

Framework for Model-Based Systems Engineering Circularity Assessment

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Abstract:

High-value circular strategies such as reuse depend on architecture decisions made before embodiment is fixed. However, reuse-relevant information is dispersed across Systems Modeling Language (SysML)/Product Lifecycle Management (PLM) artefacts, rule logic, standards and regulations, and external datasets (e.g., Lifecycle Assessment factors). This paper presents a Model-Based Systems Engineering (MBSE) framework and Artificial Intelligence (AI)-supported evidence workflow that enables traceable, reproducible assessment of reuse-oriented circularity for system structure variants at an architecture decision gate. The approach separates inputs by provenance product-specific SysML v2 variant models linked to PLM configurations, a versioned circularity rule library, and curated collections and quantitative datasets and connects them through explicit, reviewable mappings. Deterministic Key Performance Indicator (KPI) pipelines compute engineer-assessable indicators (reuse-yield proxies, non-destructive disassembly, interface standardization/interchangeability) directly from the model backbone. A Retrieval Augmented Generation (RAG) component supports evidence acquisition and semantic alignment for externally dependent KPIs (e.g., avoided embodied carbon through reuse) and for justification from standards, while maintaining human accountability. The framework is instantiated on two alternative 3D printer printhead architectures. Results highlight the integration–circularity trade-off.

Keywords:

Model-Based Systems Engineering, Product Development, Circular Economy, Artificial Intelligence

1 Introduction

The circular economy (CE) seeks to preserve material and functional value by slowing, closing, and narrowing resource flows across the product lifecycle, operationalized for example by the 9R circular strategies [1,2]. These are largely determined during development, circularity must be embedded in early architecture decisions rather than added after key choices are fixed [3,4]. Within the circular strategies, function-retaining approaches (reuse, repair, refurbish, remanufacture, reconfiguration) typically deliver higher ecological and economic benefits than recycling-centered strategies [2,5,6]. For information and communication technology, reuse and refurbishment can substantially reduce greenhouse gas emissions compared to new production or recycling [7]. Reuse-enabling design factors include modular disassembly, standardized interfaces, accessible and reversible connections, and separating wear-prone from durable components [8]. This paper addresses a practical decision point in product development: once several product structure variants exist, engineers must classify and compare them regarding end-of-life (EoL) reuse. Classic criteria such as time, cost, and quality remain necessary but are insufficient to judge reuse feasibility. We assume a defined product-structure baseline and partially specified alternatives for selected subsystems, modules, or parts, described in SysML v2 models and linked

Product Lifecycle Management (PLM) configurations. Where suitable Key Performance Indicators (KPI) definitions and rule logic exist, variants can already be compared deterministically using model-internal KPIs. Robust reuse-oriented decisions, however, require external evidence such as Lifecycle Assessment (LCA) parameters (e.g., embodied-carbon factors), disassembly knowledge, and constraints from standards and regulations. Manual retrieval and alignment of heterogeneous sources is time-consuming, error-prone, and often undermines traceability from results back to specific model elements and assumptions. Accordingly, the role of Artificial Intelligence (AI) in this work is deliberately bounded within a human-in-the-loop paradigm: AI augments evidence acquisition and semantic alignment where external sources are unstructured or inconsistent, while engineers remain accountable for interpretation and final decisions. Retrieval-augmented workflows can retrieve relevant passages from standards and curated corpora, propose mappings to external taxonomies (e.g., aligning materials and processes to LCA datasets), and store evidence with auditable provenance. Crucially, KPI computation itself remains deterministic and reproducible logic operating on the Systems Modeling Language (SysML)/PLM backbone and explicitly linked evidence. Building on this separation, we distinguish two KPI classes: (1) engineer-assessable KPIs computed directly from SysML/PLM artefacts and rule libraries, and (2) evidence-augmented KPIs that depend on external quantitative or normative evidence and therefore benefit from AI-supported retrieval and alignment. Based on this separation, we propose a model-based framework and platform concept that evaluates reuse-oriented circularity of product structure variants using inputs separated by origin: SysML v2 variant models linked to PLM, a reusable circularity rule library, and external datasets plus curated standards/regulatory corpora. The work addresses two research questions:

- How can SysML v2 and PLM-linked product structure variant models be used as a structured backbone to compute reuse-oriented circularity KPIs deterministically and traceably at an early architecture decision gate?
- How can a retrieval-augmented evidence workflow integrate standards/regulations and external datasets into the KPI pipeline via reviewable mappings and provenance so that evidence-dependent KPIs become available?

Following Design Research Methodology (DRM) [9], Section 2 reviews related work on circularity assessment, Model-Based Systems Engineering (MBSE), and AI-supported evidence retrieval (descriptive study I). Section 3 presents the proposed provenance-separated framework and hybrid KPI workflow (prescriptive study). Section 4 instantiates and evaluates the approach on a 3D printer print-head variant case study (descriptive study II). Section 5 concludes and outlines limitations and directions for future research.

2 Background and Related Work

Research on circularity assessment provides a broad spectrum of indicators and methods that aim to quantify progress toward CE objectives at product and system level [10]. Many approaches operationalize circularity through aggregated indicators that focus on material loops, recycled content, and EoL recovery rates [11]. These metrics are attractive for reporting and benchmarking, but they often abstract from product structure, joining choices, and the practical feasibility of recovering functional units. For reuse-oriented decisions, the literature therefore increasingly complements material flow indicators with design-oriented assessment approaches, including design for disassembly, design for repair, modularity evaluation, and repairability or reusability scoring [12]. Such methods translate circular intent into engineering relevant proxies, for example accessibility, reversibility of connections, interface standardization, interchangeability, and separation of wear prone and durable elements.

MBSE has been established as an approach to manage complexity by representing requirements, functions, and architectures in structured models that support consistency and traceability [13]. This

makes MBSE a candidate for embedding lifecycle considerations early, because design decisions can be related to requirements and to architectural elements before detailed embodiment is fixed [14]. Prior work has explored how sustainability information can be linked to system models, including approaches that connect SysML artefacts to LCA tools or to sustainability attributes for design tradeoffs [15–17]. In practice, however, LCA depends on data that is distributed across repositories. PLM systems provide configuration context, product structure, identifiers, revision status, and domain files, while system models capture intent and architectural relations. Variant evaluation therefore requires stable linking between model elements and PLM configuration semantics, otherwise KPI results cannot be traced to a specific assessed alternative. SysML v2 is relevant in this context because it strengthens machine readable modeling and traceability, which supports systematic querying and reproducible evaluation on a shared backbone [18]. A remaining gap is the lack of methods that explicitly operationalize variant assessment oriented toward reuse at a defined gate while maintaining traceability from KPIs to SysML and PLM artifacts and from there to the lifecycle evidence required for implementation [15,19].

Recent work on AI in engineering has demonstrated value in information intensive tasks such as requirements analysis, document classification, and retrieval of relevant content from large corpora [20]. These capabilities are particularly relevant for circularity assessment because reuse feasibility often depends on external evidence, including standards and regulatory texts, disassembly and service knowledge, and environmental datasets such as LCA factors [21]. Large language models can improve accessibility of such sources, but they also introduce risks related to unsupported statements and insufficient provenance [22]. Retrieval Augmented Generation (RAG) addresses this by constraining generation to retrieved evidence items and by enabling source grounded explanations [23]. In engineering settings, this supports an accountable workflow in which external knowledge is not used as implicit background, but is captured as explicit evidence objects linked to the assessed artefacts. A central open issue is integration. Many AI-based approaches remain document centric and detached from deterministic KPI computation, while many model based KPI approaches do not scale evidence acquisition and semantic alignment.

The approach of Lindemann et al. [15] develops a SysML-based LCA modeling framework (including an LCA-specific SysML profile as a Motego extension) and a tool interface to openLCA in order to automatically generate a product-specific LCI model in the LCA tool from the SysML system model, execute it, and write the results back to the system model. It is not yet sufficient because SysML demonstrably needs to be extended to life-cycle-wide modeling, SysML v1 is used due to the lack of finalization and tool support for SysML v2, and further research is needed for robust scalability and database/tool integration, which clearly justifies follow-up research for consistent SysML v2-based and circularity-oriented decision support. The approach of Inkermann [16] identifies the fundamental potential of MBSE-LCA integration by systematically analyzing uncertainties in the first two LCA phases and challenges in handling variants and different use cases, and deriving an initial concept for methodological and data-related integration from this. However, it is not sufficient because it is explicitly formulated as an initial concept with a focus on the early LCA phases and itself derives further fields of research, so that follow-up research remains necessary in order to develop an implemented, validated solution suitable for practical variant and strategy decisions (including circular strategies). The approach in Ghanjaoui et al. [24] presents an MBSE methodology that models production system architectures and uses sustainability data from executed processes and resources for model-based validation of requirements and optimization of sustainable concept designs. However, it is explicitly limited to target definition and inventory analysis in accordance with LCA and calls for the addition of impact assessment and interpretation as well as trade-off analyses/optimizations, which is why further research is necessary to enable a consistent, comparative assessment (especially for early variant decisions and circularity references). The approach of Paetzold-Byhain [25] proposes a concept for

assessing ecological sustainability and circularity in development that anchors LCA at the micro level and material flow analysis plus CE indicators at the macro level in information models of a sustainability-oriented PLM strategy (including derivation of requirements and implementation of an information model in SysML). At the same time, the authors identify uncertain or incomplete information as a key challenge and consider the approach to still be in the development stage, with the question of industrial scaling remaining open. This means that further research is needed to develop a robust, data- and tool-supported variant assessment that is reliable in practice.

However, these contributions do not yet operationalize reuse-focused, gate-level variant assessment on a SysML v2/PLM backbone with explicit evidence objects and reviewable mappings that preserve traceability from external sources to model elements and KPI results. These aspects are addressed and solved in Section 3.

3 Model-Based Framework for Circularity Assessment

Circular and AI-supported assessment is an essential component of this model-based approach. Figure 1 summarizes the four input classes (SysML/PLM artefacts, circularity rule/KPI library, external datasets, and standards/regulations) and the two evaluation spaces: deterministic KPI computation on the SysML/PLM backbone and a bounded RAG workflow for retrieving and aligning external evidence with traceable provenance.

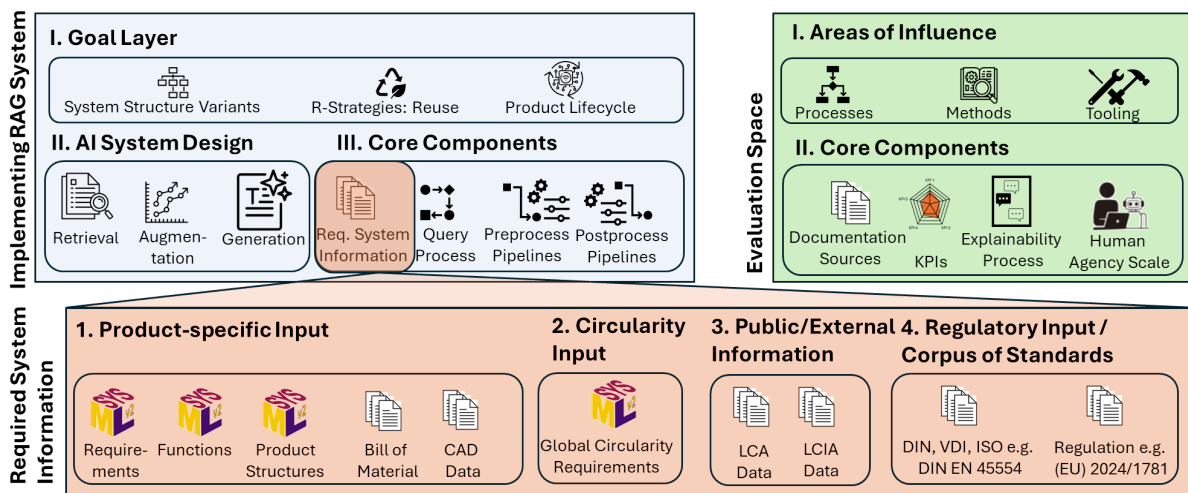


Figure 1: Framework components at the assessment gate with provenance-separated inputs and bounded AI-supported evidence retrieval

The assessment is applied at an early architecture decision gate where alternative variants exist for selected subsystems, modules, or parts, while the product structure is still adjustable. Variants may differ in module partitioning, interface concepts, joining principles, material/process selections, or service accessibility. Because reuse-relevant properties are largely determined by structure choices (modularity, separability, interface design) and are difficult to correct later, reuse criteria must be evaluated at the same gate where structure trade-offs are negotiated. Classic criteria such as time, cost, quality, risk, and performance remain necessary but are insufficient to judge reuse feasibility at EoL. In this work, reuse at EoL denotes recovery and second-life use of a product, subsystem, or module as a functional unit. It is treated as a scenario that must be classified and justified per variant. Reuse feasibility depends on non-destructive separation and accessibility, inspectability/qualification for a second life, and interface compatibility for reintegration, including relevant constraints from standards, safety, and traceability requirements.

3.1 Information landscape and SysML v2 as structured backbone

The gate is characterized by a distributed information situation. Relevant information exists, but it is split across engineering models, PLM data, and external sources. The scenario assumes that SysML v2 artefacts are available for requirements, functional structures, and physical product structure descriptions, and that the variant set is represented in a consistent way and that SysML v2 artefacts are available along the product creation process for requirements, functions, and logical/physical product structure representations, as illustrated in Figure 2. In parallel, PLM systems contain configuration and variant identifiers, product structure information such as bills of materials, version and change status, and additional domain files such as CAD or material master data. Even if SysML models are managed in the same organizational environment, configuration semantics and identifiers are often represented differently in PLM than in system models. This split becomes critical when the assessment must connect a concrete variant in the product structure model to a concrete configuration in PLM, and then to the evidence required for reuse evaluation. For reuse focused assessment, the development team also needs information that is typically not contained in SysML or PLM alone. Quantitative environmental parameters such as embodied carbon factors are often taken from LCA datasets. Knowledge about disassembly sequences, typical failure modes, and repair practices may exist in service documentation, curated internal repositories, or industry databases. Normative constraints come from standards and regulatory documents. Examples include, climatq.io, IDIS, Probas and standards such as DIN EN 45554, DIN 8580, and VDI 2243.

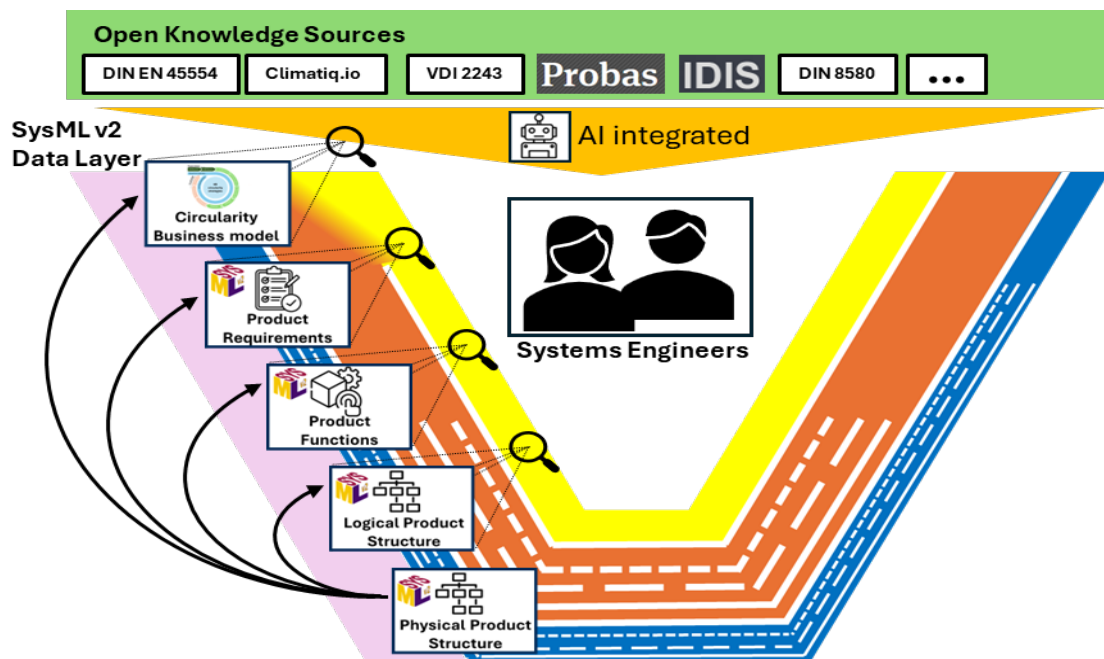


Figure 2: SysML data layer along product creation process, external knowledge sources and VDI 2206 based on [26]

Figure 2 positions the approach in the product creation process based on VDI 2206. SysML v2 provides a continuous, machine-readable data layer across circularity/business context, requirements, functions, and logical/physical product structures, while the assessment gate is located on the left branch where architectural and product structure decisions are still flexible. The AI-supported evidence layer connects this SysML/PLM backbone to open knowledge sources (e.g., standards, disassembly databases, LCA datasets) and returns traceable evidence packages, KPI results, and rationales to systems engineers. These outputs can be written back as properties and linked evidence objects to support downstream design, verification, and documentation activities within the V-model. The critical boundary condition is therefore not the absence of information, but the heterogeneity of formats, terminologies, and levels

of detail. Manual collection and alignment of these sources is slow and error prone, and it often breaks traceability because the link from a KPI result back to the exact model element, dataset entry, or normative passage is not preserved in a systematic way. This is particularly problematic at the considered gate, the decision outcome must remain explainable and auditable even as variants evolve. SysML v2 is used as the backbone. The assessment requires structured and connected engineering information. At the gate, reuse oriented KPIs and decision arguments should be computable or at least explainable from a consistent representation of requirements, functions, and product structure. SysML v2 supports this by enabling model elements to be explicitly related and queried, and by strengthening machine readability and traceability in a standardized form. These properties are essential for two reasons. First, they allow deterministic evaluation of variant properties that can be derived directly from the model, for example indicators related to the structure of the product, the definition of interfaces, or the presence of service relevant access concepts. Second, they provide stable reference points for linking external evidence to concrete engineering artefacts. Without a structured backbone, external evidence remains a collection of documents and numbers that is difficult to connect to product structure alternatives in a reproducible way.

3.2 Hybrid assessment workflow

At this gate, engineers must select or prioritize product structure variants while treating end-of-life reuse as a development parameter. This requires KPIs and decision rationales that link SysML/PLM model properties with external evidence. The approach therefore uses two interacting evaluation layers, connected via explicit links to the SysML v2 and PLM backbone. A deterministic, model-centered layer computes auditable KPIs from SysML and PLM artefacts through explicit, versioned rule logic (e.g., disassembly-effort proxies from connection/accessibility attributes, interface standardization and interchangeability indicators, and structure-based reuse-yield proxies). This layer enables fast, reproducible screening across variants and highlights design levers that can still be influenced at the gate.

A second, evidence-dependent layer addresses KPIs and constraints that require external quantitative or normative inputs (e.g., LCA factors, standards, and regulations). Here, AI is used deliberately in a bounded role to support evidence acquisition and semantic alignment for unstructured, heterogeneous sources, without generating variants or replacing engineering judgement, so that evidence-dependent indicators can be handled at scale without losing auditability. RAG operationalizes this evidence layer by deriving a structured query context from the model (materials, joining types, interfaces, requirements, access assumptions, target reuse scenario), retrieving relevant passages from indexed standards, disassembly/service knowledge, and LCA datasets, and producing a structured evidence package. The package includes concise evidence summaries, explicit source identifiers, and proposed semantic mappings (e.g., canonicalizing material/process names to LCA taxonomies with confidence and alternatives) as well as candidate constraints translated into reviewable rule statements for the rule library. Outputs are stored as evidence objects with provenance and explicit links to SysML elements, PLM configuration IDs, and KPI computations, enabling systematic re-runs when assumptions or variants change. Circular KPIs thus complement cost, time, and performance by making reuse feasibility, constraints, and expected benefit comparable across variants. They are split into engineer-assessable KPIs computed from model content and evidence-augmented KPIs whose outputs include the referenced evidence. For this to work, variants must be modeled consistently, module boundaries/interfaces/connection principles must be explicit, SysML–PLM links must remain stable, and gate outputs should include feasibility classes with documented blockers, maintaining end-to-end traceability across SysML, PLM, and external sources.

4 Use Case: 3D Printer Print Head

This section instantiates the proposed framework on a fused deposition modeling print head to demonstrate how reuse-oriented circularity can be treated as a decision parameter once product structures and development alternatives are available. The print head is suitable because it combines mechanical, thermal, and electrical functions in a compact volume, which typically creates an architectural tension between integration for performance and manufacturability and separability for reuse. The goal of the instantiation is not to model a complete end of use process in detail. Instead, it shows how variant comparison can be executed with a deterministic baseline and how additional external evidence can be incorporated in a controlled and traceable way when needed. The instantiation reflects a defined development gate. The product structure is considered established, and relevant variants exist for selected subsystems and parts. These alternatives are anchored in two backbone systems. A SysML v2 model provides a machine-readable product structure representation that includes the part decomposition, interfaces, and joining relations, as well as stable identifiers for traceability. The PLM system provides the authoritative Bill of Materials (BOM) and the configuration context that defines which parts belong to which alternative and which revision state is assessed. Each assessment run is therefore bound to a specific SysML model revision and a specific PLM configuration identifier to ensure reproducibility and audit readiness.

Two product structure variants are assessed. Variant A represents a strongly integrated print head architecture with compact housing and a tightly integrated thermal core. Functions that support extrusion and sensing are combined into dense assemblies, and key subassemblies are fixed using joining choices that are efficient for manufacturing and integration but tend to limit nondestructive separation. Electrical routing and sensor integration are closely coupled to the thermal core, and the interface concept is more variant specific, which reduces interchangeability across configurations or future generations. Variant B represents a more modular architecture that separates wear prone components from durable components and introduces clearer module boundaries that can act as exchange units. The nozzle and thermal core follow a cartridge-oriented concept with explicit mechanical interfaces, electrical interfaces are more standardized, and joining choices are selected to support separability where reuse is intended. For both variants, a mapping between SysML element identifiers and PLM part identifiers is established for the assessment run. Where a one-to-one mapping is not available at part level, the mapping is maintained at module level and refined as the engineering data matures. This mapping is treated as an explicit artefact that is versioned with the assessed configuration state. The assessment also records a completeness profile, because attribute availability is typically heterogeneous at this gate. The completeness profile indicates which parts have masses and material assignments, which joins are classified, and which interfaces are typed. This prevents false precision and turns missingness into an actionable engineering item rather than an implicit assumption.

Figure 3 depicts the assessment canvas used for the instantiation. For each product structure variant, an input package is assembled from among other things (i) the SysML v2 product-structure code (as the machine-readable backbone), (ii) the corresponding PLM configuration and BOM identifiers (as the authoritative variant context), (iii) CAD references for visual inspection and plausibility checks, and (iv) optional external evidence items such as linked LCA dataset entries. The output package consists of a KPI dashboard and a versioned explainability documentation bundle. The explainability bundle records intermediate features, rule firings, evidence identifiers, and mapping decisions so that each KPI value can be traced back to a specific SysML/PLM state and to the referenced evidence.

The instantiation is executed in two stages that correspond to the two lanes of the framework. In the baseline stage, engineers can compare variants without any AI component. The system extracts the variant specific product structure subgraph from SysML v2 and aligns it with the corresponding PLM

emission factors, while scenario assumptions are documented explicitly. In parallel, the same retrieval mechanism can index standards and regulations to capture clause-level evidence for reuse-relevant constraints. Retrieved clauses are stored with edition metadata and linked to affected joints, interfaces, or modules so that explanations remain auditable.

Overall, the use case shows that a deterministic baseline enables reproducible screening across variants and highlights reuse-relevant levers without any AI component. Evidence augmentation extends the workflow to externally dependent KPIs (e.g., avoided embodied carbon) while maintaining auditability by storing evidence links, dataset versions, and clause identifiers as explicit, reviewable artefacts bound to the assessed SysML/PLM state. Limitations mainly reflect early-phase data gaps and scenario sensitivity, which motivates completeness reporting and governance of evidence corpora and mappings.

5 Conclusion and Future Work

This paper presented a SysML v2–anchored MBSE framework and hybrid KPI workflow for reuse-oriented circularity assessment of system product structure variants at an architecture decision gate. The core contribution is a provenance-separated integration of (i) SysML v2/PLM variant representations, (ii) a versioned circularity rule and KPI library, and (iii) external quantitative and normative evidence sources (LCA datasets and standards/regulations), connected through explicit, reviewable mapping artefacts. Deterministic KPI pipelines compute engineer-assessable indicators on the SysML/PLM backbone, while a bounded retrieval-augmented evidence workflow supports retrieval and semantic alignment of external evidence and stores it as explicit evidence objects linked to the assessed configuration. The print-head instantiation demonstrated traceable KPI dashboards and explainability documentation and made the integration–circularity trade-off explicit. The more modular, reversibly connected variant improved the reuse rate, non-destructive disassembly, and interchangeability/standardization of interfaces, and achieved greater potential for avoiding CO₂ emissions through reuse, while the integrated variant created barriers to accessibility and separation.

Limitations are dominated by typical early-phase conditions, including incomplete masses and material specifications, sensitivity to scenario assumptions for reuse burdens, and the need for evidence and mapping rules. Future work should therefore (1) validate the approach on additional product classes and larger variant spaces, including controlled benchmarking of retrieval quality and agreement with expert assessments, (2) calibrate KPI definitions and intermediate features through sensitivity and uncertainty analyses to avoid false precision under data gaps, and (3) strengthen evidence and mappings, e.g. dataset versioning and change impact analysis. For the AI component, systematic reliability measures are required, including evidence-coverage metrics, contradiction and out-of-scope detection, and regression tests across corpus, embedding, and model updates. From an adoption perspective, deeper integration into MBSE toolchains and V-model processes is needed, particularly to write results back into SysML as properties, rationales, and compliance-relevant evidence links and to align outputs with evolving ecodesign and Digital Product Passport expectations.

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