CIRCULAR OPPORTUNITY MAPPING FOR ASSURED LIFE-EXTENSION AS A SERVICE IN THE HIGH-INTEGRITY SECTOR

Halidu Abu-Bakar, Fiona Charnley

Halidu Abu-Bakar; University of Exeter Business School., Faculty of Environment, Science and Economy, Rennes Dr, Exeter EX4 4PU; h.abu-bakar@exeter.ac.uk; https://orcid.org/0000-0003-3223-8585

Fiona Charnley, University of Exeter Business School., Faculty of Environment, Science and Economy, Rennes Dr, Exeter EX4 4PU; https://orcid.org/0000-0001-5533-5375

Abstract

Circular business models in high-integrity sectors (e.g., aerospace, maritime, EV powertrains and energy infrastructure) often stall where strategy meets assurance: teams struggle to identify value-retention routes that remain certifiable, warrantable and traceable. This paper specifies Opportunity Mapping (OM) as a bridging method that links circular intent to implementable, assurance-ready propositions by mapping asset boundaries, actor/custody and approval events, constraints and re-qualification checkpoints, and the minimum evidence required for release-to-service decisions (including a minimal Digital Product Passport field set). We present a five-stage OM playbook, introduce a concise worked example to demonstrate application to a representative safety-critical asset family, and define Assured Life-Extension as a Service (ALEaaS) as the service archetype operationalised by OM outputs (verification packs, decision gates and traceability requirements).

1. Introduction and Motivation

High-integrity engineering sectors, including aerospace, defence, maritime systems, EV powertrains and energy infrastructure, depend on long-lived, safety-critical assets with tightly controlled configurations. In these contexts, value-retention pathways (repair, refurbishment, remanufacture, certified-used spares and modular upgrade) are only viable where performance, provenance and liability can be demonstrated through approved tests, records and release-to-service decisions.

1.1 Barriers to Circularity in High-Integrity Sectors

Despite clear technical potential, adoption of CBMs in high-integrity industries remains limited because circular routes must be assurance-compatible: organisations need confidence that reused or remanufactured parts meet certified baselines and that evidence is sufficient to support warranties, liability allocation and safe return to service.

Regulatory and certification challenges further inhibit uptake. Aerospace and defence components are subject to stringent certification regimes that predate circular concepts, so any reused or remanufactured unit is typically required to meet "as-new" standards of performance, documentation and traceability (Rodrigues Dias et al., 2022). In commercial aviation, used serviceable material must pass the same Part-145 processes and back-to-birth traceability checks as new parts for certification, which require extensive testing and paperwork that many actors regard as a deterrent to wider remanufacture (Avitrader, 2025). At system level, policy analyses describe a patchwork of divergent rules on waste status, secondary materials and product standards across jurisdictions, raising compliance costs and creating legal uncertainty for circular flows (OECD, 2021). The net effect is high perceived risk: life-extension interventions must satisfy the same safety guarantees as new manufacture, yet stakeholders remain unsure how responsibilities and liabilities will be allocated. Industry stakeholders report that, in the absence of explicit guidance on documenting and certifying reused components, they default to conservative practices that favour replacement over remanufacture, even where the latter would be technically and environmentally superior (Brändström et al., 2024).

Overlaying these technical and institutional barriers are economic and organisational frictions. Establishing remanufacturing lines or reverse logistics networks incurs a high upfront cost, and many firms see the return on investment as uncertain (Munawar et al., 2025). There is also limited awareness or precedent: most published remanufacturing case studies concern consumer goods or commodities, not jet engines or wind turbines. Managers in critical sectors report "limited awareness, understanding, and evidence" of circular practices in their fields. This inertia means only pilot projects exist, and companies have little guidance on building viable circular-service businesses under strict safety constraints.

1.2 Evidence Gap in Circular Business Model Implementation

The literature echoes these challenges and highlights a gap in decision-support tools for these sectors (Ferreira and Gonçalves, 2021; Rizova et al., 2020). Broad reviews of remanufacturing and refurbishment show most examples focus on consumer or industrial goods; few explicitly address aerospace, energy or military equipment (Ferreira and Gonçalves, 2021; Rodrigues Dias et al., 2022). Existing frameworks tend to treat technical, economic or environmental aspects in isolation (Kerin and Pham, 2020; Russell and Nasr, 2022). For instance, the OECD identifies "product life extension" as a distinct CBM that slows material flows and reduces virgin extraction, but also notes that all circular models currently have very low market penetration (OECD, 2019). What is missing is systematic guidance on where in the value chain life-extension services are feasible under real-world constraints. Even within circular economy research, integrated approaches are scarce: most life-cycle models (MFA, LCA) and business model canvases stop short of incorporating assurance requirements. Regulators and industry both lament the lack of multi-dimensional tools that consider technical feasibility, lifecycle costs, and certification together. In practice, engineers deciding whether to remanufacture a turbine component or order a new one often rely on ad hoc judgment rather than a unified analysis.

As a result, decision-makers lack a practical method to pinpoint which assets and reverse pathways are both value-retentive and assurance-feasible, and to specify the minimum evidence chain required for auditable reuse, refurbishment or remanufacture.

1.3 Opportunity Mapping as a Bridging Approach

OM treats traceability and evidence as design requirements, not optional enablers. Candidate routes are evaluated for restoration potential and, equally, for standards alignment, approval events, and the minimum evidence needed to demonstrate provenance, condition, process route and authorisations (for example through DPP-compatible records where relevant).

Opportunity Mapping (OM) is proposed as a bridging methodology that connects strategic circular intent with implementable, assurance-compatible CBMs in high-integrity sectors. It is a structured process linking: (i) value-retention options (remanufacture, refurbishment, certified-used spares, modular upgrade) (Amaitik et al., 2023; UNESCO, 2018); (ii) regulatory and standards regimes that govern certification, liability and compliance (Rodrigues Dias et al., 2022; UNESCO, 2018); (iii) traceability architectures, including Digital Product Passports and digital-thread implementations (Munawar et al., 2025; Neligan et al., 2023); and (iv) lifecycle performance metrics (environmental, economic and reliability outcomes). The output is a practical “map” of where interventions are viable and what assurance and traceability conditions must be met, building on value-chain mapping approaches used to identify circular hotspots and stakeholder roles (CEIC, 2023).

1.4 Opportunity Mapping in High-Integrity Systems

OM for circular economy sits at the intersection of value-chain analysis, supply-chain configuration and lifecycle assessment. Value chains describe value-adding activities (design, production, service), while supply chains describe the network and logistics connecting them (Dubey et al., 2020). In circular settings, both are used to locate where value is destroyed and where it can be retained through reuse, remanufacturing or high-quality recycling (Farooque et al., 2019; Research Institute (IFPRI), 2016).

Value-chain approaches often combine MFA, LCA and stakeholder mapping to identify hotspots; for example, Meglin et al. (2022) integrate MFA, LCA and input-output analysis to identify high-impact nodes for circular policy and investment. CSCM research focuses more on reverse logistics and closed-loop configuration: Farooque et al. (2019) and Lahane et al. (2020) map collection points, remanufacturing hubs and recycling partners, while Julianelli et al. (2020) frame reverse-logistics success factors and argue that take-back network design is a precondition for value capture.

For high-integrity sectors, this provides an important but incomplete foundation. Value-chain mapping improves lifecycle transparency but often treats safety, warranty and regulatory approval as context. Supply-chain approaches clarify partner roles and reverse-logistics feasibility, but rarely embed assurance pathways or failure-critical reliability constraints. Profitability models for remanufacturing similarly emphasise margins while giving limited attention to certification constraints, data availability and decision transparency (Vogt Duberg et al., 2023). The result is a gap: existing tools show where impacts and actors sit, but not the conditions under which circular interventions can be deployed safely and legally. An assurance-oriented OM framework is intended to address this gap.

2. Review of Related Work or Current State of the Technology Industry Uses

2.1 Review of Related Work

CE and CBM research has expanded rapidly, but most frameworks remain generic and only partly suited to high-integrity sectors (aerospace, energy, advanced machinery). Kalmykova et al. (2018) synthesise over 100 CE cases and tools and show a dominant focus on aggregate loops and city or sector transitions, with limited attention to how circularity is operationalised in safety-critical product systems or how VRPs are prioritised along value chains (Kalmykova et al., 2018). The International Resource Panel similarly positions remanufacturing, refurbishment and repair as high-value retention processes, but notes that evidence remains concentrated in automotive and industrial equipment and that methods for identifying feasible VRPs in complex supply chains are still underdeveloped (UNESCO, 2018).

CBM typologies are well established, yet operational guidance for high-integrity contexts remains sparse. Okorie et al. (2021) argue that much of the literature remains conceptual or oriented to low-integrity consumer goods, with limited engagement with certification, reliability and risk. Hossain et al. (2024) report a similar pattern across more than 150 CE review papers: emphasis on general principles, recycling or macro policy, with safety-critical industrial implementation rarely treated in depth.

This gap is evident in electrical-machine circularity. Tiwari et al. (2021) find that strategies for high-value machines emphasise recyclability and material substitution, while life extension, remanufacturing and service-based models are comparatively rare. Nordelöf et al. (2018) likewise show that LCAs of traction motors and powertrains typically assume recycling and replacement rather than controlled reuse or remanufacture, and that reliability and failure-mode data gaps constrain assessment of life-extension routes. Methodologically, FEMM introduces a multi-criteria gating approach combining technical feasibility, economic attractiveness and organisational readiness (Abu-Bakar and Charnley, 2025), but does not fully integrate certification pathways or cross-actor assurance responsibilities.

2.2 Current State of the Technology Industry Uses

Industrial programmes increasingly operationalise circular strategies in high-integrity settings. The ReMake Value Retention Centre (RVRC), led by NMIS and partners, focuses on VRPs for high-value manufacturing with demonstrators in renewables, aerospace and advanced machinery (RVRC, 2025). Platform 1 explores remanufacturing and high-integrity repair routes for metallic components, thermoplastic composites and FAST-consolidated metals, supported by in-process NDT and digital-thread architectures. NMIS work with partners including Renewable Parts shows remanufactured wind-turbine components can meet performance and reliability requirements while reducing lead times and costs (NMIS, 2024). These cases support technical and commercial viability, but remain project-specific; feasibility across wider value chains and allocation of assurance responsibilities across OEMs, MROs and asset owners is often implicit rather than codified as a reusable opportunity-mapping method.

On data and assurance, pilots increasingly test blockchain, IoT and DPPs. Centobelli et al. (2022) propose the Triple RE-TRY framework linking recycle, redistribute and remanufacture with trust, traceability and transparency; Prajapati et al. (2022) demonstrate a blockchain- and IoT-embedded closed-loop supply chain improving visibility in returns and recovery; and Ahmed and MacCarthy (2023) argue that traceability design (scope, width and depth) must align with assurance objectives to scale. Policy and review work reinforces this: Psarommatis and May (2024) position DPPs as a tool for capturing composition, process history and environmental performance; Jensen et al. (2023) and Zhang and Seuring (2024) stress alignment of data models, access rights and update regimes; and European analyses highlight integration with contracting and regulatory approval as a condition for value-chain circularity (Ikenze and Rizos, 2025).

3. The Approach: The Opportunity Mapping Playbook

The OM playbook is developed as a design-science artefact to address a practical industrial problem: identifying and prioritising assured circular life-extension opportunities in high-integrity sectors. It evolved iteratively through problem diagnosis, artefact construction and evaluation with demonstrators. OM integrates systems-lifecycle thinking (PLM, systems engineering), life-cycle sustainability assessment (MFA/LCA/LCC) and circular business model logic, but reconfigures these tools around assurance, traceability and regulatory requirements. Its structure reflects insights from RVRC Platform 1 demonstrators (metallic value retention, thermoplastic composites, FAST-sintered metals) and Platform 3 CBM research, supporting practical deployment (RVRC, 2025).

Figure 1 provides an at-a-glance overview of the OM playbook and how inputs are organised into a staged, assurance-embedded process. Table 1 then specifies the method in detail, summarising the purpose, key activities, evidence and outputs for each stage.

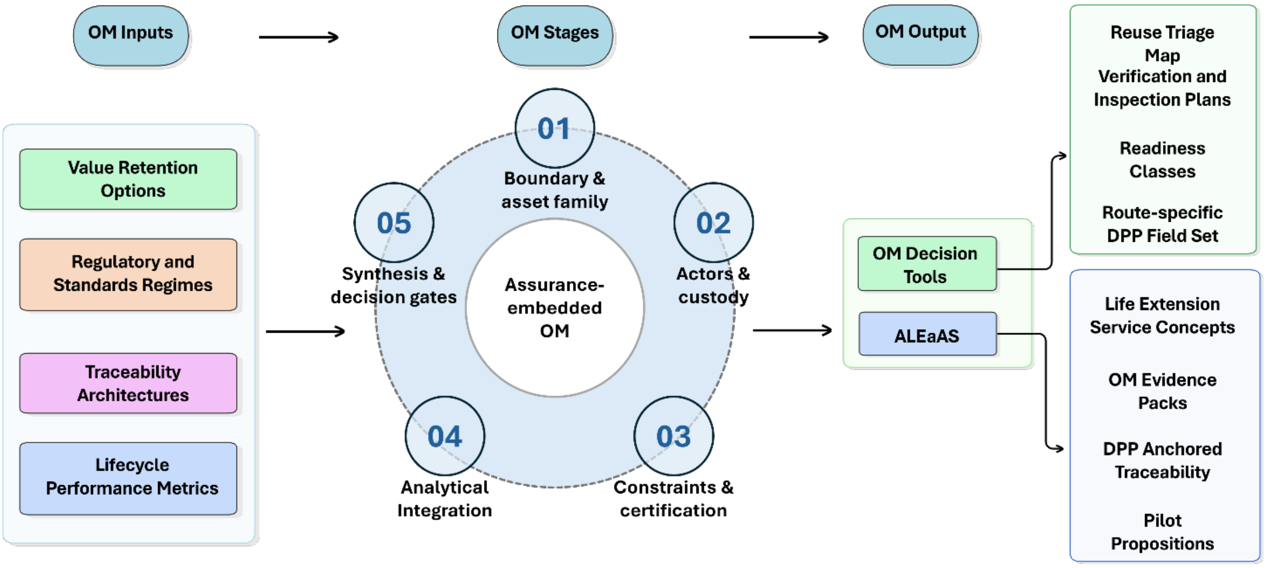

Figure 1. High-level overview of the proposed OM framework, illustrating how key inputs are organised into a staged, assurance-embedded process that leads to decision tools and life-extension service concepts.

Table 1. The Opportunity Mapping Playbook - Staged Methodology

Stage	Purpose	Key Activities	Analytical Tools / Evidence Types	Primary Outputs
1. Define Boundary & Asset Family	Define OM unit of analysis plus functional, regulatory and reliability context for life-extension in high-integrity sectors (e.g. aerospace, energy, transport). (UKCMIC, 2023; Animah et al., 2017; UNESCO, 2018)	Select critical asset families (e.g. turbine blades, nacelles, traction motors, grid housings) aligned to value-retention opportunities in remanufacturing/refurbishment studies. Define function, standards, failure modes and replacement behaviour to frame VRPs. (Ferreira & Gonçalves, 2021; Peng et al., 2022; University of Strathclyde, 2024)	PLM/systems-engineering records; reliability and degradation data; LCA functional-unit definitions; regulatory and warranty requirements. (Kalmykova et al., 2018; Animah et al., 2017; Rodrigues Dias et al., 2022)	Defined component/subassembly family; service baseline; functional and regulatory context bounding later stages and candidate routes.
2. Map Actor Roles & Custody Events	Map forward/reverse socio-technical flows: asset handling, data generation and approval rights. (Farooque et al., 2019; Lahane et al., 2020)	Identify OEMs, operators, MROs, repair houses, recyclers and regulators and their roles. Map custody, data-creation and approval events; identify DPP scan points and traceability blind spots. (CEIC, 2023; Julianelli et al., 2020; Munawar et al., 2025; Ahmed & MacCarthy, 2023)	Value-chain/CSCM mapping; stakeholder/process mapping; traceability models and DPP/digital-thread design, including blockchain custody chains. (Research Institute IFPRI, 2016; Santana & Ribeiro, 2022; Centobelli et al., 2022; Prajapati et al., 2022)	Actor–event map (physical, data, approval); traceability gaps; role-specific DPP and data responsibilities informing assurance/evidence design.
3. Identify Constraints & Certification Pathways	Test technical, legal and commercial viability under safety, warranty and liability regimes. (Rodrigues Dias et al., 2022; OECD, 2021)	Specify degradation limits, performance constraints and inspection requirements. Map requalification rules, warranties, liability and regulatory pathways; note "as-new" certification requirements; identify incomplete/contested evidence chains. (Animah et al., 2017; Avitrader, 2025; Brändström et al., 2024)	Reliability/durability analyses; safety-critical remanufacturing studies; sector regulatory/certification guidance; warranty/liability documentation. (Kerin & Pham, 2020; Rodrigues Dias et al., 2022; OECD, 2019, 2021)	Constraint/pathway overlays on candidate loops; preliminary screening; assurance bottlenecks and evidence gaps to address in OM design.
4. Analytical Integration	Quantify environmental, material and economic value and define evidence architecture, including DPP content. (Ferreira & Gonçalves, 2021; Russell & Nasr, 2022)	Run MFA, LCA and TEA/LCC for baseline and candidate routes to estimate material savings, carbon benefits and cost/risk. Identify hotspots, leakage points and cost thresholds. Specify minimal viable DPP schema (fields, update events, access rules) for certification-grade traceability. (Meglin et al., 2022; Peng et al., 2022; Munawar et al., 2025; Psarommatis & May, 2024; Jensen et al., 2023; Zhang & Seuring, 2024)	MFA; LCA (ISO 14040/44); LCC/TEA; risk-adjusted costing; digital-thread/DPP schema design aligned to regulatory expectations for data scope, width and depth. (Russell & Nasr, 2022; Ahmed & MacCarthy, 2023; Ikenze & Rizos, 2025)	Quantified flows/impacts/costs per route; DPP and evidence architecture specification; comparative evaluation combining circular potential and assurance readiness.
5. Synthesis of OM Outputs	Convert analytics into operational decision tools supporting ALEaaS pilots. (Abu-Bakar & Charnley, 2025; RVRC, 2025)	Build reuse triage map (repair, remanufacture, upgrade, replace); specify route inspection and data requirements; define readiness classes and decision gates for pilots. Package outputs for contracting/governance (e.g. verification packs, service-level discussions). (Vogt Duberg et al., 2023; Centobelli et al., 2022; Psarommatis & May, 2024)	Multi-criteria decision/feasibility assessment; assurance and performance-based service design; RVRC demonstrator lessons and related high-integrity case work. (Ferreira & Gonçalves, 2021; Okorie et al., 2021; RVRC, 2025)	Reuse triage map; route verification and inspection plans; readiness classifications; criteria for ALEaaS pilots linking OM outputs to certifiable, traceable life-extension services.

Applying OM to a High-Integrity Asset Family

This worked example summarises an OM exercise undertaken with an anonymised UK-based aerospace MRO provider. It is included to demonstrate execution of the stages in Table 1 rather than to report proprietary results.

Stage 1: Boundary and asset family. The unit of analysis is a safety-critical structural component family, for example titanium or nickel-alloy parts removed at scheduled maintenance. The service function is defined in operational terms, and candidate routes are scoped alongside replacement: repair/refurbishment, remanufacture, certified-used spares, and modular upgrade.

Stage 2: Actors, custody and events. The chain is mapped across typical MRO operations, including receiving, teardown, inspection, restoration, reassembly, and reinstallation. The actor set covers design-authority interfaces, the operator or owner, specialist repair houses, logistics providers, and where relevant an independent approver. Custody events are separated from evidence-generation (inspection, certification, and configuration records) and approval events (release-to-service sign-off) to expose handover-related evidence gaps.

Stage 3: Constraints and approval pathway. Routes are screened against failure-critical limits, mandatory inspection and NDT, re-qualification checkpoints, and warranty or liability boundaries. Only routes with a credible approval pathway and clear decision rights are retained.

Stage 4: Analytical integration and minimal evidence schema. Feasible routes are compared on a per-service basis using MFA, LCA, and TEA with risk-adjusted life-cycle costing. A minimal DPP-compatible evidence set is specified and linked to the events at which it must be created or updated: identity and provenance, configuration, condition, inspection outcomes, process route, and approvals.

Stage 5: Synthesis and decision gates. Outputs include a reuse triage map, a route-specific verification pack that assigns evidence responsibilities and timing, and explicit go or no-go gates for piloting. The outcome is a conditionally feasible life-extension pathway with defined assurance and evidence requirements.

Assured Life-Extension as a Service (ALEaaS) as an OM Output

We use the term Assured Life-Extension as a Service (ALEaaS) to denote a life-extension proposition that is contractible in high-integrity settings: availability or performance outcomes are delivered under explicit assurance conditions, supported by verifiable provenance, inspection and approval records.

In OM, ALEaaS is the practical endpoint: the reuse triage map, verification pack, inspection plan, approval events and minimal DPP field set specify the smallest evidence chain needed for defensible release-to-service decisions and governance across OEM, MRO and operator roles.

4. Discussion

This paper makes a specific contribution to circular economy scholarship by repositioning OM from a generic hotspot-scanning exercise to an assurance-embedded, traceability-aware decision framework for high-integrity sectors. Existing lifecycle-based mapping approaches have demonstrated how MFA/LCA and stakeholder mapping can reveal environmental and economic hotspots across value chains, but they typically remain agnostic about whether identified loops can ever satisfy the requalification, warranty and liability requirements that govern aerospace, energy and similar domains. Likewise, feasibility frameworks for circular manufacturing, including recent work on multi-criteria assessment of remanufacturing options in high-value machine systems, stop short of integrating formal approval events, evidence chains and digital traceability architectures into the core of the method.

The worked example in the Approach section shows how OM turns a candidate life-extension route into a conditionally feasible pathway with defined evidence requirements, re-qualification checkpoints and decision gates. The ALEaaS subsection then clarifies the service logic that OM enables, and the concrete assurance artefacts required to make life extension auditable and contractible.

The OM playbook advances this state of knowledge in three ways. First, it integrates Value Chain Mapping with assurance logic: every candidate loop is evaluated simultaneously on circular potential (via MFA/LCA/TEA) and on "assurance readiness" (clarity of standards, tests, decision rights and liability), addressing the evidence gaps that international assessments have repeatedly highlighted for value-retention processes in manufacturing. Second, it endogenises traceability and Digital Product Passports: rather than treating DPPs and blockchain/IoT systems as generic enablers, the minimum viable passport and event logic are derived from mapped custody and approval events for each asset family, operationalising recent insights on scope–width–depth trade-offs in traceability design. Third, it concretises these ideas for failure-critical contexts by embedding them in a staged, design-science methodology tested against Platform 1 demonstrators (metallic remanufacture, thermoplastic remoulding, FAST-sintered metals), and expressing the outputs as triage maps, verification packs and explicit decision gates for ALEaaS.

Taken together, these contributions move the debate beyond "where are the circular hotspots?" to "which specific life-extension routes are both materially attractive and certifiable, and under what data and governance conditions?". The framework thus adds to theory by proposing a conceptual and methodological bridge between circular business model research and assurance/traceability scholarship, and to practice by offering high-integrity manufacturers, MROs and policy makers a structured way to move from abstract circular intent to a small set of pilot-ready, evidence-backed ALEaaS propositions that can be negotiated, audited and scaled.

5. Conclusion

This paper has argued that high-integrity sectors face a particular kind of circularity challenge: not a lack of technical potential, but a lack of assurance-ready pathways from strategic intent to implementable business models. OM has been introduced as a design-science response to this problem, re-framing "where are the circular hotspots?" as "under what technical, regulatory and data conditions can life-extension be safely and credibly deployed?". By integrating value-chain and supply-chain perspectives with explicit certification pathways, traceability requirements and Digital Product Passport logic, the OM playbook provides a structured route from dispersed evidence to pilotable ALEaaS propositions.

Conceptually, the work contributes to circular economy scholarship by extending Value Chain Mapping approaches with an assurance layer, and by treating traceability architectures not as generic "enablers" but as co-designed components of the opportunity space. In practice, it offers OEMs, MROs, and asset owners a step-by-step method for selecting asset families, mapping custody and approval events, screening feasible recovery routes, and quantifying material, environmental, and economic value alongside "assurance readiness". The resulting triage maps, verification packs and decision gates are intended to be directly usable in procurement and contracting discussions for ALEaaS pilots.

Future work will need to deepen and test this framework across a broader set of demonstrators and regulatory regimes, and to explore how OM outputs can be embedded in digital engineering toolchains and policy instruments. Nonetheless, the analysis here suggests that when OM is explicitly coupled to assurance, high-integrity circularity moves from aspiration to a manageable design problem, one that can be negotiated, evidenced and scaled rather than postponed indefinitely.

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