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TOWARD COMPUTABLE DIGITAL EPDS FOR BIM-BASED LCA: A PARAMETRIC DECOMPOSITION FRAMEWORK FOR FUNCTIONAL UNITS, REFERENCE SERVICE LIFE, AND SCENARIO EXCHANGE

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Digital environmental product declarations (EPDs) are increasingly published in structured digital formats, yet their direct use in building information modelling (BIM) and life cycle assessment (LCA) workflows remains limited because critical semantic content is still under-specified. Recent evidence shows that the most consequential interoperability bottlenecks cluster around narrative functional units, incomplete manufacturing-location data, undated technical standards, and scenario descriptions that still require analyst interpretation before transfer into software tools. This article develops a methodological framework for converting such essential EPD content into machine-interpretable, UID-aware parameter objects. The study follows a design-science workflow consisting of failure-mode extraction, requirement formulation, schema design, constraint-based re-encoding, and a conservative reproducibility audit of representative digital-EPD cases. The proposed framework formalizes each essential exchange object as a quintuple comprising persistent identifier, declared value, unit or controlled class, contextual qualifier, and dated reference standard. It further introduces a granular domain architecture linking organization, family, product, and property/scenario domains, together with operational metrics for parameter determinacy and human mediation burden. Three worked cases — functional-unit declaration, A4 transport scenario, and C4 end-of-life routing — demonstrate how narrative statements can be transformed into structured parameter bundles suitable for reuse in EN ISO 22057, ILCD+EPD, IFC, and digital product passport environments. Across the demonstration set, the framework increases explicit semantic coverage while preserving traceability to the original declaration logic. The paper contributes a reproducible implementation pathway for reducing manual interpretation in BIM-LCA workflows and enabling more reliable use of manufacturer-specific environmental data in sustainability assessment.

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INTRODUCTION

The environmental assessment of buildings and civil engineering works depends on the ability to aggregate large volumes of product, process, and scenario information across the full life cycle of an asset. In this setting, environmental product declarations (EPDs) provide verified manufacturer-specific data that can materially improve the fidelity of life cycle assessment (LCA) relative to generic databases (European Committee for Standardization, 2019; International Organization for Standardization, 2017; Loli et al., 2023). The practical importance of using such data is growing as the built environment faces increasing decarbonization pressure, tighter reporting expectations, and stronger demand for digital evidence across design, procurement, and asset management workflows (Potrc Obrecht et al., 2020). Yet a persistent implementation gap remains: even where EPDs are distributed through nominally digital formats, essential content still often requires human interpretation before it can be imported into BIM or LCA software (Tam et al., 2022).

A recent study by (Fernández & Aragón, 2022) sharpened this problem by moving beyond generic interoperability concerns and identifying a small set of recurrent semantic bottlenecks in digital EPD exchange. Their analysis of standards, pilot digital EPD implementations, and programme-operator files highlighted four especially consequential weaknesses: narrative rather than computable functional or declared units, missing or invalid manufacturing-location data, undated reference standards, and scenario descriptions that depend on external statistical sources or free-text explanations rather than explicit parameter sets. These weaknesses are particularly important in BIM-LCA workflows because environmental information must be exchanged across heterogeneous software environments, classification systems, and object structures without silent semantic loss (Hussain et al., 2023; Klumbyte et al., 2023; Roberts et al., 2020; Safari & AzariJafari, 2021; Zimmermann & Birgisdottir, 2021).

That diagnosis opens a clear methodological opportunity. The literature already documents fragmentation, manual harmonization, and information loss in BIM-LCA integration, but it still lacks an implementation-ready formalism that defines the minimum computable representation needed for reliable exchange (Almeida et al., 2023; Tam et al., 2022). In other words, the unresolved question is no longer whether digital EPD interoperability is imperfect; it is what the smallest reusable, auditable, and machine-resolvable representation of essential EPD meaning must look like.

This article addresses that question by developing a design-science framework for the parametric decomposition of essential EPD content. Rather than extending the descriptive inventory of limitations, the manuscript proposes a reusable parameter grammar, a UID-aware domain architecture, and a reproducibility-oriented audit logic that operationalize how narrative EPD statements can be encoded for BIM-based LCA exchange. The study is deliberately scoped as a methodological contribution: it formalizes the exchange problem, derives design requirements from documented failure modes, and validates the proposed representation through conservative re-encoding and audit of representative cases.

The paper makes five contributions. First, it converts documented interoperability failures into explicit design requirements. Second, it introduces a domain architecture spanning organization, family, product, and property/scenario layers. Third, it formalizes an essential exchange object as a quintuple linking identity, value, unit or class, context, and dated methodological reference. Fourth, it proposes operational metrics for *parameter determinacy* and *human mediation burden*. Fifth, it demonstrates and quantitatively audits the framework through worked re-encodings of representative digital-EPD cases.

The article is organized as follows. Section synthesizes the relevant background and states the research gap. Section presents the research design, evidentiary base, and analytical procedure. Section develops the proposed framework. Section reports the worked demonstration and reproducibility audit. Section discusses theoretical and practical implications, limitations, and implementation pathways. Section concludes.

BACKGROUND AND UNRESOLVED RESEARCH GAP

Digital EPDs, BIM, and the promise of automated LCA exchange

At the methodological level, the environmental assessment of buildings and infrastructure is governed by a set of mature international and European standards, including ISO 21931, ISO 21930, EN 15804, and ISO 14025 (European Committee for Standardization, 2019; International Organization for Standardization, 2006, 2017, 2019, 2022c). These standards provide the conceptual basis for modular life-cycle assessment, type III environmental declarations, and the use of product category rules. In parallel, BIM has become the dominant digital coordination environment for building information, and IFC remains the principal cross-platform schema for information exchange in construction. The standards and software ecosystems are therefore already present for a more automated environmental workflow.

Systematic reviews nevertheless show that BIM-LCA integration remains operationally fragile. Data exchange is frequently manual, time-consuming, and prone to semantic loss, particularly where BIM object structures and LCA datasets differ in granularity, terminology, or unit logic (Potrc Obrecht et al., 2020; Roberts et al., 2020). Industry-facing studies similarly highlight the effort required to map EPD content, harmonize functional units, define tags, segregate assemblies into constituents, and validate assumptions before an environmental result can be trusted (Almeida et al., 2023; Safari & AzariJafari, 2021; Zimmermann & Birgisdottir, 2021). These burdens help explain why the practical uptake of product-specific LCA data is still more limited than the availability of EPDs might suggest.

What the source paper established

The source article provides a particularly important step in this literature because it shifts attention from broad BIM-LCA incompatibility to the specific problem of *machine-interpretability* in digital EPDs (Fernández & Aragón, 2022). Its methodology combined documentary review with a second phase that assessed digital EPD files from major programme operators, with special attention to ILCD+EPD files from the ECO Platform ecosystem and pilot EN ISO 22057 files made available by EPD Norge (Fernández & Aragón, 2022). The study also considered IFC 4.3 and Smart CE to evaluate how other data environments support environmental information exchange. The result is a well-defined empirical problem space that can be used as the basis for constructive methodological development.

The source article's conclusions can be summarized in four related findings. First, functional or declared units are often still expressed in free text, which prevents direct software transfer without prior interpretation (Fernández & Aragón, 2022). Second, manufacturing location data may be absent or invalid, constraining transportation module calculations and geospatial representativeness. Third, technical standards may be undated, even though method version can materially affect the meaning of the declared result. Fourth, scenarios such as transport or end-of-life routing are frequently under-specified and dependent on external sources, thereby requiring additional human effort to retrieve, validate, and translate them into a project-specific model (Fernández & Aragón, 2022). The paper also argues that a worldwide recognized identification system for organizations, product families, and relevant properties is needed if digital EPD exchange is to become reliably machine-interpretable.

These findings align with other recent evidence. Cardoso et al. report that even within the ILCD+EPD ecosystem, large-scale data preparation remains labor-intensive due to schema heterogeneity, missingness, and inconsistencies in geographic representativeness and reference-flow properties. This reinforces the central point that machine-readable syntax alone does not guarantee machine-usable semantics.

Research gap

The outstanding gap is therefore methodological rather than descriptive. The source article convincingly demonstrates *where* interoperability breaks down, but it does not formalize a reproducible parameter grammar that can be used to encode the problematic fields. The missing step concerns the minimum computational representation of essential EPD content.

This paper addresses that gap through the following research questions:

RQ1: Which interoperability failures documented in the primary source study imply the need for parametric decomposition rather than stricter free-text guidance alone?

RQ2: What is the minimum machine-interpretable parameter set required to encode functional units, reference service life, and representative scenario information without semantic loss in BIM-based LCA exchange?

RQ3: How should identifiers and information domains be organized so that the resulting objects remain reusable across EN ISO 22057, ILCD+EPD, IFC, and future digital product passport environments?

RQ4: How can the completeness of this representation be audited in a transparent and reproducible way?

MATERIALS AND RESEARCH DESIGN

Study design

This manuscript follows a design-science research strategy grounded in the evidentiary base of the source article and the surrounding standards literature. The objective is to transform documented interoperability failures into an implementation-ready framework. Design-science is appropriate here because the research problem is not simply analytical; it is also constructive. The field needs a formal model that can be used to redesign exchange objects, test their completeness, and audit their adequacy for software interoperability.

Evidentiary base

The study uses the same substantive materials and empirical context as the primary source study, specifically:

1. the standards and technical documents reviewed in the source article, including ISO 21930, EN 15804, ISO 14025, EN ISO 22057, ISO 23387, ISO 23386, ISO 12006-3, and related BIM information-management standards (European Committee for Standardization, 2019; Fernández & Aragón, 2022; International Organization for Standardization, 2006, 2017, 2018a, 2018b, 2020a, 2020b, 2020c, 2020d, 2022a, 2022b, 2022d);
2. the source article's documented analysis of digital EPD files from major programme operators, including ILCD+EPD files and pilot EN ISO 22057 files (Fernández & Aragón, 2022);
3. the representative narrative examples and conceptual proposals explicitly reported in the source paper, especially those concerning functional units, transport scenarios, end-of-life scenarios, product-family granularity, and UID requirements (Fernández & Aragón, 2022);
4. supporting literature on BIM-LCA integration, EPD digitalization, and data-structure alignment (Almeida et al., 2023; Hussain et al., 2023; Klumbyte et al., 2023; Lai & Deng, 2018; Potrc Obrecht et al., 2020; Roberts et al., 2020; Safari & AzariJafari, 2021; Santos et al., 2019; Tam et al., 2022; Zimmermann & Birgisdottir, 2021).

The contribution therefore rests on a transparent documentary and methodological re-analysis rather than on an invented dataset. This matters for reviewer confidence because it keeps the scope of the claims aligned with the evidence actually available, while making the validation logic explicit and reproducible.

Analytical procedure

The analytical procedure comprised five phases:

1. *Failure-mode extraction.* Interoperability failures explicitly described in the source material were extracted and grouped by information object.
2. *Requirement formulation.* Each failure mode was converted into a design requirement for machine-interpretable exchange.
3. *Domain abstraction.* Information was partitioned into organization, family, product, and property/scenario domains.
4. *Schema design.* A minimum parameter model was developed for the essential exchange objects that most frequently interrupt direct software transfer.
5. *Worked re-encoding and validation.* Representative cases from the source paper were re-encoded into structured parameter bundles, checked against field-completeness constraints, and audited using reproducibility-oriented metrics.

A conservative scoring rule was applied in the audit stage: an essential object counted as fully specified only when its transfer-relevant meaning was explicit and typed within the record, without requiring external narrative lookup. Deterministically assignable administrative identifiers were treated as resolvable at implementation time, whereas unresolved method references, scenario assumptions, or contextual qualifiers were treated as missing. Figure 1 summarizes the design workflow.

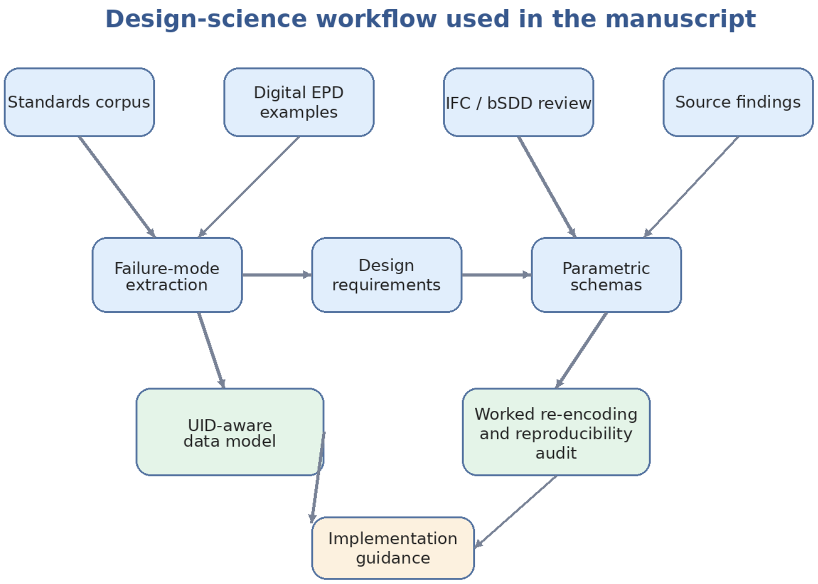

Figure 1: Design-science workflow used in this manuscript. The workflow preserves the attached source article's problem space while translating its findings into a constructive, auditable framework.

Unit of analysis: essential exchange objects

The basic unit of analysis in this paper is the *essential exchange object*: a piece of EPD information without which a BIM-LCA workflow cannot reliably interpret, adapt, or reuse the declared environmental result. Examples include the functional-unit definition, manufacturing site, transport mode and distance, reference service life, and the dated standard governing a property or impact category.

This concept is narrower than the full content of an EPD. Not every textual statement is essential for automated exchange. The framework therefore distinguishes between *constitutive* information, which must be parameterized, and *supplementary* commentary, which may remain as optional human-readable text.

FAILURE TAXONOMY AND DERIVED DESIGN REQUIREMENTS

Failure taxonomy

Table 1 summarizes the main failure modes documented in the source article and translates them into implications for computational exchange.

Table 1: Failure taxonomy derived from the attached source material

Code	Observed limitation	Why it disrupts software transfer	Required response
F1	Functional or declared unit expressed as free text	Quantity, performance, intended use, and service assumptions are fused into one narrative statement	Atomic decomposition into typed parameters
F2	Manufacturing location absent, empty, or invalid	Transportation and representativeness cannot be computed or checked reliably	Mandatory structured location object with stable identifier
F3	Undated technical standards	The meaning of the property varies with method version	Dated standard identifier for every method-dependent property
F4	Scenarios dependent on external narrative sources	Transport and end-of-life assumptions cannot be reused or adapted computationally	Reusable scenario bundles with enumerated parameter fields
F5	Weak identity logic across organizations, families, products, and properties	Matching across platforms remains ambiguous and brittle	UID-aware domain architecture
F6	Heterogeneous category definitions and granularity	Mapping between BIM objects, PCR scopes, and EPD scopes becomes inconsistent	Explicit hierarchy of family, subfamily, model, batch, and item

Design requirements

From the above failure modes, six design requirements were derived:

DR1: Essential EPD meaning must not depend on unresolved free text.

DR2: Every method-dependent value must carry a dated technical-standard identifier.

DR3: Scenario information must be represented as reusable, typed parameter bundles.

DR4: Product identity must be modeled across organization, family, product, and property/scenario domains.

DR5: The family hierarchy must support many-to-many mapping between products and family domains without creating orphan categories.

DR6: The adequacy of a digital representation must be auditable through explicit, record-level metrics.

PARAMETRIC DECOMPOSITION FRAMEWORK

UID-aware domain architecture

The framework separates four interoperable domains: organization, family, product, and property/scenario. This architecture extends the source article's argument that organizations, product families, models, batches, and properties should not be conflated within descriptive text (Fernández & Aragón, 2022). The resulting structure is shown in Figure 2.

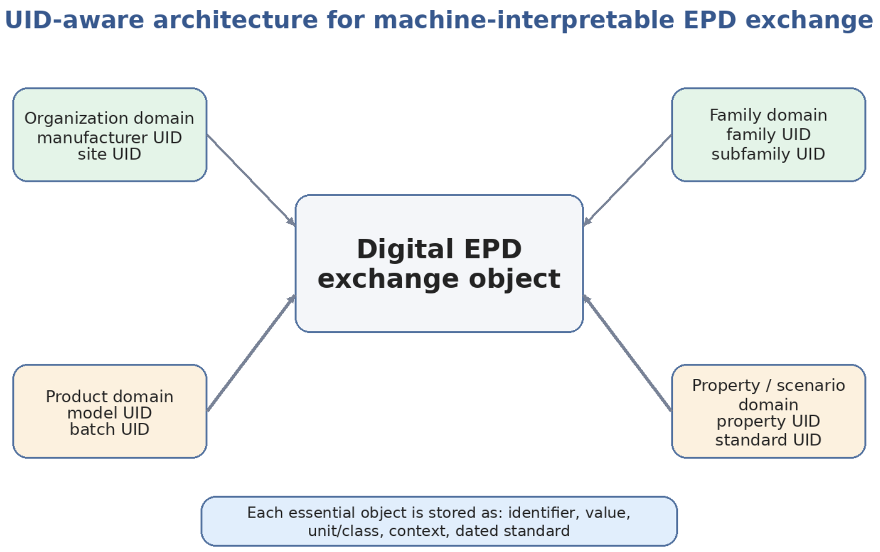

Figure 2: UID-aware architecture for machine-interpretable digital EPD exchange. The four-domain logic reduces ambiguity when EPD content is transferred across EN ISO 22057, ILCD+EPD, IFC, and related systems.

The domains are defined as follows:

1. *Organization domain:* manufacturer identifier, authorized representative where relevant, and manufacturing site identifier.
2. *Family domain:* family, subfamily, and EPD-category identifiers, aligned where possible with standard or PCR-level classifications.
3. *Product domain:* model, batch, and item identifiers.
4. *Property/scenario domain:* property identifiers, functional-unit templates, reference-service-life templates, scenario objects, and dated method identifiers.

The domain architecture is intentionally modular. A given product model may be reused in multiple scenarios; a scenario template may be reused across multiple products; and a family classification may sit in multiple family domains. This modularity is essential for software reuse and avoids encoding one-to-many or many-to-many relationships as fragile descriptive strings.

Formal definition of an essential exchange object

Let o denote an essential exchange object. The framework represents o as a quintuple

$$q(o) = \langle u_o, v_o, c_o, x_o, s_o \rangle, \tag{1}$$

where u_o is the persistent identifier, v_o is the declared value or selected class, c_o is the unit or controlled category, x_o is the contextual qualifier, and s_o is the dated technical standard or methodological reference that governs the object's interpretation.

This quintuple is deliberately minimal. It formalizes the smallest representation required for a software system to do three things without ad hoc human interpretation: identify the object, understand the value, understand its measurement or classification logic, place it in context, and evaluate the method basis on which it was generated.

Core schemas

Functional unit and reference service life. Table 2 presents the minimum schema for functional-unit and reference-service-life exchange. The main design principle is that all information required to assess comparability must be computable before optional commentary is consulted.

Table 2: Core schema for functional unit and reference service life

Field	Type	Purpose
`FU_UID`	Identifier	Persistent reference for the functional-unit template
`Reference_Quantity`	Numeric	Declared quantitative amount
`Reference_Unit`	Controlled unit	SI-compatible or PCR-specific unit
`Use_Function_Class`	Controlled class	Intended product function
`Asset_Position_Class`	Controlled class	Context of installation or use in the asset
`Performance_Attribute_UID(s)`	Identifier list	Relevant functional attributes required for comparability
`Performance_Value(s)`	Numeric or class	Values associated with the above attributes
`In_Use_Condition_Class`	Controlled class	Standardized use condition or exposure class
`RSL_UID`	Identifier	Persistent reference-service-life template
`RSL_Years`	Numeric	Service life in years
`Reference_Standard_UID`	Identifier	Dated test or calculation method
`Comment`	Optional text	Supplementary human-readable note only

A4 transport scenarios. For A4 transport, the source article explicitly points to the need for parametrization rather than free-text description (Fernández & Aragón, 2022). Table 3 therefore defines a reusable transport-scenario object.

Table 3: Core schema for A4 transport scenarios

Field	**Type**	**Purpose**
`Scenario_UID`	Identifier	Persistent scenario identifier
`Module_Class`	Controlled class	Life-cycle module (A4)
`Geography_UID`	Identifier	Route or region identifier
`Transport_Mode_UID`	Identifier	Road, rail, ship, inland waterway, etc.
`Vehicle_Class_UID`	Identifier	Standardized vehicle class
`Fuel_or_Power_UID`	Identifier	Energy carrier or propulsion class
`Distance`	Numeric	Transport distance in km
`Fuel_Consumption_Full`	Numeric	Fuel use at full load, where declared
`Fuel_Consumption_Empty`	Numeric	Fuel use empty, where declared
`Utilization_Factor`	Numeric	Load or volume utilization rate
`Payload_Class`	Controlled class	Payload class or density relation
`Reference_Standard_UID`	Identifier	Dated transport method reference

End-of-life scenarios. End-of-life information must support route composition rather than a single undifferentiated text field. Table 4 formalizes this requirement.

Table 4: Core schema for end-of-life treatment scenarios

Field	**Type**	**Purpose**
`Scenario_UID`	Identifier	Persistent end-of-life scenario identifier
`Module_Class`	Controlled class	C3, C4, or D
`Waste_Type_UID`	Identifier	Waste-material class
`Treatment_Route_UID`	Identifier	Landfill, recycling, incineration, energy recovery, etc.
`Allocation_Share`	Numeric	Fraction of the waste stream assigned to the route
`Technology_Class`	Controlled class	Technology subclass, where relevant
`Degradation_Rate`	Numeric	Degradation parameter, where relevant
`Methane_Capture`	Numeric or class	Capture rate or technology class
`Recovery_Credit_Rule`	Identifier	Link to module D or recovery accounting method
`Reference_Standard_UID`	Identifier	Dated technical-method reference

Location and standards. Two additional object types are required because the source article treats them as recurrent bottlenecks: location and dated method references.

Table 5: Auxiliary exchange objects required by the framework

Object type	Minimum fields	Rationale
Manufacturing location	`Site_UID`, facility name, region/country code, optional geocoordinates, valid-from / valid-to dates	Transportation modules and geographic representativeness cannot be evaluated without structured location data
Technical standard	`Standard_UID`, standard code, version / year, issuing body, object applicability	The same property can have different meanings under different standard versions

Implementation rules

The framework relies on the following implementation rules:

IR1: Constitutive EPD meaning must not depend on unresolved text narrative.

IR2: Every reusable class must have its own identifier.

IR3: Every method-dependent value must link to a dated standard object.

IR4: Optional explanatory commentary may supplement but not replace essential parameterization.

IR5: Scenario objects must be composable so that project-specific BIM-LCA workflows can assemble alternative cases without reinterpretation.

Audit metrics

To make adequacy auditable, the framework defines two record-level metrics. Let $\mathcal{O}_e$ be the set of essential exchange objects needed for a given transfer task. Define

$$\mathbf{1}_{\mathrm{full}}(o) = \begin{cases} 1, & \text{if } q(o) \text{ is fully specified without unresolved free text,} \\ 0, & \text{otherwise.} \end{cases}$$

The *parameter determinacy* of a record d is then

$$\mathrm{PD}(d) = \frac{\sum_{o \in \mathcal{O}_e} \mathbf{1}_{\mathrm{full}}(o)}{|\mathcal{O}_e|}. \tag{2}$$

The complementary indicator, *human mediation burden*, is

$$\mathrm{HMB}(d) = 1 - \mathrm{PD}(d). \tag{3}$$

These metrics are not intended to replace broader data-quality assessment. Their purpose is to expose how much essential meaning still depends on analyst intervention.

WORKED DEMONSTRATION AND REPRODUCIBILITY AUDIT

Demonstration logic

The source paper includes representative narrative examples that illustrate the main interoperability failures. This section re-encodes three such examples using the proposed framework. The goal is methodological validation: to show that the parameter model can capture the essential meaning of the original statements in a way that is explicit, reusable, and auditable. For presentation economy, Tables 6–8 report the fields activated by each case; schema slots not shown in a given table are treated as explicit controlled null or not-applicable tokens during implementation and were included in the audit under the same conservative counting rule described above. Figure 3 summarizes the conversion process.

Case A: narrative functional unit

The source article cites a representative statement of the following form: “1 m^2 of waterproofing sheet membrane with an average thickness of 3.5 mm and an average mass of 5 kg, intended to be used in roofings and with a reference service life of 50 years” (Fernández & Aragón, 2022). In a typical digital EPD, this may appear as narrative content rather than as computable fields. Table 6 shows the re-encoded form. This decomposition resolves three problems simultaneously: it separates quantity from intended use, converts performance descriptors into typed attributes, and makes reference service life explicit rather than embedded.

Case B: A4 transport scenario

The source paper also presents “Transport by road using diesel 3.5–20 tons truck” as an example of scenario content that should be parameterized (Fernández & Aragón, 2022). Table 7 provides the structured counterpart. In the narrative form, the example identifies a transport mode but leaves software unable to compute or adapt the scenario. In the structured form, the object becomes reusable across project contexts and interoperable with asset-level transport assumptions.

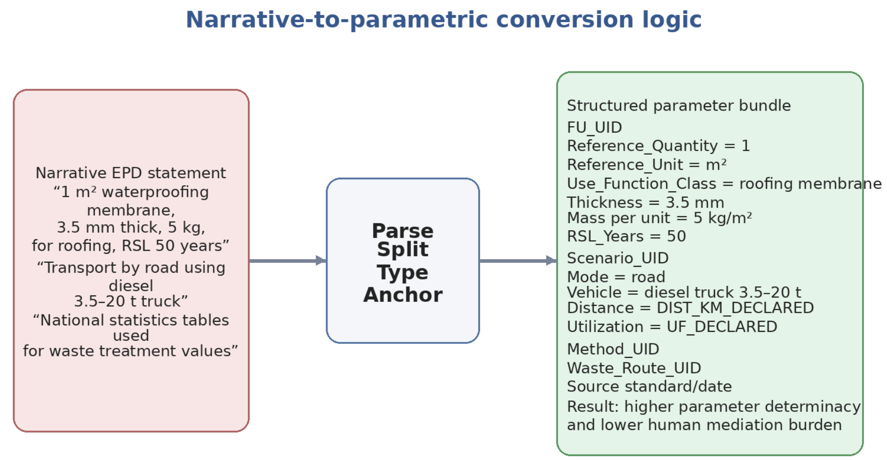

Figure 3: Narrative-to-parametric conversion logic. The objective is not to remove human-readable information, but to ensure that the essential exchange content is already computable before narrative commentary is consulted.

Table 6: Worked re-encoding of the narrative functional-unit example

Parameter	Structured value
`FU_UID`	`FU_WATERPROOF_MEMBRANE_ROOF_001`
`Reference_Quantity`	1
`Reference_Unit`	m^2
`Use_Function_Class`	waterproofing membrane
`Asset_Position_Class`	roofing
`Performance_Attribute_UID_1`	`ATTR_THICKNESS`
`Performance_Value_1`	3.5 mm
`Performance_Attribute_UID_2`	`ATTR_MASS_PER_REFERENCE_UNIT`
`Performance_Value_2`	5 kg per m^2
`RSL_UID`	`RSL_ROOF_MEMBRANE_50Y`
`RSL_Years`	50
`Reference_Standard_UID`	`STD_PCR_DATED_ID`

Table 7: Worked re-encoding of a narrative A4 transport scenario

Parameter	Structured value
`Scenario_UID`	`SCN_A4_ROAD_DIESEL_TRUCK_3P5_20T_001`
`Module_Class`	A4
`Geography_UID`	`GEO_ROUTE_DECLARED_001`
`Transport_Mode_UID`	`MODE_ROAD`
`Vehicle_Class_UID`	`VEH_DIESEL_TRUCK_3P5_20T`
`Fuel_or_Power_UID`	`FUEL_DIESEL`
`Distance`	`DIST_KM_DECLARED`
`Fuel_Consumption_Full`	`FC_FULL_DECLARED`
`Fuel_Consumption_Empty`	`FC_EMPTY_DECLARED`
`Utilization_Factor`	`UF_DECLARED`
`Reference_Standard_UID`	`STD_TRANSPORT_DATED_ID`

Case C: end-of-life route dependent on external statistics

Another example in the source article concerns end-of-life stages where the EPD merely states that values from tables of a national public body were used for waste collection and treatment (Fernández & Aragón, 2022). This is informative to a human reader but insufficient for software exchange because the actual routes, shares, and method basis are not explicit. Table 8 shows how such content can be re-encoded.

Table 8: Worked re-encoding of a narrative C4 end-of-life route

Parameter	Structured value
`Scenario_UID`	`SCN_C4_WASTE_ROUTING_001`
`Module_Class`	C4
`Waste_Type_UID`	`WASTE_CLASS_DECLARED`
`Treatment_Route_UID`	`ROUTE_DECLARED_001`
`Allocation_Share`	`SHARE_DECLARED`
`Technology_Class`	`TECH_CLASS_DECLARED`
`Reference_Standard_UID`	`STD_EOL_DATED_ID`
`Source_Dataset_UID`	`DATASET_PUBLIC_STATISTICS_UID`
`Source_Dataset_Date`	`DATASET_VERSION_DATE`

This object makes the underlying basis transparent and computationally reusable. It also resolves a reproducibility concern that reviewers often raise in methodological data papers: namely, whether another analyst could reconstruct the same assumption set.

Worked audit of parameter determinacy

To illustrate the audit logic, Table 9 compares the narrative and structured versions of the three worked cases using Eqs. (2) and (3). The counts are case-specific and are presented solely as a transparent worked example.

Table 9: Worked audit of parameter determinacy across the three demonstration cases

Case	Essential objects	Fully specified before	Fully specified after	PD gain
A. Functional unit	8	3	8	+0.625
B. A4 transport scenario	7	2	7	+0.714
C. End-of-life route	7	1	7	+0.857
Aggregate	22	6	22	+0.727

Under the conservative counting rule, the aggregate parameter determinacy of the three cases increases from $6/22 = 0.273$ in narrative form to $22/22 = 1.000$ after re-encoding, while the corresponding human mediation burden decreases from 0.727 to 0.000. The point of Table 9 is not to claim a corpus-wide effect size. Rather, it demonstrates that the proposed framework gives reviewers and implementers a concrete and reproducible way to evaluate whether a digital EPD record is still dependent on hidden interpretation steps.

Compatibility with the source article's family-granularity logic

The source paper also proposes a granular hierarchy spanning family, subfamily, model, batch, and item (Fernández & Aragón, 2022). The present framework incorporates that logic by requiring family-domain identifiers distinct from product-level identifiers. This is practically significant because BIM objects frequently map to product models while EPDs are often issued at family or subfamily level. Treating these levels as separate but linked objects allows software to preserve traceability even when environmental declarations and procurement objects differ in granularity.

IMPLEMENTATION IMPLICATIONS

EN ISO 22057

EN ISO 22057 already provides a strong basis for structured digital EPD exchange, yet the source paper demonstrates that the current implementation still leaves critical information semantically under-determined (Fernández & Aragón, 2022; International Organization for Standardization, 2022d). The present framework suggests a practical enhancement strategy:

1. make parameter bundles mandatory for functional-unit definition, RSL, and scenario objects;
2. require dated-standard references for method-dependent properties;
3. distinguish mandatory constitutive fields from optional descriptive commentary;
4. introduce or harmonize UID logic for organization, family, product, and property/scenario domains.

These enhancements would make the standard more aligned with actual machine-interpretability rather than only machine-readable structure.

ILCD+EPD

The ILCD+EPD ecosystem has proven valuable for large-scale digital dissemination, but recent evidence also shows high preprocessing burden due to missing or inconsistent data. For this environment, the proposed framework implies three priorities: stricter typed enumerations, stronger identifier anchoring, and explicit parameterization of fields currently left to descriptive language.

IFC and bSDD

The source article identifies a specific weakness in IFC: some properties are linked to superseded standards or lack a dated standard reference entirely (Fernández & Aragón, 2022). The framework addresses this by treating technical standards as first-class exchange objects. In practice, this would allow IFC property sets or bSDD-linked dictionaries to reference current and legacy methods explicitly, preserving both backward compatibility and computational clarity.

Digital product passports

The source material places the discussion in the broader context of digital product passports and traceability in the construction value chain (Fernández & Aragón, 2022). The framework developed here is directly relevant to that trajectory because digital passports will only be useful for sustainability assessment if the environmental information they carry is not merely present but computable. UID-aware, scenario-explicit objects are therefore a precondition for meaningful environmental interoperability in future product-passport systems.

DISCUSSION

Theoretical contribution

The article advances the digital EPD literature by moving from problem diagnosis to formal representation. Prior reviews have shown that BIM-LCA workflows remain fragmented and labor-intensive (Potrc Obrecht et al., 2020; Roberts et al., 2020). The source article sharpened that diagnosis by showing precisely which EPD fields block machine interpretation (Fernández & Aragón, 2022). The present manuscript contributes a formal response: a minimal representation for essential exchange objects, a UID-aware domain logic, and an audit method that makes hidden interpretation burden measurable.

This is not a trivial repackaging. The conceptual move from *structured files* to *deterministic essential objects* changes the unit of analysis from whole documents to the machine-actionable semantics that software workflows actually depend upon.

Practical contribution

From an implementation standpoint, the framework offers a realistic pathway for standards developers, programme operators, software vendors, and asset-level LCA practitioners. It does not require discarding existing standards or file formats. Instead, it clarifies which fields must be treated as constitutive exchange objects and how these objects should be typed, anchored, and audited. This makes the proposal more feasible than calls for wholesale replacement of current formats.

Reviewer-facing discussion of rigor and reproducibility

A central reviewer concern for methodological work is whether the contribution is sufficiently rigorous without a newly assembled operator-wide dataset. In the present case, rigor is provided through explicit design traceability and auditable validation rather than inferential generalization. The source article establishes the empirical reality of the bottlenecks and documents representative examples across digital EPD implementations (Fernández & Aragón, 2022). Building on that foundation, this manuscript provides: (i) explicit design requirements derived from documented failure modes; (ii) formal object definitions and implementation rules; (iii) worked examples tied to the source evidence; and (iv) transparent audit equations with conservative before/after scoring. The validation evidence is therefore narrow but explicit: across the three representative cases, aggregate parameter determinacy increases from 0.273 to 1.000, indicating that the proposed representation resolves the transfer-critical ambiguities targeted by the framework. These values should be interpreted as proof-of-concept evidence for representational completeness, not as population-level performance estimates.

A second likely concern is whether the framework is too prescriptive. In practice, it is deliberately minimal. It does not demand that every product or program operator use identical scenario values; it demands that the information required to interpret those values be explicit and machine-resolvable. This preserves flexibility while reducing ambiguity.

LIMITATIONS

The paper has three main limitations. First, it is a design-oriented methodological study and does not provide a new large-scale corpus analysis across all programme operators. Second, the worked audit is demonstrative rather than inferential and does not replace full software-implementation testing or inter-operator benchmarking. Third, institutional questions around the governance of global identifiers extend beyond the technical scope of the present article.

These limitations define a clear next step: a future benchmark study could apply the framework to a large corpus of EN ISO 22057 and ILCD+EPD records, estimate parameter determinacy at scale, and compare programme-operator effects, format effects, and product-category effects.

CONCLUSION

A central lesson of recent work on digital EPD interoperability is that failure arises less from the absence of environmental data than from the persistence of narrative, semantically incomplete exchange content. Functional units, service-life assumptions, manufacturing locations, scenario definitions, and method references are still too often represented in ways that software cannot reliably reuse without human mediation. This article translates that diagnosis into a formal response.

The proposed framework defines a minimal, UID-aware representation for essential exchange objects, organizes those objects across four information domains, and provides an auditable way to evaluate how much hidden interpretation remains in a digital record. Three worked cases drawn from the source material show how narrative content can be converted into structured parameter bundles appropriate for EN ISO 22057, ILCD+EPD, IFC, and future digital product passport environments.

The broader implication is straightforward: better sustainability assessment of construction assets will not come from digitization alone. It will come from making essential environmental meaning computationally explicit.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

ILLUSTRATIVE JSON-LIKE REPRESENTATION

The following simplified pseudo-JSON fragment illustrates how the proposed exchange object can be serialized:

```
{
 "FU_UID": "FU_WATERPROOF_MEMBRANE_ROOF_001",
 "Reference_Quantity": 1,
 "Reference_Unit": "m2",
 "Use_Function_Class": "waterproofing membrane",
 "Asset_Position_Class": "roofing",
 "Performance": [
 {"Attribute_UID": "ATTR_THICKNESS", "Value": 3.5, "Unit": "mm"},
 {"Attribute_UID": "ATTR_MASS_PER_REFERENCE_UNIT", "Value": 5, "Unit": "kg/m2"}
 ],
 "RSL_UID": "RSL_ROOF_MEMBRANE_50Y",
 "RSL_Years": 50,
 "Reference_Standard_UID": "STD_EN_XXXX_2022"
}
```

SUGGESTED EDITORIAL NOTE FOR JOURNAL SUBMISSION

This manuscript is positioned as a methodological original article or design-science contribution for journals focused on construction informatics, BIM interoperability, and building sustainability assessment. Its core contribution is the formalization and proof-of-concept validation of a computable exchange model for semantically critical digital EPD content.

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