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Design for Traceability (DfT): How to enhance transparency and accountability by designing products and materials with features that allow their entire lifecycle to be tracked and documented?

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Abstract: As global industries confront mounting complexity, regulatory mandates, and urgent sustainability targets, end-to-end transparency has become nonnegotiable. Design for Traceability (DfT) delivers a transformative blueprint—encoding traceability into the very DNA of products and materials. By harnessing Smart Identification Technologies (SIT)— including Radio-Frequency Identification (RFID), Near Field Communication (NFC), QR codes, IoT sensors, and blockchain—DfT establishes immutable "digital DNA," realized through interoperable Digital Product Passports (DPPs) and Material Passports (MPs). These passports grant real-time visibility, secure authentication, and frictionless data exchange, catalyzing circular resource loops while ensuring compliance with evolving regulations.The DfT framework is anchored by five interdependent pillars: *Lifecycle-Centric Design:* Embeds traceability at inception via modular architecture, durable materials, and design-for-disassembly, extending product life and simplifying end-of-life recovery. *Digital Traceability Infrastructure:* Constructs a secure, interoperable data ecosystem by integrating SIT and distributed ledger technology, enabling continuous monitoring, analytics, and decision support through DPP and MP integration. *Circular Business Models:*Transitions from one-time sales to service-based offerings, remanufacturing, and R-strategies (Reduce, Reuse, Recycle), unlocking new revenue streams and preserving asset value. *Stakeholder Collaboration:* Builds shared platforms and decentralized governance to unite manufacturers, regulators, consumers, and recyclers in transparent data-sharing networks, strengthening trust and supply-chain resilience. *Regulatory Alignment:* Integrates traceability into corporate strategy to anticipate stringent sustainability mandates, leveraging digital audits and transparent reporting for streamlined compliance. By interweaving these pillars, DfT empowers organizations to mitigate supply-chain risks, optimize resource utilization, and accelerate the shift toward a resilient, transparent circular economy. This holistic framework equips policymakers, industry leaders, and designers with actionable strategies to embed sustainability, accountability, and innovation at every stage of the product lifecycle.

Introduction

Traceability is a strategic enabler for managing complex global systems, offering precise tracking of products, components, and data to mitigate risks, ensure quality, and reinforce trust across supply chains (Guilherme Pulita, J., 2022; Ringsberg, H., 2014) . In food systems, it supports preparation, response, and recovery during recalls, while advanced digital platforms replace paper-based methods and facilitate vast data management. Current research frames traceability around four risk-focused pillars: logistics, information, production, and quality management [1].

Cutting-edge technologies are redefining traceability by enhancing transparency, security, and operational efficiency. Blockchain delivers tamper-proof, decentralized ledgers that fortify Enterprise Resource Planning (ERP) integrations for real-time, cost-effective traceability (Alwi, A., 2024; Kusnadi, A., 2023; Srivastava, A., 2022). IoT and RFID sensors enable end-to-end visibility—from livestock lifecycle tracking to smart-city data networks—and support critical material tracing (e.g., cobalt in manufacturing) (Dawood, M.N., 2024; Otte, S., Sufian, 2024).

Methodologically, traceability system design employs structured frameworks tailored by scope, granularity, and integration level—distinguishing chain-wide from localized models in food supply chains (Guilherme Pulita, J., 2022; Ringsberg, H., 2014). Modified waterfall System Development Life Cycle (SDLC) approaches ensure compliance in sectors like halal meat and ceramics (Kusnadi, A., 2023; Barata, J., 2018; Kusnadi, A., 2024). Human-centered design, demonstrated in smart-city implementations, emphasizes "automatic and transparent" data capture to minimize disruption and maximize usability (Mora-Mora, H., 2015).

Emerging trends focus on sustainability integration. Research on Environmental, Social, and Governance (ESG) integration illustrates how coupling traceability with environmental, social, and governance criteria can bolster consumer trust, regulatory compliance, and ethical supply-chain practices (Putri, W.S., 2025). This convergence of traceability and sustainability principles promises to address mounting concerns over environmental impacts and global ethics in supply chains.

Towards a Comprehensive Traceability Framework

Effective traceability design demands integrated tech, organizational, and regulatory alignment. As transparency becomes essential, innovative frameworks address complex supply chain challenges. This study synthesizes current DfT research, detailing methodologies, sector applications, and emerging technologies for resilient, accountable, and sustainable systems.

Implementing circular strategy

Implementing a circular strategy in Design for Traceability (DfT) integrates circular economy principles to track products, parts, and materials throughout their lifecycle. This approach extends product lifespans by enabling reuse, repair, refurbishing, remanufacturing, and upgrading—pillars of a sustainable circular economy (Terzi, S., 2006; Mesa, J. A., 2023). Effective DfT incorporates lifecycle thinking through design for disassembly, sustainable material selection, and waste minimization. Technologies such as RFID, QR codes, and blockchain facilitate seamless lifecycle tracking. Circular business models—sharing, leasing, and product-as-a-service—further emphasize durability, repairability, and upgradeability (Mesa, J. A., 2023; Bandini, G., 2023). The article "Structuring Circular Objectives Design Strategies for the Circular Economy" presents a multi-hierarchical framework that maps design strategies to five circular objectives: maintenance/longevity, reuse, refurbishment, remanufacture, and recycling (Table 1). This framework guides managers and designers in creating traceable systems that support multiple product lifecycles (Franconi, A., 2022).

Patagonia embeds durability and maintenance into its design strategy, providing free DIY repair guides and affordable repairs at its Reno, NV center when self-repair isn't possible. Their 2011 "Don't Buy This Jacket" ad actively discouraged needless purchases. Through the Worn Wear program, Patagonia sells guaranteed, high-quality pre-owned garments and accepts trade-ins for store credit, thereby

Table 1 Circular objectives exemplification. © (Franconi, A., 2022).

Circular Objective	Description	Design Strategies
Maintenance / Longevity	Aims to extend product lifespan through maintenance, reducing resource depletion and obsolescence. Aligns with strategies for long-lasting, upgradable, or easily repairable products.	Reliability, maintainability, repairability, product-life extension.
Reuse	Enables products or components to be reused with minimal alteration, often in a new cycle. Focuses on retaining value and reducing waste generation.	Collaborative logistics, return incentives, robust and standardised design.
Refurbishing	Restores product functionality by reworking only failed parts. Enhances consumer acceptance through tested aesthetics and reliability.	Disassembly, reassembly, repair, reconditioning.
Remanufacturing	Fully restores products to like-new or better condition, integrating cleaning, inspection, and testing. Considered highly impactful for circular economy.	Disassembly, cleaning, inspection, reassembly, upgrading.
Recycling	Final strategy when reuse is unfeasible. Focuses on material recovery through careful sorting, processing, and design for disassembly.	Disassembly, sorting, consumer acceptance of recycled content.

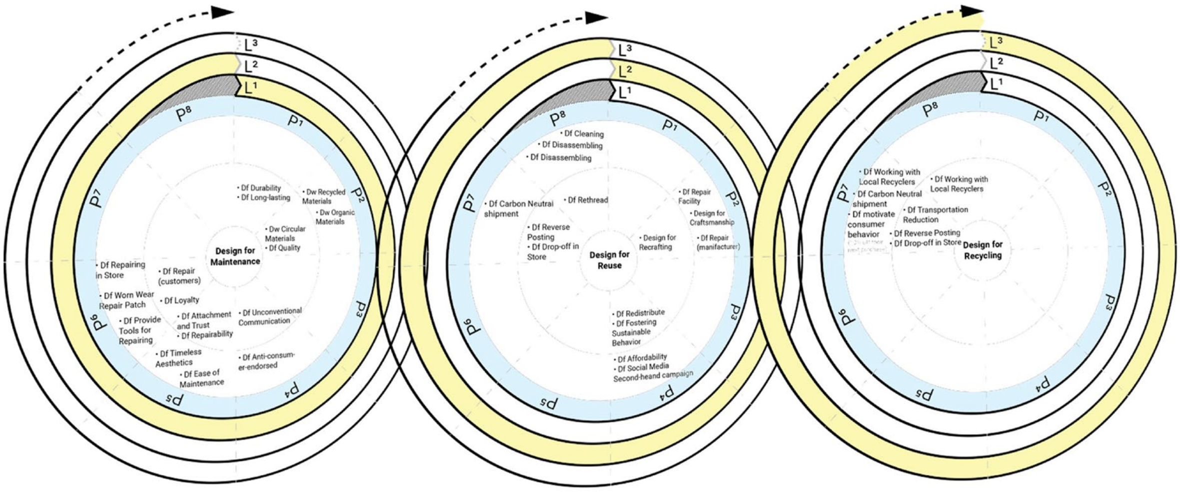

Figure 1 Patagonia case analysis. © (Franconi, A., 2022).

extending product lifespans. Items deemed irreparable are recycled—95 tons of clothing were processed into polyester fibers between 2005 and 2016—establishing a clear circular stage for each lifecycle phase (Bürklin, N., 2019; Rattalino, F., 2018). This blend of design for longevity, consumer engagement, and circular infrastructure exemplifies practical strategies for sustainability. The company has defined a specific circular stage for each life cycle, as depicted in Figure 1.

In terms of Design for Traceability, it is implied that understanding the journey of a product through its life cycle stages and being able to track and optimize this journey is crucial. This can lead to more sustainable and efficient use of resources, contributing to the goals of the circular economy (Franconi, A., 2022).

Here are some key points to consider when implementing a circular strategy in DfT:

Design for X (DFX) Tools

The 51-rule Design for Circularity and Durability (DFCD) guideline applies targeted DFX interventions—reuse, repair, refurbishing, remanufacturing, and recycling—to generate multiple lifecycle loops and extend product longevity (Bürklin, N., 2019). Its novelty lies in (i) defining dedicated circularity rules and (ii) organizing them by design stage. Derived from a literature review and mapping DFX rules to circular-economy strategies, DFCD delivers a structured framework that enables designers to embed both durability and circularity throughout product development, ensuring systematic, stage-specific guidance for sustainable, resilient design.

The article also presents a case study demonstrating the implementation and benefits of applying the DFCD guideline in practice. The article proposes an integrated DFX-based approach and design guidelines for the tricycle to help designers and companies incorporate circularity and durability into product design and development (Mesa, J. A., 2023). (Figure 2).

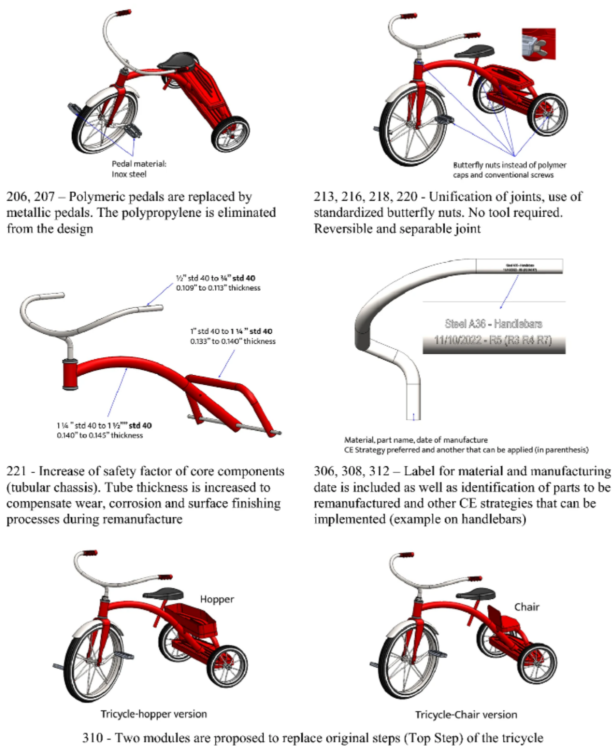

Figure 2. Modifcations using DFCD guidelines for Remanufacturing (R5)—embodiment and detailed design. © (Mesa, J. A., 2023).

Circular Economy (CE) Strategies Align design rules with Circular Economy R-strategies—Reduce, Reuse, Repair, Refurbish, Remanufacture, and Recycle—to slow and close the loop of products, parts, and materials (Davari, S., 2023). See Figure 3.

Traceability Framework
Develop a traceability framework that covers the main purposes of traceability enabling CE principles, the role of traceability across asset lifecycle stages, the type of data needed to support traceability, and the value of collaboration among industry stakeholders [18].

Lifecycle Information Management
Consider environmental, economic, societal, and technical impacts across the whole lifecycle, involving many considerations, disciplines, and indicators (Davari, S., 2023). (Figure 4).

Digital Threading
Digital threading enables tracing a product's development, identifying causal relationships between processes, and ensuring data consistency (Nowacki, S., 2023). It integrates data from diverse systems to create a unified

Figure 3. Key concepts related to traceability for sustainable development. © (Davari, S., 2023).

digital representation, supporting collaboration and data-driven decisions (Domskienė, J., 2024). In the Circular Economy (CE), traceability is vital for tracking materials and products throughout their lifecycle. However, achieving traceability in the built asset industry is challenging due to complex projects and limited awareness of its benefits. In Canada, 27% of municipal waste comes from construction, with over 75% potentially recyclable, salvaged, or reused (Davari, S., 2023).

Smarter product use and manufacture	R0	Refuse	Make product redundant by abandoning its function or by offering the same function with a radically different product
	R1	Rethink	Make product use more intensive (e.g. through sharing products or by putting multi-functional products on market).
	R2	Reduce	Increase efficiency in product manufacture or use by consuming fewer natural resources
Extend lifespan of product and its parts	R3	Reuse	Re-use by another consumer of discarded product which is still in good condition and fulfils its original function
	R4	Repair	Repair and maintenance of defective product so it can be used with its original function
	R5	Refurbish	Restore an old product and bring it up to date
	R6	Remanufacture	Use parts of discarded product in a new product with the same function
	R7	Repurpose	Use discarded products or its part in a new product with a different function
Useful application of materials	R8	Recycle	Process materials to obtain the same (high grade) or lower (low grade) quality
	R9	Recovery	Incineration of material with energy recovery

Figure 4. R-strategies in CE. © (Davari, S., 2023).

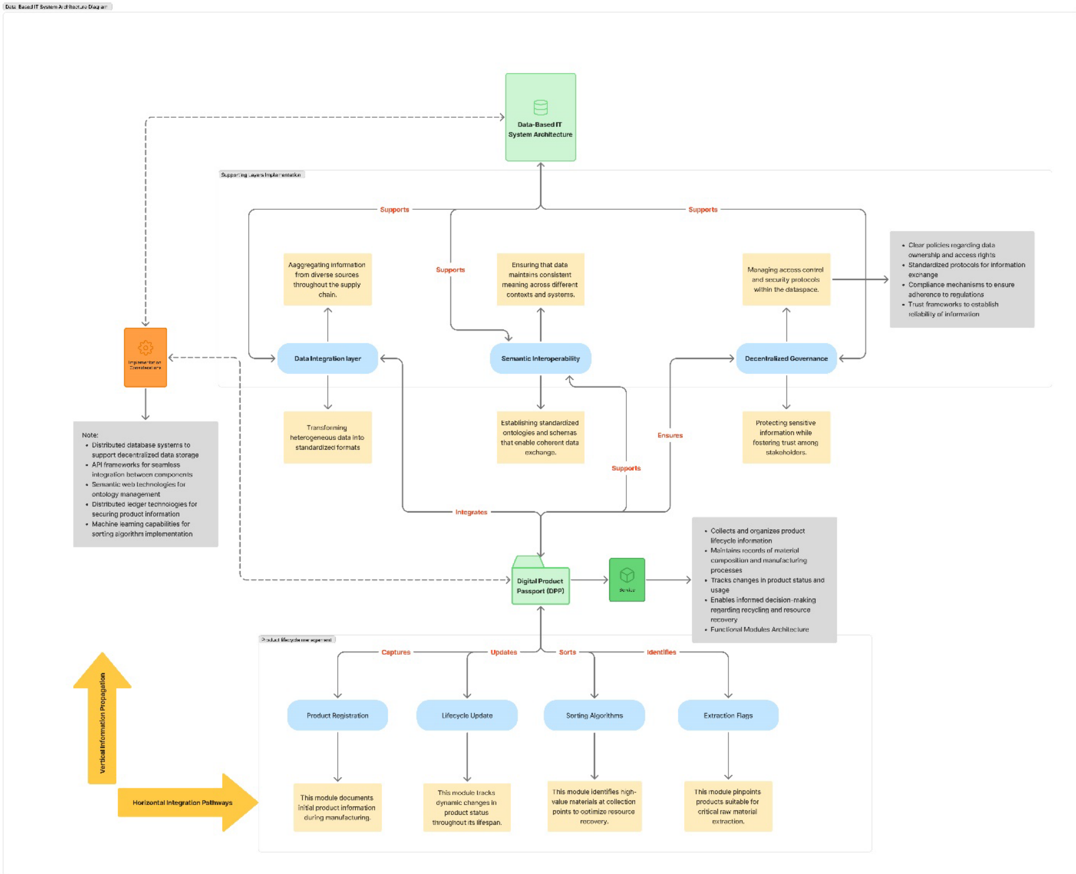

Figure 5. Visual Diagram for Dataspace-Based IT Systems Architecture with Digital Product Passport Modules. An enlarged version of the image is provided through `[![Design-for-Traceability.jpg](https://i.postimg.cc/tJ5KmfNz/Design-for-Traceability.jpg)]`

Modern Technology Enablers for Traceability

Smart Identification Technologies (SIT)

Smart tags integrate physical identifiers with digital systems to deliver secure, traceable product identities, enabling supply-chain visibility and circular economy goals. Blockchain integration and EU regulations like the Digital Product Passport initiative boost adoption. Embedded digital identities enhance transparency, sustainability, and end-of-life management while solving authentication and traceability challenges. Digital Product Passports (DPPs) are comprehensive digital documents that accompany products throughout their lifecycle, containing data on materials, manufacturing methods, distribution, environmental impacts, usage, and end-of-life stages (Nowacki, S., 2023). Introduced by the EU Green Deal to advance the circular economy, DPPs will be required for recyclable textiles by 2030, providing essential infrastructure for secure data collection and sharing across supply chains (Domskienė, J., 2024).

Dataspace-Based IT Systems Architecture

The following diagram presents an architecture that embeds Digital Product Passports (DPPs) into a dataspace-based IT system, enhancing transparency, circularity, and raw-material stewardship across product lifecycles. (Figure 5)

At its core, a **Dataspace-Based IT Architecture** serves as the network's brain, enabling bidirectional flows—from strategic decisions to operational tasks—and horizontal integration across systems. Three supporting layers enable functionality:

- **Data Integration Layer:** Aggregates heterogeneous supply chain data into standardized formats.
- **Semantic Interoperability:** Applies shared ontologies to ensure consistent data interpretation.

- **Decentralized Governance:** Manages access, security, and trust without centralized authority.

The **DPP node** acts as a digital twin, storing key lifecycle data to guide repair, recycling, or reuse. Its capabilities are extended by four **functional modules**:

- **Product Registration** (captures manufacturing details)
- **Lifecycle Updates** (records status changes)
- **Sorting Algorithms** (optimizes material recovery)
- **Extraction Flags** (identifies critical-material candidates)

Information flows vertically (architecture → layers → modules) and horizontally (across layers and modules), fostering coherent collaboration. **Implementation** relies on distributed databases, APIs, semantic web tools, and machine learning. **Governance and standards alignment** embed policies for data ownership, access rights, and interoperability, ensuring compliance and stakeholder trust.
Governance models support academic discussion on circular supply chains and critical-material management (Koppelaar, R. H., 2023). Smart tag–enabled digital identities facilitate secure authentication and anti counterfeiting (Falcone, A., 2021), full lifecycle traceability from raw material sourcing to recycling (Felicetti, C., 2023), and the capture of reuse, refurbishment, and recycling data to drive circular economy initiatives (Voulgaridis, K., 2023).

Successful deployment depends on coordinated participation by manufacturers, distributors, consumers, and recyclers within a unified digital ecosystem.

Smart Tag Technologies for Digital Product Identity

Implementing digital product identities relies on diverse smart tag technologies—RFID, NFC, QR codes, and PUF tags—each tailored to specific roles within the digital identity ecosystem (Benčić, F. M., 2019).

RFID: Comprising microchips and antennas, RFID tags enable contactless, bulk reading and are available in passive, semi passive, and active formats with varying read ranges and memory capacities (Sudhakaran, S., 2024). Widely used in retail inventory, smart checkout, and industrial logistics, they significantly enhance traceability and operational efficiency (Gowtham, R., 2024; Chen, Z., 2024).

NFC: Building on RFID principles, NFC tags facilitate secure, short range interactions via smartphones, supporting consumer engagement, authentication, and seamless payment integration (Benčić, F. M., 2019).

QR Codes: As cost effective optical identifiers, QR codes require only a smartphone camera for scanning, making them ideal for early Digital Product Passport (DPP) deployment in cost sensitive sectors like textiles (Domskienė, J., 2024). Laser engraved 2D barcodes further improve durability and tamper resistance for long lifecycle products (Hakola, L., Hakola, E., 2024).

Physically Unclonable Function (PUF) tags: Leveraging random hardware variations, PUF tags generate unforgeable "digital fingerprints," offering high security authentication for valuable goods (Falcone, A., 2021; Felicetti, C., 2023).
Selecting the optimal tag balances cost, durability, security, and user interaction. Comparative studies in reusable packaging demonstrate that properly protected RFID, NFC, and laser engraved codes withstand repeated washing and heat exposure (Hakola, L., Hakola, E., 2024).
Moreover, anchoring tag data in blockchain or distributed ledger technologies creates tamper evident records, underpinning DPPs and material passports for circular resource recovery (Benčić, F. M., 2019). By enabling automated lifecycle updates, predictive analytics, and stakeholder collaboration, smart tags form the backbone of resilient, transparent supply chain ecosystems aligned with circular economy goals.

Materials passports (MPs)

Digital Product Passports (DPPs) are dynamic tools that document material properties across lifecycles, enabling reuse, recycling, and resource efficiency in construction, manufacturing, and agriculture (Abedi, F., 2024). Powered by blockchain and QR codes, they transform static records into shareable digital platforms. Central to the EU Green Deal's circular economy, DPPs face interoperability and standardization challenges but benefit from emerging legal frameworks and structured data governance (Piétron, D., 2023; Kasimatis, C.N., 2024).

Material Passports similarly track materials throughout a product's lifecycle, crucial in construction—responsible for nearly 40% of global CO_2 emissions—by bridging data gaps from production to end-of-life and guiding retrofit versus demolition decisions (Abedi, F., 2024; Kasimatis, C.N., 2024). They capture composition, origin, and environmental product declarations (EPDs) (Wang, L., 2024), though aligning multiple passport formats remains a sector-wide challenge.

Here are some examples of MPs:

Buildings As Material Banks (BAMB)
BAMB organizes material and product data across hierarchical levels—properties, certifications, logistics—and offers a digital platform linking building components to market values, effectively turning structures into material banks.

3XN Architects
This passport framework guides the collection of circular-economy data at each building lifecycle stage. It connects technical and functional specifications to a centralized database, ensuring full traceability of components.

Madaster
Madaster structures MP data by building layers (structure, skin, services) and integrates circularity indicators to quantify virgin, recycled, reused, and renewable materials. Its cloud platform interfaces with BIM models, allowing users to generate bespoke passports for buildings or elements (Davari, S., 2023).

These MP initiatives exemplify how standardized, interoperable digital passports can transform material management into a measurable, market-driven circular economy. (Figure 6)

Blockchain Integration for Enhanced Security and Trust
Integrating blockchain with smart tags advances digital product identity systems by enhancing data integrity, trust, and decentralized verification (Felicetti, C., 2023). Blockchain's distributed ledger ensures transparent, tamper-proof tracking, while smart tags establish physical-digital linkages. Ethereum-based tools like Distributed Ledger

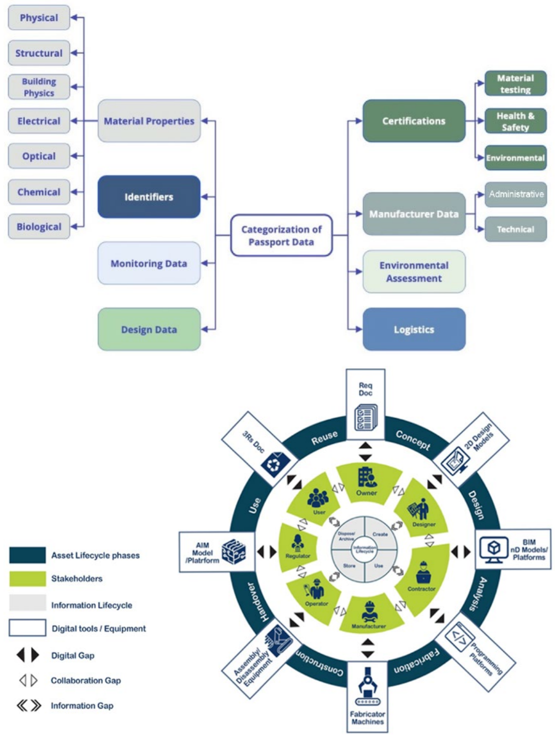

Figure 6. From up to down: Categorization of MP data & Overview of current gaps in asset lifecycle phases. © (Davari, S., 2023).

Technology (DLT) DL-Tags allow consensus across stakeholders without central control (Benčić, F. M., 2019). Smart contracts automate authentication, ownership transfer, and access control, reducing fraud and human error (Falcone, A., 2021; Abedi, F., 2024). Combined with PUF tags and elliptic curve cryptography (ECC), blockchain strengthens anti-counterfeiting efforts (Falcone, A., 2021; Benčić, F. M., 2019). Privacy-focused cryptographic methods safeguard sensitive data while enabling traceability (Benčić, F. M., 2019). Together, these technologies offer secure, decentralized, and privacy-preserving systems for managing identities in complex global supply chains.

IOTA's Distributed Ledger Technology
IOTA's distributed ledger technology offers a scalable, fee-less solution for tracking materials throughout product lifecycles, enhancing traceability, compliance, and sustainability in circular economy applications. Its Tangle architecture—a Directed Acyclic Graph (DAG)—supports parallel, miner-free transaction validation, ideal for IoT-enabled Digital Product Passports (DPPs). Unlike blockchain, each transaction validates two

previous ones, leveraging a Markov Chain Monte Carlo algorithm and lightweight proof-of-work for confirmation (Leivadaros, S., 2021). Transactions accrue cumulative weight, replacing traditional mining consensus, enabling energy-efficient, real-time validation. This architecture addresses key challenges in interoperability and secure data exchange, positioning IOTA as a foundational technology for decentralized and transparent digital product identity systems.

Digital Product Passports (DPP): Tracking Materials Across Lifecycles

IOTA's Digital Product Passport (DPP) prototypes leverage distributed ledger technology to ensure immutable, traceable, and transparent product records across all lifecycle stages. Recognized by the European Union, DPPs are pivotal to circular economy goals, enabling interoperable data exchange among stakeholders. These passports document materials across four lifecycle phases: (1) raw material acquisition, (2) production with component-level identification, (3) usage tracking (repairs, upgrades, ownership changes), and (4) end-of-life processing (recycling, disposal) (Blockchain News. (n.d.), IOTA Foundation. (n.d.)).

Sector Applications

In electronics, IOTA collaborated with the Technical University of Catalonia to prototype a DPP from production to recycling (IOTA Foundation. (n.d.)). Automotive battery tracking is supported via a partnership with Eviden (EV Magazine. (n.d.)), while pharmaceutical traceability is enhanced through authentication and cold-chain monitoring (Suhail, S., 2019). IOTA has also worked with TradeMark East Africa (TMEA) to digitize Kenyan exports, utilizing EPCIS 2.0 to streamline cross-border trade documentation (ScyllaDB. (2023, February 9).

Technical Architecture

IOTA integrates lightweight IoT nodes for decentralized data issuance and secure transaction validation through proof-of-work. Full nodes validate transactions, while a central coordinator confirms milestone checkpoints (recycling, disposal) (Blockchain News. (n.d.), IOTA Foundation. (n.d.), EV Magazine. (n.d.)). The architecture supports real-time data integrity and scalability for IoT ecosystems.

Benefits and Challenges

IOTA offers feeless microtransactions, high scalability (Leivadaros, S., 2021), immutable product records, and strong alignment with circular economy practices (Blockchain News. (n.d.)., IOTA Foundation. (n.d.)). However, challenges remain in IoT device security (Leivadaros, S., 2021), integration with legacy systems, and achieving broad standardization despite EPCIS 2.0 adoption (ScyllaDB. (2023, February 9).

Sectoral Applications of Material Passports (MPs) & Digital Product Passports (DDP)

Material Passports in Construction and Building Materials

Material passports are emerging as critical tools in the construction industry, addressing the sector's substantial resource use and environmental impact. By documenting comprehensive material data, they enable reuse and recycling at a building's end-of-life phase (Costa, A.R., 2024). In Turkey, BIM-integrated studies demonstrate how material passports improve lifecycle tracking, boost recovery rates, and reduce construction waste (Topraklı, A.Y., 2024). Their relevance spans both new and renovated structures, preserving vital material data across long building lifespans and project stakeholder turnover (Incorvaja, D., 2022; Byers, B.S., 2023).

Material Passports in CDW Management

In Construction and Demolition Waste (CDW) management, passports address data fragmentation. Platforms such as Madaster, Concular, and CB'23 provide standardized templates to enhance traceability and facilitate high-value material recovery (Honic, M., 2024).

From Data Templates to Passports & Enabling Business Models

The shift from static data templates to advanced material and digital product passports (DPPs) marks a critical advancement in construction and demolition waste (CDW) management. These tools ensure standardized, lifecycle-based documentation of material composition, origin, and reuse potential, enhancing data consistency and stakeholder interoperability. Technologies such as blockchain and QR codes enable real-time traceability, despite ongoing challenges in capturing dynamic performance data (Aryblia, M., 2023). Emerging platforms exemplify scalable business models: Madaster increases material residual value by 15–25% (Honic, M., 2024), Concular facilitates reuse of up to 80% of demolition waste, and CB’23 promotes broad adoption through open-source material passport frameworks.

Impact on Circular Economy Goals

Passports support over 90% reuse of materials like steel and concrete, aligning with circular economy objectives. They help quantify embedded carbon, aiding the EU’s target of 55% emissions reduction by 2030. Platforms such as Concular facilitate secondary material markets and challenge traditional linear supply chains (Honic, M., 2024; Aryblia, M., 2023).

Digital Material Banks for Circular Construction

Despite the EU’s 70% CDW reuse target, actual reuse remains at ~50%, with just 3% upcycled. Digital Material Banks (DMBs) provide cloud-based inventories of reusable components. A post-earthquake Italian case study showed selective demolition and digital tools enhance recovery and carbon savings (Cocco, P.L., 2023).

Cross-Jurisdictional Trading of Construction Materials

The article proposes a blockchain-based framework using non-fungible tokens (NFTs) to improve cross-jurisdictional trading of construction waste materials (CWM) and reduce information asymmetry. It introduces a Waste Material Passport (WMP) system where each material is tokenized into a unique NFT to prevent duplication, enhance transparency, and ensure secure, immutable transaction records. Blockchain’s distributed ledger and decentralized consensus mechanisms boost authentication and trading efficiency. A prototype and case study validated the approach, showing that blockchain and NFT integration significantly improve trust, traceability, and efficiency in CWM transactions (Wu, L., 2023). This supports broader adoption of Material and Digital Product Passports in construction.

DPPs in the Fashion Industry

DPPs address fashion’s environmental impact—projected to contribute 26% of global GHG emissions by 2050—by enhancing supply chain transparency and supporting ethical sourcing. They help brands comply with sustainability regulations and meet eco-conscious consumer expectations. A case study of a sustainable fashion SME shows that collaborative innovation and digital twin adoption enable even small firms to implement DPPs (Re, N.U., 2024). Moreover, DPPs may reshape trademark law by redefining authenticity through digital records, reducing reliance on traditional brand identifiers (Gösken, C., 2025).

DPPs in Electronics and E-waste Management

DPPs hold significant promise in electronics manufacturing by extending product lifetimes and improving e-waste management. In one case, DPPs enabled assessment of washing machines for reuse and refurbishment by providing lifecycle data on durability, repairability, and upgrade potential (Stiksma, F., 2024). Another case from plastics recycling—relevant to electronics—traced the transformation of 486.7 kg of bottle caps into 363.2 kg of products using R-Cycle’s DPP system based on GS1 standards (Rumetshofer, T., 2024). The initiative underscores the importance of standardized datasets and infrastructure, while highlighting challenges in balancing transparency with protection of proprietary data—crucial for electronics sector DPP deployment.

DPPs are emerging as transformative tools in electronics manufacturing, fostering supply chain transparency and sustainable production. By embedding lifecycle data, environmental and social indicators, and absolute sustainability metrics (Psarommatis, F., 2024; Panza, L., 2023), DPPs support informed decision-making and resource efficiency. Implemented through cyber-physical systems and the Asset Administration Shell (AAS) framework (Kühn, M., 2025), they enable traceability and secure data sharing via blockchain (Kim, M.J., 2025). Applications in sectors such as electronics and batteries (e.g., the EU battery passport) illustrate their scalability (Kühn, M., 2025). Strategic gains include improved stakeholder trust, competitive advantage (Haase, L.M., 2025), and adaptive capacity in industrial ecosystems through federated learning and orchestration mechanisms (Kim, M.J., 2025; Jensen, S.F., 2024).

Applications in Agriculture and Food Systems

Digital Product Passports (DPPs) enhance agricultural traceability by providing immutable records of inputs, methods, and origins—supporting organic certification and the EU Green Deal (Abedi, F., 2024). Dynamic DPPs for organic and geographically indicated foods update in real time to improve auditability and fraud prevention, requiring stakeholder collaboration and regulatory compliance (Lekawska-Andrinopoulou, L., 2024). IoT integration fortifies supply chains via real-time monitoring and data sharing, while blockchain ensures transparency from farm to table (Kale, M.D., 2023). Combined with Material Passports (MPs), DPPs offer a digital framework that delivers verifiable data on resource use and environmental impact to advance circular economy objectives and food safety, guiding stakeholders in sustainable, data-driven agricultural practices.

Robust technical infrastructure leverages blockchain, IoT, and federated learning (Kim, M.J., 2025) via frameworks like the Asset Administration Shell (Kühn, M., 2025) and cyber-physical systems (Rumetshofer, T., 2024). Strong data governance ensures high-quality, validated, and privacy-compliant information flows. Product tracing integrates QR/RFID, smart contracts, and real-time logging for full traceability. Sustainability is assessed through life cycle analysis, planetary boundaries (Panza, L., 2023), and circularity metrics (Fassio, F., 2023). Stakeholder engagement, seamless value chain integration, and rigorous regulatory compliance ensure system-wide adoption, resilience, and credibility.

Design for Traceability Framework

The framework promotes transparency and accountability by integrating circular economy principles, advanced digital technologies, and collaborative strategies. It encompasses five pillars: Lifecycle-Centric Design, Digital Traceability Infrastructure, Circular Business Models, Stakeholder Collaboration, and Regulatory Alignment, ensuring sustainability, traceability, and compliance across product and material lifecycles.

The DfT framework embeds traceability across lifecycles through five pillars: lifecycle-centric design, digital infrastructure, circular models, collaboration, and regulation. It begins with modular, durable design using DFCD tools and BIM for long-term decisions. RFID, NFC, and IOTA's blockchain-enabled DPPs support data interoperability, while IoT and BIM monitor material performance. Circular business models like leasing and remanufacturing leverage AI and digital twins. Public-private collaboration, IOTA's marketplace, and BIM promote secure, transparent data sharing. Regulatory alignment with EU DPP policies ensures compliance (Table 2 and Table 3). DfT enhances longevity, resource optimization, and circularity by enabling end-to-end transparency and building consumer trust, Figure 7.

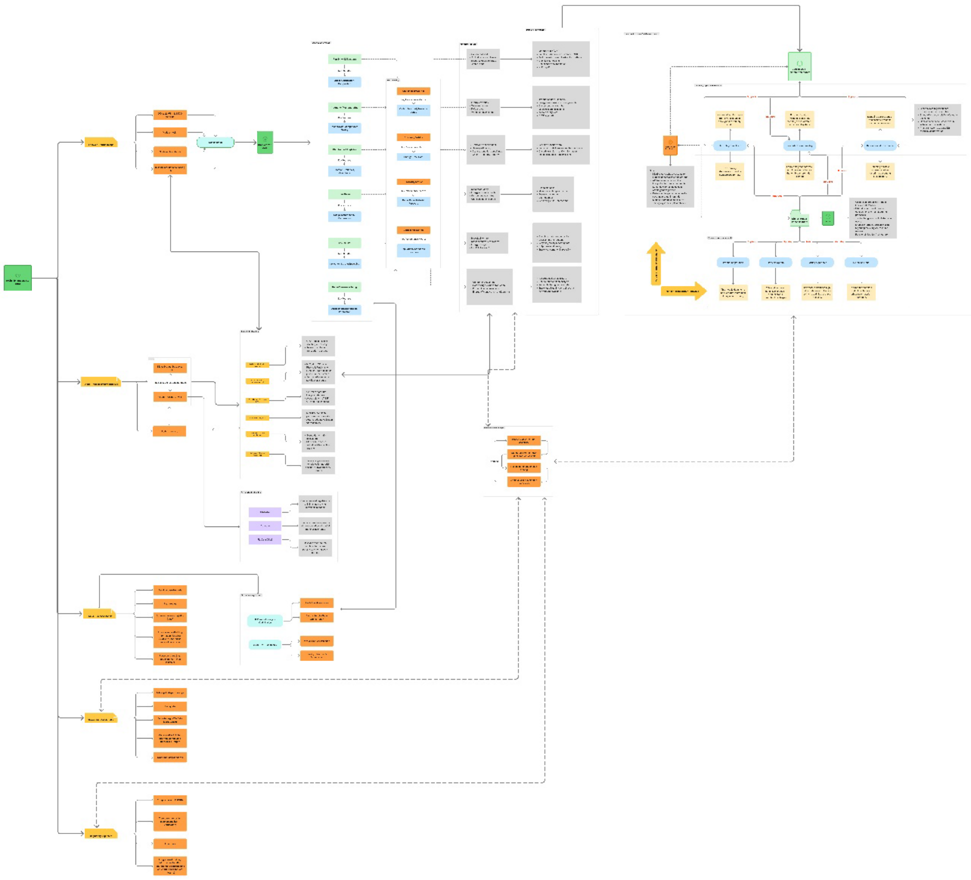

Figure 7 Visual Representation of the Framework. An enlarged version of the image is provided through `[![Design-for-Traceability.jpg](https://i.postimg.cc/tJ5KmfNz/Design-for-Traceability.jpg)](https://postimg.cc/YLvDvdV4)`

Table of the Framework

Table 2. Design for Traceability Framework: Pillars for Sustainable Integration.

Pillar	**Key Strategies**	**Expected Outcomes**
Lifecycle-Centric Design	Modular design, sustainable materials, DFX tools, *Building Information Modeling (BIM)*	Longer product lifecycles, efficient recycling, detailed lifecycle data for built assets (Standardized labeling)
Digital Traceability Infrastructure	Smart tags (RFID, QR, NFC, BUF), blockchain-enabled DPPs, dataspace IT systems, sensor networks, *IOTA Technology*, *IOTA Streams*	Real-time tracking, immutable records, enhanced decision-making, continuous monitoring of product performance, secure data validation
Circular Business Models	Service-based models, reuse programs, R-strategies, optimized reverse logistics (*IOTA*), adaptive reuse (*Building Information Modeling (BIM)* with *IOTA-based material passports*)	Waste reduction, new revenue streams, stronger consumer trust, optimized resource use through adaptive reuse
Stakeholder Collaboration	Public-private partnerships, living labs, cross-industry consortia, data sharing (*IOTA Data Marketplace*), collaborative *Building Information Modeling (BIM) (IOTA Tangle*)	Accelerated adoption, harmonized standards, improved stakeholder engagement and data sharing
Regulatory Alignment	Compliance with EU DPPs, transparent reporting mechanisms (*IOTA verification*), incentives, integration of *Building Information Modeling (BIM)* standards into building codes (*IOTA DLT for data integrity*)	Regulatory compliance, competitive advantage, broader adoption of traceability, enhanced sustainability in the built environment

Lifecycle Integration Layers Framework for Design for Traceability

These tables (Table 2 and 3) provide a structured, systematic, and technology-driven approach to lifecycle integration for traceability, ensuring sustainability, accountability, and efficiency throughout the entire product lifecycle.

Table 3 Lifecycle integration layers framework for integrating Design for Traceability.

Lifecycle Stage	Traceability Mechanisms	Data Elements Captured	Key Metrics Tracked	Relevant Strategies
Raw Material Sourcing	-Geo-tagged sourcing certificates on blockchain (IOTA) -DPP initialization -NFC tagging at source -BIM for material specification & standardized labeling -PUF-based material authentication	- Material origin (GPS) - Supplier certifications (Fair Trade, FSC) - Environmental impact & extraction methods - Chemical composition - Compliance documentation - NFC Tag ID	- Carbon footprint - Ethical labor compliance - Resource depletion rates - Water usage	- Lifecycle-Centric Design (Sustainable Material Selection) - Digital Traceability (Blockchain, DPP, NFC, PUF) - Regulatory Compliance
Production/Manufacturing	- NFC/RFID smart tagging - DPP updates with real-time manufacturing data - Digital Twin integration - DFCD tools - BIM for process visualization & quality control - PUF for component authenticity	- Production date & location - Energy, water usage & waste generation - Component serial numbers - ML insights - Worker safety data - DFCD application	- Energy efficiency - Waste reduction - Defect rates - Worker safety incidents	- Modular & Lifecycle-Centric Design - Digital Threading (Smart tags, Digital Twin, PUF) - Circular Business Models (Remanufacturing design)
Distribution & Logistics	- IoT-enabled GPS tracking - Blockchain/IOTA supply-chain mapping - NFC scanning at custody transfer - BIM for route & storage modeling - PUF tagging for tamper-evident transit packs	- Real-time location data - Transport mode & environmental conditions - Custody transfer & routing info - Transportation carbon emissions	- Emissions per shipment - Delivery efficiency - Storage condition compliance - Chain-of-custody integrity	- Digital Traceability Infrastructure (Blockchain, IoT, PUF) - Stakeholder Collaboration (Supply-Chain Integration) - Regulatory Compliance
Use Phase	- IoT-enabled usage monitoring - NFC/QR-enabled DPP access for maintenance & repair - Predictive analytics - BIM-driven maintenance scheduling - PUF on high-value parts for service authenticity	- Usage statistics - Maintenance & repair history - Energy consumption - User feedback - Sensor logs & IoT interactions	- Repair frequency - Energy efficiency trends - Component wear rates - User satisfaction scores	- Lifecycle-Centric Design (Maintenance-focused) - Circular Business Models (Service-based) - Digital Traceability (IoT, DPP, PUF)
End-of-Life (Collection, Sorting, Recycling)	- DPP for disassembly & recovery info - Smart tags for sorting - Blockchain/IOTA for recycling docs - BIM for end-of-life facility planning	- Complete material composition - Disassembly instructions - Recycling facility & sorting data - Output material quality	- Recyclability rate - Material recovery efficiency - Energy savings - Landfill diversion %	- Lifecycle-Centric Design (Recyclability-focused) - Circular Business Models (R-strategies) - Digital Traceability (Smart tags, Blockchain, PUF)

	- PUF for material batch verification	- Energy consumption in recycling		
Reuse / Remanufacturing	- DPP-based product history tracking - Smart tags for component ID - Quality assessment - BIM-supported remanufacturing planning - PUF to certify remanufactured components	- Full product lifecycle history - Component condition analysis - Remanufacturing process data - Energy use & quality control records - Warranty renewal data	- Component reuse rate - Cost savings vs. new production - Product lifespan extension - Remanufacturing energy efficiency	- Lifecycle-Centric Design (Remanufacturing-focused) - Circular Business Models (Reuse programs) - Digital Traceability (DPP, NFC, Blockchain, PUF)

Conclusion

Embracing the Traceable Future – DfT as the Cornerstone of a Sustainable and Accountable Circular Economy

Design for Traceability (DfT) is embedded in the DNA of products and materials as "digital DNA", making it a crucial pillar for a sustainable, accountable circular economy. It integrates Circular Economy (CE) principles, shifting from "take-make-dispose" models to optimize resource use, reduce waste, and increase consumer trust. Through tools like Design for X (DFX) and SIT, DfT enables informed decisions and minimizes environmental impact.

A multi-hierarchical framework aligns strategies with circular goals, as demonstrated by Patagonia's focus on durability and reuse. DfT requires collaboration among designers, manufacturers, and consumers, supported by Digital Product Passports (DPPs) that provide product data, including origins and end-of-life options.

Key to DfT's success is cross-disciplinary collaboration, standardization, transparency incentives, and empowering consumers. Advanced technologies like, AI, and digital twins enhance security and optimize resource allocation, enabling a closed-loop system. In conclusion, DfT is the catalyst for embedding sustainability and longevity in the product lifecycle.

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