the automotive industry? Retrieved 16/04/2025 from https://plasticseurope.org/sustainability/sustainable-use/sustainable-mobility-transport/why-are-plastics-critical-for-the-automotive-industry/

[69] ARN. 2025. Plastics in today's cars will still be used in car parts 20, 30 and even 40 years' time Retrieved 16/04/2025 from https://arn.nl/en/plastics-in-todays-cars-will-still-be-used-in-car-parts-20-30-and-even-40-years-time/

[70] Plastics Europe. 2024. Achieving greater circularity for automotive plastics through the End-of-Life Vehicles Regulation Retrieved 16/04/2025 from https://plasticseurope.org/knowledge-hub/end-of-life-vehicles-regulation-position/

[71] Simon Stotz, Ralf A. Brickau, Christoph Moss, and Daniel Meierhof. 2022. *Measuring and Restoring customer trust: An explorative research based on the VW Diesel gate scandal*. BoD–Books on Demand.

[72] European Environment Agency 2024. *New registrations of electric vehicles in Europe*. City.

[73] Tim McPhie, and Ana Crespo Parrondo *Zero emission vehicles: first 'Fit for 55' deal will end the sale of new CO2 emitting cars in Europe by 2035*. European Commission, City.

[74] S. Hemavathi, and A. Shinisha. 2022. A study on trends and developments in electric vehicle charging technologies. *Journal of Energy Storage* 52 https://doi.org/10.1016/j.est.2022.105013

[75] Lei Zhang, Xikun Zhao, Qingdi Ke, Wanfu Dong, and Yanjiu Zhong. 2021. Disassembly Line Balancing Optimization Method for High Efficiency and Low Carbon Emission. *International Journal of Precision Engineering and Manufacturing-Green Technology* 8, 1, https://doi.org/10.1007/s40684-019-00140-2

[76] 2023. *Regulation (EU) 2023/1542 of the European Parliament and of the Council of 12 July 2023 concerning batteries and waste batteries, amending Directive 2008/98/EC and Regulation (EU) 2019/1020 and repealing Directive 2006/66/EC (Text with EEA relevance)*. City.

[77] Tero Kaarlela, Enrico Villagrossi, Alireza Rastegarpanah, Alberto San-Miguel-Tello, and Tomi Pitkäaho. 2024. Robotised disassembly of electric vehicle batteries: A systematic literature review. *Journal of Manufacturing Systems* 74 https://doi.org/10.1016/j.jmsy.2024.05.013

[78] Responsible Minerals Initiative. What are conflict minerals? Retrieved 15/05/2025 from https://www.responsiblemineralsinitiative.org/about/faq/general-questions/what-are-conflict-minerals/

[79] Dirk Große-Loheide, and Esra Aydin 2024. *Responsible Raw Materials Report 2023*. Volkswagen Group, City.

[80] Peter Glavič, and Rebeka Lukman. 2007. Review of sustainability terms and their definitions. *Journal of Cleaner Production* 15, 18, https://doi.org/10.1016/j.jclepro.2006.12.006

[81] Michael Lieder, and Amir Rashid. 2016. Towards circular economy implementation: A comprehensive review in context of manufacturing industry. *Journal of Cleaner Production* 115 https://doi.org/10.1016/j.jclepro.2015.12.042

[82] 2008. *Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives*. City.

[83] M. M. Hasan, M. G. Rasul, M.M.K. Khan, N. Ashwath, and M. I. Jahirul. 2021. Energy recovery from municipal solid waste using pyrolysis technology: A review on current status and developments. *Renewable and Sustainable Energy Reviews* 145 https://doi.org/10.1016/j.rser.2021.111073

[84] Ahmed Alengebawy, Yi Ran, Ahmed I. Osman, Keda Jin, Mohamed Samer, and Ping Ai. 2024. Anaerobic digestion of agricultural waste for biogas production and sustainable bioenergy recovery: A review. *Environmental Chemistry Letters* 22, 6, https://doi.org/10.1007/s10311-024-01789-1

[85] Moritz Hoffmann, Abderrahim Krini, Andreas Mueller, and Steffi Knorn. 2025. Remanufacturing production planning and control: Conceptual framework for requirement definition. *Journal of Remanufacturing* 15, 1, https://doi.org/10.1007/s13243-025-00149-8

[86] Martin Ruhrberg. 2006. Assessing the recycling efficiency of copper from end-of-life products in Western Europe. *Resources, Conservation and Recycling* 48, 2, https://doi.org/10.1016/j.resconrec.2006.01.003

[87] Jörg Woidasky, and Andreas Stolzenberg 2003. *Verwertungspotenzial für Kunststoffteile aus Altfahrzeugen in Deutschland: Gutachten*. German Environment Agency, City.

[88] Catherine M. Rose, Kurt A. Beiter, and Kosuke Ishii 1999. *Determining end-of-life strategies as a part of product definition*. City.

[89] Valtteri Ranta, Leena Aarikka-Stenroos, Paavo Ritala, and Saku J. Mäkinen. 2018. Exploring institutional drivers and barriers of the circular economy: A cross-regional comparison of China, the US, and Europe. *Resources, Conservation and Recycling* 135 https://doi.org/10.1016/j.resconrec.2017.08.017

[90] Bishal Bhari, Junya Yano, and Shin-ichi Sakai. 2021. Comparison of end-of-life vehicle material flows for reuse, material recycling, and energy recovery between Japan and the European Union. *Journal of Material Cycles and Waste Management* 23, 2, https://doi.org/10.1007/s10163-020-01154-8

[91] European Environment Agency. end-of-life vehicle: EEA Glossary Retrieved 11/05/2025 from https://www.eea.europa.eu/help/glossary/eea-glossary/end-of-life-vehicle

[92] Christian Kitazume, Regina Kohlmeyer, and Ines Oehme 2020. *Effectively tackling the issue of millions of vehicles with unknown whereabouts: European priority measure: establishing leakage-proof vehicle registration systems*. German Environment Agency, City.

[93] Solange A. Numfor, Geoffrey B. Omosa, Zhengyang Zhang, and Kazuyo Matsubae. 2021. A Review of Challenges and Opportunities for End-of-Life Vehicle Recycling in Developing Countries and Emerging Economies: A SWOT Analysis. *Sustainability* 13, 9, https://doi.org/10.3390/su13094918

[94] Jianbing Gao, Junfeng Huang, Xiaopan Li, Guohong Tian, Xiaochen Wang, Ce Yang, and Chaochen Ma. 2022. Challenges of the UK government and industries regarding emission control after ICE vehicle bans. *Science of The Total Environment* 835 https://doi.org/10.1016/j.scitotenv.2022.155406

[95] Federica Cucchiella, Idiano D'Adamo, Paolo Rosa, and Sergio Terzi. 2015. Scrap automotive electronics: A mini-review of current management practices. *Waste Management & Research* 34, 1, https://doi.org/10.1177/0734242x15607429

[96] Idiano D'Adamo, Massimo Gastaldi, and Paolo Rosa. 2020. Recycling of end-of-life vehicles: Assessing trends and performances in Europe. *Technological Forecasting and Social Change* 152 https://doi.org/10.1016/j.techfore.2019.119887

[97] Lea Zuber, and Sara Simonini 2025. *Commission fines car manufacturers and association €458 million over end-of-life vehicles recycling cartel*. European Commission, City.

[98] Federica Cucchiella, Idiano D'Adamo, Paolo Rosa, and Sergio Terzi. 2016. Automotive printed circuit boards recycling: An economic analysis. *Journal of Cleaner Production* 121 https://doi.org/10.1016/j.jclepro.2015.09.122

[99] Vuk Petronijević, Aleksandar Đorđević, Miladin Stefanović, Slavko Arsovski, Zdravko Krivokapić, and Milan Mišić. 2020. Energy Recovery through End-of-Life Vehicles Recycling in Developing Countries. *Sustainability* 12, 21, https://doi.org/10.3390/su12218764

[100] Svetlana Dabic-Miletic, Vladimir Simic, and Selman Karagoz. 2021. End-of-life tire management: A critical review. *Environmental Science and Pollution Research* 28, 48, https://doi.org/10.1007/s11356-021-16263-6

[101] W. B. Kindzierski, Z. Hashisho, W. Khan, and M. Fayaz. 2010. Automotive wastes. *Water Environment Research* 82, 10, https://doi.org/10.2175/106143010x12756668801374

[102] Jin Tian, and Ming Chen. 2014. Sustainable design for automotive products: Dismantling and recycling of end-of-life vehicles. *Waste Management* 34, 2, https://doi.org/10.1016/j.wasman.2013.11.005

[103] Paulo Ferrão, and José Amaral. 2006. Assessing the economics of auto recycling activities in relation to European Union Directive on end of life vehicles. *Technological Forecasting and Social Change* 73, 3, https://doi.org/10.1016/j.techfore.2004.03.010

[104] GME Recycling. 2025. What is Zorba Aluminium Scrap? Retrieved 8/25/2025 from https://www.gme-recycling.com/zorba-aluminium-scrap-a-comprehensive-guide/

[105] Naffisah Othman, Zaliha Ismail, Mohamad I. Selamat, Siti H. Sheikh Abdul Kadir, and Nur A. Shibraumalisi. 2022. A Review of Polychlorinated Biphenyls (PCBs) Pollution in the Air: Where and How Much Are We Exposed to? *International Journal of Environmental Research and Public Health* 19, 21, https://doi.org/10.3390/ijerph192113923

[106] Luca Campisi, Concettina La Motta, and Dorota Napierska. 2025. Polyvinyl chloride (PVC), its additives, microplastic and human health: Unresolved and emerging issues. *Science of The Total Environment* 960 https://doi.org/10.1016/j.scitotenv.2024.178276

[107] Per Ola Darnerud. 2003. Toxic effects of brominated flame retardants in man and in wildlife. *Environment International* 29, 6, https://doi.org/10.1016/s0160-4120(03)00107-7

[108] Ike van der Veen, and Jacob de Boer. 2012. Phosphorus flame retardants: Properties, production, environmental occurrence, toxicity and analysis. *Chemosphere* 88, 10, https://doi.org/10.1016/j.chemosphere.2012.03.067

[109] Francesco Arpino, Idiano D'Adamo, Massimo Gastaldi, and Shabbir H. Gheewala. 2024. A review on European sustainable practices in end-of-life vehicles management. *Waste Management & Research* https://doi.org/10.1177/0734242x241299098

[110] Jonas Schreijäg, and Stella Peters 2025. *Spanische Behörde sanktioniert Volkswagen: Verstoß gegen Recycling-Pflichten*. tagesschau, City.

[111] Magnus Andersson 2016. *Innovating recycling of end-of-life car*. LICENTIATE OF ENGINEERING, Chalmers University of Techology, 2016.

[112] Ramesh Singh. 2016. *Chapter 7 - Welding Nonferrous Metals and Alloys* Applied Welding Engineering (Second Edition), Butterworth-Heinemann. https://doi.org/10.1016/b978-0-12-804176-5.00019-0

[113] Alexis Schmid, Pascale Naquin, and Rémy Gourdon. 2013. Incidence of the level of deconstruction on material reuse, recycling and recovery from end-of life vehicles: An industrial-scale experimental study. *Resources, Conservation and Recycling* 72 https://doi.org/10.1016/j.resconrec.2013.01.007

[114] Q. Guo. 2018. *Thermosets*. Elsevier.

[115] Abel Ortego, Guiomar Calvo, Alicia Valero, Marta Iglesias-Émbil, Antonio Valero, and Mar Villacampa. 2020. Assessment of strategic raw materials in the automobile sector. *Resources, Conservation and Recycling* 161 https://doi.org/10.1016/j.resconrec.2020.104968

[116] Hajime Ohno, Kazuyo Matsubae, Kenichi Nakajima, Yasushi Kondo, Shinichiro Nakamura, and Tetsuya Nagasaka. 2015. Toward the efficient recycling of alloying elements from end of life vehicle steel scrap. *Resources, Conservation and Recycling* 100 https://doi.org/10.1016/j.resconrec.2015.04.001

[117] Sinikiwe A. Mvokwe, Opeoluwa O. Oyedeji, Mojeed A. Agoro, Edson L. Meyer, and Nicholas Rono. 2025. A Critical Review of the Hydrometallurgy and Pyrometallurgical Recovery Processes of Platinum Group Metals from End-of-Life Fuel Cells. *Membranes* 15, 1, https://doi.org/10.3390/membranes15010013

[118] Gavin Harper, Roberto Sommerville, Emma Kendrick, Laura Driscoll, Peter Slater, Rustam Stolkin, Allan Walton, Paul Christensen, Oliver Heidrich, Simon Lambert, Andrew Abbott, Karl Ryder, Linda Gaines, and Paul Anderson. 2019. Recycling lithium-ion batteries from electric vehicles. *Nature* 575, 7781, https://doi.org/10.1038/s41586-019-1682-5

[119] Weidong Li, Yiqun Peng, Yu Zhu, Duc Truong Pham, Andrew Y.C. Nee, and Soh Kim Ong. 2024. End-of-life electric vehicle battery disassembly enabled by intelligent and human-robot collaboration technologies: A review. *Robotics and Computer-Integrated Manufacturing* 89 https://doi.org/10.1016/j.rcim.2024.102758

[120] Jens Gieseke, and Paulius Saudargas *Circularity requirements for vehicle design and management of end-of-life vehicles (REFIT): In "A new plan for Europe's sustainable prosperity and competitiveness"*. European Parliament and Council, City.

[121] Valentina de Simone, Valentina Di Pasquale, Paola Farina, and Raffaele Iannone. 2025. Exploring human-robot interaction in remanufacturing: Bibliometric insights. *International Journal on Interactive Design and Manufacturing (IJIDeM)* 16 https://doi.org/10.1007/s12008-025-02259-w

[122] Hengyu Wang, Qingjin Peng, Jian Zhang, and Peihua Gu. 2017. Selective Disassembly Planning for the End-of-life Product. *Procedia CIRP* 60 https://doi.org/10.1016/j.procir.2017.02.003

[123] Íñigo Elguea-Aguinaco, Antonio Serrano-Muñoz, Dimitrios Chrysostomou, Ibai Inziarte-Hidalgo, Simon Bøgh, and Nestor Arana-Arexolaleiba. 2022. Goal-Conditioned Reinforcement Learning within a Human-Robot Disassembly Environment. *Applied Sciences* 12, 22, https://doi.org/10.3390/app122211610

[124] Gwendolyn Foo, Sami Kara, and Maurice Pagnucco. 2022. Challenges of robotic disassembly in practice. *Procedia CIRP* 105 https://doi.org/10.1016/j.procir.2022.02.085

[125] Anwar Al Assadi, Lasse Höltge, Max Brower-Rabinowitsch, Frank Nägele, Werner Kraus, and Marco F. Huber. 2024. Towards Circular Economy: Process Description, Requirements, and Data Set for Robot-based Disassembly of Small Electrical Appliances. *Procedia CIRP* 130 https://doi.org/10.1016/j.procir.2024.10.183

[126] Pedro Rovira-Menaya, Carmelo Pina, and Jorge Sierra-Pérez. 2025. Existing barriers to consumer repair of small household appliances from a product design approach: A scoping review. *Proceedings of the 6th Product Lifetimes and the Environment Conference (PLATE2025)*, 6, https://doi.org/10.54337/plate2025-10288

[127] Yinong Yang, Samira Keivanpour, and Daniel Imbeau. 2023. Integrating X-reality and lean into end-of-life aircraft parts disassembly sequence planning: A critical review and research agenda. *The International Journal of Advanced Manufacturing Technology* 127, 5, https://doi.org/10.1007/s00170-023-11581-0

[128] Mohamad Bdiwi, Rashid Aquib, Pfeifer Marko, and Putz Matthias. 2017. *Disassembly of Unknown Models of Electrical Vehicle Motors Using Innovative Human Robot Cooperation* Proceedings of the Companion of the 2017 ACM/IEEE International Conference on Human-Robot Interaction, Association for Computing Machinery, Vienna, Austria. https://doi.org/10.1145/3029798.3038425

[129] Mohamad Bdiwi, A. Rashid, and M. Putz 2016. *Autonomous disassembly of electric vehicle motors based on robot cognition*. City.

[130] Matteo Beghi, Francesco Braghin, and Loris Roveda. 2023. Enhancing Disassembly Practices for Electric Vehicle Battery Packs: A Narrative Comprehensive Review. *Designs* 7, 5, https://doi.org/10.3390/designs7050109

[131] J. Y. C. Chen, and M. J. Barnes. 2014. Human–Agent Teaming for Multirobot Control: A Review of Human Factors Issues. *IEEE Transactions on Human-Machine Systems* 44, 1, https://doi.org/10.1109/thms.2013.2293535

[132] Roman Gerbers, Kathrin Wegener, Franz Dietrich, and Klaus Dröder. 2018. *Safe, Flexible and Productive Human-Robot-Collaboration for Disassembly of Lithium-Ion Batteries* Recycling of Lithium-Ion Batteries: The LithoRec Way, Springer International Publishing, Cham. https://doi.org/10.1007/978-3-319-70572-9_6

[133] Jan F. Hellmuth 2020. *Study of the Automation of Disassembly of Electric Vehicle Batteries*. Master Thesis, University of Rhode Island, 2020.

[134] Jan F. Hellmuth, Nicholas M. DiFilippo, and Musa K. Jouaneh. 2021. Assessment of the automation potential of electric vehicle battery disassembly. *Journal of Manufacturing Systems* 59 https://doi.org/10.1016/j.jmsy.2021.03.009

[135] Quan Liu, Wupeng Deng, Duc Truong Pham, Jiwei Hu, Yongjing Wang, and Zude Zhou. 2023. A Two-Stage Screw Detection Framework for Automatic Disassembly Using a Reflection Feature Regression Model. *Micromachines* 14, 5, (27/04/2023), https://doi.org/10.3390/mi14050946

[136] Hendrik Poschmann, Holger Brüggemann, and Daniel Goldmann. 2021. Fostering End-of-Life Utilization by Information-driven Robotic Disassembly. *Procedia CIRP* 98 https://doi.org/10.1016/j.procir.2021.01.104

[137] Kai Meng, Guiyin Xu, Xianghui Peng, Kamal Youcef-Toumi, and Ju Li. 2022. Intelligent disassembly of electric-vehicle batteries: A forward-looking overview. *Resources, Conservation and Recycling* 182 https://doi.org/10.1016/j.resconrec.2022.106207

[138] Heikki Saariluoma, Mika Luimula, Joonas Pekkarinen, Victor Blanco Bataller, and Timo Haavisto. 2025. Review of current state of technologies enabling circular economy in vehicle batteries and a role of laser processing and remote operation via metaverse. *Journal of Laser Applications* 37, 1, https://doi.org/10.2351/7.0001573

[139] Vivek Saxena. 2025. Enhancing EV battery lifecycle management: Robotic disassembly, design for disassembly, and sustainable solutions. *Journal of Energy Storage* 119, 14, https://doi.org/10.1016/j.est.2025.116368

[140] Enrico Villagrossi, and Tito Dinon. 2023. Robotics for electric vehicles battery packs disassembly towards sustainable remanufacturing. *Journal of Remanufacturing* 13, 3, https://doi.org/10.1007/s13243-023-00134-z

[141] Y. Zang, and Y. Wang 2022. *Robotic disassembly of electric vehicle batteries: An overview*. City.

[142] Hao Yin, Jinhua Xiao, and Guoxian Wang 2022. *Human-Robot Collaboration Re-Manufacturing for Uncertain Disassembly in Retired Battery Recycling*. City.

[143] Yue Zang, Mo Qu, Duc Truong Pham, Roger Dixon, Farzaneh Goli, Yongquan Zhang, and Yongjing Wang. 2024. Robotic disassembly of electric vehicle batteries: Technologies and opportunities. *Computers & Industrial Engineering* 198 https://doi.org/10.1016/j.cie.2024.110727

[144] Hengwei Zhang, Yisheng Zhang, Zhigang Wang, Shengmin Zhang, Huaicheng Li, and Ming Chen. 2023. A novel knowledge-driven flexible human–robot hybrid disassembly line and its key technologies for electric vehicle batteries. *Journal of Manufacturing Systems* 68, 5, https://doi.org/10.1016/j.jmsy.2023.04.005

[145] Ian Kay, Siamak Farhad, Ajay Mahajan, Roja Esmaeeli, and Sayed R. Hashemi. 2022. Robotic Disassembly of Electric Vehicles' Battery Modules for Recycling. *Energies* 15, 13, https://doi.org/10.3390/en15134856

[146] Yu-Chung Tsao, and Ho Thi Thu Ai. 2024. Remanufacturing electric vehicle battery supply chain under government subsidies and carbon trading: Optimal pricing and return policy. *Applied Energy* 375 https://doi.org/10.1016/j.apenergy.2024.124063

[147] Simon Mangold, Christian Steiner, Marco Friedmann, and Jürgen Fleischer. 2022. Vision-Based Screw Head Detection for Automated Disassembly for Remanufacturing. *Procedia CIRP* 105 https://doi.org/10.1016/j.procir.2022.02.001

[148] Vivian Ambiado 2023. *Enhancing Circular Practices in the Automotive Manufacturing Industry*. Master Thesis, University of Gothenburg, 2023.

[149] Ahmed ElSayed, Elif Kongar, Surendra M. Gupta, and Tarek Sobh. 2012. A Robotic-Driven Disassembly Sequence Generator for End-Of-Life Electronic Products. *Journal of Intelligent & Robotic Systems* 68, 1, https://doi.org/10.1007/s10846-012-9667-8

[150] J. Wang, and Ming Chen 2013. *Technology innovation of used automotive electronic control components recycling in China*. City.

[151] Jie Jiao, Guangsheng Feng, and Gang Yuan. 2024. Research on the Human–Robot Collaborative Disassembly Line Balancing of Spent Lithium Batteries with a Human Factor Load. *Batteries* 10, 6, https://doi.org/10.3390/batteries10060196

[152] Philipp Blenkinsop *Europe set to miss potential for battery material recycling*. Reuters, City.

[153] Apostolos Axenopoulos, Leire Bastida, Petros Daras, Eugenio Garnica, Dimitros Giakoumis, Ioannis Kostavelis, Ozgur S. Oguz, Alexis Papadimitriou, Georgios T. Papadopoulos, Sara Sillaurren, Dimitros Tzovaras, Paul F. M. J. Verschure, Vasiliki Vouloutsi, and Dirk Wollherr 2019. *A Hybrid Human-Robot Collaborative Environment for Recycling Electrical and Electronic Equipment*. City.

[154] Hendrik Poschmann, Holger Brüggemann, and Daniel Goldmann. 2020. Disassembly 4.0: A Review on Using Robotics in Disassembly Tasks as a Way of Automation. *Chemie Ingenieur Technik* 92, 4, https://doi.org/10.1002/cite.201900107

[155] Wei Hua Chen, Kathrin Wegener, and Franz Dietrich 2014. *A robot assistant for unscrewing in hybrid human-robot disassembly*. City.

[156] Mohammed Eesa Asif, Alireza Rastegarpanah, and Rustam Stolkin. 2024. Robotic disassembly for end-of-life products focusing on task and motion planning: A comprehensive survey. *Journal of Manufacturing Systems* 77 https://doi.org/10.1016/j.jmsy.2024.09.010

[157] Anwar Al Assadi, Thomas Götz, Andreas Gebhardt, Oliver Mannuß, Bernd Meese, Johannes Wanner, Soumya Singha, Lorenz Halt, Peter Birke, and Alexander Sauer. 2024. Automated Disassembly of Battery Systems to Battery Modules. *Procedia CIRP* 122 https://doi.org/10.1016/j.procir.2024.01.005

[158] Soran Parsa, and Mozafar Saadat. 2021. Human-robot collaboration disassembly planning for end-of-life product disassembly process. *Robotics and Computer-Integrated Manufacturing* 71 https://doi.org/10.1016/j.rcim.2021.102170

[159] Jun Huang, Duc Truong Pham, Ruiya Li, Mo Qu, Yongjing Wang, Mairi Kerin, Shizhong Su, Chunqian Ji, Omar Mahomed, Riham Khalil, David Stockton, Wenjun Xu, Quan Liu, and Zude Zhou. 2021. An experimental human-robot collaborative disassembly cell. *Computers & Industrial Engineering* 155 https://doi.org/10.1016/j.cie.2021.107189

[160] Luca Quattrucci, Marco Ceccarelli, Marco Santoro, and Matteo Russo. 2024. *Problems and Requirements for the Robotic Disassembly of Lithium-Ion Batteries in the Automotive Industry* Advances in Italian Mechanism Science, Springer Nature Switzerland Springer, Cham. https://doi.org/10.1007/978-3-031-64569-3_17

[161] Maximilian Held, Nicolas Rosat, Gil Georges, Hermann Pengg, and Konstantinos Boulouchos. 2021. Lifespans of passenger cars in Europe: Empirical modelling of fleet turnover dynamics. *European Transport Research Review* 13, 1, https://doi.org/10.1186/s12544-020-00464-0

[162] 2010. *Human-robot interaction and future industrial robotics applications*. City.

[163] Valeria Villani, Fabio Pini, Francesco Leali, and Cristian Secchi. 2018. Survey on human–robot collaboration in industrial settings: Safety, intuitive interfaces and applications. *Mechatronics* 55 https://doi.org/10.1016/j.mechatronics.2018.02.009

[164] R. B. Gillespie, J. E. Colgate, and M. A. Peshkin. 2001. A general framework for cobot control. *IEEE Transactions on Robotics and Automation* 17, 4, https://doi.org/10.1109/70.954752

[165] Marc-André Weber, and Sascha Stowasser. 2018. Ergonomische Arbeitsplatzgestaltung unter Einsatz kollaborierender Robotersysteme: Eine praxisorientierte Einführung. *Zeitschrift für Arbeitswissenschaft* 72, 4, https://doi.org/10.1007/s41449-018-0129-4

[166] S. Haddadin, A. Albu-Schaffer, A. De Luca, and G. Hirzinger 2008. *Collision Detection and Reaction: A Contribution to Safe Physical Human-Robot Interaction*. City.

[167] Peter A. Hancock, Deborah R. Billings, Kristin E. Schaefer, Jessie Y. C. Chen, Ewart J. de Visser, and Raja Parasuraman. 2011. A Meta-Analysis of Factors Affecting Trust in Human-Robot Interaction. *Human Factors* 53, 5, https://doi.org/10.1177/0018720811417254

[168] Jeffrey M. Stanton. 2000. Reactions to Employee Performance Monitoring: Framework, Review, and Research Directions. *Human Performance* 13, 1, https://doi.org/10.1207/s15327043hup1301_4

[169] Raja Parasuraman, Thomas B. Sheridan, and Christopher D. Wickens. 2008. Situation Awareness, Mental Workload, and Trust in Automation: Viable, Empirically Supported Cognitive Engineering Constructs. *Journal of Cognitive Engineering and Decision Making* 2, 2, https://doi.org/10.1518/155534308x284417

[170] Aparajita Chowdhury, Aino Ahtinen, Roel Pieters, and Kaisa Vaananen. 2020. *User Experience Goals for Designing Industrial Human-Cobot Collaboration: A Case Study of Franka Panda Robot* Proceedings of the 11th Nordic Conference on Human-Computer Interaction: Shaping Experiences, Shaping Society, Association for Computing Machinery, Tallinn, Estonia. https://doi.org/10.1145/3419249.3420161

[171] Alex W. Stedmon, Sarah Sharples, Robert Littlewood, Gemma Cox, Harshada Patel, and John R. Wilson. 2007. Datalink in air traffic management: Human factors issues in communications. *Applied Ergonomics* 38, 4, https://doi.org/10.1016/j.apergo.2007.01.013

[172] 2003. *Matching robot appearance and behavior to tasks to improve human-robot cooperation*. City.

[173] Victoria Groom, Leila Takayama, Paloma Ochi, and Clifford Nass. 2009. *I am my robot: The impact of robot-building and robot form on operators* Proceedings of the 4th ACM/IEEE international

conference on Human robot interaction, Association for Computing Machinery, La Jolla, California, USA. https://doi.org/10.1145/1514095.1514104

[174] M. Mori, K. F. MacDorman, and N. Kageki. 2012. The Uncanny Valley [From the Field]. *IEEE Robotics & Automation Magazine* 19, 2, https://doi.org/10.1109/mra.2012.2192811

[175] C. Esterwood, and L. P. Robert 2022. *A Literature Review of Trust Repair in HRI*. City.

[176] Samuele Vinanzi, Massimiliano Patacchiola, Antonio Chella, and Angelo Cangelosi. 2019. Would a robot trust you? Developmental robotics model of trust and theory of mind. *Philosophical Transactions of the Royal Society B: Biological Sciences* 374, 1771, https://doi.org/10.1098/rstb.2018.0032

[177] Birsen Donmez, Linda Ng Boyle, John D. Lee, and Daniel V. McGehee. 2006. Drivers' attitudes toward imperfect distraction mitigation strategies. *Transportation Research Part F: Traffic Psychology and Behaviour* 9, 6, https://doi.org/10.1016/j.trf.2006.02.001

[178] Randall D. Spain, and James P. Bliss. 2008. The effect of sonification display pulse rate and reliability on operator trust and perceived workload during a simulated patient monitoring task. *Ergonomics* 51, 9, https://doi.org/10.1080/00140130802120234

[179] Sara Jacob, Nathalie Klement, Richard Bearee, and Marie-Pierre Pacaux-Lemoine 2024. *Human-Robot Cooperation in Disassembly: A Rapid Review*. SCITEPRESS - Science and Technology Publications, City.

[180] Mengling Chu, and Weida Chen. 2023. Human-robot collaboration disassembly planning for end-of-life power batteries. *Journal of Manufacturing Systems* 69 https://doi.org/10.1016/j.jmsy.2023.06.014

[181] Wenjun Xu, Quan Tang, Jiayi Liu, Zhihao Liu, Zude Zhou, and Duc Truong Pham. 2020. Disassembly sequence planning using discrete Bees algorithm for human-robot collaboration in remanufacturing. *Robotics and Computer-Integrated Manufacturing* 62 https://doi.org/10.1016/j.rcim.2019.101860

[182] Gang Yuan, Xiaojun Liu, Chaoyong Zhang, Duc Truong Pham, and Zhiwu Li. 2023. A new heuristic algorithm based on multi-criteria resilience assessment of human–robot collaboration disassembly for supporting spent lithium-ion battery recycling. *Engineering Applications of Artificial Intelligence* 126 https://doi.org/10.1016/j.engappai.2023.106878

[183] Debasmita Mukherjee, Kashish Gupta, Li Hsin Chang, and Homayoun Najjaran. 2022. A Survey of Robot Learning Strategies for Human-Robot Collaboration in Industrial Settings. *Robotics and Computer-Integrated Manufacturing* 73 https://doi.org/10.1016/j.rcim.2021.102231

[184] Frank Wallhoff, Jürgen Blume, Alexander Bannat, Wolfgang Rösel, Claus Lenz, and Alois Knoll. 2010. A skill-based approach towards hybrid assembly. *Advanced Engineering Informatics* 24, 3, https://doi.org/10.1016/j.aei.2010.05.013

[185] Yi Yang, and Lin Liu. 2019. Strategic uncertainty, coordination failure and emergence: A game theory study on agency-structure interactions. *Journal for the Theory of Social Behaviour* 49, 4, https://doi.org/10.1111/jtsb.12215

[186] Chenguang Yang, Chao Zeng, Yang Cong, Ning Wang, and Min Wang. 2019. A Learning Framework of Adaptive Manipulative Skills From Human to Robot. *IEEE Transactions on Industrial Informatics* 15, 2, https://doi.org/10.1109/tii.2018.2826064

[187] Imen Belhadj, Mahdi Aicha, and Nizar Aifaoui. 2022. Product disassembly planning and task allocation based on human and robot collaboration. *International Journal on Interactive Design and Manufacturing (IJIDeM)* 16, 2, https://doi.org/10.1007/s12008-022-00908-y

[188] Marco Wurster, Marius Michel, Marvin Carl May, Andreas Kuhnle, Nicole Stricker, and Gisela Lanza. 2022. Modelling and condition-based control of a flexible and hybrid disassembly system with manual and autonomous workstations using reinforcement learning. *Journal of Intelligent Manufacturing* 33, 2, https://doi.org/10.1007/s10845-021-01863-3

[189] Kathrin Wegener, Wei Hua Chen, Franz Dietrich, Klaus Dröder, and Sami Kara. 2015. Robot Assisted Disassembly for the Recycling of Electric Vehicle Batteries. *Procedia CIRP* 29, 8, https://doi.org/10.1016/j.procir.2015.02.051

[190] Ruiya Li, Duc Truong Pham, Jun Huang, Yuegang Tan, Mo Qu, Yongjing Wang, Mairi Kerin, Kaiwen Jiang, Shizhong Su, Chunqian Ji, Quan Liu, and Zude Zhou. 2020. Unfastening of Hexagonal

Headed Screws by a Collaborative Robot. *IEEE Transactions on Automation Science and Engineering* 17, 3, https://doi.org/10.1109/tase.2019.2958712

[191] Fei Tao, Luning Bi, Ying Zuo, and Andrew Y.C. Nee. 2017. Partial/Parallel Disassembly Sequence Planning for Complex Products. *Journal of Manufacturing Science and Engineering* 140, 1, https://doi.org/10.1115/1.4037608

[192] Fernando Torres, Santiago Puente, and Carolina Díaz. 2009. Automatic cooperative disassembly robotic system: Task planner to distribute tasks among robots. *Control Engineering Practice* 17, 1, https://doi.org/10.1016/j.conengprac.2008.05.013

[193] Feng Guo, XiWang Guo, MengChu Zhou, Weitian Wang, Shujin Qin, and Qi Kang 2024. *Hybrid Disassembly Line Balancing for Human-robot Collaborative Remanufacturing*. City.

[194] Lei Guo, Zeqiang Zhang, Tengfei Wu, Yu Zhang, Yanqing Zeng, and Xinlan Xie. 2024. Green and efficient-oriented human-robot hybrid partial destructive disassembly line balancing problem from non-disassemblablity of components and noise pollution. *Robotics and Computer-Integrated Manufacturing* 90 https://doi.org/10.1016/j.rcim.2024.102816

[195] Kai Li, Quan Liu, Wenjun Xu, Jiayi Liu, Zude Zhou, and Hao Feng. 2019. Sequence Planning Considering Human Fatigue for Human-Robot Collaboration in Disassembly. *Procedia CIRP* 83 https://doi.org/10.1016/j.procir.2019.04.127

[196] Zude Zhou, Jiayi Liu, Duc Truong Pham, Wenjun Xu, F. Javier Ramírez, Chunqian Ji, and Quan Liu. 2018. Disassembly sequence planning: Recent developments and future trends. *Proceedings of the Institution of Mechanical Engineers, Part B* 233, 5, https://doi.org/10.1177/0954405418789975

[197] Hwai-En Tseng, Chien-Cheng Chang, Shih-Chen Lee, and Yu-Ming Huang. 2018. A Block-based genetic algorithm for disassembly sequence planning. *Expert Systems with Applications* 96 https://doi.org/10.1016/j.eswa.2017.11.004

[198] Yuanjun Laili, Fei Tao, Duc Truong Pham, Yongjing Wang, and Lin Zhang. 2019. Robotic disassembly re-planning using a two-pointer detection strategy and a super-fast bees algorithm. *Robotics and Computer-Integrated Manufacturing* 59 https://doi.org/10.1016/j.rcim.2019.04.003

[199] Jiayi Liu, Zude Zhou, Duc Truong Pham, Wenjun Xu, Chunqian Ji, and Quan Liu. 2018. Robotic disassembly sequence planning using enhanced discrete bees algorithm in remanufacturing. *International Journal of Production Research* 56, 9, https://doi.org/10.1080/00207543.2017.1412527

[200] Meng-Lun Lee, Xiao Liang, Boyi Hu, Gulcan Onel, Sara Behdad, and Minghui Zheng. 2023. A Review of Prospects and Opportunities in Disassembly with Human-Robot Collaboration. *ArXiv* abs/2310.13643

[201] Zitong Liu, Quan Liu, Wenjun Xu, Zhihao Liu, Zude Zhou, and Jie Chen. 2019. Deep Learning-based Human Motion Prediction considering Context Awareness for Human-Robot Collaboration in Manufacturing. *Procedia CIRP* 83 https://doi.org/10.1016/j.procir.2019.04.080

[202] Jan Jungbluth, Wolfgang Gerke, and Peter Plapper. 2017. An Intelligent Agent-Controlled and Robot-Based Disassembly Assistant. *IOP Conference Series: Materials Science and Engineering* 235, 1, https://doi.org/10.1088/1757-899x/235/1/012005

[203] Anjar Priyono, Winifred Ijomah, and Umit Bititci. 2016. Disassembly for remanufacturing: A systematic literature review, new model development and future research needs. *Journal of Industrial Engineering and Management* 9, 4, https://doi.org/10.3926/jiem.2053

[204] Kees Dorst. 2015. *Frame Innovation: Create new thinking by design*. Design thinking, design theory The MIT Press, Cambridge Massachusetts.

[205] Eleonora Desnica, M. Vulic, and M. Nikolic. 2016. AHP method in the function of adequate equipment choice for ELV detoxification in Serbia and EU. *Applied Engineering Letters* 1, 4,

[206] Shameem Ahmed, Shamsuddin Ahmed, Md. Rezaul Hasan Shumon, Elham Falatoonitoosi, and M. Abdul Quader. 2016. A comparative decision-making model for sustainable end-of-life vehicle management alternative selection using AHP and extent analysis method on fuzzy AHP. *International Journal of Sustainable Development & World Ecology* 23, 1, https://doi.org/10.1080/13504509.2015.1062814

[207] Kees Dorst. 2019. Design beyond Design. *She Ji: The Journal of Design, Economics, and Innovation* 5, 2, https://doi.org/10.1016/j.sheji.2019.05.001

[208] Louis L. Bucciarelli. 1994. *Designing engineers*. Inside technology MIT Press, Cambridge Mass.

[209] Kees Dorst. 2019. Co-evolution and emergence in design. *Design Studies* 65 https://doi.org/10.1016/j.destud.2019.10.005

[210] Simone Kondruweit-Reinema, and Jessica Jantz *Circular Economy for the Future – Wolfsburg's OHLF Research Campus Enters a New Funding Phase in March*. Fraunhofer Institute for Surface Engineering and Thin Films, City.

[211] Xavier Castañer, and Nuno Oliveira. 2020. Collaboration, Coordination, and Cooperation Among Organizations: Establishing the Distinctive Meanings of These Terms Through a Systematic Literature Review. *Journal of Management* 46, 6, https://doi.org/10.1177/0149206320901565

[212] Robert Holahan, and Mark Lubell. 2022. *Collective action theory* Handbook on Theories of Governance, Edward Elgar Publishing. https://doi.org/10.4337/9781800371972.00009

[213] Mohammadali Vosooghidizaji, Atour Taghipour, and Béatrice Canel-Depitre. 2020. Supply chain coordination under information asymmetry: A review. *International Journal of Production Research* 58, 6, https://doi.org/10.1080/00207543.2019.1685702

[214] Nevena Ivanovic, Aaron Schecter, Thomas Arend de Vries, and Gerben S. Van Der Vegt. 2023. Short and Long-Term Informal Coordination for Resilience: A Relational Event Modeling Approach. *Academy of Management Proceedings* 2023, 1, https://doi.org/10.5465/AMPROC.2023.15267abstract

[215] Ying Yin, Amy Rader Olsson, and Maria Håkansson. 2016. The role of local governance and environmental policy integration in Swedish and Chinese eco-city development. *Journal of Cleaner Production* 134 https://doi.org/10.1016/j.jclepro.2015.10.087

[216] Yan Xiao, Colin F. Mackenzie, and Rhona Patey. 1998. Team Coordination and Breakdowns in a Real-Life Stressful Environment. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* 42, 3, https://doi.org/10.1177/154193129804200301

[217] Dietmar Fehr. 2017. Costly communication and learning from failure in organizational coordination. *European Economic Review* 93 https://doi.org/10.1016/j.euroecorev.2017.01.006

[218] David A. Marshall. 2002. Financial crises and coordination failure: A comment. *Journal of Banking & Finance* 26, 2, https://doi.org/10.1016/s0378-4266(01)00233-3

[219] Yuqing Ren, Sara Kiesler, and Susan R. Fussell. 2008. Multiple Group Coordination in Complex and Dynamic Task Environments: Interruptions, Coping Mechanisms, and Technology Recommendations. *Journal of Management Information Systems* 25, 1, https://doi.org/10.2753/mis0742-1222250105

[220] Dunxing Wang, Qin Gao, Haibo Tan, Zhaopeng Liu, Liwei Zhou, Liu Jia, and Zhizhong Li. 2020. Coordination breakdowns in nuclear power plant control rooms: Cause identification and behaviour-sequence analysis. *Ergonomics* 63, 6, https://doi.org/10.1080/00140139.2020.1755060

[221] Fu Gu, Jianfeng Guo, Philip Hall, and Xinjian Gu. 2019. An integrated architecture for implementing extended producer responsibility in the context of Industry 4.0. *International Journal of Production Research* 57, 5, https://doi.org/10.1080/00207543.2018.1489161

[222] Stefan Seidel, Leona Chandra Kruse, Nadine Székely, Michael Gau, Daniel Stieger, Ken Peffers, Tuure Tuunanen, Björn Niehaves, and Kalle Lyytinen. 2018. Design principles for sensemaking support systems in environmental sustainability transformations. *European Journal of Information Systems* 27, 2, https://doi.org/10.1057/s41303-017-0039-0

[223] J. Johnson, J. M. Bradshaw, P. J. Feltovich, R. R. Hoffman, C. Jonker, B. v. Riemsdijk, and Sierhuis M. 2011. Beyond Cooperative Robotics: The Central Role of Interdependence in Coactive Design. *IEEE Intelligent Systems* 26, 3, https://doi.org/10.1109/mis.2011.47

[224] Matthew Johnson, Jeffrey M. Bradshaw, Paul J. Feltovich, Catholijn M. Jonker, M. Birna van Riemsdijk, and Maarten Sierhuis. 2014. Coactive design: Designing support for interdependence in joint activity. *J. Hum.-Robot Interact.* 3, 1, https://doi.org/10.5898/JHRI.3.1.Johnson

[225] Hongping Yuan, Xiaozhi Ma, and Bo Xia. 2024. Mega infrastructure project affordance: A new perspective to improve stakeholder management and project sustainability. *Frontiers of Engineering Management* 11, 4, https://doi.org/10.1007/s42524-024-4063-1

[226] Nathan Kunz, Kieren Mayers, and Luk N. van Wassenhove. 2018. Stakeholder Views on Extended Producer Responsibility and the Circular Economy. *California Management Review* 60, 3, https://doi.org/10.1177/0008125617752694

[227] Ignacio Castañeda-Rodríguez, and Andrea Teresa Espinoza Pérez. 2025. Multi-objective model for end-of-life tires reverse logistics: Enhancing sustainability through a techno-political framework. *Expert Systems with Applications* 291 https://doi.org/10.1016/j.eswa.2025.128203

[228] Peter H. Carstensen, and Carsten Sørensen. 1996. From the social to the systematic. *Computer Supported Cooperative Work (CSCW)* 5, 4, https://doi.org/10.1007/bf00136712

[229] Brigham Frandsen, Michael Leslie Powell, and James B. Rebitzer. 2015. Persistently Inefficient? Organizational Fragmentation, Coordination Failures, and Common Agency Problems in the US Healthcare System.

[230] David J. Cooper. 2006. Are Experienced Managers Experts at Overcoming Coordination Failure? 6, 2, https://doi.org/10.2202/1538-0637.1479

[231] John Rolfe, Delwar Akbar, Azad Rahman, and Darshana Rajapaksa. 2022. Can cooperative business models solve horizontal and vertical coordination challenges? A case study in the Australian pineapple industry. *Journal of Co-operative Organization and Management* 10, 2, https://doi.org/10.1016/j.jcom.2022.100184

[232] Richard C. Feiock. 2008. Metropolitan Governance and Institutional Collective Action. *Urban Affairs Review* 44, 3, https://doi.org/10.1177/1078087408324000

[233] Henri Tajfel, and John C. Turner. 2004. *The Social Identity Theory of Intergroup Behavior* Political Psychology, Psychology Press.

[234] Audley Genus, and Andy Stirling. 2018. Collingridge and the dilemma of control: Towards responsible and accountable innovation. *Research Policy* 47, 1, https://doi.org/10.1016/j.respol.2017.09.012

APPENDIX A

Initial Coding Scheme

- Block A - Theory Resonance (TR)
    - **TR1**: Volume & ROI as Automation Bottleneck
    - **TR2**: Material Complexity and the Plastic Dilemma
    - **TR3**: Uncertainty and Variance in Disassembly
    - **TR4**: Lifecycle Economics and Misaligned Incentives
- Block B - Novel Frames (NR)
    - **NR1**: Responsibility Diffusion & Systemic Misalignment
    - **NR2**: Market Logic as Control Barrier
    - **NR3**: Regulation Without Structure
    - **NR4**: Friction at the Human-Machine Interface
    - **NR5**: Information Silos and Missing Feedback Loops
    - **NR6**: Automation between Promise and Pragmatism
    - **NR7**: Embodied Expertise and Hidden Labor
    - **NR8**: Ergonomics, Improvisation, and Tool Realities
    - **NR9**: Design-Use-Reuse Misalignment
    - **NR10**: Technological Traps in Circular Design
    - **NR11**: Regulatory Complexity and Path Dependence
    - **NR12**: System Inertia and Deferred Sustainability

Recurring topics

Volume shortage & throughput risk for automation

- Vehicle *scarcity* / Volatility *(vehicle scarcity)*

- ROI dependent on volume *(automation ROI needs volume)*

Material complexity, with a focus on plastics

- Multi-material designs vs. recyclability

- Diversity of plastics as a core problem

- Performance optimization vs. dismantlability

Disassembly ≠ Assembly: automation under uncertainty

- Visibility/access problems & contamination

- Variants/unknown condition

- Data precision vs. process uncertainty

Digital discontinuity: Physically there, digitally not

- Physically present, digitally non-existent

- Data passport/DPP missing or unusable

- Variance explosion

New topics:

Diffusion of responsibility & systemic misalignment

- Responsibility vacuum

- Particular logics *(actor-specific optimization)*

- Patchwork interventions

- Lack of common objectives

Recycling as a burden & cost center (market failure)

- **Recycling = burden** (*recycling as burden)*
- **No sales / stigmatization of recyclate** (*no market / recyclate stigma)*

- Mandatory expansion without recycling pathway (*obligations w/o pathway)*
- Technically *feasible*, economically not (*tech feasible, econ weak)*

Regulation: overambitious, under-implemented, conflicting incentives

- Ambition vs. reality *(reg ambition vs ops reality)*

- Under-enforcement / gaps in evidence (*under-enforcement)*
- *Protectionism* vs circularity (*protectionism trade-offs)*
- REACH uncertainty (*regulatory unpredictability)*

Communication & data governance breaches

- Data not maintained / not accessible *(data gaps & access)*
- Data protection as a blockade pretext (*privacy as blanket barrier)*
- Compliance theater (*paperwork ≠ practice)*
- Willingness to cooperate *overestimated (overestimated collaboration)*

Logistics & packaging as underestimated enablers/bottlenecks

- Packaging as a “secondary activity ” *(packaging undervalued)*
- Throughput constraints (throughput constraints)
- Location & space reality *(space & layout limits)*
    - Legacy *specs* untested (*legacy specs inertia)*
    - Engineering *omniscience* myth (*engineer omniscience)*
    - Shredder default (*shredder bias)*
    - Closed-loop rhetoric vs. reality (*green loop rhetoric)*
    - Ideas from practice (*shop-floor ideas)*
    - Heuristics/tricks (*tacit routines)*

  - Acceptance conditions
  - Full-automation skepticism (full-automation skepticism)
  - **Silver bullet belief (sensor technology)** (*sensor silver bullet)*
  - **Phase logic & use cases** *(phased hybridization)*

Automation narratives: polarization & path selection

Worker-driven micro-innovation & tacit knowledge

Path dependency & specification myths (shredder bias incl.)

Visions, solution aspects & possible automation strategies

- *Automation strategies* & technologies *(automation strategies)*

- Design-for-disassembly & product design levers *(design levers)*

- Market & business models *(market solutions)*

- *Human-centric enablers (human-centric enablers)*

APPENDIX B

Interview Protocol

Section 1: Introduction and Consent

Purpose:

- Explain project scope and interview process
- Reconfirm voluntary participation and anonymity
- Obtain consent for audio recording

“Before we begin: This interview is part of a research project on automation and human-robot collaboration in vehicle disassembly. The aim is to explore your perspective and experience—there are no right or wrong answers. Everything is anonymous and confidential. Do you have any other questions and do you consent to this conversation being recorded and transcribed?”

Section 2: Role and Relationship to the Field

Purpose: Establish participant context and day-to-day experience.

Questions:

- Can you briefly describe your current role and how it relates to vehicle take-back, dismantling, or recycling?
- What aspects of dismantling or recycling are most relevant to your daily work?
- What has changed in your work over the past years—and what has remained the same?
- What trends or developments are you currently observing most closely?
- Have you been involved in any automation or robotics-related projects?
- [If dismantling company:] How do disassembly processes typically unfold at your site?
- [If material recycler:] How is the nature of the materials you work with changing?
- [If technology provider:] What are the most common challenges you hear from clients?

Section 3: Situational Constraints and Operational Dynamics

Purpose: Explore systemic frictions, decision-making challenges, and workflow issues.

Questions:

- What are some of the biggest challenges you encounter in your current processes?”
- Where do you see bottlenecks—technical, logistical, or organizational?
- Are there components or systems that are particularly difficult to handle?
- Are there typical goal conflicts or points of friction in your work?

- What kinds of decisions are particularly difficult—and why?
- Where do you encounter inefficiencies, detours, or recurring issues?
- Are there specific work steps you find particularly frustrating or strenuous?
- Are there steps that, in contrast, work well—or are even enjoyable?

Section 4: Values, Principles, and Professional Perspective

Purpose: Surface implicit values, priorities, and overlooked aspects of the system.

Questions:

- What is personally or professionally important to you in your work?
- Are there principles or perspectives that you feel are often overlooked?
- When you think of a moment when things went particularly well—what was different from usual?
- What tools or machines do you enjoy working with—and why?
- Are there devices or processes you find clunky, difficult, or disruptive?

Section 5: Perceptions of Change and Technology

Purpose: Capture views on automation, technical change, and organizational readiness.

Questions:

- What types of changes or innovations give you hope for the future of this field?
- In which areas are you more skeptical or unsure about upcoming changes?
- Are there specific tasks or routines you could imagine being transformed—perhaps through technical support?
- How do you experience the introduction of new technologies—what tends to go well, and what less so?
- What would a genuinely helpful change in your day-to-day work look like—technical or otherwise?
- If new equipment or machines have been introduced in your context: Which of them were helpful—and which were not?
- What role do you think automation could or should play in dismantling processes?”
- Have you experienced or observed human–robot collaboration in your work environment?
- What do you consider to be potential risks or unintended consequences of introducing more automation?
- What should be preserved or improved in the way humans currently work in dismantling?

Section 6: Future Outlook and Scenario Thinking

Purpose: Support future-facing reflection and speculative thinking.

Questions:

- If you could design the ideal disassembly process from scratch, what would it look like?
- If you look 10 years into the future—what would you ideally like to see changed?
- What gives you hope for such a future—and what causes concern?
- What capabilities, structures, or technologies are currently missing to reach that ideal state?
- Is there anything in your field that you feel could be made significantly easier—but hasn't been yet?
- What constraints today do you feel are taken for granted—but could actually be changed?
- If you could remove one major limitation in your field, what would that be—and what might become possible?

Section 7: Role Perception and Position in the System

Purpose: Understand participants' view of their place within the larger system.

Questions:

- What role do you see your work (or your company's work) playing in the larger dismantling or recycling process?
- How do you see yourself in relation to other actors in the field?
- Is your work perceived as central or peripheral—and how do you experience that?
- How do you think others view your role—and does that match your own perception?
- How would you or your organization like to be positioned in this field going forward?

Section 8: Additional Perspectives and Closing Reflection

Purpose: Create space for deeper insights, overlooked topics, and emerging themes.

Questions:

- What topics would you like to discuss more often with other stakeholders—but that rarely come up?
- Is there anything you think I might be overlooking—or something you believe I should understand before thinking about new approaches to automation or disassembly?

Would you like to receive a summary of the research results after the thesis is completed?

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End-of-life vehicle recycling faces systemic obstacles: fragmented dismantling practices, economic pressures, and regulatory misalignments
undermine circular material flows. Automation is often reduced to task substitution, yet its potential lies in serving as a coordination platform
that integrates human expertise, technology, and institutional frameworks. This thesis applies Dorst’s Frame Creation methodology,
combining literature analysis with 27 expert interviews across dismantlers, recyclers, OEMs, suppliers, and regulators. The study identifies
eight recurring themes—ranging from market barriers to information gaps—summarized in the overarching construct of “systemic
coordination failure.” Building on this diagnosis, the thesis develops strategic frames that reconceptualize automation as boundary
infrastructure. Rather than replacing labor, robotic systems and human integration are positioned to align economic drivers, embodied work
practices, and regulatory demands. The results demonstrate that scalable and sustainable vehicle disassembly requires automation
embedded in broader coordination architectures, linking information, incentives, and human capabilities.  €€€€,
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Återvinning av uttjänta fordon möter systemiska hinder: fragmenterade demonteringspraktiker, ekonomiska påfrestningar och regulatoriska
missanpassningar undergräver cirkulära materialflöden. Automatisering reduceras ofta till uppgiftsersättning, men dess verkliga potential
ligger i att fungera som en samordningsplattform som integrerar mänsklig expertis, teknik och institutionella ramverk. Denna avhandling
tillämpar Dorsts Frame Creation-metodik och kombinerar litteraturanalys med 27 expertintervjuer med aktörer från demontering, återvinning,
OEM:er, leverantörer och myndigheter. Studien identifierar åtta återkommande teman – från marknadshinder till informationsluckor – vilka
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sammanfattas i det övergripande begreppet ”systemiskt samordningsmisslyckande”. Utifrån denna diagnos utvecklar avhandlingen strategiska ramar som omtolkar automatisering som gränsinfrastruktur. I stället för att ersätta arbete positioneras robotsystem och mänsklig integration som medel för att samordna ekonomiska drivkrafter, kroppsligt förankrade arbetspraktiker och regulatoriska krav. Resultaten visar att skalbar och hållbar fordonsdemontering kräver automatisering som är inbäddad i bredare samordningsarkitekturer, där information, incitament och mänskliga förmågor kopplas samman. €€€€,
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