AIRCRAFT DISMANTLING PROCESS AUTOMATION

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The aviation sector plays an important role in advancing the transition toward a circular economy. As the Netherlands aims to achieve full circularity by 2050, it is essential that high-value materials used in aircraft manufacturing are effectively separated and recycled. This enables their reuse not only within the aviation industry but also across other sectors, thereby contributing to resource efficiency and environmental sustainability.

In addition, both the European Union and the Netherlands seek to reduce their dependency on external sources for raw materials. One key strategy to achieve this goal is the high-grade reuse of materials already present within domestic industrial cycles. Furthermore, the European Union has introduced the Critical Raw Materials Act (CRMA) to safeguard access to essential raw materials. Notably, aluminium and titanium—commonly found in aircraft fuselages—are listed as critical materials under this legislation. Their recovery and reintegration into the production cycle are therefore of strategic importance.

This graduation project report focuses on a conceptual design for controlled disassembly of an aircraft fuselage, resulting in monostreams of high-value materials. It was initiated in response to the current crude teardown methods that fail to optimally recycle valuable materials such as aluminum and titanium. Today's practice of cutting and shredding fuselages results in downcycling and material contamination.

This project is a cooperation between Grimbergen Industrial Systems and Aethos, which share a common objective: to advance circular processes within the industrial sector. Grimbergen offers technical expertise aimed at developing a more efficient dismantling process. Aethos contributes specialized knowledge and a robust network in both the aviation and recycling industries. Through this strategic collaboration, a practical and scalable solution is being developed that supports the sustainability goals of the aircraft recycling industry.

Aviation is continuously growing. The number of aircraft is still increasing, yet every aircraft has a finite service life. When an aircraft owner determines that the aircraft is no longer viable for resale, the maintenance program is discontinued, and the dismantling process is initiated by specialized companies. This process involves the systematic removal and recovery of valuable components such as engines, avionics, seating systems, and other high-value parts. Once these elements are extracted, the remaining fuselage is segmented using hydraulic shears and subsequently shredded into smaller fragments. Currently, all fuselage material is delivered to recyclers as a single contaminated stream, which lowers the market price, especially for aluminium. Research indicates that monostream recycling is more profitable: clean aluminium and titanium earn much higher per-tonne prices than mixed or contaminated aluminium because they require less downstream separation and have greater purity.

Therefore, the **project goal** is to create a conceptual dismantling process that separates high-value materials into clean monostreams, which lowers the dismantling process' environmental footprint while improving its economic yield. This includes:

1. Mapping and costing of the current dismantling process by building a process model.
2. Producing a first CAD concept that combines selected methods and technologies to produce clean, recyclable material streams
3. A technically substantiated, step-by-step process describing how the fuselage can be dismantled efficiently, safely and systematically using the conceptual design.
4. Preparing a business case that compares costs and benefits and evaluates whether investment in the new system is economically justified.

The following customer requirements were considered:

1. Maximise recovery of valuable materials (aluminium, titanium) to raise revenue and support circular-economy goals.
2. Keep operational and lifecycle costs low to ensure a cost-effective concept.
3. Meet environmental regulations and minimise waste and ecological footprint.
4. Comply with safety regulations so the method is safe in practice.
5. Design for scalability and reproducibility across narrow-body aircraft types.
6. Minimise dismantling time while preserving material recovery quality.
7. Ensure high reliability and long operational uptime to reduce downtime and increase throughput.

The scope is limited to a fully stripped fuselage, excluding cockpit, wings, tail and components under the floor. Deliverables are a conceptual design and a step-by-step process design demonstrating technical feasibility, illustrated in CAD but without detailed equipment specifications. The design references the Boeing 737 and must be scalable to other narrow-body types. Only required software functions are to be defined, not implemented. The concept must meet all applicable safety, health and environmental regulations.

To establish the conceptual design's theoretical foundation, the following relevant theories and concepts were reviewed.

Aircraft dismantling

The study examined the economic and technical (including environmental) aspects of aircraft decommissioning and recycling. When an aircraft is declared unsellable, maintenance ceases, and specialist dismantlers begin work. Reusable components — engines, avionics, seats and other valuable parts — are removed first, leaving mainly the fuselage. Fuselage sections are cut with hydraulic shears and then shredded; metals and other materials are separated using magnetic, eddy-current and density (float/sink) methods.

The current dismantling approach adheres to the principles of the **Ladder of Lansink**, a hierarchical framework for waste management that ranks methods from most to least environmentally responsible:

- **Prevention**: The most effective strategy for minimizing waste. However, aircraft are not yet designed with recyclability as a primary consideration.
- **Reuse**: Reusing components offers both economic and environmental advantages. Parts may be reintegrated into other aircraft or repurposed for alternative applications.
- **Recycling**: Materials such as aluminium and other metals are recyclable, though certain composites and specialized materials require additional treatment.
- **Energy Recovery**: Non-recyclable materials may be incinerated to generate energy, serving as a secondary recovery method.
- **Landfilling**: Considered the least desirable option, reserved only for materials that cannot be reused or recycled.

This structured approach ensures that aircraft dismantling is conducted with a strong emphasis on sustainability, resource efficiency, and environmental stewardship.

Dismantling requires coordination among many stakeholders before work begins: project managers (regulatory compliance, risk assessment, scheduling), the aircraft owner (which parts to retain), aviation authorities (certification for reused parts), airport operators (site and environmental planning), fire services (flammability and explosion risk), and security (to prevent illicit trade). Hazardous materials — for example depleted uranium components, asbestos and pressurised systems — must be removed safely. Reusable parts must be dismantled and documented in line with EASA rules. After interiors and contaminants that would damage shredders are removed, cut parts go to shredders and then to recyclers.

Van Heerden highlights that shredding mixes materials, increasing the need for efficient separation, and stresses the financial and regulatory challenges involved. While material separation and recycling support sustainability, they add costs compared with direct component reuse. These findings inform the practical design of a more efficient, cost-effective dismantling process, but actual dismantling costs should be validated with companies currently performing the work.

However, for dismantling companies, the recycling of materials represents a significant cost factor. Compared to the recovery of high-value components such as engines and avionics, the financial return from recycling bulk materials is relatively limited within the overall aircraft dismantling process.

Nevertheless, addressing this cost burden is essential to mitigate the environmental impact associated with end-of-life aircraft. One effective strategy is the creation of monostreams—pure, single-material flows—of high-grade materials. By implementing monostream separation in future dismantling operations, the recycling process can be optimized, costs reduced, and the quality of recovered materials preserved for reuse in aviation or other industrial sectors.

Critical Materials

The European Commission introduced the Critical Raw Materials Act CRMA. The decision was adopted to secure the EU's access to essential raw materials. Raw materials are crucial for the European economy. They form a strong industrial base and produce a wide range of goods and applications used in everyday life and modern technologies. To maintain reliable and unhindered access to certain raw materials, the European Commission compiled a list of critical raw materials CRM for the EU. CRM combine essential materials that are vital to the EU economy and that carry a significant supply risk. The CRMA recognises and supports strategic projects that help strengthen the value chain of critical raw materials including aluminium and titanium.

The main CRMA targets for 2030 are:

- **Extraction**: secure at least 10% of annual consumption of strategic materials from sources within the EU.
- **Processing**: process at least 40% of these materials inside the EU.
- **Recycling**: source at least 25% of annual consumption from recycling.
- **Diversification**: ensure no more than 65% of annual consumption of a strategic material is imported from a single third country.

The theory underscores the need for efficient material recovery and circular strategies to reduce supplier dependence and increase supply-chain resilience. Aluminium and titanium — both present in aircraft and listed in the CRMA — should be recovered in clean monostreams to improve Europe's resource security.

Process Optimization

Process optimization is essential for improving efficiency, minimising waste and raising process quality. Approaches such as Lean Manufacturing, Six Sigma, the Theory of Constraints and the PDCA cycle enable continuous improvement by identifying bottlenecks, streamlining workflows and enhancing overall performance.

Combined, they enable a more efficient, cost-effective and sustainable aircraft dismantling process; their principles were applied in the process design.

Waste management

Waste management plays a crucial role in promoting sustainability and circularity within industrial processes. Several waste management theories and methods were studied—such as the circular economy, the R-ladder and Industrial Ecology—that promote keeping materials in use, closing material loops and prioritising higher-value strategies (refuse, reduce, reuse, repair, recycle, recover). Material Flow Analysis (MFA) and Life Cycle Assessment (LCA) map flows and quantify environmental impacts to identify efficiency and reduction opportunities.

Applied to aircraft dismantling, these principles favour selective disassembly and separate material streams to preserve quality, boost high-value recycling, lower primary resource dependence and improve environmental and economic performance.

Rivet detection methods

Fast, accurate rivet detection—also mapping fuselage shape—enables automatic localisation and improves material recovery, supporting efficient separation and a circular economy; the chosen method depends on the concept application.

Based on Bosch and Jansen (2023), several NDT techniques were assessed for exterior rivet detection on fuselages (>40,000 rivets).

- Ultrasonic Phased Array Testing (PAUT)
- Eddy Current Array (ECA)
- Optical Lock-In Thermography (OLT)
- 3D Structural Light Scanning

Optical Lock-In Thermography was found best due to its speed, large field of view and non-contact operation, enabling precise rivet mapping, targeted material separation and more efficient dismantling and recycling of high-value materials like aluminium and titanium.

The framework provides the scientific foundation for a controlled fuselage disassembly process by combining aircraft dismantling theory, critical materials knowledge, process optimization and waste-management strategies to enable efficient separation, reuse and recycling of materials, with rivet detection highlighted as a necessary element for effective disassembly concepts.

Considering the above, a structured research plan is needed to develop a robust design process for the controlled disassembly of aircraft fuselages. The main research question is:

How can a controlled dismantling process for stripped aircraft fuselages be developed that enables efficient separation of high-quality monostreams, such as aluminium alloys and titanium, and thereby renders at least 80% of the total material suitable for high-quality recycling?

The following sub-questions, grouped into three categories: exploratory, process-design and detailing studies, were formulated:

Exploratory studies:

1. How does the current fuselage dismantling process operate and what inefficiencies and limitations exist?
2. How is a fuselage constructed, and which materials compose it?
3. Which composite materials are used in modern fuselages and how do they affect dismantling?
4. To what extent is it economically viable to recycle monostreams instead of mixed residual streams?

Process-design studies:

5. Which methods and technologies can be applied to fuselage dismantling?
6. Which dismantling approaches best enable efficient separation of high-value materials like aluminium and titanium for recycling?
7. What safety, health and environmental (VGM) requirements and standards apply to an efficient and safe fuselage dismantling process?

Detailing study:

8. To what extent is a new dismantling process that recovers monostream materials economically viable compared with the current process that recovers mixed residual streams?

These sub-questions were examined in depth and provided important input for the design.

1. *Current Aircraft Disassembly Process*

The investigation into the current aircraft fuselage dismantling process shows it comprises several stages: component removal, fuselage disassembly and material recycling, see Appendix A for a visual overview. For this graduation project, fuselage disassembly is the primary focus and the process analysis reveals multiple inefficiencies and constraints in the current method.

2. Aircraft Fuselage Structure

The fuselage is a complex load-bearing structure (stringers, frames, skin) typically built as a semi-monocoque to balance strength, weight and damage resistance. Main materials are aluminium alloys (2024-T3, 6061-T6, 7075-T6), with steel and titanium for heavily stressed parts. Joints use solid and blind rivets, bolts/screws and adhesives; welding is limited.

3. Composites in Fuselages

Composites (carbon, glass, aramid fibres in epoxy matrices) are increasingly used in fuselages, complicating dismantling: tools wear faster, fibre–matrix separation is difficult and recycling options are limited, causing environmental and safety issues. Many composite-rich aircraft will retire from the late 2030s, so urgent research into efficient disassembly and improved recycling methods is needed.

4. Economic Relevance of Monostreams

Recycling clean monostreams (aluminium, titanium) is more profitable than mixed scrap due to higher purity, fewer separation steps and substantially higher prices (e.g., aluminium monostreams €1,170–€1,750/t vs. contaminated aluminium €140/t). European scrap rates vary and depend on recycler agreements, but €300/t extra for aluminium monostreams is reported. Therefore, a controlled dismantling process that produces separated monostreams is both strategically justified and economically beneficial.

5. Methods and Technologies

Various cutting methods exist for fuselage dismantling: mechanical tools (versatile, low cost but less precise), diamond wire (controlled, low thermal impact), plasma/laser (fast, high-temperature), and waterjet (precise, no thermal distortion but costly). Automation, robotics, and AI/ML will increasingly optimise accuracy, repeatability and efficiency by combining cutting methods and adapting to different structures.

6. Dismantling Approach to Enable Efficient Separation of Materials

The study outlines three dismantling approaches for maximizing recovery of high value materials: extracting skin panels, removing rivets by drilling, and removing rivets by cutting. Extracting skin panels is the quickest, allowing large sections to be separated into clean material streams. Drilling out rivets achieves the best material recovery because parts are detached individually, but it is slow because of the sheer number of rivets and adhesive joints. Cutting rivets combines high recovery with faster execution than drilling yet still demands significant labour. Multiple viable techniques exist, each with trade-offs, and growing automation is expected to improve efficiency.

7. Safety, Health and Environmental Requirements

Fuselage dismantling requires strict SHE controls although no aircraft-specific dismantling laws exist; European machinery directives and standards (e.g., ISO 12100, ISO 14001, EN ISO 13849-1) apply. Compliance protects people and the environment and is essential for safe, efficient and sustainable recycling; the conceptual design must meet these requirements.

Based on the theories, findings and studies above, a function tree was developed to break down fuselage dismantling into essential subfunctions: choose strategy; identify materials and geometry; locate cuts; cut and position tools; transport and store sections; remove waste; and separate materials, see Appendix B.

Furthermore, a Program of Requirements was derived from client needs and the theoretical studies. As the concept is an initial CAD model and not a fully testable design, compliance will be assessed qualitatively using client and engineering expertise. Requirements are prioritised as 1 (must) or 2 (preferred), agreed with Grimbergen and Aethos.

The next step is to develop the design, guided by the solutions from the morphological overview.

The morphological chart maps candidate sub-solutions to every function defined in the function tree. Where a sub-solution can satisfy multiple functions, functions have been merged. The solution options were developed from research and brainstorming, and the chart highlights two concepts by framing their selected sub-solutions. In several cases a function is met by two complementary sub-solutions that together form the full solution.

Concept 1 targets fast, efficient dismantling with good material recovery. It uses internal access, 3D scanning, a tracked robotic arm, laser cutting, vacuum gripping and a belt loader with extendable rollers to move and sort parts into monostream containers.

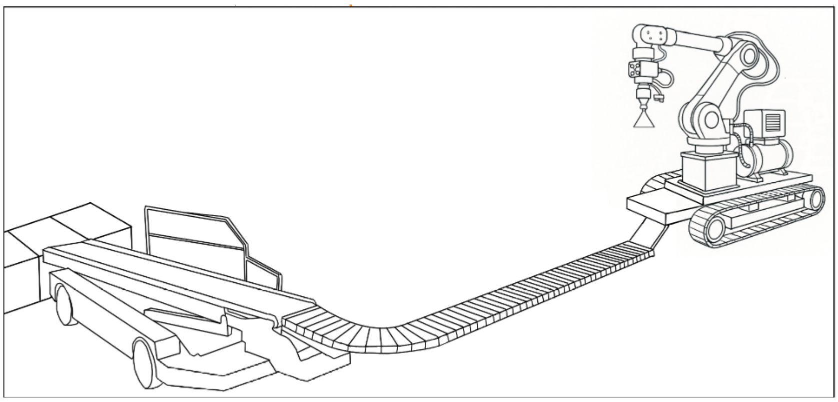


Figure 1 – Concept 1

Concept 2 prioritizes maximum material yield by cutting out rivets from the outside. It pairs OLT rivet detection with 3D scanning, a robotic arm on a circular rail, and precision waterjet cutting; parts are caught and conveyed to containers for separation.

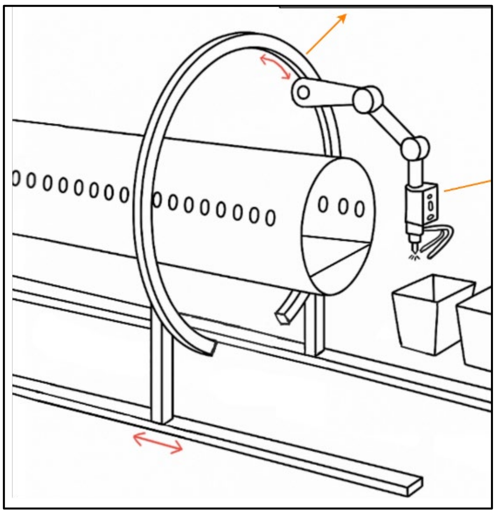


Figure 2 – Concept 2

Both concepts were evaluated against the Program of Requirements and compared using weighted success criteria from the weighted-criteria method. Overall, concept 1 scores highest and will be developed into a conceptual design—an initial CAD model showing the combined methods and technologies.

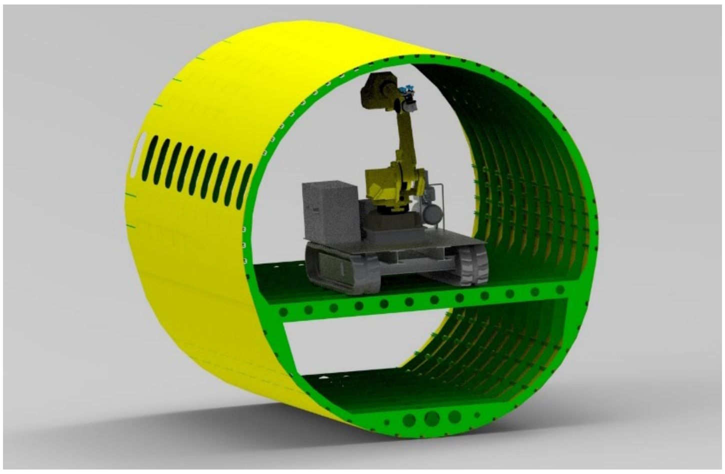


Figure 3 – Robot inside fuselage

The conceptual dismantling workflow begins with preparatory tasks: ordering collection containers, stripping the fuselage, and removing wings, tail and cockpit so a robot can be positioned. From inside the fuselage, the robot disassembles structural elements. A camera scans the interior and generates a cutting plan. A laser head then cuts sequentially between fuselage frames, first detaching skin panels, then stringers and other residuals, and finally the adjacent frame. Cut pieces are gripped and conveyed to a sorting system that separates them into clean monostreams. The robot advances and repeats the cutting and sorting sequence section by section until the upper fuselage is fully removed.

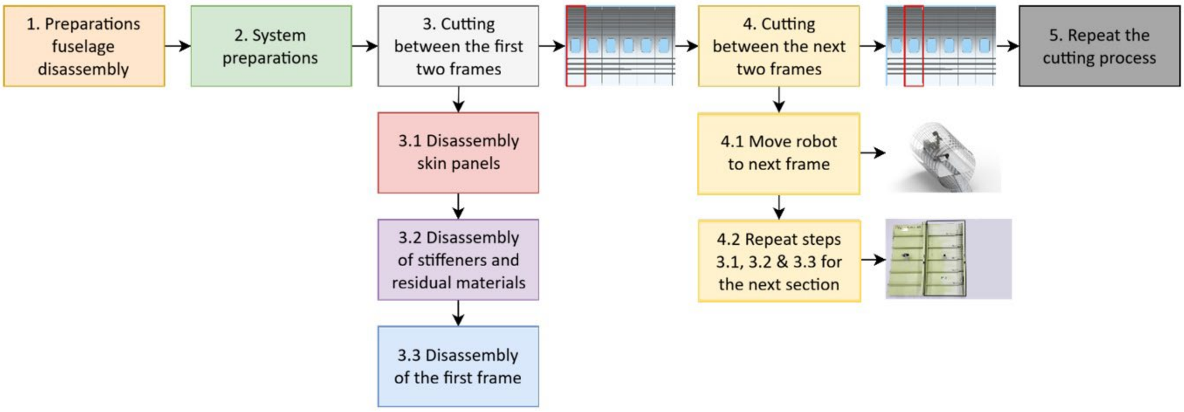
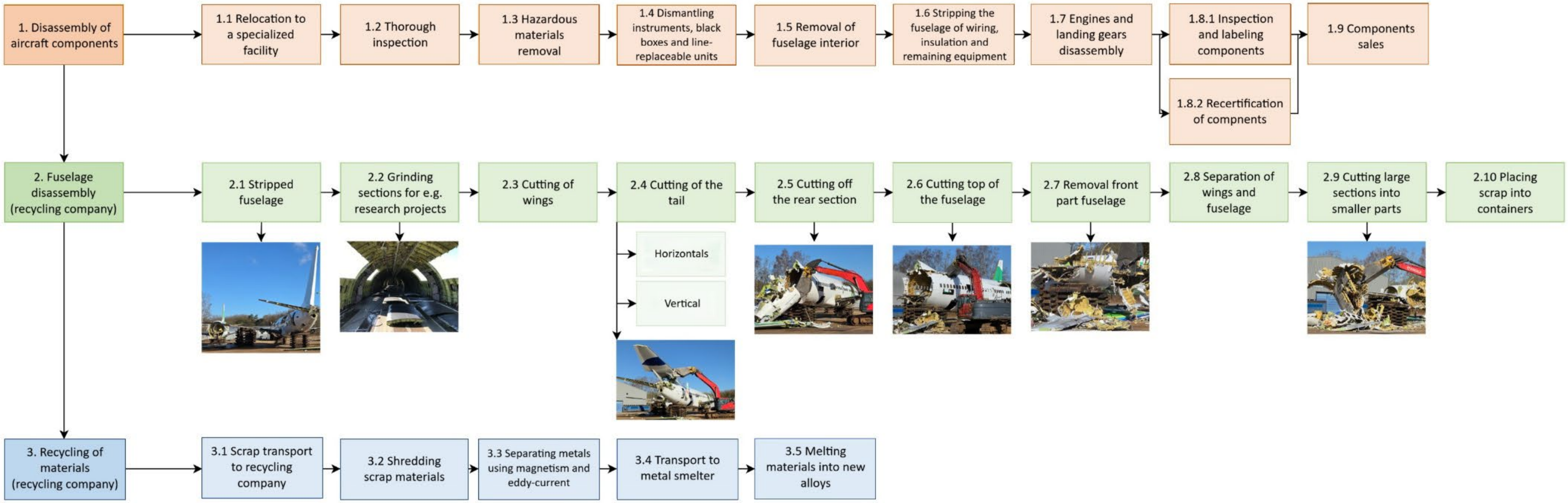


Figure 4 – Schematic overview of the conceptual dismantling process

The economic relevance of this new disassembly approach was also substantiated. By comparing costs and revenues per aircraft for the current versus proposed process, we demonstrated that the new method is economically viable. Projecting ten aircraft per year over a ten-year span showed that revenues and costs break even in year 4, recouping the initial investment in the conceptual design.

Further investigation confirmed the feasibility of using a robotic arm with a vacuum gripper. In summary, this research proves that it is both technically and economically feasible to develop a controlled disassembly process capable of separating at least 80 percent of a fuselage's material into high-value monostreams. This design represents a crucial step toward more efficient, safer, and sustainable aircraft recycling, aligning with both EU circularity goals and the ambitions of industry stakeholders.

APPENDIX A Current aircraft fuselage dismantling process



APPENDIX B Function tree