



Circular and Dynamic Manufacturing Supply Chain Orchestration and Optimisation

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Abbreviations

Acronym	Description
AAS	Asset Administration Shell
API	Application Programming Interface
BPMN	Business Process Model and Notation
CLT	Cross-Laminated Timber
CMRA	Circular Manufacturing Reference Architecture
CPS	Cyber-Physical System
CRUD	Create, Read, Update, Delete operations
DIDs	Decentralized Identifiers
DIH	Digital Innovation Hub
DPP	Digital Product Passport
ERP	Enterprise Resource Planning
IAM	Identity and Access Management
IT	Information Technology
IoT	Internet of Things
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
MES	Manufacturing Execution System
MSMEs	Manufacturing Small and Medium sized Enterprises
MPMS	Manufacturing Process Orchestration
MVP	Minimum Viable Product
NGSI-LD	Next Generation Service Interfaces - Linked Data
OEE	Overall equipment effectiveness
PaaS	Product-as-a-Service
PEP	Policy Enforcement Point
PoC	Proof of Concept
RAMI4.0	Reference Architectural Model Industrie 4.0
RAMP	Robotics and Automation Marketplace

RBAC	Role-based access control
SCDT	Supply Chain Digital Twin Tool
SCPO	Supply Chain Process Orchestration and Execution Tool
SME	Small and Medium-sized Enterprise
VC	Verifiable Credentials
VP	Verifiable Presentations
WMS	Warehouse Management System

1 Executive Summary

This document describes the Circular Manufacturing Reference Architecture (CMRA), a foundational output of the CIRCULOOS project, funded under the Horizon Europe programme (Grant Agreement No. 101092295). The CMRA serves as a comprehensive technical blueprint for designing and implementing interoperable, data-driven digital solutions that support the transition to a circular economy within manufacturing supply chains. It is intended for a technical audience, including developers, project partners, European Commission reviewers, and the broader open innovation ecosystem, to provide the necessary architectural understanding for developing and integrating innovative circularity solutions aligned with the CIRCULOOS ecosystem.

The core of this report elaborates on the CMRA's vision, its guiding design principles (modularity, reusability, security), and its multi-layered architectural model. The architecture is structured around two primary digital threads:

1. **A Factory Context (Local Digital Thread)**, which captures granular data from shop-floor Cyber-Physical Systems (CPS) and IT systems to create a high-fidelity digital representation of local manufacturing and business management operations.
2. **A Product Context (Global Digital Thread)**, which enables secure and sovereign inter-organizational data sharing across the entire product lifecycle, connecting disparate actors in the value chain.

Bridging these two threads is a central **Digital Twin Data Management Platform**. This platform provides secured access and policy enforcement, and it contextualizes the data into two distinct operational paradigms: a **Smart Manufacturing Context (Industry 4.0)**, aimed at optimizing operational efficiency and resilience, and a **Circular Manufacturing Context (Industry 5.0)**, focused on advancing sustainability, inter-organizational collaboration, and market-driven circular innovations.

Furthermore, this document details the concrete reference implementation of this architecture within the **CIRCULOOS Platform**. It provides a technical description of key components, including the FIWARE-based data platform, the security and policy enforcement framework, and the integrated suite of platform tools for circular manufacturing. These tools include GRETA for sustainability assessment, SCOPT for AI-driven supply chain optimization, SCPO for process orchestration, and SCDT for 3D digital twin simulation.

While the conceptual foundations of the CMRA were established by M18 as planned, the consortium strategically utilized an additional refinement period to address a critical real-world challenge: the low baseline level of digitization within manufacturing SMEs. Initial pilot deployments revealed that theoretical circularity strategies often faced "moving targets" due to fragmented or manual data collection on the shop floor. Consequently, the CMRA underwent multiple iterations of testing and adjustment to move from abstract models to a finalized, convenient approach that accommodates low-digitization environments while still enabling advanced circular orchestration. This version (v1.0) reflects a framework that has been pragmatically adjusted to bridge the digitization gap, providing a validated technical blueprint for the broader European manufacturing ecosystem.

2 Introduction

2.1 Purpose of the Document

The primary purpose of this document is to define and describe the Circular Manufacturing Reference Architecture (CMRA) that underpins the CIRCULOOS project. Building upon the conceptual foundations laid out in the D2.2 CMRA Specification (M9), this M18 deliverable details how the architecture has evolved from theoretical models into a validated, pragmatic framework, particularly adjusted to accommodate the low baseline level of digitization often found in manufacturing SMEs. It aims to provide a clear and comprehensive understanding of the architectural framework, its components, and the principles guiding its design. This specification serves as a key foundational asset for initiatives which look beyond the requirements addressed by CIRCULOOS, enabling them to align their proposed solutions and demonstrators with the project's established technical and operational environment. While this document primarily addresses the technical challenges within CIRCULOOS, it also clearly delineates the essential role of human expertise versus the scope of system-to-system automation in the CMRA framework.

2.2 What is CMRA?

The Circular Manufacturing Reference Architecture (CMRA) provides a structured framework for developing and integrating digital enablers that support circular economy practices in manufacturing. The document contributes illustrative examples of actual software components which implement digital enablers to help understand their scope and purpose. Such examples are contextualized within the CIRCULOOS project ecosystem, including the centralized Data Platform, GRETA for dynamic sustainability assessment, the Supply Chain Orchestrator (SCPO) for workflow management, the Supply Chain Optimization tool (SCOPT), the Supply Chain Digital Twin (SCDT), and the RAMP Marketplace for stakeholder collaboration. In the end, all of them aim to contribute relevant building blocks to integrated digital solutions which aim to facilitate a holistic approach to product lifecycle management—spanning from design and material sourcing to use, reuse, remanufacturing, and recycling. To deliver tangible gains in sustainability and circularity, the architecture achieves this through three core pillars, all of which are powered by a combination of automated processes and critical human oversight: data-driven decision-making, interoperability across diverse systems, and the seamless orchestration of complex supply chains.

2.3 Target Audience

This document is primarily targeted at:

- **Technical Teams and Developers:** Individuals and teams responsible for designing, implementing, and integrating solutions within the CIRCULOOS ecosystem, needing to understand automation boundaries.

- **CIRCULOOS Project Partners and Stakeholders:** To ensure a common understanding of the architectural foundation, including the interplay of automated systems and human expertise.
- **Broader Open Innovation Ecosystem for Circular Value Chains:** This group includes external organizations such as SMEs, startups, research institutions, and Digital Innovation Hubs (DIHs), particularly those interested in participating in the CIRCULOOS Open Calls. This document acts as a technical briefing, enabling them to understand how the CIRCULOOS ecosystem is leveraging data, digital tools, and stakeholder collaboration to create new value in the circular economy.

2.4 Relation to CIRCULOOS Project Goals

The CMRA is central to achieving the CIRCULOOS project's vision of empowering Micro, Small, and Medium-sized Enterprises (MSMEs) to become full members of circular manufacturing value chains. It provides the architectural backbone for the CIRCULOOS platform and its suite of tools, which aim to support a number of interesting features for accelerating circular value chains:

- Orchestrate and optimize supply chains end-to-end, often through automated data analysis and workflow execution, guided by human-defined strategies.
- Enable transparent communication and data sharing, facilitated by system-to-system interfaces but reliant on human-defined data models and governance.
- Calculate product sustainability and circularity profiles, an automated process once data is appropriately structured and inputted by human experts or systems.
- Support the implementation of R-strategies (Reduce, Reuse, Repair, Refurbish, Remanufacture, Recycle, Repurpose) through a combination of digital tools and expert-driven process re-engineering.
- Foster a collaborative ecosystem for circular manufacturing, enabled by digital platforms but thriving on human interaction and agreement.

3 The Circular Manufacturing Reference Architecture

3.1 Vision and Core Principles

The CMRA is built upon a vision of interconnected, intelligent, and sustainable manufacturing ecosystems. Its design is guided by the following core principles:

- **Enabling Circular Manufacturing:** The architecture must inherently support various circularity strategies (R-strategies) and business models, facilitating the transition from linear to circular paradigms through tools that automate data handling while enabling human experts to design and manage circular processes.
- **Data-Driven Decision Making:** Centralizing and leveraging data from across the supply chain to provide actionable insights, often via automated analytics, for human operators and researchers to make informed decisions for optimizing processes, improving resource efficiency, and enhancing sustainability.
- **Modularity and Interoperability:** Designing components as modular services with well-defined interfaces (e.g., APIs) to ensure flexibility, scalability, and seamless system-to-system integration of diverse tools and systems. The definition and extension of these interfaces may require human technical expertise.
- **End-to-End Supply Chain Orchestration:** Providing mechanisms for modeling (a human-led task, e.g., BPMN creation) and then managing and optimizing complex interactions and workflows among multiple actors in a value chain, potentially through automated execution engines.
- **Dynamic Sustainability Assessment:** Integrating tools for continuous Life Cycle Assessment (LCA) and Life Cycle Costing (LCC). While the calculations are automated by tools like GRETA, the initial data collection, scenario definition, and interpretation of results heavily rely on human experts and researchers.
- **Security and Trust:** Implementing robust cybersecurity measures, identity and access management, and data governance frameworks. While enforcement can be automated, the definition of policies and ongoing security management requires human oversight and expertise.
- **Harmonized Semantics and Data Types:** Promoting the use of common data models and ontologies, developed and maintained by human experts, to ensure that data can be understood and utilized consistently across different automated systems and stakeholders.

3.2 Architectural Concerns

The CMRA's tools and services are organized into two distinct functional contexts, addressing different but complementary concerns:

Smart Manufacturing Context (Industry 4.0)

This context focuses on the internal efficiency, productivity, and resilience of manufacturing operations. It leverages data from the Factory Context to enable capabilities such as:

- **Operational Stability & Productivity:** Monitoring and improving Overall Equipment Effectiveness (OEE) and resource utilization.
- **Agility & Efficiency:** Enabling flexible production scheduling and rapid response to operational changes.
- **Continuous Risk Awareness & Predictability:** Using data analytics for predictive maintenance and identifying potential disruptions.

Circular Manufacturing Context (Industry 5.0)

This context extends beyond the single factory to address the broader goals of sustainability, collaboration, and circularity across the supply chain. It leverages the global Product Context to enable capabilities such as:

- **Sustainability & Environmental Impact:** Assessing the lifecycle impact of products and processes.
- **Collaboration & Traceability:** Enabling secure data sharing and material tracking across multiple organizations.
- **Agile Reconfiguration:** Facilitating the dynamic formation and optimization of circular value chains in response to market opportunities (e.g., new uses for by-products).

3.3 Architectural Overview

The CMRA is conceptualized as a multi-level architecture built around two distinct but interconnected digital threads: the **Factory Context** at the local level and the **Product Context** at the global, inter-organizational level. These are enabled and managed by a central data platform that offers a suite of services and applications for circular manufacturing.

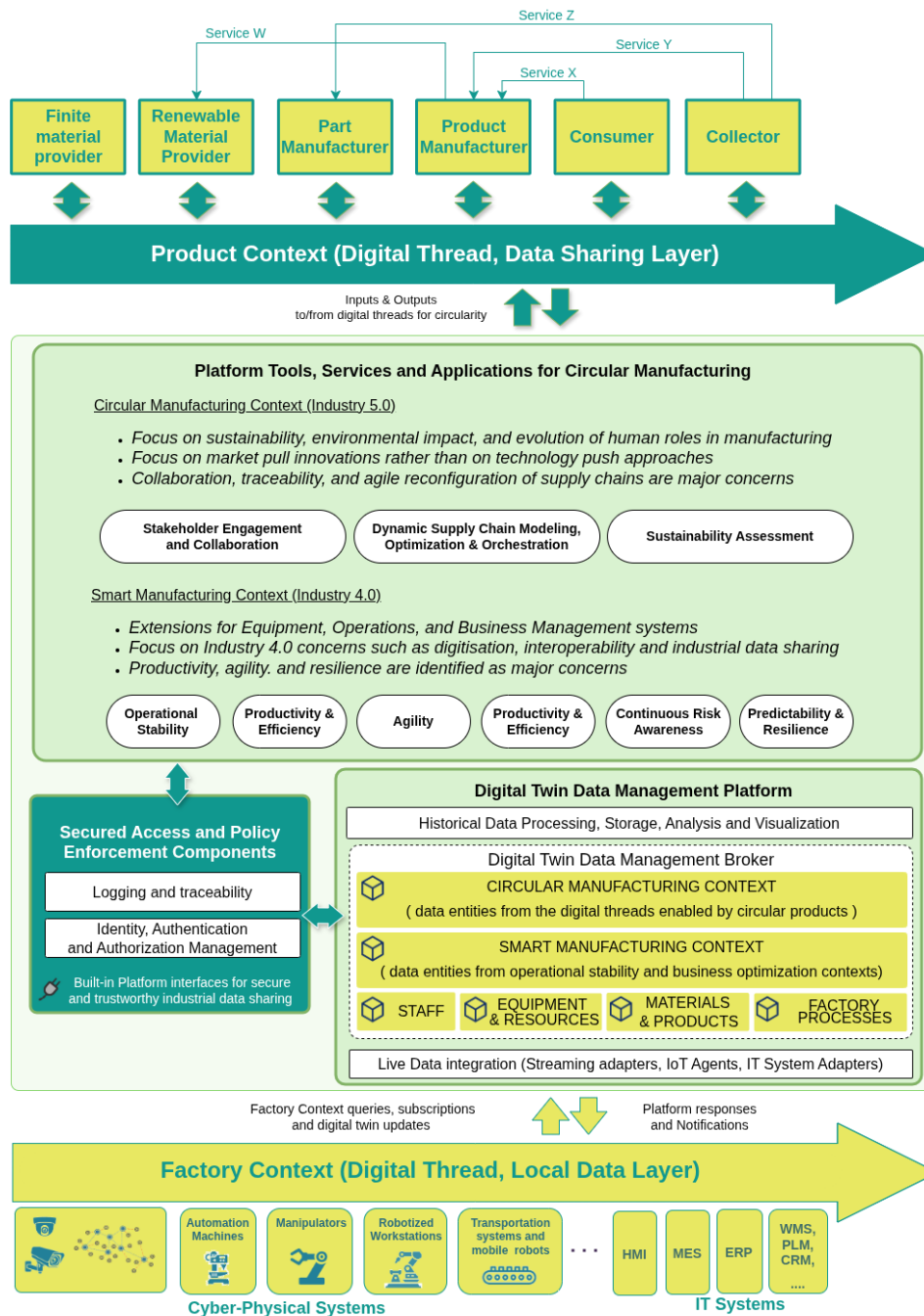


Figure 1: The Circular Manufacturing Reference Architecture

The architecture consists of four primary layers:

1. **Factory Context (Local Digital Thread¹):** This foundational layer represents the shop floor, comprising Cyber-Physical Systems (e.g., automation machines, robots) and IT Systems (e.g., MES, ERP, WMS). It is the source of granular operational data, forming a local digital thread within a single manufacturing facility.
2. **Digital Twin Data Management Platform:** This central layer acts as the bridge between the factory and the wider supply chain. It ingests, processes, stores, and provides secure access to both historical and live data from the Factory Context. It is responsible for managing the digital twin data models.
3. **Platform Tools, Services, and Applications:** This functional layer offers a suite of applications that consume data from the management platform to provide value-added services. These tools are organized into two distinct contexts reflecting different industrial paradigms.
4. **Product Context (Global Digital Thread):** This top layer represents the data sharing ecosystem across the entire supply chain, connecting various actors like material providers, manufacturers, consumers, and collectors. It forms a global digital thread that enables traceability, collaboration, and the execution of circular strategies.

In practice, smart data platforms based on the CMRA consider a hybrid deployment model that distinguishes between local (organization-specific) and global (cross-organizational) data layers.

- **Local data layers**, typically deployed on-premises or in a private cloud, manage core manufacturing operations and sensitive internal data. This model ensures each organization maintains sovereign control and strict governance over its primary assets and processes.
- **Global data layers**, conversely, provide advanced services for supply chain collaboration and inter-organizational data exchange. Their implementation can range from utilizing a common, shared infrastructure to adopting more sophisticated, decentralized topologies. These advanced topologies often leverage emerging paradigms like data spaces and digital marketplaces to establish a framework of trust, enforce data usage policies, and guarantee data sovereignty for all participants in the value chain.

1 <https://www.ibm.com/think/topics/digital-thread-vs-digital-twin>

3.4 Building Blocks

The CMRA is defined by abstract building blocks representing the essential capabilities shown in the architectural diagram (Figure 1).

- **Factory Context (CPS & IT Systems):** The source of real-world data from the shop floor. This includes sensor data, production states, and operational metrics from various machines and enterprise systems.
- **Digital Twin Data Management Platform:** The core data engine. It provides historical data processing, storage, and visualization, as well as live data integration from streaming adapters and IoT agents. It is responsible for creating and maintaining the digital representations of all assets and processes.
- **Secured Access and Policy Enforcement Components:** The security foundation. This block provides identity, authentication, and authorization management, along with logging and traceability to ensure secure and trustworthy data sharing.
- **Stakeholder Engagement and Collaboration:** The community and marketplace functionality. It enables supply chain participants to connect, discover opportunities, and collaborate on circular initiatives.
- **Dynamic Supply Chain Modeling, Optimization & Orchestration:** The "brains" of the supply chain. This block provides tools for modeling complex business processes (e.g., with BPMN), optimizing logistics and resource flows, and executing multi-actor workflows.
- **Sustainability Assessment:** The environmental and economic analysis engine. This block provides tools to quantify the impacts of different circular strategies using methodologies like Life Cycle Assessment (LCA) and Life Cycle Costing (LCC).

Building on these conceptual foundational areas of the CMRA, the following building blocks are considered core to realize them in actual platforms.

3.4.1 Data Management & Integration Service

- **Justification in CMRA:** Circular manufacturing thrives on comprehensive data spanning the entire product lifecycle and diverse supply chain actors. A fundamental capability is required to ingest data from heterogeneous sources (IoT, ERPs, manual inputs), cleanse, store, manage, model (semantically), and provide secure, governed access to this data. This service ensures data is a reliable asset for all other services and decision-making processes.
- **Automation/Human Interplay:** Automated ingestion from connected systems and data validation are key. However, human experts are crucial for defining data models, ontologies for semantic interoperability, data quality rules, governance policies, and for integrating new or legacy data sources.

3.4.2 Sustainability Assessment Service

- **Justification in CMRA:** To validate circular strategies and make informed choices, it's imperative to quantify their environmental (e.g., LCA) and economic (e.g., LCC) impacts. This building block provides the capability to perform such assessments dynamically, comparing scenarios and tracking performance over time.
- **Automation/Human Interplay:** The calculation of impact indicators based on established methodologies and data is automated. However, the collection and structuring of detailed Life Cycle Inventory (LCI) data, the definition of assessment scope and scenarios, and the interpretation of complex results to derive actionable insights are heavily reliant on human domain experts and researchers.

3.4.3 Process Orchestration & Workflow Management Service

- **Justification in CMRA:** Circular value chains are characterized by complex, dynamic, and often novel interactions between multiple, independent organizations (producers, recyclers, logistics providers, consumers). A core building block is needed to model these collaborative business processes, manage their execution, monitor their status, and handle exceptions. This ensures that materials, products, and information flow efficiently and transparently across the extended supply network.
- **Relevance of BPMN-based Implementation:** This building block is of particular relevance in CMRA and is implemented in CIRCULOOS as a BPMN-based Supply Chain Orchestrator. The use of a standardized, visual notation like Business Process Model and Notation (BPMN) is crucial because it allows human experts from different organizations (business analysts, process owners) to collaboratively design, understand, and agree upon complex multi-actor processes. These human-defined models then serve as direct input for an orchestration engine, which can automate the execution of many workflow steps, manage task assignments (to humans or systems), and track progress. This combination of human-centric design with automated execution provides both clarity and agility, which are vital for establishing and adapting circular supply chains.
- **Automation/Human Interplay:** Human experts design and model the business processes (e.g., using BPMN). The orchestration engine then automates the execution of these process models, including task routing, system integrations via APIs, and notifications. Human intervention is required for handling exceptions, making complex decisions within a process, and evolving the process models themselves.

3.4.4 Supply Chain Analytics & Optimization Service

- **Justification in CMRA:** To truly enhance circularity and efficiency, operations within and between enterprises need to be continuously analyzed and optimized. This building block provides capabilities for advanced analytics, simulation (digital twins), and optimization algorithms to improve resource utilization, logistics, inventory management, and overall supply chain performance in the context of circularity goals.

- **Automation/Human Interplay:** Analytical algorithms and simulation engines run automatically. However, human experts are needed to formulate the right questions, build and calibrate the underlying models, define constraints and objectives, and interpret the analytical outputs to make strategic or operational improvements.

3.4.5 Circular Economy Marketplace & Collaboration Service

- **Justification in CMRA:** A key challenge in circular economies is connecting entities that have secondary materials or end-of-life products with those who can utilize them. This building block provides a platform or service to facilitate discovery, matchmaking, negotiation, and potentially transaction support for recovered resources, components, and circular products/services. It fosters a vibrant ecosystem of circular actors.
- **Automation/Human Interplay:** Automated search, filtering, and notification functionalities are essential. However, the creation of listings, the definition of needs, negotiation of terms, and the establishment of trust and business relationships are primarily human-driven interactions, supported by the platform.

3.4.6 Specialized Circularity Enablers Integration Service

- **Justification in CMRA:** Many specific circular operations, such as advanced material sorting, robotic disassembly, or specialized chemical recycling processes, rely on dedicated technologies (hardware and software). The reference architecture must provide a standardized way to integrate these "CM-Specific Tools" into the broader data and process ecosystem, allowing them to consume relevant data and provide operational feedback.
- **Automation/Human Interplay:** The specialized enablers themselves often perform automated tasks. Their integration into the CMRA, including API development, data mapping, and operational monitoring, requires human technical expertise. The initial setup, calibration, and maintenance of these tools are also human-intensive.

3.4.7 Identity, Security & Trust Services

- **Justification in CMRA:** Collaborative environments, especially those involving data sharing across organizational boundaries, fundamentally depend on robust security, reliable identity management for all actors (humans and systems), and mechanisms to establish and maintain trust. This building block provides the foundational services for authentication, authorization, data integrity, confidentiality, and auditable trails. Technologies like Blockchain can offer significant value by providing decentralized, immutable, and transparent record-keeping, enhancing trust without relying on a single central authority.
- **Automation/Human Interplay:** Automated enforcement of security policies, cryptographic operations, and access control mechanisms are critical. Blockchain transactions, once initiated, are automatically validated and recorded by the network. However, the definition of overall security policies, risk assessment, the design of smart contracts for blockchain, security monitoring, incident response, and overall governance of the trust framework (including decisions on what data is on-chain vs. off-chain) are human responsibilities requiring specialized expertise.

4 CMRA Implementation: the CIRCULOOS Platform

4.1 Data Management within the Platform

- **Importance of Standardized Data Models:** Development and agreement on standardized data models are human-led, collaborative efforts crucial for enabling subsequent automated data exchange and interpretation by various tools.
- **Data Flow and Exchange Mechanisms:** While APIs enable automated system-to-system data exchange, the design, implementation, and maintenance of these APIs require skilled human developers.
- **Data Governance and Ownership:** Defining data governance policies, ownership rights, and ethical usage guidelines is a complex task requiring human expertise and stakeholder consensus. Automated systems then enforce these human-defined rules.

4.2 Recommendations for Implementing Solutions

- **Integrating with the CIRCULOOS Data Platform:**
 - **Data Provision:** The initial collection, formatting, and validation of data to be fed into the platform will often be a human-intensive task, especially for SMEs without fully digitized operations. Over time, system-to-system automation for data ingestion from operational systems should be the goal.
- **Leveraging CIRCULOOS Tools:**
 - **GRETA:** Beneficiaries will perform human-led LCI data collection, with expert support from SUPSI, before GRETA can automatically process it.
 - **SCOPT/SCDT/Orchestrator:** These tools require significant human input for process modeling, scenario definition, and parameter setting before their automated analytical or execution capabilities can be utilized. Interpretation of outputs to make business decisions remains a human responsibility.
- **Documenting Processes (BPMN):** This is a manual, expert-driven task where beneficiaries map their circular value chains. The resulting models can then be used by automated orchestration engines.
- **Measuring and Reporting Impact (LCA with GRETA):** As stated, data collection is largely manual or requires human-configured interfaces, while GRETA's calculations are automated. The analysis and reporting of this impact require human interpretation.

- **Data Security and Sovereignty:** Currently implemented through a centralized data platform².

4.3 Platform Components

The CIRCULOOS ecosystem is operationalized through a reference implementation of the CMRA, which provides the structural framework for integrating heterogeneous digital tools into a unified circular economy environment (See Figure 4.3.1). The core of this reference implementation is the CIRCULOOS Data Platform (CDP), acting as the central nervous system for data sovereignty and contextual awareness. By utilizing the Orion-LD Context Broker for real-time state management and Mintaka for historical time-series persistence within TimescaleDB, the CMRA ensures a consistent, standardized data flow. Connectivity across the implementation is managed via an API Proxy layer, enforcing NGSI-LD standards and JSON-LD formats to enable seamless communication between the manufacturing orchestration (MPMS), stakeholder collaboration (RAMP), and specialized analytical tools like SCOPT for optimization and GRETA for sustainability. This architecture mandates that while individual pilot systems may operate locally, a synchronized "digital twin" of all relevant data is maintained within the CDP, ensuring a single, verifiable source of truth for the entire manufacturing lifecycle.

² As an extension to the current case, CIRCULOOS is exploring alternative approaches such as a decentralized framework utilizing Verifiable Credentials (VC) to lower the barrier for SME adoption while maintaining high security standards (see Section 4.3.5 and Case Study I).

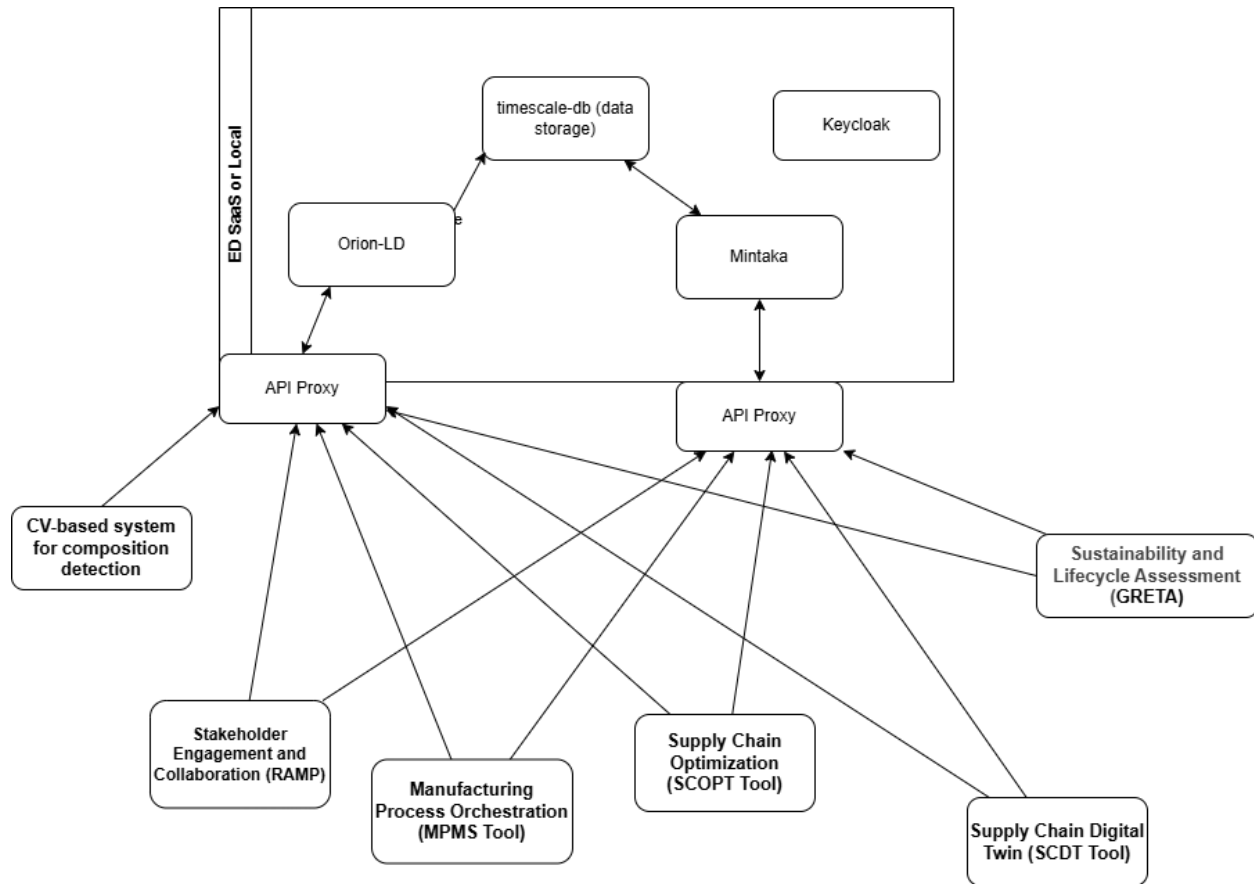


Figure 4.3.1. Main CMRA platform components integrated in CIRCULOOS implementation

4.3.1 CIRCULOOS Data Platform (based on RAMP)

- **Role:** The central data hub. (Instantiates: Data Management & Integration Service)
- **Interactions:**
 - **Automated:** Data ingestion from connected IoT devices and integrated enterprise systems; automated data validation checks; API-driven data exchange with other CMRA tools.
 - **Human-Expert Mediated:** Initial connection and configuration of data sources; extension of data models for new business entities or data types; manual data entry or correction where necessary; definition of data sharing and access control policies.
- **Key Features for CMRA adopters:** adopters will need to ensure their data can be fed into the platform, which may involve human-led data mapping or automated system integration.

4.3.2 Dynamic Sustainability Assessment (GRETA)

- **Role:** LCA/LCC tool
- **Main Architectural Concern:** Sustainability Assessment Service
- **Interactions:**
 - **Automated:** Retrieval of operational data from the CIRCULOOS Data Platform; calculation of environmental and cost indicators once LCI data and scenarios are defined.

- **Human-Expert Mediated:** Collection and structuring of Life Cycle Inventory (LCI) data (a significant task for beneficiaries); definition of system boundaries and assessment scenarios; interpretation of GRETA's output reports for insights and decision-making. SUPSI provides expert support for these human-led tasks.
- **Key Features for CMRA adopters:** Beneficiaries must actively collect and provide LCI data, with support from experts, to enable GRETA's automated assessments.

4.3.3 Supply Chain Orchestration & Optimization

4.3.3.1 Supply Chain Orchestrator

- **Role:** Modeling and executing business processes (BPMN-based)
- **Main Architectural Concern:** Process Orchestration & Workflow Management Service
- **Interactions:**
 - **Automated:** Execution of defined workflows; triggering notifications; system-to-system communication based on process logic.
 - **Human-Expert Mediated:** Design and modeling of BPMN diagrams representing the circular value chains; configuration of orchestration rules; handling exceptions or steps in the process that require human decision or intervention.
- **Key Features for CMRA adopters:** adopters need to define their processes in BPMN, a human-led task, which then enables automated or semi-automated orchestration. This component is pivotal for managing the collaborative nature of circular value chains.

4.3.3.2 Supply Chain Optimization Tool (SCOPT)

- **Role:** Decision support for logistics and supply chain configurations
- **Main Architectural Concern:** Supply Chain Analytics & Optimization Services
- **Interactions:**
 - **Automated:** Running optimization algorithms based on provided data and models; generating potential solutions.
 - **Human-Expert Mediated:** Provision of detailed input data (factory resources, processes, costs, constraints); defining optimization goals and parameters; evaluating and selecting from the solutions proposed by SCOPT.
- **Key Features for CMRA adopters:** While SCOPT automates complex calculations, its effectiveness depends on the quality of human-provided data and strategic input.

4.3.3.3 Supply Chain Digital Twin (SCDT)

- **Role:** Simulating and visualizing factory operations and supply chains
- **Main Architectural Concern:** Supply Chain Modeling
- **Interactions:**
 - **Automated:** Running simulations based on models and data from the Data Platform or SCOPT; visualizing processes and data flows dynamically.
 - **Human-Expert Mediated:** Building and calibrating the digital twin models; defining simulation scenarios; interpreting simulation results to understand system behavior and make decisions.
- **Key Features for CMRA adopters:** SCDT offers automated visualization and simulation, but model creation and insightful analysis require human expertise.

4.3.4 Cyber-Physical Tools (e.g., Machine Perception/Actuation, Robotics, and Sensors)

- **Role:** Supporting specific circularity tasks.
- **Main Architectural Concern:** Process/Product Traceability and Quality Control
- **Interactions:**
 - **Automated:** Execution of specialized tasks (e.g., robotic sorting of plastics, automated disassembly).
 - **Human-Expert Mediated:** Design, development, integration, and maintenance of these specialized tools; training of AI models for machine vision which often requires curated datasets and expert knowledge.
- **Key Features for CMRA adopters:** These tools can automate specific physical or analytical tasks, but their implementation and optimization are human-intensive.

4.3.5 Cybersecurity and Data Sovereignty Framework

- **Role:** Ensuring secure and trusted data sharing
- **Main Architectural Concern:** Identity, Security & Trust Service
- **Interactions:**
 - **Automated:** Enforcement of access control policies; encryption/decryption; anomaly detection (potentially). If Blockchain is used, transaction validation and recording are automated by the network.
 - **Human-Expert Mediated:** Definition of security policies and data governance rules; identity and access management configuration; monitoring security events and responding to incidents; legal and ethical oversight of data sharing. If Blockchain is used, this includes designing smart contracts and defining what data is recorded on-chain.
- **Key Features for CMRA adopters:** While the framework provides automated security features, adopters must actively manage their users' access and comply with human-defined governance policies. The potential integration of technologies like Blockchain can enhance trust and transparency in specific use cases. Despite the centralized data platform establishes the baseline security implementation of the CMRA, alternative decentralized approaches like Blockchain and Verifiable Credentials (VCs) are currently explored and implemented as optional advanced capabilities rather than mandatory requirements.

4.3.6 RAMP Marketplace

- **Role:** Hub for actors, resources, collaboration
- **Main Architectural Concern:** Marketplace & Stakeholder Collaboration Services
- **Interactions:**
 - **Automated:** Filtering and searching listings based on defined criteria; notification systems for new listings or bids.
 - **Human-Expert Mediated:** Registration of entities and users; creation of service/material listings; negotiation and agreement between parties; defining search criteria and preferences.
- **Key Features for CMRA adopters:** The Marketplace facilitates connections, but forming business relationships and agreements typically requires human interaction.

5 CMRA in Practice: Pilot Examples and Extended Case Studies

This section grounds the architectural concepts in practice. First, it details the application of the CMRA within the project's three core pilots, illustrating how the blueprint manifests in specific, real-world contexts. While these initial pilot descriptions focus primarily on the fundamental data services driving integration, it is important to note that the specific usage and implementation of the Supply Chain Digital Twin (SCDT) and Supply Chain Optimization Tool (SCOPT) are extensively detailed in CIRCULOOS deliverables D3.4 and D3.8. It then presents extended case studies for key technologies and components that, while part of the broader CIRCULOOS toolkit, may not be the central focus of the initial pilots, offering a wider perspective for CMRA adopters.

5.1 Wood Pilot: Blueprint for Product-as-a-Service

In an effort to create a more sustainable and efficient business model, three independent wood-related companies in the Netherlands—**Circu Leren** (modular wood projects), **HERSO** (waste wood processing), and **Plennid** (repurposing urban timber)—have joined forces to produce sustainable construction panels. This pilot aims to integrate their operations, fostering a circular economy approach that maximizes resource utilization and minimizes waste. The core of the pilot is establishing a "Wood-as-a-Service" model focused on modular design for assembly and disassembly, allowing materials to be returned and reused.

Blueprint Target, Scope, and Value

The **target** of this blueprint is to enable a "**Product-as-a-Service**" (**PaaS**) **business model**, shifting from selling products to selling their use. The **scope** involves integrating the data and processes of the three SMEs to manage the full lifecycle of modular construction panels. This includes tracking reclaimed urban and waste wood, supporting "design-for-disassembly", and orchestrating reverse logistics for product take-back and reuse. The **intended added value** is to create a new, high-value PaaS revenue stream, enhance competitiveness, and improve profitability by maximizing resource utilization and demonstrably minimizing waste.

Role of Data Services

The data services (Data Platform, Marketplace, and GRETA) act as the digital backbone for this PaaS model. The **Data Platform** is responsible for tracking the inventory and flow of wood materials, forming the basis of a material passport. The **Marketplace** service facilitates the discovery of these reclaimed materials. **GRETA** serves as the assessment engine, consuming data from the platform to quantify the sustainability benefits of this circular model compared to traditional alternatives.

Interaction Patterns

- **Automated:** Sustainability benefit assessment via **GRETA's automated LCA calculations**. The Data Platform's automated tracking of wood movements and inventory (once initial data is entered). Marketplace search and filter functions for reclaimed materials.
- **Human-Expert Mediated: Design of modular products** by Circu Leren for assembly and disassembly. HERSO's expert processing of waste wood and Plennid's expert processing of urban timber. Negotiation and definition of the "Wood-as-a-Service" contracts and reverse

logistics, where wood from temporary applications (e.g., pavilions) **returns to HERSO for reuse**. Human-led data collection and scenario definition for the GRETA assessment to quantify advantages over traditional CLT.

5.2 Plastic Pilot: Blueprint for Quality-Assured Recycled Content Integration

This pilot brings together three independent companies in the plastics sector: **Thermolympic**, which manufactures automotive components; **Contenedores Lolo**, which collects and processes waste plastics ; and **Canonical Robots**, which provides advanced robotic and vision-based sorting technology. This pilot aims to integrate their operations to produce plastic components with recycled content, fostering a circular economy approach that maximizes resource utilization, minimizes waste, and enhances competitiveness.

Blueprint Target, Scope, and Value

The **target** of this blueprint is to enable and increase the use of **quality-assured recycled plastics** in high-specification manufacturing, specifically for the automotive industry. The **scope** focuses on creating a tight data feedback loop between the technology provider (Canonical Robots) , the recycler (Contenedores Lolo) , and the manufacturer (Thermolympic). It specifically covers the integration of automated robotic sorting and **composition analysis data** into the manufacturer's procurement and quality control processes. The **intended added value** is to enable Thermolympic to meet stringent customer quality requirements while using recycled content , thereby reducing waste incineration , minimizing reliance on virgin plastics, and enhancing profitability and market position in the sustainable automotive supply chain.

Role of Data Services

The data services are crucial for **enabling quality assurance through traceability**. The **Data Platform** acts as the central hub for logging critical quality data, specifically the **plastic composition identified by Canonical Robots' vision system**. This service integrates with Thermolympic's operational systems (like ERP) to guide procurement decisions and provide data to the **Orchestrator** for managing orders. **GRETA** uses this data to quantify the environmental impact reduction achieved by substituting virgin plastics.

Interaction Patterns

- **Automated: Robotic and vision-based sorting** of plastic waste by Canonical Robots' system. This system **automatically identifies the composition** of the reclaimed plastic, a critical feature for Thermolympic. Automated logging of this composition data to the Data Platform. System-to-system data exchange between Thermolympic's ERP and the Orchestrator for orders. **Automated LCA calculations in GRETA** to quantify benefits.
- **Human-Expert Mediated:** Thermolympic defining the **high-quality, functional, and aesthetic specifications** for recycled plastics required by automotive customers. Contenedores Lolo oversees the collection and processing of waste plastics. Human-led data

collection and scenario definition for the GRETA assessment to compare against virgin plastic use. Initial setup, calibration, and training of the robotic sorting system.

5.3 Leather Pilot: Blueprint for Waste Valorization and Inter-SME Collaboration

Two independent companies in the Hungarian leather goods industry, **Mototextil** (a leather goods manufacturer) and **B&A** (a producer of smaller leather goods), are collaborating to improve the sustainability of their products by repurposing leftover leather scraps for craft activities. This pilot aims to foster a circular economy approach that valorizes waste, minimizes incineration, and enhances competitiveness.

Blueprint Target, Scope, and Value

The **target** of this blueprint is industrial symbiosis, specifically the **valorization of leather scraps** to reduce incineration. The **scope** involves implementing a **marketplace-centric collaboration model** that connects the waste generator (Mototextil) with a primary upcycler (B&A) and a wider network of secondary users (like NGOs and kindergartens). The blueprint covers the processes for listing and discovering materials, managing the subsequent collaborative workflows, and performing a comparative LCA with GRETA to validate the environmental benefits. The **intended added value** is to create a new revenue stream for Mototextil from its scraps (reducing disposal costs and environmental impact from incineration), provide B&A with a lower-cost, sustainable source of materials, and enhance the overall profitability and market position of both SMEs.

Role of Data Services

The data services are the **primary enabler of this new inter-SME marketplace**. The **Marketplace service** is central, providing the platform for Mototextil to list its available scraps and for B&A (and others) to discover and procure them. The **Orchestrator** service supports this by managing the workflow of ordering and fulfillment once a match is made. **GRETA** provides the validation service, consuming data from the platform to conduct a comparative LCA and prove the sustainability benefits of this collaboration.

Interaction Patterns

Automated: The **shared marketplace's search, filter, and notification functions** for available leather scraps. Automated workflow steps in the Orchestrator for order processing once a deal is initiated. **Automated comparative LCA calculations in GRETA** to determine the benefits of this integrated approach.

Human-Expert Mediated: Mototextil **manually cataloging and listing** its leather scraps (type, quantity, quality) on the marketplace. B&A experts visually inspecting and **selecting suitable scraps** for their products. Negotiation of price and logistics between Mototextil and B&A, or with other interested parties. **Design of new products by B&A** based on the available scraps. Human-led data input and scenario definition for the comparative LCA in GRETA.

5.4 Extended CMRA Case Studies

This subsection explores hypothetical blueprints for key CMRA capabilities or specific CIRCULOOS tools that offer significant potential for circular manufacturing but may not be the primary focus of the initial three pilot demonstrators. These case studies aim to inspire potential adopters by illustrating broader applications of the CMRA.

Case Study I: Cybersecure and Sovereign Data Sharing for Circular Value Chains

Tool(s) in Focus:

- **Cybersecurity and Data Sovereignty Framework**
- **CIRCULOOS Data Platform (based on RAMP)**
- **Blockchain Integration**

CMRA Building Block(s) Addressed:

- Identity, Security & Trust Services
- Data Management & Integration Service

Hypothetical Scenario/Challenge: In a circular value chain for high-value components—such as EV batteries or industrial electronics—multiple independent SMEs must share sensitive operational data to enable "R-strategies" like remanufacturing or recycling. The primary challenge is the lack of trust: organizations are hesitant to share proprietary data (e.g., material composition or usage history) without guaranteed sovereignty, verifiable audit trails, and secure identity management.

Proposed Blueprint for Cybersecure Data Sharing: This blueprint integrates decentralized identity and blockchain technologies into the CMRA to establish a framework of trust:

- **Digital Product Identity & Passports:** Each high-value component is assigned a unique digital identity. Key lifecycle events—such as maintenance, battery health checks, or ownership changes—are recorded as immutable transactions on a **Blockchain**. This creates a "Digital Product Passport" (DPP) that provides a verifiable history without requiring a central authority.
- **Sovereign Data Management:** The **CIRCULOOS Data Platform** stores granular operational data in a hybrid model. Sensitive data remains in local layers under the owner's control, while the Global Layer uses **Verifiable Credentials (VC)** and **Verifiable Presentations (VP)** to manage secure access for platform users.
- **Policy Enforcement:** Automated **Policy Enforcement Points (PEP)** and smart contracts ensure that data is only shared according to human-defined governance rules and legal agreements.

Interaction Patterns:

- **Automated:** * Cryptographic enforcement of access control and encryption/decryption.
 - Automated validation and recording of blockchain transactions (e.g., ownership transfers).
 - System-to-system verification of compliance with recycling standards via smart contracts.
- **Human-Expert Mediated:**
 - Security experts define overall governance policies, risk assessments, and data usage rules.
 - Human developers design and audit smart contracts and blockchain architecture.
 - Stakeholders manage user identities and respond to security monitoring incidents.

Expected Benefits:

- **Increased Trust:** Enables secure collaboration between competitors by guaranteeing data sovereignty.
- **Enhanced Traceability:** Provides a tamper-evident audit trail for regulatory compliance, such as the EU Battery Passport.
- **Market Growth:** Facilitates secondary markets by providing buyers with verified, trustworthy data on a product's condition and history.

Relevance for CMRA adopters: adopters dealing with products requiring high levels of authenticity verification or multi-lifecycle management—such as those in the electronics, battery, or luxury goods sectors—can leverage this blueprint to propose solutions that utilize the CMRA's trust and security services.

Case Study II: Supply Chain Optimization Tool for Dynamic Multi-Resource Circular Flows

- **Tool(s) in Focus:** Supply Chain Optimization Tool (SCOPT) (Section 4.3.2).
- **CMRA Building Block(s) Addressed:** Supply Chain Analytics & Optimization Service; Data Management & Integration Service.
- **Hypothetical Scenario/Challenge:** A regional ecosystem involves multiple SMEs generating diverse industrial by-products (e.g., metal offcuts, plastic regrind, textile scraps) and several other SMEs capable of processing these by-products into new materials or products. The challenges are to dynamically match supply and demand, optimize logistics for collecting and distributing these secondary resources, and select the most economically and environmentally viable processing routes, considering fluctuating availability, processing capacities, and market prices.
- **Proposed Blueprint Integrating SCOPT:**
 - **Data Integration:** The CIRCULOOS Data Platform collects real-time or near real-time data from participating SMEs on: available by-product types, quantities, locations, and quality specifications; processing capabilities, capacities, costs, and lead times of potential recyclers/remanufacturers; demand for specific secondary materials or circular products.

- **Automated Interactions:** SCOPT's algorithms would automatically process this data, along with pre-defined constraints (e.g., transport distances, CO2 emission targets from GRETA), to generate optimized plans for material flows. This could include optimal batching for collection, routing for logistics, and allocation of by-products to specific processors.
- **Human-Expert Mediated Interactions:** Human experts (e.g., from a coordinating DIH or a lead SME) would initially configure SCOPT by defining the network of actors, available transport options, cost models, and optimization objectives (e.g., minimize cost, minimize CO2, maximize resource utilization). They would also review SCOPT's recommendations, make final decisions, and potentially adjust parameters for re-optimization based on qualitative factors or unforeseen events. The Supply Chain Orchestrator could then execute the human-approved optimized plan.
- **Expected Benefits:** Reduced logistics costs, minimized waste to landfill, increased utilization of secondary resources, improved overall economic viability of the circular ecosystem, and quantifiable reductions in environmental impact.
- **Relevance for CMRA adopters:** adopters aiming to establish complex, multi-actor circular ecosystems for industrial symbiosis or large-scale material recovery can propose using SCOPT to manage and optimize these flows, demonstrating significant efficiency and sustainability gains.

Case Study (III): Supply Chain Digital Twin for Accelerating Novel Circular Business Models

Tool(s) in Focus:

- **Supply Chain Digital Twin (SCDT)**
- **CIRCULOOS Data Platform**
- **Sustainability Assessment (GRETA)**

CMRA Building Block(s) Addressed:

- **Supply Chain Analytics & Optimization Service**
- **Data Management & Integration Service**

Hypothetical Scenario/Challenge: An SME manufacturing domestic appliances, such as washing machines, aims to transition from a linear sales model to a **Product-as-a-Service (PaaS)** model. A critical challenge in this shift is managing the lifecycle of complex sub-assemblies, such as the **washing machine tray**. The company needs to simulate how designing these components for durability and easy disassembly affects long-term operational costs, take-back logistics, and the viability of remanufacturing operations.

Proposed Blueprint Integrating SCDT: This blueprint utilizes the SCDT to create a high-fidelity virtual representation of the circular value chain:

- **Detailed Component Modeling:** Using entities from the **CIRCULOOS Data Platform**, human experts build a digital twin that includes specific parameters for the washing

machine tray, such as material composition (e.g., recycled plastic content), assembly checkpoints, and wear-and-tear sensors.

- **Automated Life Cycle Simulation:** The SCDT runs automated simulations to predict the "failure rate" of trays under different usage scenarios. It visualizes how many units will require refurbishment versus total recycling over a five-year PaaS contract.
- **Integration with Sustainability Metrics:** The simulation data is fed into **GRETA** to automatically calculate the environmental impact reduction of reusing a tray versus manufacturing a new one from virgin plastics.

Interaction Patterns:

- **Automated:**
 - Running simulations based on historical data and current design specifications.
 - Visualizing material flows, inventory levels, and potential bottlenecks in the reverse logistics chain.
 - Automated LCA/LCC calculations via GRETA for the simulated scenarios.
- **Human-Expert Mediated:**
 - Process engineers define "what-if" scenarios, such as "What is the impact of changing the tray's plastic resin to a higher-grade recycled polymer?".
 - Experts calibrate the digital twin models based on real-world feedback from pilot testing.
 - Business strategists interpret simulation outputs to decide on regional vs. centralized refurbishment hubs.

Expected Benefits:

- **Risk Reduction:** Validates the feasibility of the PaaS model before making significant capital investments in take-back infrastructure.
- **Optimized Design:** Identifies specific components (like the tray) that benefit most from "design-for-disassembly," improving overall product longevity.
- **Improved Resource Planning:** Better estimation of the secondary materials market potential by accurately predicting the volume of returned components.

Relevance for CMRA adopters: adopters proposing complex circular business models (e.g., leasing, extensive take-back schemes) can use the SCDT and the established data entities for plastic components to model and validate their concepts. This is particularly powerful for those working in sectors with complex assemblies like white goods or automotive parts.

Case Study (IV): Dynamic Sustainability Assessment for Real-Time Circularity Validation

Tool(s) in Focus:

- GRETA (Sustainability Assessment Service)
- CIRCULOOS Data Platform
- Factory Context (Cyber-Physical Systems & IT Systems)

CMRA Building Block(s) Addressed:

- Sustainability Assessment
- Data Management & Integration Service

Hypothetical Scenario/Challenge: A manufacturer of plastic components, such as the **washing machine tray**, wants to move beyond static, yearly sustainability reports toward **dynamic Life Cycle Assessment (LCA)**. The challenge lies in the variability of the shop floor: energy prices fluctuate, the ratio of recycled to virgin plastic changes per batch, and machine efficiency (OEE) varies. Without real-time data integration, the company cannot accurately prove the carbon footprint reduction of a specific "circular" production run to its customers.

Proposed Blueprint Integrating GRETA: This blueprint demonstrates how GRETA evolves from a standalone calculator into a dynamic validation engine by connecting directly to the digital thread:

- **Real-Time Data Ingestion:** The **CIRCULOOS Data Platform** automatically ingests live power consumption data from sensors on the injection molding machines and material throughput from the ERP. For the washing machine tray, this includes the precise weight of plastic used and the energy consumed during the "washing" and "molding" phases.
- **Automated Impact Calculation:** Once human experts define the initial **Life Cycle Inventory (LCI)** and system boundaries, GRETA automatically pulls the live operational data to update environmental and cost indicators.
- **Batch-Level Circularity Labels:** The system generates a "Sustainability Profile" for every production batch. If a batch uses 40% recycled content from a provider like Contenedores Lolo, GRETA immediately quantifies the CO2 savings compared to a 100% virgin plastic run.

Interaction Patterns:

- **Automated:**
 - Retrieval of operational data (energy, materials, waste) from the Data Platform.
 - Calculation of environmental impact (LCA) and economic cost (LCC) indicators.
 - Comparison of real-time performance against pre-defined "green" benchmarks.
- **Human-Expert Mediated:**
 - Researchers and domain experts collect and structure the initial LCI data and define assessment scenarios.
 - Experts define the scope, system boundaries, and functional assessment units.
 - Humans interpret the complex output reports to make strategic decisions about material sourcing or process improvements.

Expected Benefits:

- **Transparency and Trust:** Provides customers with verifiable, data-driven proof of sustainability claims.
- **Operational Optimization:** Identifies specific stages in the manufacturing process (e.g., a specific machine or shift) that are causing unexpected environmental impacts.
- **Regulatory Readiness:** Simplifies compliance with emerging EU regulations requiring detailed product carbon footprints and digital passports.

Relevance for CMRA adopters: adopters can propose solutions that use GRETA to validate the "circularity" of their innovations in real-time. This is particularly relevant for those developing new recycling technologies, bio-based materials, or energy-efficient manufacturing processes where demonstrating a lower environmental impact is a core value proposition.

6 Conclusion and Future Outlook

The Circular Manufacturing Reference Architecture (CMRA) provides a robust and flexible framework, balancing automated system capabilities with the indispensable role of human experts and researchers. Reflecting on the progress since the initial D2.2 specification in M9, this final M18 deliverable highlights a critical transition: the CMRA has successfully moved from abstract theoretical models to a validated technical blueprint that pragmatically accommodates the low-digitization realities of manufacturing SMEs. By defining a common architectural vision, core components, and integration guidelines, the CMRA empowers businesses to develop and implement innovative circular solutions. The successful application of CMRA lies in the intelligent interplay between automated processes that handle scale and complexity, and human expertise that provides strategic direction, creative problem-solving, and contextual understanding. As the CIRCULOOS project evolves, further emphasis will be placed on refining the interfaces between automated systems and human decision-makers to create an even more effective and user-centric circular manufacturing ecosystem.

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