



A Framework for Industry 4.0 Implementation in Circular Aerospace Manufacture

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Abstract. The shift in aerospace utilisation of Sustainable Aviation Fuels (SAF), is redirecting environmental emission towards manufacturing. Significant amounts of aerospace structural components are made from aluminium or titanium alloys, contributing to the bulk of Greenhouse Gas (GHG) emissions from the manufacturing process. Due to the regulatory and mechanical properties of aerospace-grade alloys, strict recycling and material control are required to ensure the same grade is used for new parts, hence the reliance on virgin material. “Aircraft graveyards” are growing with a new fleet of aircraft being manufactured in the coming decades. Due to their untracked nature and a long, complex paper trail, identifying material types for recyclability into new planes is unfeasible. A strategy to move aerospace materials to the circular economy is critical in curbing the sector’s GHG emissions.

Industry 4.0 (I4.0) is vital in moving efficient, smart and sustainable manufacturing. At the fundamental level, I4.0 requires Internet of Things (IoT) sensors to collect and transmit data for a relevant function. This paper looks at implementing a framework for recording part manufacturing emissions, material type and processing to enhance recyclability by leveraging multiple aspects of I4.0, creating digital product passports.

Keywords: Aerospace · Digitalisation · Circular Economy · Industry 4.0

1 Introduction

The aerospace sector is facing a significant challenge in reaching net zero. Aerospace emissions have steadily increased since 2000, contributing 2.5% of global CO₂ emissions in 2023 [1]. The use phase dominates the emission profile, but SAF such as hydrogen, bio-jet kerosene, hydrogen fuel cells and electric-powered propulsion are moving the emission trends the use to operations, manufacturing, and End-of-Life (EoL) phases. Concurrently, aerospace manufacturers are under increased pressure to reduce emissions, driving a new age of sustainable manufacturing. Approximately 70% of aircraft are made from aluminium alloys, with 72% in the A320 airframe, with the next largest share being titanium alloys [2, 3]. During aluminium manufacture, the embodied CO₂ and input energy are the highest contributors to an aluminium product’s environmental impact [4]. Comparatively, recycling aluminium uses 95% less energy, producing fewer

emissions [5]. According to the European Union Aviation Safety Agency, an estimated 650 aircraft are decommissioned annually, an increase of 30% from the previous decade, with a current estimated 6000 decommissioned aircraft in aircraft cemeteries [6, 7]. Components like the engine, power units and landing gear are repurposed and reused. Whereas fuselage and wings are dismantled and recycled into lower-value alloys rather than aerospace-grade materials, keeping the industry reliant on virgin aluminium [3, 6]. The limitation in aerospace recycling stems from a lack of transparency in part makeup, part traceability, structured material separation, dismantling techniques and processes that align with European and worldwide legislation [3].

The 4th industrial revolution has improved throughput and efficiencies, creating a significant economic boost in manufacturing. However, the environmental improvement has not come to fruition. Some aerospace recycling challenges can be addressed through Digital Product Passports (DPP) integrated with Blockchain (BC) and Internet of Things (IoT) technologies. These tools enable secure, continuous lifecycle tracking, replacing inconsistent paper-based records. DPPs enhance supply chain transparency by providing verifiable data on sourcing, environmental impact, and sustainability claims. This supports informed, ethical decisions to facilitate closed-loop recycling [8]. This paper develops a framework for informed decisions on aerospace-grade aluminium and titanium for accurate EoL recycling by leveraging digital tools such as DPP, IoT and BC, to reduce emissions through digitalisation and big data tracking. The paper structure includes this introduction, literature review, framework structure, discussion, conclusions and further work.

2 Literature Review

Circular aerospace recycling was trialled by Boeing and Airbus. Process for Advanced Management of End of Life of Aircraft (PAMELA) demonstrated 85% recycling of decommissioned aircraft [9]. However, industrial practice finds that 20% of aircraft aluminium is recycled into new products, most of which are lower-grade aluminium [10, 11]. PAMELA and others have led to legislation such as the Aircraft Metal Recycling Association (AMRA), formed in 2006 by Boeing. AMRA is a membership-based EoL service connecting companies across the supply chain, creating an accredited, globally recognised Best Management Practice standard [12]. Disassembly requires careful segregation of material grades before shredding, ensuring alloys don't get downcycled. This process is further complicated by the legislative directives. Unlike road vehicles, which are covered under unified EU waste directives, aircraft are classified under multiple waste streams, like Waste Electronics and Electronic Equipment, Packaging Waste, and Chemicals, rather than a single directive [7]. Improving recycled aluminium will reduce environmental impact and reduce reliance on virgin materials, translating to cost savings [13]. Aerospace alloys require high-strength, low-density, good machinability and formable alloys due to their strictly legislated elemental composition [14]. Hence, cross-contamination disrupts the recasting process of aerospace-grade alloys.

Digitalisation through IoT sensors, connecting machines with data servers and finding data trends that improve production performance and lower costs are foundational to improving traceability and manufacturing. Airbus began implementing digitalisation

to remain competitive with low-cost economies [15, 16]. One study interviewed three aerospace manufacturers on I4.0, identifying it as an enabler for circularity by optimising processes using digital tools for drawings, testing and reports; drone use for AI-driven maintenance and automated additive manufacturing. BC has emerged as a successful tool for traceable, closed-loop recycling. Airbus and Boeing explored BC for digitising maintenance records to control part certification, risk mitigation and compliance [17, 18]. Lockheed Martin introduced material tracking for supply chain risk management [19]. GE Aviation incorporated Microsoft's Azure BC to track aerospace parts, streamlining its supply chain, and improving financial efficiency [16].

3 Framework Structure

The foundation of digitalisation is data. The proposed framework, Fig. 1, consists of multiple data layers tracking aircraft parts for EoL management. An A320 consists of about 320,000 parts. These can be grouped into product families like wing structures, including ribs, wing skins and reinforcements, which have geometric differences, but share manufacturing processes, reducing data load when uploaded to the BC network [4]. The cradle-to-grave framework excludes service parts like landing gear or engines, as these are already managed for circularity [3]. While maintenance data can be integrated modularly, the focus is on metallic alloy parts to enable material circularity.

Material data is recorded along the supply chain by designers, manufacturers and distributors. Core data collected includes part number, current owner, recycled material rate, production and storage details, certification, transportation conditions, surface treatments, painting, contamination risks, mass, and assembled aircraft number. Data can be collected manually or automatically with IoT sensors connected to manufacturing equipment, transmitting data like energy or material use data. Sensors should be calibrated periodically, ensuring accurate readings with a 1 s measurement rate. Sensor specification is out of scope for this project. A DPP is created at production and incrementally updated along the product's life. Data records align with Product Part Approval Process (PPAP), International Aerospace Quality Group Standards and the AMRA best practice framework [12]. At the use phase, data records are reduced to age, maintenance advisories, CO₂e and social impact scoring through social and environmental life cycle assessments (LCA).

During data collection, an asset ledger is submitted to a secured BC layer where it is validated, submitted, processed and stored. The user interface accesses a decision support layer through the accessibility layer, which evaluates part condition, possible contamination, manufacturing inputs, and recertification requirements. The structure is formed of four layers: data collection, secure BC and data processing, decision-making criteria and user interface. The framework can be integrated with other frameworks to track environmental or social metrics using LCA [20, 21].

To ensure a cyber-physical link, each part upon completion of manufacture is tagged using non-destructive methods like barcode stickers or paint markings to prevent stress concentrations or points of weakness due to strict regulations. This enables a cyber-physical link to the digital record of parts' properties, materials history, and social and environmental scores. At EoL, parts can be scanned through Radio Frequency Identification Detection (RFID) or a Virtual Reality map to each part's DPP.

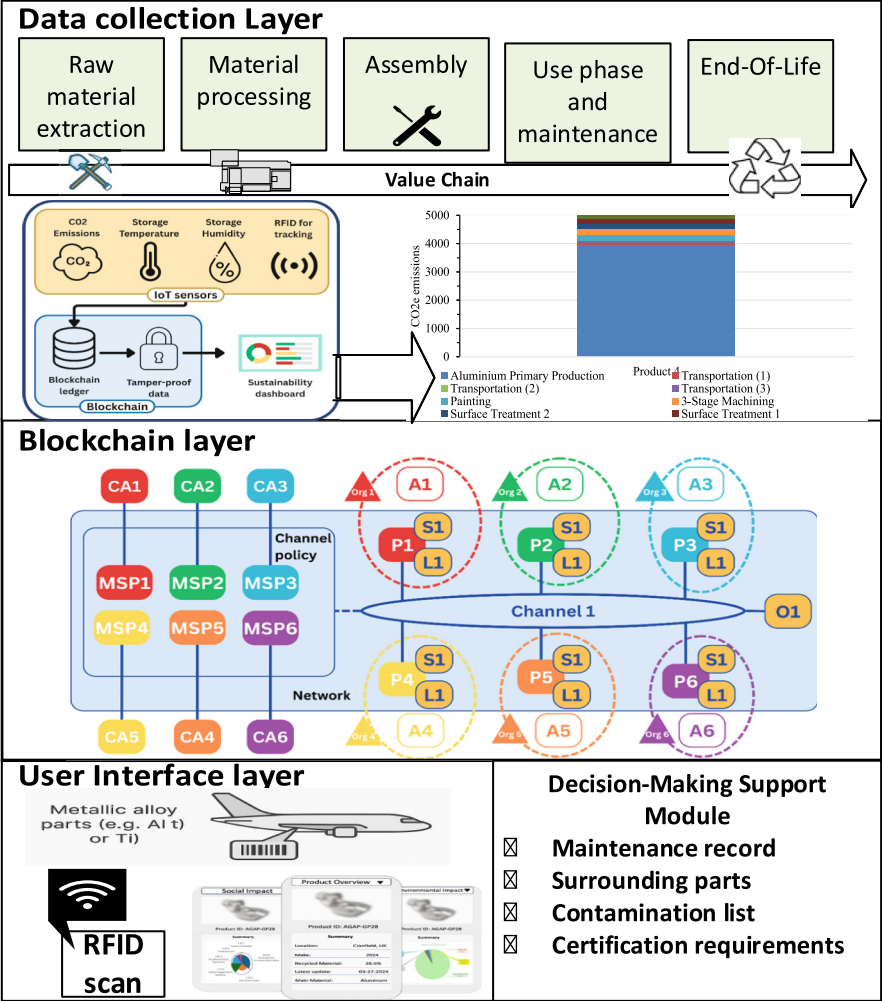


Fig. 1. Framework for BC and DPP integration for circular aerospace manufacture.

The framework proposed in Fig. 1 consists of the data collection (top) during the manufacture and usage, followed by the BC layer where peers (P) within the network manage and upload the chain code or smart contract (SC). The immutable ledger (L) stores past and current SC's. The organisation (O) is the peer owner that has its own administration identity (A), authenticating the SC through the Certification Authority (CA) and Membership Service Provider (MSP). All communication occurs through the secure channel. SC data is uploaded periodically to the DPP throughout the lifecycle. At EoL, the decision support layer provides critical information for recycling companies on part condition, use history, potential contamination and certification requirements. The final user interface enables interaction at both ends of the lifecycle, linking cyber-physical systems through RFID, IoT sensors, and manual data uploads.

4 Case Study

Parts of the framework were created using a concept BC with Hyperledger v2.5 test network and additional modules including an IoT Arduino humidity and temperature sensor, Excel data streamer for transport data capture, RFID part tracking as in Fig. 2. Hyperledger fabric, an enterprise grade open-source platform was selected for modular environment, and scalability in recent releases (v3.x). Benchmarking tests demonstrate its performance in handling large transactions per second with low latency across multiple channels [22]. In the aerospace application, organisations can allocate channels to departments like quality, procurement, and engineering to improve throughput. Backend databases such as CouchDB or LevelDB, enhance read/write performance, while firewalls and encryption increase security but increase computational load. While test Hyperledger networks can run from a laptop device, production networks require high-performance computing. Each organisation maintains its manufacturing data in a cloud-based database that serves as the platform for BC SC, enabling automation ledger updates. BC data stores cumulative energy usage and carbon intensity. Humidity and temperature data are collected every second, but only specific part exposures, such as 60% humidity at 35 °C+ for over 3 h, are uploaded to the BC to prevent data overload. Similarly, local environmental and social data feeds into the LCA module, which updates the overall environment that the BC cloud network provides updates to the LCA to update the overall part social and environmental scores into the BC chain code. Upon manufacture, each part is assigned a unique identification and DPP, creating the initial ledger by the orderer as in Fig. 3.

TIME	CH1	CH2	CH3	CH4	ID	RFIDUID	Humidity	Temperature	CO2
12:31:16.35		48	16	636	panelA320_1	5B781405	40.5	15	898
12:31:11.31		48	16	636	panelA320_2	B6B02711	30.7	29.4	1156
12:31:06.27		48	16	633	panelA320_3	54702606	25.6	17.4	804
12:31:01.23		48	16	630	panelA320_4	D8C62557	22.4	18.9	937
12:30:56.19		48	16	627	panelA320_5	43691505	48	16	636

Fig. 2. Automatic update of a locally stored ledger using Excel Data Streamer

As the part travels through the supply chain, each peer scans the part to transfer ownership and update the ledger with new processing and material conditions, as in Fig. 3. Once aircraft assembly is complete, parts can be tracked in service to calculate a total CO₂e and social impact through ongoing LCA integration. At EoL, the entire data trail, from material, ownership, and environmental exposure, to support recycling decisions and trace feedback to original suppliers, enabling closed-loop recycling.

ID	RFIDUID	ProductType	Quantity	Material	Location	InCharge
panelA320_1	5B781405	panel	1	Al765	Supplier 1	Supplier 2
panelA320_2	B6B02711	panel	3	Al765	Supplier 2	Supplier 3
panelA320_3	54702606	panel	1	Al793	Supplier 3	Supplier 5
panelA320_4	D8C62557	panel	2	Al7170	Supplier 4	Supplier 6
panelA320_5	43691505	panel	2	Al746	Supplier 5	Supplier 5
ID	RFIDUID	ProductType	Quantity	Material	Location	InCharge
panelA320_1	5B781405	panel	1	Al765	Supplier 1	Supplier 2
panelA320_2	B6B02711	panel	3	Al765	Supplier 2	Supplier 3
panelA320_3	54702606	panel	1	Al793	Supplier 3	Supplier 5
panelA320_4	D8C62557	panel	2	Al7170	Supplier 4	Supplier 6
panelA320_5	43691505	panel	2	Al746	Supplier 6	Supplier 6

Fig. 3. Change to the ledger when a specific RFID is scanned

5 Discussion

The framework is designed to trace part origins within aerospace supply chains, supporting a closed-loop economy, reducing emissions and costs. Disassembly companies should be integrated as BC peers to identify material locations via VR mapping, understand alloy segregation importance and provide economic feedback when disassembling. Immutable material logs of parts lifecycles facilitate circular manufacturing. Incorporating material circularity indicators into the DPP promotes recyclability by design, reducing reliance on virgin materials. The Corporate Sustainability Reporting Directive becomes streamlined via an untamperable, permanent digital log. IoT data collection supports predictive anomaly detection during manufacturing, reducing part spoilage and waste [15]. Digital visualisation tools like Virtual or Augmented Reality assist recyclers in locating and categorising components using DPP-linked maintenance records [23]. As Hyperledger Fabric is open-source, implementation costs include developers (in-house or subcontracted), cloud services such as AWS, Azure, Google Drive and sensors. Some services offer integrated Hyperledger Fabric solutions, but it is recommended for a supply-chain-led aerospace BC due to security. Despite setup and maintenance costs, aerospace manufacturers are envisaged to benefit through improved traceability and resource management.

However, several challenges remain. If virgin material remains cheaper than recycled, the circular process becomes unviable. Capital investment for digital technologies would be significant and labour-intensive [23]. Without government incentives, material circularity is less likely to be adopted, particularly by Small to Medium Enterprises [23]. Particularly if increasing use of carbon fibre with limited recyclability may reduce the economic feasibility of circular practices, undermining recycling efforts in aerospace manufacturing [6]. An aircraft with 340000 parts requires vast data storage and management. To minimise network load, product families submit updates at the end of the manufacturing stage can be implemented to the BC with local manufacturing data stored at manufacturing facilities. This approach limits data overload, ensuring that SC are in the KB range, and even at 1MB per chain code approximates to 1821 TB per annum. Previous BC benchmarks process this 1500+ SC within this range per second.

[13] reported aerospace companies show a positive relationship toward material circularity adoption; however, their focus remains on extending life, increasing material and

design improvements, often overlooking the inevitable EoL scenario. Using a trackable digital part infrastructure allows the inclusion of MCIs, which follow the ISO59020 standard. Although aerospace is one of the most regulated industries and BC aims to streamline regulatory checks, with BC in a premature stage of regulation framework development, integrating current compliance of aerospace manufacture into BC could become problematic, requiring multiple back-and-forth between relevant regulatory bodies to ensure compliance.

6 Conclusion and Future Work

This paper provides a framework for integrating BC and DPPs for aerospace alloys to re-enter the sector within a closed-loop economy. The framework recommends a modular approach to add improved value to the framework and ensure there is alignment with current aerospace standards to identify and assist decommissioning of aircraft. Sustainable manufacturing by recirculating materials is the core of this paper's aim. Through cyber-physical systems, digital logs and robust, secure and trackable part information, a recycler at the EoL can scan the part and separate and disassemble it into the correct alloy pile. The research can be developed further by integrating more detailed LCA strategies, implementing example AI anomaly detection during manufacture or operation from maintenance logs.

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References

1. Gössling, S., Humpe, A.: The global scale, distribution and growth of aviation: implications for climate change. *Glob. Environ. Change* **65** (2020). <https://doi.org/10.1016/j.gloenvcha.2020.102194>
2. Zhang, X., Chen, Y., Hu, J.: Recent advances in the development of aerospace materials. *Prog. Aerosp. Sci.* **97**, 22–34 (2018). <https://doi.org/10.1016/j.paerosci.2018.01.001>
3. Dunand, L.: End-of-life Reusing, recycling, rethinking | Airbus (2022). <https://aircraft.airbus.com/en/newsroom/news/2022-11-end-of-life-reusing-recycling-rethinking>. Accessed 13 May 2025
4. Cox, R., Venkatapuram, R.S.R., Afy-Shararah, M., Carter, J.L., Artingstall, J., Salonitis, K.: Evaluating LCA product families in an approach to determine baseline emissions within aerospace manufacturing. *Procedia CIRP* **122**, 915–920 (2024). <https://doi.org/10.1016/j.procir.2024.01.125>
5. Das, S., Gilbert Kaufman, J.: Recycling aluminum aerospace alloys (2007)
6. Habib, M.A., et al.: Current practices in recycling and reusing of aircraft materials and equipment. *Mater. Circ. Econ.* **7**(1), 1–36 (2025). <https://doi.org/10.1007/S42824-025-00165-W>
7. Sustainability in the end-of-life phase of aircraft - What happens after airplanes fly their last trip | EASA (n.d.). <https://www.easa.europa.eu/en/light/topics/sustainability-end-life-phase-aircraft>. Accessed 13 May 2025

8. Panza, L., Bruno, G., Lombardi, F.: A collaborative architecture to support circular economy through digital material passports and internet of materials. *IFAC-PapersOnLine* **55**, 1491–1496 (2022). <https://doi.org/10.1016/J.IFACOL.2022.09.601>
9. Airbus, S.A.S.: Process for advanced management of end-of-life of aircraft (PAMELA). Champniers, France (2008)
10. Asmatulu, E., Twomey, J., Overcash, M.: Evaluation of recycling efforts of aircraft companies in Wichita. *Resour. Conserv. Recycl.* **80**, 36–45 (2013). <https://doi.org/10.1016/J.RESCONREC.2013.08.002>
11. Sabaghi, M., Cai, Y., Mascle, C., Baptiste, P.: Sustainability assessment of dismantling strategies for end-of-life aircraft recycling. *Resour. Conserv. Recycl.* **102**, 163–169 (2015). <https://doi.org/10.1016/J.RESCONREC.2015.08.005>
12. Aircraft Fleet Recycling Association, (n.d.). <https://afraassociation.org/about-us/>. Accessed 15 May 2025
13. Salesa, A., León, R., Moneva, J.M.: Aero-circularity: charting the flight path between circular economy and sustainability performance. *Bus Strategy Environ.* **34**, 4766–4784 (2025). <https://doi.org/10.1002/BSE.4235;SUBPAGE:STRING:FULL>
14. Li, S.S., et al.: Development and applications of aluminum alloys for aerospace industry. *J. Mater. Res. Technol.* **27**, 944–983 (2023). <https://doi.org/10.1016/J.JMRT.2023.09.274>
15. Javaid, M., Haleem, A., Singh, R.P., Rab, S., Suman, R.: Significance of sensors for industry 4.0: Roles, capabilities, and applications. *Sens. Int.* **2**, 100110 (2021). <https://doi.org/10.1016/J.SINTL.2021.100110>
16. Carou, D.: Aerospace Transformation Through Industry 4.0 Technologies. *SpringerBriefs in Applied Sciences and Technology*, pp. 17–46 (2021). https://doi.org/10.1007/978-3-030-67849-4_3/COVER
17. Tan, W.C., Sidhu, M.S.: Review of RFID and IoT integration in supply chain management. *Oper. Res. Perspect.* **9** (2022). <https://doi.org/10.1016/j.orp.2022.100229>
18. Taj, S., Imran, A.S., Kastrati, Z., Daudpota, S.M., Memon, R.A., Ahmed, J.: IoT-based supply chain management: a systematic literature review. *Internet Things* **24** (2023). <https://doi.org/10.1016/j.iot.2023.100982>
19. Kshetri, N.: 1 Blockchain's roles in meeting key supply chain management objectives. *Int. J. Inf. Manag.* **39**, 80–89 (2018). <https://doi.org/10.1016/J.IJINFOMGT.2017.12.005>
20. Yuksek, Y.A., Haddad, Y., Cox, R., Salonitis, K.: A unit product energy mapping framework for operation management in manufacturing industries. *Procedia CIRP* **122**, 873–878 (2024). <https://doi.org/10.1016/J.PROCIR.2024.01.119>
21. Haddad, Y., Yuksek, Y.A., Jagtap, S., Jenkins, S., Pagone, E., Salonitis, K.: Eco-social sustainability assessment of manufacturing systems: an LCA-based framework. *Procedia CIRP* **116**, 312–317 (2023). <https://doi.org/10.1016/J.PROCIR.2023.02.053>
22. Guggenberger, T., Sedlmeir, J., Fridgen, G., Luckow, A.: An in-depth investigation of the performance characteristics of hyperledger fabric. *Comput. Ind. Eng.* **173**, 108716 (2022). <https://doi.org/10.1016/J.CIE.2022.108716>
23. Rodrigues Dias, V.M., Jugend, D., de Camargo Fiorini, P., do A. Razzino, C., Paula Pinheiro, M.A.: Possibilities for applying the circular economy in the aerospace industry: practices, opportunities and challenges. *J. Air Transp. Manag.* **102**, 102227 (2022). <https://doi.org/10.1016/J.JAIRTRAMAN.2022.102227>

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