

Requirements Traceability and Software Quality in Enterprise Application Development

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Abstract

Purpose: Enterprise teams invest heavily in traceability, yet the claim that trace links improve software quality rests on thinner evidence than practice guidance assumes. This review treats trace links as an engineered asset with a creation cost, a recovery error, a decay rate and a measurable return. **Design:** A protocol-driven integrative review of requirements engineering, software maintenance, testing and assurance literature published up to 2024 addresses four questions: how link types, granularity and traceability information models shape utility; how accurately information retrieval and learning methods recover links; how links decay and what upkeep costs; and what evidence connects traceability to defect density and change impact accuracy. **Findings:** Vector space and latent semantic indexing recovery reaches useful recall only at precision levels that move cost into analyst vetting, and benchmark results transfer poorly to enterprise repositories. Link value concentrates in volatile, high-criticality requirements, whereas uniform coverage mandates produce stale links whose false assurance can be worse than an honest gap. Evidence relating completeness to lower defect density is directionally consistent but largely correlational. **Contribution:** The Trace Asset Value Model defines link quality through completeness, correctness, currency and granularity fit, routes it through impact analysis, test selection and audit channels, and states six falsifiable propositions with tests. **Implications:** Maintenance effort should follow change exposure and criticality, and link currency deserves the audit attention that coverage receives today.

Keywords: requirements traceability, trace link recovery, latent semantic indexing, trace decay, traceability information model, change impact analysis, defect density, regulated software

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1 Introduction

Enterprise applications such as enterprise resource planning suites, core banking platforms, insurance claims systems and customer relationship management estates change continuously. Each change request raises the same engineering question: which requirements, design elements, code units, configuration items and tests does this change touch, and which of them must be re-verified before release?

Requirements traceability is the discipline that promises an answer. In its classic formulation it is the ability to describe and follow the life of a requirement in both a forward and a backward direction, from its origin through specification, implementation and verification (Gotel & Finkelstein, 1994). Standards codify the expectation: the requirements engineering standard treats bidirectional traceability as a property of a well-formed requirements set, and the software testing process standard expects traceability between the test basis and test cases (ISO/IEC/IEEE, 2018).

Traceability is nevertheless expensive, and its costs arrive long before its benefits. Gotel and Finkelstein (1994) located most practical difficulty in the pre-requirements-specification phase, where the provenance and rationale of a requirement are lost, while enterprise practitioners more often report the post-specification problem: links between requirements, code and tests are produced retrospectively, frequently just before an audit, and degrade soon afterwards. Business analysis research makes the upstream half of the same point: a requirement that is not structured from an explicit statement of the business problem at elicitation carries no recoverable rationale, and no later link can supply one (Alieme et al., 2024). Ramesh and Jarke (2001) documented a split between low-end users, who maintain traceability because a customer or regulator mandates it, and high-end users, who capture rationale and use links to manage change. Later surveys confirmed that tool support, not motivation alone, determines which of these patterns an organisation can sustain (Winkler & von Pilgrim, 2010; Cleland-Huang et al., 2012).

Three research streams address the problem, but largely in isolation. The first, automated trace link recovery, has since the early 2000s applied information retrieval to propose candidate links between textual artifacts, and has reported its results as precision and recall against reference answer sets (De Lucia et al., 2007; Borg et al., 2014). The second stream concerns traceability information models, which specify the artifact types and link types an organisation will maintain and the queries those links must answer (Cleland-Huang et al., 2012). The third stream, the testing literature, measures verification through coverage and adequacy criteria that presuppose a mapping from requirements to tests (Zhu et al., 1997; Ammann & Offutt, 2016). Each stream evaluates an intermediate quantity. Comparatively few studies follow the chain to the outcomes that justify the investment, namely fewer escaped defects, lower defect density in maintained components and more accurate change impact estimates (Daka & Fraser, 2014; Borah et al., 2022).

The gap addressed here is therefore specific. First, the literature lacks an integrated account of link quality: a link can be present but wrong, correct but stale, or current but too coarse to support the question an engineer asks, and these failure forms have different causes and remedies. Second, recovery accuracy and maintenance cost are studied separately, although they are two sides of one economic question about how an organisation acquires and keeps a stock of reliable links. Third, the evidence connecting traceability to quality outcomes is scattered across repository studies, industrial case reports and certification practice, and much of it is confounded by process maturity, since organisations that trace well tend to do many other things well (Dybå & Dingsøyr, 2008; Runeson & Höst, 2009). The review does not examine how defects arise within requirement statements, how natural language processing detects those defects, or why requirements change; it treats requirement quality and volatility as inputs and asks what happens to the links that connect requirements to the rest of the system.

Four research questions follow. RQ1 asks how link types, link granularity and traceability information models shape the cost and utility of trace links in enterprise development. RQ2 asks how accurately information retrieval and learning-based techniques recover trace links, and what limits their use as a

substitute for manual linking. RQ3 asks how trace links decay as artifacts evolve and what maintaining them costs. RQ4 asks what evidence relates traceability completeness and quality to defect density, change impact analysis accuracy and audit outcomes, and under which conditions, including safety-regulated and financially audited settings.

The article makes four contributions. (1) It synthesises the recovery, modelling, maintenance and quality literatures under a single asset perspective and adjudicates their conflicting results rather than listing them. (2) It defines four dimensions of link quality, namely completeness, correctness, currency and granularity fit, together with formal measures that can be computed from enterprise repositories. (3) It proposes the Trace Asset Value Model (TAVM), which routes link quality through three use channels (change impact analysis, regression test selection and audit evidence) to measurable quality outcomes, moderated by change exposure, criticality and regulatory regime. (4) It states six falsifiable propositions with operational tests and a repository-based validation design that separates the effect of traceability from the effect of general process maturity. The model is a design proposition in the sense of design science research: it is an artefact to be evaluated, not a validated result (Hevner et al., 2004; Wieringa, 2014).

Section 2 sets out definitions and theory, Section 3 the review protocol, and Sections 4 to 7 the synthesis for each research question. Section 8 presents the TAVM, its propositions, a validation design and a worked scenario; Section 9 discusses implications, objections and validity threats; Section 10 states limitations and a research agenda. Cross-domain evidence from safety engineering, pharmaceutical quality and financial control is used only where the analogy is structural, for instance where an inspection record or reconciliation trail plays the evidential role of a trace link (Atta et al., 2022; Dogbatsey et al., 2019).

2 Theoretical Grounding and Core Definitions

A trace link is defined here as a tuple $l = (s, t, \tau, \rho, \pi, \theta)$, in which s and t are the source and target artifacts, τ is the link type, ρ is an optional rationale, π records provenance (who or what created the link and by which method) and θ is the timestamp or artifact version at which the link was last confirmed. The additional fields determine whether a link can be trusted when it is used, and Ramesh and Jarke (2001) anticipated this richer structure in their reference models, which distinguish the stakeholder who records a trace, the object traced and the source that documents it, and which show that high-end users record rationale and dependency types that low-end users omit. Winkler and von Pilgrim (2010) added the distinction between explicit links recorded by people and implicit links that model transformations generate as a by-product, a distinction that matters for cost because implicit links are nearly free to create but inherit every error in the transformation.

2.1 Links as Assets Rather Than Documentation

Treating links as an asset means accounting for them the way an organisation accounts for any engineered stock: acquisition cost when they are created or recovered, carrying cost while they are maintained, impairment when they decay, and a return only when they are queried to support a decision. This framing departs from the documentation view, in which a traceability matrix is a deliverable whose value is realised at the moment it is signed off. The documentation view explains why so many matrices are complete on the day of an audit and misleading a quarter later (Cleland-Huang et al., 2012). The asset view also exposes a property that the documentation view hides: a stale link has negative value, since it

directs an engineer towards the wrong artifacts with the authority of a formal record. Non-functional requirements sharpen the problem, because security, performance and usability qualities crosscut many components and therefore demand many-to-many links whose maintenance cost grows with the architecture rather than with the requirement (Mairiza et al., 2010; Ladapo et al., 2023b).

2.2 Information Foraging and the Navigation Value of Links

Information foraging theory models a person searching for information as a forager moving between patches, guided by cues (information scent) and trading the expected gain of a patch against the cost of travelling to it. An engineer assessing a change to a payment limit rule must locate the patches that matter, such as the requirement, the rule engine configuration, the service method, the database constraint and the regression tests, among thousands of artifacts. Without trace links, scent comes from identifiers, comments and personal memory; with links, scent is formalised and travel cost falls to a query. Recovery research implicitly relies on the same logic, since information retrieval methods exploit the vocabulary shared between requirements and code as a proxy for scent (De Lucia et al., 2007; Borg et al., 2014).

The foraging view generates two predictions that the asset view needs. First, the value of a link is proportional to the travel cost it saves, which is highest where the vocabulary gap between artifacts is largest, for example between business-language requirements and code written in a platform-specific idiom or generated by a low-code tool. These are exactly the cases in which text-based recovery performs worst, so manual links are most valuable where automated recovery is weakest. Second, a misleading link is worse than no link, because a forager who trusts strong scent stops searching early; the resulting impact set is confidently incomplete, a failure that human error research classifies as a mistake induced by a trusted cue rather than a slip of execution (Obriki & Arumosoye, 2020). Studies of monitoring and visualisation in business settings report the analogous effect that an authoritative but out-of-date dashboard suppresses independent checking (Ogbole et al., 2021; Tonoyan et al., 2024b).

2.3 Trace Debt, Incentive Alignment and the Economics of Maintenance

Link maintenance poses an incentive problem inside the development team: the developer who changes code bears the cost of updating links, while the benefit accrues to others, often later, such as the tester selecting regression tests, the analyst assessing the next change or the auditor. Value-based software engineering treats tracing as an investment justified by the queries it serves, and the technical debt metaphor supplies the dynamic view (Cleland-Huang et al., 2012; Ramesh & Jarke, 2001). Each change committed without the corresponding link update incurs trace debt, a liability that is invisible when it is taken on, accrues interest as further changes build on unrecorded relations, and is repaid either by later reconstruction or by the cost of a missed impact. Incentive alignment explains when the debt is taken on: where the person who updates a link also consumes it, for example through impact analysis shown on their own pull request, cost and benefit fall on the same person and updating is rational; where links are consumed only by auditors, updating is a pure cost to the developer and debt accumulates until an audit forces repayment. The account predicts that gate-only regimes, which reject commits lacking a requirement key, will yield high link counts with low correctness, whereas low-friction capture combined with visible use by the people who create links yields fewer but more reliable links (Anichukwueze et al., 2022).

For a link stock L maintained over a horizon of change events E , net value is $NV(L) = \sum_{e \in E} q(e) \cdot \Delta L_{\text{miss}}(e) - C_{\text{create}} - \sum_t C_{\text{maint}}(t) - C_{\text{vet}} - C_{\text{false}}$, where $q(e)$ is the probability that the links are consulted for change e , $\Delta L_{\text{miss}}(e)$ is the reduction in expected loss from missed impacts when they

are, C_create and C_maint are creation and carrying costs, C_vet is the analyst effort spent confirming recovered candidates, and C_false is the expected loss caused by acting on incorrect or stale links. The expression makes three claims explicit: value is realised only through use, it scales with change frequency and with the consequence of a missed impact, and maintenance and correctness enter the same ledger as creation. Cost accounting of this type is standard in process optimisation and enterprise risk management but is rarely applied to traceability (Tonoyan et al., 2022b; Falemi et al., 2024; Akhigbe et al., 2024).

3 Review Protocol

The review follows the guidance for systematic literature reviews in software engineering and the reporting items of PRISMA 2020 where they apply to a mixed-method integrative review (Kitchenham et al., 2009; Page et al., 2021). Searches covered IEEE Xplore, the ACM Digital Library, Scopus, Web of Science, SpringerLink and ScienceDirect, complemented by backward and forward snowballing from two anchor works, the systematic mapping of information retrieval approaches to traceability and the edited volume on software and systems traceability (Borg et al., 2014; Cleland-Huang et al., 2012). The publication window opens in 1994, the year in which the traceability problem was first analysed as a distinct research problem, and closes at the end of 2024 (Gotel & Finkelstein, 1994). Standards and bodies of knowledge were searched directly at their issuing organisations.

3.1 Search Strings and Concept Blocks

The core search string combined three concept blocks: (traceab* OR "trace link*" OR "trace recovery" OR "traceability matrix") AND (requirement* OR "test case*" OR "source code") AND ("information retrieval" OR "vector space" OR "latent semantic" OR "machine learning" OR maintenance OR decay OR co-evolution OR defect* OR fault* OR "change impact" OR certification OR audit). Additional strings targeted regression test selection and prioritisation informed by requirements, and traceability obligations in safety and financial regulation. Strings were adapted to the syntax of each database and piloted against a set of known relevant studies drawn from the anchor works, so that a string was accepted only when it retrieved that set. The testing literature was included because coverage and prioritisation research supplies the verification side of the traceability chain (Catal & Mishra, 2013; Li et al., 2007).

3.2 Eligibility, Screening and Appraisal

Eligible sources were primary empirical studies of trace link creation, recovery, maintenance or use; systematic reviews and mapping studies; standards and bodies of knowledge that specify traceability obligations; and conceptual works that specify a mechanism relating traceability to a quality outcome. Excluded were vendor material without an evaluation, studies of product traceability in physical supply chains except where used explicitly as analogy, and recovery studies that did not report their dataset, answer set or evaluation metric. Supply chain visibility research was retained in that analogical role because it treats end-to-end traceability as infrastructure whose value depends on transparency and compliance use across many organisational handoffs, a structure that parallels the multi-artifact chains of enterprise development (Nnabueze et al., 2021). General theories of rule compliance developed for obligations to public authorities were considered and set aside as a theoretical basis, because trace maintenance is an obligation among colleagues whose costs and benefits sit inside the delivery team

(Alm, 2019; Kirchler, 2007). Screening proceeded in three stages: title and abstract, full text, and snowballing of included works. Table 1 records the protocol decisions and the safeguard attached to each.

Appraisal used two instruments. Quality criteria adapted from software engineering reviews were applied to all empirical work, covering the clarity of aims, the description of context, the adequacy of the sample of artifacts or participants, and the handling of threats to validity (Dybå & Dingsøyr, 2008; Runeson & Höst, 2009). Recovery studies received additional checks drawn from known weaknesses of that literature: provenance of the dataset, construction of the answer set and whether it was produced independently of the technique under test, the cut-off strategy for candidate lists, reporting of precision and recall at more than one threshold, and the use of statistical comparison. Outcome studies were appraised for temporal ordering between traceability measurement and defect measurement, control of size and churn, and the method used to attribute defects to components. Evidence was graded as strong, moderate, weak or analogical, and analogical evidence was never used to support a quantitative claim (Easterbrook et al., 2008; Yusuf & Abdulrazaq, 2018).

Table 1. Review protocol for the traceability evidence base and the safeguard attached to each decision

Protocol element	Specification in this review	Safeguard against bias
Sources	IEEE Xplore, ACM Digital Library, Scopus, Web of Science, SpringerLink, ScienceDirect; standards bodies; snowballing from two anchor works	Search string piloted against a known set of relevant studies before use
Time window	1994 to end of 2024	Window anchored to the first analysis of the traceability problem; later works screened by the same rules
Concept blocks	Traceability terms AND artifact terms AND recovery, maintenance, decay, defect, change impact, certification or audit terms	Separate strings for test selection and for regulatory obligations to avoid under-retrieval
Inclusion	Empirical studies of link creation, recovery, maintenance or use; reviews and mappings; standards; mechanism-specifying conceptual work	Each included work coded to at least one research question
Exclusion	Vendor material without evaluation; physical supply-chain traceability except as flagged analogy; recovery studies without dataset, answer set or metric	Exclusion reason recorded at full-text stage
Appraisal of recovery studies	Dataset provenance, answer-set independence, cut-off strategy, metrics at several thresholds, statistical comparison	Results without independent answer sets downgraded one evidence level
Appraisal of outcome studies	Temporal order of link and defect measures, size and churn controls, defect attribution method	Shared-mechanism attribution flagged as a threat, not silently accepted
Synthesis	Four strands by research question; mechanism, context and outcome coding;	Conflicts explained by measurement before being treated

Protocol element	Specification in this review	Safeguard against bias
	contradictions retained	as substantive
Analogical evidence	Safety, pharmaceutical, financial control and data governance sources	Never used to support a quantitative software claim

3.3 Synthesis Logic

Synthesis proceeded in four strands corresponding to the research questions: link semantics and information models, automated recovery, decay and maintenance, and quality outcomes. Within each strand, findings were coded by mechanism (what the link does), context (domain, artifact types, repository scale, regulatory regime) and outcome (the quantity measured), and contradictions were retained and examined rather than averaged away. Where studies disagreed, the synthesis asked whether the disagreement could be explained by a difference in dataset, granularity, answer-set construction or outcome definition before treating it as a substantive conflict. Figure 1 summarises the sequence from source identification to the construction of the model and its propositions (Wieringa, 2014; Onwuzulike et al., 2024).

Because this is an integrative review, no pooled effect size is computed and no count of records is presented as a finding. The heterogeneity of metrics, datasets and outcome definitions would make a pooled estimate misleading, a problem also noted in reviews of anomaly detection and fraud analytics where evaluation datasets differ in base rates and labelling practice (Atakpa & Abetoh, 2022; Adebayo et al., 2023). Evidence from regulated industries outside software, such as pharmaceutical quality assurance, welding inspection and remote infrastructure monitoring, is used to illuminate how evidential chains are governed, not to estimate software effects (Asiedu & Asiedu, 2024b; Atta et al., 2021; Dagodzo & Ahiaeké Patrick, 2020).

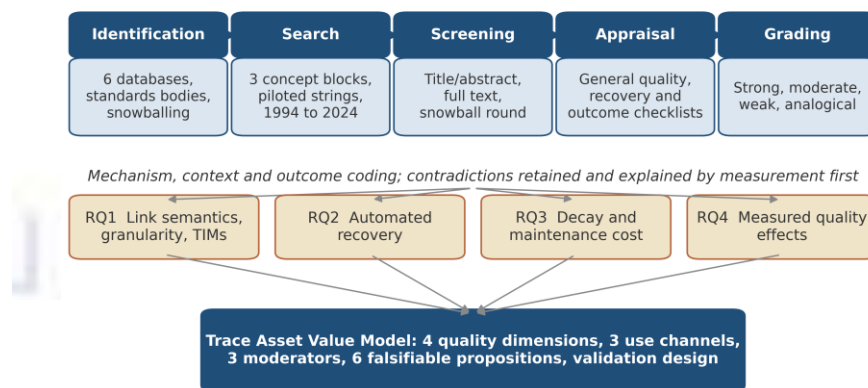


Figure 1. Review protocol from source identification through appraisal to the four synthesis strands and model construction

4 Link Semantics, Granularity and Information Models

RQ1 concerns what a trace link says, at what resolution, and within which designed structure. The three questions are linked: a link type fixes the relation asserted, granularity fixes the endpoints between which

it is asserted, and the traceability information model fixes which types and granularities an organisation commits to maintain. Decisions at this level are made early and are expensive to reverse, much as design standards fix the operating envelope of a service network before its first day of use (Ogbete et al., 2022). A controlled vocabulary of link types also plays the role that a hazard taxonomy plays in risk control, since it makes omissions visible (Obogo et al., 2019; Winkler & von Pilgrim, 2010).

4.1 Link Types and Their Semantic Commitments

Link types differ in what they assert, and therefore in how they fail. A satisfies link from a code unit to a requirement asserts that the unit contributes to the required behaviour; a verifies link from a test to a requirement asserts that the test's pass or fail verdict is evidence about that behaviour; a refines link asserts that one requirement decomposes another; a depends-on link asserts that a change in one artifact may invalidate another; and a rationale link connects a decision to the argument that justified it. Ramesh and Jarke (2001) grouped such links into product-related and process-related families, and their reference models showed that organisations with mature practice use a richer set of types. Richer typing enables more precise queries, for example the set of verifies links for requirements affected by a change, but it also multiplies the ways a link can be wrong, since a correct pair (s, t) can carry an incorrect type.

The semantic commitment of a link type determines which quality outcome it can influence. Verifies links bear directly on verification coverage and hence on escaped defects, because a requirement without a verifying test is a requirement whose failure will be discovered in production (Myers et al., 2011; Kaner et al., 1999). Satisfies and depends-on links bear on change impact analysis, because they define the reachable set from a changed artifact. Rationale links bear on audit and on the avoidance of regressions caused by reversing a decision whose reasons were forgotten. A consequence is that a single completeness ratio across all link types is uninformative; an organisation can be fully traced in satisfies links and still blind in verifies links, including for security policies derived from privacy requirements (Ladapo et al., 2024; Badmus et al., 2024).

4.2 Granularity: From Requirement-to-Component to Requirement-to-Method

Granularity is the resolution at which link endpoints are defined. At coarse granularity a requirement links to a component, module or service; at intermediate granularity to a file or class; at fine granularity to a method, a configuration key or an individual commit. Coarse links are cheap to create and slow to decay, because a component persists while its internals change, but they produce inflated impact sets that make change impact analysis imprecise. Fine links support precise impact sets and targeted regression test selection, but they decay quickly under refactoring and are expensive to create by hand. Recovery research has mostly operated at class or file level for pragmatic reasons, since that is where textual artifacts are large enough for retrieval models to work (De Lucia et al., 2007; Borg et al., 2014).

The trade-off can be expressed as granularity fit: the match between the resolution of the link and the resolution of the question the link must answer. Regression test selection asks which tests exercise the changed code and requires method or statement resolution; audit asks whether each regulated requirement has been verified and is satisfied by test-case to requirement links at any code resolution; release planning asks which features are affected and is served by component links. Test adequacy research has long shown that coverage criteria at different resolutions are not interchangeable, since statement, branch and path criteria subsume one another in known ways and detect different faults (Zhu et al., 1997; Ammann & Offutt, 2016). The same logic applies to trace granularity, much as early layout decisions in laboratory planning constrain later diagnostic accuracy and throughput (Ogbete et al., 2018).

A practical implication is that a traceability information model should state granularity per link type rather than globally.

4.3 Traceability Information Models and Enterprise Toolchains

A traceability information model (TIM) is a metamodel that specifies which artifact types exist, which link types may connect them, with what multiplicity, and which queries the link set must support. The TIM concept, developed in the traceability research community, moves traceability from an ad hoc matrix to a designed structure whose completeness can be checked against a specification (Cleland-Huang et al., 2012). In model-driven development, TIMs are partly realised by transformation traces, which record correspondences between source and target model elements automatically (Winkler & von Pilgrim, 2010). In enterprise toolchains, the TIM is usually implicit in the configuration of an issue tracker, a version control system, a test management tool and a continuous integration server, and the links are the keys that tie a commit to a work item and a test run to a requirement.

Implicit TIMs have a characteristic weakness: they encode what the tools can record rather than what the organisation needs to ask. A commit message that cites a work item creates a link with provenance and timestamp but no type and no granularity below the commit, and a work item that aggregates several requirements blurs which requirement the commit serves. Enterprise data governance research reports the same pattern for data lineage, where lineage captured automatically by pipelines is complete in form but ambiguous in meaning until classification rules are added (Aliliele et al., 2024a; Mbonu et al., 2021a). Designing an explicit TIM requires the same governance moves: named owners for each artifact type, rules for link creation at defined workflow events and a query catalogue that justifies each link type by the decision it serves (Sakya et al., 2022b; Edivri & Oteri, 2024).

5 Automated Trace Link Recovery

Information retrieval based recovery treats one artifact type as queries and another as documents, ranks candidate pairs by textual similarity and presents the ranked list to an analyst for confirmation. In the vector space model, each artifact is represented as a vector of term weights, typically $w(t, d) = \text{tf}(t, d) \cdot \log(N / \text{df}(t))$, where tf is the frequency of term t in artifact d , N is the number of artifacts and $\text{df}(t)$ is the number containing t ; similarity is the cosine of the angle between vectors, $\text{sim}(q, d) = (q \cdot d) / (\|q\| \|d\|)$. Preprocessing splits identifiers such as `computeInterestAccrual` into their component words, removes stop words and applies stemming, steps that matter more for code than for prose because identifiers carry most of the vocabulary shared with requirements (De Lucia et al., 2007; Borg et al., 2014).

5.1 Latent Semantic Indexing and the Vector Space Baseline

Latent semantic indexing addresses synonymy and polysemy by applying a truncated singular value decomposition to the term-by-document matrix, $A \approx U_k \Sigma_k V_k^T$, and comparing artifacts in the k -dimensional latent space. In principle this allows a requirement that speaks of a customer's credit ceiling to match code that speaks of an account limit. De Lucia et al. (2007) integrated latent semantic indexing into an artifact management system and reported a finding that has proved durable: retrieval can reach high recall only by accepting low precision, and below a similarity threshold the effort of discarding false candidates grows faster than the number of true links found. The systematic mapping by Borg et al. (2014) found that the vector space model and latent semantic indexing dominated the field, that more

elaborate models did not consistently outperform the vector space baseline, and that most evaluations used small datasets from academic or open-source projects.

Individual studies report latent semantic indexing ahead of the vector space model on some datasets and behind it on others. The disagreement is explained largely by corpus size and the choice of k : latent semantic indexing needs enough documents for the decomposition to capture stable co-occurrence patterns, and small datasets combined with an untuned k degrade it towards noise. The adjudicated conclusion is that neither technique dominates, that the vector space model is the defensible default for small and medium enterprise repositories, and that reported differences below a few points of average precision should not drive tool selection (Borg et al., 2014; Wedraogo & Sanni, 2024). Table 2 summarises the technique families, their characteristic failure modes and the caveats that apply to their published evaluations.

Table 2. Trace link recovery technique families, their characteristic failure modes and caveats on published evaluations

Technique family	Representation and scoring	Main strength	Characteristic failure mode	Evaluation caveat
Vector space model	Term vectors with tf-idf weights; cosine similarity	Transparent, fast, strong baseline	Vocabulary mismatch between business language and code	Sensitive to identifier splitting and stemming choices
Latent semantic indexing	Truncated SVD of term-by-document matrix; similarity in k dimensions	Partial handling of synonymy	Degrades on small corpora or untuned k	Gains over the vector space model are dataset dependent
Probabilistic and topic models	Distributional divergence or topic mixtures	Captures thematic relatedness	Topics too broad for fine-grained links	Results broadly comparable to the vector space baseline
Supervised classifiers	Pairwise features: several similarities, shared identifiers, co-change, structural proximity	Combines textual and behavioural signals	Learns omissions present in training links	Class imbalance makes accuracy meaningless; report precision at operating threshold
Neural language models	Contextual embeddings of requirements and code, fine-tuned for link prediction	Narrows vocabulary gap	Opaque rationale; costly retraining as artifacts change	Benchmarks rarely resemble enterprise repositories
Convention and structure based	Issue keys in commits, naming rules, model transformation traces	Near-zero creation cost; clear provenance	Coarse granularity; no link type; depends on discipline	Rarely evaluated for correctness, only for presence

5.2 From Probabilistic Models to Supervised and Neural Recovery

Later work moved in two directions. Probabilistic and topic models, such as the Jensen-Shannon divergence model and latent Dirichlet allocation, replaced geometric similarity with distributional comparisons, with results broadly comparable to the vector space model (Borg et al., 2014). Supervised learning then reframed recovery as classification: given a pair of artifacts, predict whether a link exists, using features such as textual similarity under several models, shared identifiers, co-change history in version control and structural proximity in the code. Classifiers can combine weak signals that no single similarity measure captures, and co-change features in particular let recovery exploit behavioural evidence rather than vocabulary alone.

Neural language models extend this direction by learning contextual representations of requirements and code jointly, which narrows the vocabulary gap that defeats term-based methods. Positive links are rare relative to the space of possible pairs, often by several orders of magnitude, so accuracy is meaningless and precision at operational thresholds is fragile, a difficulty well documented in fraud and anomaly detection with similarly imbalanced classes (Atakpa & Abetoh, 2022; Atakpa & Fobellah, 2023). Training labels come from existing links, which are themselves incomplete and partly stale, so a model can learn to reproduce the organisation's past omissions. Interpretability also matters more than in many prediction tasks, since an analyst deciding whether to accept a link needs to see why it was proposed (Komi & Adamolekun, 2021). Governance proposals for machine learning components, including release gating based on model evaluation, apply directly to a recovery model placed in a delivery pipeline (Nwakamma et al., 2024a).

5.3 The Evaluation Problem: Answer Sets, Metrics and Analyst Vetting

Recovery studies report precision $P = |C \cap T| / |C|$ and recall $R = |C \cap T| / |T|$, where C is the set of candidate links returned above a threshold and T is the answer set of true links, together with F-measures $F_\beta = (1 + \beta^2) P R / (\beta^2 P + R)$, mean average precision over queries and, in some studies, the lag between a true link and the false links ranked above it. The field has conventionally favoured recall, often reporting F_2 , on the argument that an analyst can discard false positives but cannot find links the tool never showed. Analyst effort grows with $|C|$, so the expected vetting cost per true link found is c_v / P , where c_v is the cost of vetting one candidate; at a precision of 0.2 an analyst inspects five candidates for each link confirmed.

Two further evaluation problems limit transfer to enterprise settings. First, the answer set is usually the set of links the original developers recorded, and it is therefore incomplete in unknown ways; a technique that finds a genuine link missing from the answer set is penalised as a false positive. Second, benchmark datasets are small, textually clean and domain-homogeneous, whereas enterprise repositories mix languages, generated code, configuration files and requirements written by many authors over many years (Borg et al., 2014). The measurement analogy from analytical chemistry is instructive: a detection method validated on clean reference samples reports limits of detection that do not hold in contaminated field samples, and validation must therefore be repeated in the matrix of use (Tawose et al., 2023). For traceability, this means that a recovery technique should be validated on a sample of the organisation's own artifacts, with an independently constructed answer set, before its output is admitted as evidence.

Automated recovery is valuable as a candidate generator that lowers the cost of creating links and as an auditor that flags likely missing or suspicious links in an existing set. It is not a substitute for recorded links where links serve as compliance evidence, because its precision at useful recall leaves too many

errors for an unattended record. The strongest use case in enterprise development is recovery against a partly linked repository, where existing links provide both training data and a sanity check, and where the analyst's task is to confirm a short list rather than to construct a matrix from nothing (Ogundairo & Ayivi-Donkor, 2024b; Sanni et al., 2023).

6 Trace Decay, Maintenance and Cost

Trace decay is the loss of correctness in a link stock as the artifacts at its endpoints evolve without corresponding link updates. Four mechanisms can be distinguished. Endpoint deletion or renaming breaks the link outright and is the only mechanism that tools detect easily. Semantic drift occurs when an endpoint persists but its content changes so that the asserted relation no longer holds, for example when a method that satisfied a requirement is repurposed. Omission occurs when new artifacts, such as a new service or a new test, relate to a requirement but are never linked. Type drift occurs when a relation changes kind, as when a test that verified a requirement is reduced to a smoke check. Only the first mechanism produces visible errors; the other three produce links that look valid and are wrong, which is why decay is chiefly a correctness problem rather than a completeness problem (Cleland-Huang et al., 2012; Winkler & von Pilgrim, 2010).

6.1 A Hazard Model of Trace Decay

A simple hazard model captures the dynamics. Let $S(t)$ be the probability that a link confirmed at time 0 is still correct at time t . If each change to an endpoint invalidates the link with probability δ and is captured by maintenance with probability m , and endpoints change at rate λ , then the hazard is $h = \lambda \delta (1 - m)$ and $S(t) = \exp(-\lambda \delta (1 - m) t)$. The model makes predictions that match practitioner experience: decay is fastest in volatile components, fine-grained links decay faster than coarse ones because their endpoints change more often, and improving the capture probability m is more effective than periodic re-audit when λ is high. The parameters are illustrative, and estimating λ , δ and m from repository histories is part of the research agenda (Shittu et al., 2023; Komi, 2023).

6.2 Maintenance Strategies

Three maintenance strategies appear in the literature and in practice. Periodic audit re-validates the link stock at fixed intervals, typically before a release or an external audit; it is simple to govern but allows decay to accumulate between audits and concentrates effort at the least convenient moment. Event-based maintenance attaches link updates to development events, so that a commit, a pull request or a change to a requirement triggers a check of affected links; it keeps links current at the cost of a small, continuous overhead and depends on developers accepting that overhead. Rule-based and recovery-assisted maintenance uses change patterns, for example the recognition that a method was moved or split, to propose link updates automatically and then asks an analyst to confirm them (Cleland-Huang et al., 2012). Change management research in small-business digital transformation reports the same trade-off between batch and continuous control of process artifacts (Eyetsemitan et al., 2023a).

The trace debt account of Section 2.3 predicts which strategies endure. Periodic audit repays debt on a fixed schedule: links are reconstructed before inspection, interest accumulates between audits, and developers experience the work as a cost imposed by consumers they never see (Cleland-Huang et al., 2012). Event-based maintenance settles the debt when it is incurred and is sustainable when the tooling makes the update nearly free and developers see links used, for instance when a pull request

automatically lists affected requirements and tests, as workflow research finds for controls embedded in routine work (Uchechi et al., 2018; Eyetsemitan et al., 2024a). Safety leadership research reaches a similar conclusion about walkthrough frequency and coverage: visible, regular use of an inspection record sustains its quality better than rare formal reviews (Obriki & Arumosoye, 2019; Obogo et al., 2019a).

Figure 2 illustrates the implications with the hazard model. Under an assumed endpoint change rate typical of an actively maintained service, the link stock without maintenance loses most of its correctness within a year, periodic audit produces a saw-tooth pattern whose troughs sit well below the audit-day value, and event-based capture keeps correctness high with a slow residual decline caused by semantic drift that events do not detect. Panel (b) shows the second implication: when maintenance effort is allocated to requirements ranked by change exposure and criticality, net value rises steeply over the first portion of the ranking and then flattens or declines, because the remaining requirements change rarely and carry low consequence. Uniform full coverage is therefore rarely the value-maximising allocation outside regimes that mandate it (Tonoyan et al., 2023; Adesuyi et al., 2024).

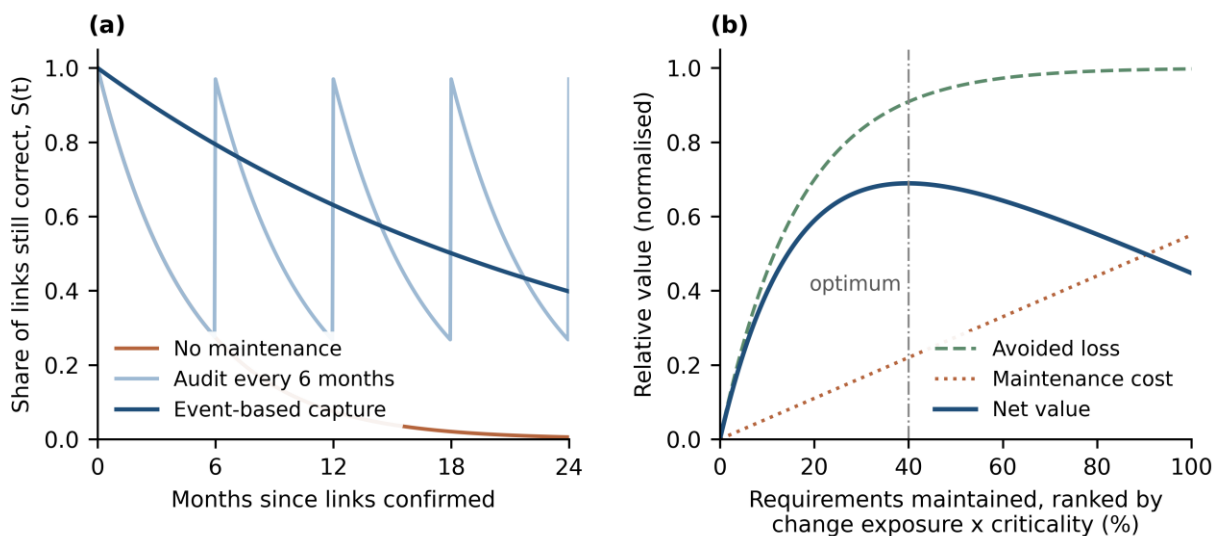


Figure 2. Illustrative trace decay under three maintenance strategies (a) and net value of risk-ranked maintenance coverage (b); parameters are assumed for exposition

6.3 Cost-Benefit Evidence and Risk-Weighted Coverage

Direct cost-benefit studies of traceability are few, and the review found none that measured the full ledger of Section 2.3 in an enterprise setting. The evidence consists of three kinds: effort studies of recovery and vetting, which show that tool-assisted creation reduces the time needed to build a matrix but not the time needed to confirm it; case reports from regulated development, where traceability is a condition of certification and its cost is treated as unavoidable; and experience reports of value-based or risk-based tracing, which argue for concentrating links on high-value requirements (Cleland-Huang et al., 2012; De Lucia et al., 2007).

Risk-weighted coverage replaces the unweighted completeness ratio with $TC_w = \frac{\sum_r w_r \cdot 1[r \text{ is linked, correct and current}]}{\sum_r w_r}$, where w_r combines the criticality of requirement r with its expected change exposure. The measure rewards the links that the asset view says matter and exposes the pattern in which a matrix is nominally complete because low-risk requirements are fully traced while the volatile

core is not. Risk-based assurance models in cybersecurity and cloud configuration monitoring apply the same weighting logic to control coverage and report that unweighted control counts overstate protection, and data-driven safety risk control allocates inspection effort in the same way (Fadayomi et al., 2019; Aliliele et al., 2023a; Obriki & Arumosoye, 2018). The boundary condition is regulatory: where a standard requires every requirement to be traced, risk weighting governs the order and depth of maintenance effort, not whether a link exists at all (ISO/IEC/IEEE, 2018; Eze et al., 2022b).

7 Traceability and Measured Software Quality

RQ4 asks whether and how traceability changes measured quality. Four outcome channels are examined: defect density in maintained components, the accuracy of change impact analysis, verification coverage and the effectiveness of regression testing, and the audit and certification outcomes that dominate regulated settings. For each channel the synthesis identifies the link quality dimension on which the mechanism depends, the measurement design of the available studies and the confounders that limit inference, and the section closes by adjudicating the conflicts that recur across channels. A quality claim is accepted only where the measurement of links precedes the measurement of outcomes (Runeson & Höst, 2009; ISO/IEC/IEEE, 2018).

7.1 Completeness and Defect Density

The most direct quality claim is that components whose requirements are completely traced have lower defect density, measured as post-release defects per thousand lines of code or per function point. Three mechanisms could produce the effect. Verification completeness: requirements with verifies links are more likely to be tested, so their defects are found before release (Myers et al., 2011). Comprehension: developers who can navigate from code to requirement make fewer misinterpretation errors when they modify code, which is the foraging mechanism. Discipline: teams that maintain links also review, test and document more carefully, which is a confounder rather than a mechanism. Surveys of traceability research note that empirical evaluation of benefits lags far behind technique development (Winkler & von Pilgrim, 2010; Cleland-Huang et al., 2012).

The repository studies available by 2024 that relate trace completeness to later defects are consistent in direction, reporting fewer defects where requirements are more completely linked to code, but they share design features that limit causal interpretation. Completeness and defects are often measured over overlapping periods, so defects discovered may prompt links to be added and reverse the direction of the relation. Defects are attributed to components through commit messages and issue keys, the same mechanism that creates trace links, so components whose developers write disciplined commit messages score higher on both measures. Attribution modelling in marketing analytics faces a closely analogous problem, where the channel that records touches most completely receives most of the credit (Sanni et al., 2022). The adjudicated reading is that the association is plausible and worth testing with stronger designs, not that its size is known (Runeson & Höst, 2009; Miller et al., 2015).

Let D_i be the count of post-release defects in component i over a window after a baseline at which link quality is measured. A negative binomial model $\log E[D_i] = \beta_0 + \beta_1 TC_{w,i} + \beta_2 Cur_i + \beta_3 \log(KLOC_i) + \beta_4 Churn_i + \beta_5 Authors_i + \beta_6 Age_i + u_{team}$, with Cur_i the proportion of links confirmed since the endpoint's last change, separates completeness from currency, controls for size and churn, and absorbs team discipline in a random effect. Measuring link quality strictly before the outcome window and using issue-tracker defect records independent of commit messages addresses the reverse-

causation and shared-measurement problems. Evaluation design research in other fields makes the same point about separating exposure from outcome measurement in time (Ilodigwe & Adesemoye, 2024a; Michael & Ogunsola, 2021d).

7.2 Change Impact Analysis Accuracy

Change impact analysis estimates the set of artifacts affected by a proposed change. Its accuracy is measured by comparing the estimated impact set EIS with the actual impact set AIS, the artifacts that were in fact modified or failed as a result: $\text{precision_I} = |\text{EIS} \cap \text{AIS}| / |\text{EIS}|$ and $\text{recall_I} = |\text{EIS} \cap \text{AIS}| / |\text{AIS}|$. Low recall means missed impacts, which surface as regressions; low precision means over-estimation, which inflates re-verification effort and delays release. Trace links feed impact analysis by defining the reachable set from the changed requirement or artifact, often combined with dependency analysis of the code (IEEE Computer Society, 2014; Cleland-Huang et al., 2012).

Each link quality dimension maps to a specific impact analysis error. Missing links reduce recall. Incorrect links reduce precision. Stale links do both, since the link points to an artifact that no longer implements the requirement and misses the one that now does. Coarse granularity reduces precision because a component link includes every artifact in the component. The mapping makes a prediction that the literature has not yet tested directly: holding completeness constant, currency should explain more variance in impact recall than completeness does in actively developed systems. Research on dependency mapping in enterprise risk frameworks makes a comparable argument that a map's recency, not its breadth, determines whether it supports incident response, and risk pathway models make the same demand of every intermediate step between an initiating event and its consequence (Mbonu et al., 2020a; Okoruwa et al., 2024; Arumosoye & Obriki, 2022).

7.3 Verification Coverage and Test Selection

Requirements-to-test links enable two quality mechanisms beyond coverage reporting. Requirements-based regression test selection chooses the tests linked to changed requirements, reducing regression effort, and requirements-aware prioritisation orders tests so that those verifying high-risk or changed requirements run first. Prioritisation effectiveness is conventionally measured by the average percentage of faults detected, $\text{APFD} = 1 - (\text{TF}_1 + \dots + \text{TF}_m) / (n \cdot m) + 1 / (2n)$, where n is the number of tests, m the number of faults and TF_j the position of the first test that reveals fault j (Li et al., 2007; Catal & Mishra, 2013). Search-based and coverage-based prioritisation techniques are well studied; requirement-based prioritisation depends on the correctness of the requirements-to-test links, so a stale link can demote a test that would have revealed a regression.

Coverage research warns against reading requirement coverage as fault detection capability. A test linked to a requirement may exercise it weakly, and unit testing surveys report that developers commonly write tests that execute code without strong assertions (Daka & Fraser, 2014). Requirement coverage is therefore a necessary rather than a sufficient indicator of verification: it shows that a verifying test exists, not that the test would fail if the requirement were violated. The appropriate complement is a check on test strength, for example mutation analysis of the code that satisfies high-criticality requirements (Ammann & Offutt, 2016). User acceptance testing frameworks for lean environments make a parallel point that acceptance criteria linked to requirements only protect quality when the criteria are specific enough to fail (Eysetsemitan et al., 2023b; Kaner et al., 1999).

7.4 Regulated Domains: Safety Certification and Financial Audit

Regulated domains supply the clearest evidence that traceability can be sustained at high completeness, and the clearest warnings about what completeness alone achieves. Safety standards for airborne software, medical device software and road vehicle electronics require bidirectional traceability between requirements, design, code and verification evidence, and certification authorities inspect it. Pharmaceutical regulatory science shows the same pattern for manufacturing and approval evidence, where the evidential chain from specification to batch record is audited and gaps delay approval (Eze et al., 2024b; Asiedu & Asiedu, 2024b). Critical infrastructure compliance regimes likewise require that security controls be traceable to requirements and evidence (Adegbite et al., 2020; Ahmed et al., 2021).

Financial settings add a different demand. Internal control over financial reporting requires that changes to systems affecting financial data be authorised, tested and traceable to an approved request, and auditors sample changes to verify the chain. Service contracts that allocate liability for defects increasingly call for the same evidence of verification against specified requirements (Uchechi & Ominyi, 2019). The trace link here is audit evidence: its role is to demonstrate that a control operated, not only to support engineering decisions. Reconciliation and workflow control research emphasises that evidence trails fail audit when they are reconstructed after the fact rather than produced by the controlled process (Dogbatsey et al., 2019; Mbonu et al., 2021). Tamper-evident ledgers have been proposed for cloud configuration management for the same reason, binding each configuration change to an immutable audit trail at the moment the change is made rather than reconstructing the trail for inspection (Oshoba et al., 2020). Data protection regimes impose comparable demands on the traceability of personal data processing to lawful purposes and impact assessments (Mbonu et al., 2022a; Atakpa & Abolaji, 2022; Mbonu et al., 2018), and emerging regulation of artificial intelligence extends documentation and traceability obligations to model components (Ominyi et al., 2024b).

The regulated domains therefore present a natural experiment on the difference between completeness and currency. Because completeness is mandated, variation in quality outcomes among regulated organisations cannot be explained by completeness and must come from correctness, currency, granularity and use. Governance research on regulated procurement and joint ventures shows that mandated documentation can coexist with weak operational control when the documentation is produced for the regulator rather than used by the operator, and survey evidence on information security in administrative offices shows formal policy coexisting with divergent practice (Okonkwo et al., 2021; Eyetsemitan et al., 2020; Onche et al., 2023). The same risk applies to traceability, and it motivates Proposition P5 on the moderating role of regulatory regime (Anioke & Atima, 2023a; Sanni & Attah, 2023c).

7.5 Adjudicating Conflicting Evidence

Three apparent conflicts in the literature can be resolved by attention to measurement. The first concerns whether traceability pays for itself. Experience reports from regulated development describe traceability as indispensable, whereas agile teams frequently describe it as overhead with little return. The conflict dissolves under the asset view: in regulated settings $q(e)$, the probability that links are consulted, is close to one because audits and impact assessments consult them, whereas in unregulated agile settings links are often created but never queried, so their net value is negative by construction (Dybå & Dingsøyr, 2008; Ramesh & Jarke, 2001).

The second conflict concerns whether automated recovery is ready for practice. Laboratory studies report encouraging recall and mean average precision, whereas practitioner uptake remains low. The resolution lies in the evaluation problems of Section 5.3: benchmark answer sets understate true links, benchmark datasets overstate textual cleanliness, and laboratory metrics ignore vetting cost. A technique can be genuinely better than chance and still not reduce the total cost of a reliable link stock (Borg et al., 2014; Quainoo et al., 2024). The third conflict concerns whether completeness predicts quality. Associations reported in repository studies coexist with case reports of fully traced systems that failed badly. The resolution is that completeness is necessary for the verification mechanism but that correctness and currency govern the impact analysis mechanism, so completeness predicts some outcomes and not others (Anichukwueze et al., 2022; Uchechi et al., 2022).

8 The Trace Asset Value Model

The Trace Asset Value Model (TAVM) integrates the synthesis into a causal structure with four layers, shown in Figure 3. The acquisition layer describes how links enter the stock: manual creation, tool-captured creation at workflow events, transformation-generated links and recovered links confirmed by an analyst. The stock layer describes the link set at a point in time through four quality dimensions: completeness (the weighted share of required links present, TC_w), correctness (the share of present links whose asserted relation holds), currency (the share confirmed since the last change to either endpoint) and granularity fit (the match between endpoint resolution and query resolution). Decay acts on the stock continuously, and maintenance counteracts it (Cleland-Huang et al., 2012; Hevner et al., 2004).

8.1 Use Channels, Moderators and Feedback

The use layer contains the three channels through which links influence quality: change impact analysis, regression test selection and prioritisation, and audit and certification evidence. The outcome layer contains change impact precision and recall, post-release defect density, escaped defects in changed areas and audit findings. Three moderators condition the paths: change exposure, because value scales with the frequency of changes that consult the links; criticality, because value scales with the consequence of a missed impact; and regulatory regime, because mandated completeness shifts the binding constraint from completeness to currency. A feedback path runs from outcomes to acquisition and maintenance: escaped defects traced to missing or stale links should change where maintenance effort is spent. The structure is a claim about mechanism, and each arrow is a proposition that could fail (Wieringa, 2014; Ilodigwe & Adesemoye, 2024b).

The model differs from maturity-based accounts of traceability in two respects. It does not assume that more links are better, since links have carrying cost and stale links carry negative value. It also does not treat the use channels as automatic: a link stock of high quality that no process consults produces no outcome, which is why the model places use between stock and outcome rather than treating quality as directly causal. Organisational learning models in safety management make a comparable distinction between the existence of a safety record and its incorporation into decisions (Arumosoye & Obriki, 2021; Obogo et al., 2023), and technology adoption research similarly separates the availability of a tool from employees' readiness to use it (Akin-Oluyomi & Akhigbe, 2023b).

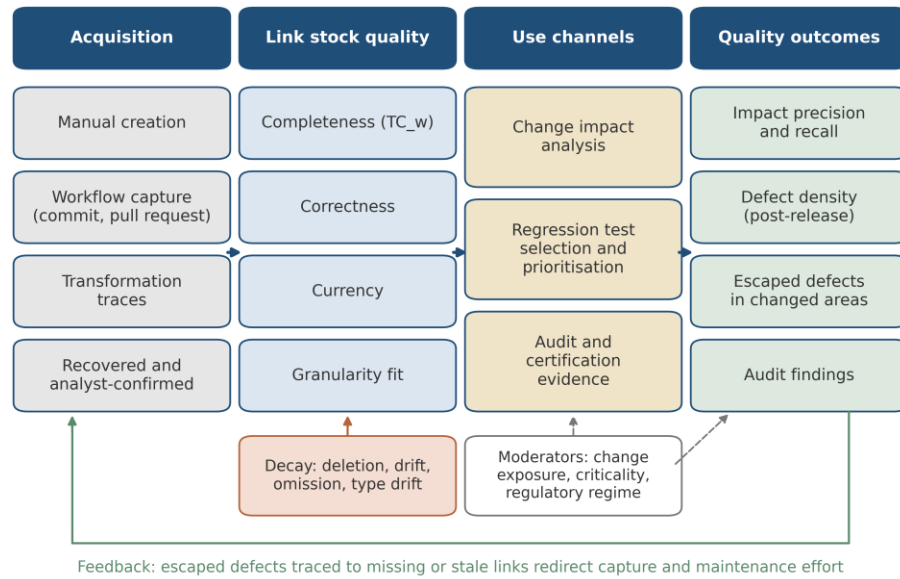


Figure 3. The Trace Asset Value Model: acquisition routes, link stock quality, use channels and quality outcomes, with moderators and feedback

8.2 Propositions and Tests

Six propositions follow from the model. Each specifies an observable relation, the direction expected and a result that would count against it; Table 3 lists the operational measure and test for each. P1 (currency over completeness): in components with high change exposure, link currency explains more variance in change impact recall than link completeness does. The proposition fails if, with both measured at baseline, completeness has the larger standardised coefficient in components above the median change rate. P2 (verification channel): requirements with at least one verifies link to a test of adequate strength show lower post-release defect density than requirements without one, after controlling for size, churn and team. It fails if the difference vanishes once test strength and team effects are controlled (Catal & Mishra, 2013; Zhu et al., 1997).

P3 (false assurance): stale links reduce impact recall more than absent links do, because engineers terminate search earlier when a link is present. The test is an experiment in which participants perform impact analysis tasks with link sets seeded with either stale or missing links at equal rates; the proposition fails if recall is equal or higher in the stale condition. P4 (capture route): links created by event-based capture at workflow events have higher correctness twelve months after creation than links created in batch before an audit, holding link type and component constant. It fails if the correctness difference is absent or reversed. P4 draws on the trace debt and incentive alignment account of Section 2.3 (Ramesh & Jarke, 2001; Cleland-Huang et al., 2012).

P5 (regulatory moderation): in regulated settings, where completeness is mandated and near its ceiling, variation in escaped defects is associated with currency and granularity fit but not with completeness; in unregulated settings completeness retains predictive value. The test is a moderated regression across organisations or business units with different regimes, and the proposition fails if the interaction between regime and completeness is absent. P6 (recovery as auditor): using automated recovery to flag suspected

missing and suspect links in an existing stock improves correctness per analyst hour more than using it to generate links from scratch. The test compares correctness gain per hour of analyst effort in the two modes on the same repository; the proposition fails if generation from scratch is at least as efficient (De Lucia et al., 2007; Borg et al., 2014).

Table 3. Propositions of the Trace Asset Value Model with operational measures and disconfirming results

Proposition	Operational measure	Test and disconfirming result
P1 Currency over completeness	Currency and TC_w at baseline; impact recall in the following window, by component change rate	Fails if completeness has the larger standardised coefficient in high-change components
P2 Verification channel	Presence of a verifies link to a test above a mutation-score threshold; post-release defects per KLOC	Fails if the difference disappears after controls for size, churn, team and test strength
P3 False assurance	Impact recall and time in seeded tasks with stale versus missing links at equal rates	Fails if recall with stale links is equal to or higher than with missing links
P4 Capture route	Correctness of links twelve months after creation, by creation route	Fails if event-captured links are not more correct than audit-batch links
P5 Regulatory moderation	Escaped defects regressed on completeness, currency and granularity fit, with regime interaction	Fails if the regime by completeness interaction is absent
P6 Recovery as auditor	Correctness gain per analyst hour in audit mode versus generation mode	Fails if generation from scratch is at least as efficient

8.3 Validation Design

The validation design, shown in Figure 4, is repository-based and longitudinal, with an embedded experiment for the proposition that requires controlled conditions. Link reconstruction extracts explicit links from work-item keys, test management links and requirement management tools, and a stratified sample of links is vetted by two analysts against the artifacts at each endpoint to estimate correctness and currency, with agreement reported as Cohen's kappa. Exposure measures, namely TC_w, correctness, currency and granularity fit, are computed at baseline points, and outcome measures, namely impact recall and precision, defect density and escaped defects in changed areas, are computed in the following window. Staged roll-out of event-based capture across teams permits a difference-in-differences comparison (Runeson & Höst, 2009; Onwuzulike et al., 2024).

The design addresses the known confounders explicitly. Team discipline is modelled as a team random effect and proxied by independent indicators such as code review coverage; component size, churn, age and author count enter as controls; and defect attribution uses issue-tracker records that do not depend on commit message conventions. The embedded experiment for P3 uses realistic change tasks drawn from the organisation's history and seeded link sets, with recall and time as outcomes. Each measure is tied in advance to a maintenance decision, so that a result changes practice rather than a report (Sakya et al., 2022b).

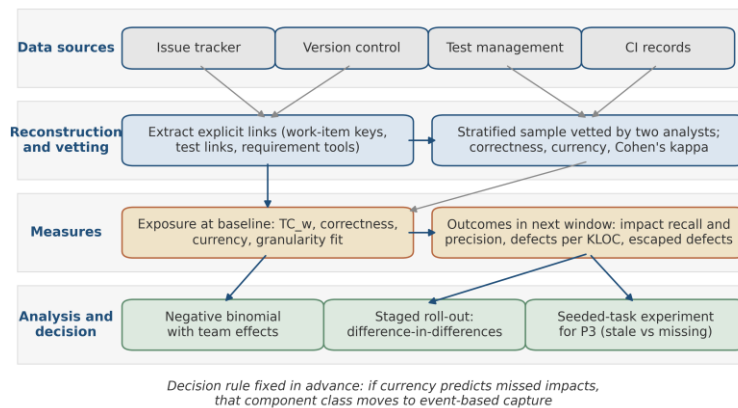


Figure 4. Repository-based validation design with embedded experiment, linking data sources to exposure measures, outcome measures, analysis and maintenance decisions

8.4 Illustrative Scenario: A Payment Limit Change

Consider a core banking platform in which a regulatory change lowers the daily limit for a class of cross-border payments. The requirement is linked to a rule in the payments engine, two service methods, a database constraint, eleven regression tests and an audit control that samples limit breaches. The rule and one service method were refactored eight months earlier, and the links to them were not updated; a new validation step added in a separate onboarding service, which also enforces the limit, was never linked. Impact analysis based on the link stock returns the database constraint, the old method name, eleven tests and the audit control. An engineer who trusts the result updates the constraint and the tests, misses the onboarding service and discovers the inconsistency when a customer's payment is accepted by one path and rejected by another (Kumuyi et al., 2024b; Jones & Ominyi, 2024b).

The scenario isolates each TAVM dimension. Completeness is nominally high, since every link the model required exists; correctness and currency are low for two of them; and the omission of the onboarding service is decay by omission. Under the hazard model, the payments engine is a high- λ component, and the missing capture at the refactoring commit is the maintenance failure. The scenario also shows why coverage audits did not catch the problem: they counted links rather than checking them (Adegbite et al., 2022; Dosunmu & Ogundele, 2020).

9 Discussion

The synthesis and the model carry consequences for theory, for enterprise practice and for the design of future studies, and they invite objections, some of which mark genuine limits on where the model applies. It begins with theory, turns to practice, answers the strongest objections and closes with the threats that any test of the propositions must manage. The recurring theme is that traceability is an evidence infrastructure whose worth depends on the reliability of its evidence at the moment of use. Performance measurement systems show the same dependency: indicators lose their value once the people who must act on them stop trusting them, whatever their formal completeness (Sakyi et al., 2022b; Uchechi et al., 2022).

9.1 Theoretical Implications

The review supports three theoretical moves. First, traceability research should treat link quality as multidimensional. Completeness, correctness, currency and granularity fit arise from different processes and act through different mechanisms, and a single coverage ratio hides the failures that matter most in evolving systems. Second, the recovery and maintenance literatures belong in one economic account, because both concern the cost of acquiring and keeping reliable links; recovery research that ignores vetting cost and maintenance research that ignores recovery-assisted updating each optimise half of the ledger. Third, traceability benefits are mediated by use. The foraging account explains why links help when consulted and hurt when stale, and the trace debt account explains why the capture route determines whether links stay correct, since links stay current only where the people who update them also use them (Cleland-Huang et al., 2012; Anichukwueze et al., 2022).

The model also links traceability to wider theories of evidence in organisations. Decision support research shows repeatedly that the value of an information system depends on whether its outputs enter decisions at the right time, and that accurate outputs can still produce poor decisions if they are not trusted or not timely (Ilodigwe & Adesemoye, 2024a; Edivri & Oteri, 2024). Measurement research in forecasting adds a warning that optimising a single accuracy metric can degrade other properties that stakeholders care about, which applies to recovery techniques tuned for F2 at the expense of vetting cost (Komi, 2023).

9.2 Practical Implications for Enterprise Teams

Four practical implications follow. First, define an explicit traceability information model that names each link type, its granularity and the query it serves, and remove link types that no query uses. Second, measure currency alongside completeness: for each link, record the version at which it was last confirmed and flag links whose endpoints have changed since. Third, move link creation into the workflow, so that pull requests require or propose requirement keys and test management records link tests to requirements at creation, and make links visible where they are used, for example by listing affected requirements and tests on each pull request. Fourth, allocate maintenance by risk-weighted coverage, prioritising volatile and critical requirements, and accept lower coverage elsewhere where regulation permits (ISO/IEC/IEEE, 2018; Aliliele et al., 2024a).

Automated recovery is best deployed as an auditor rather than an author. Recovery models placed in pipelines should be governed like any other model: validated on the organisation's own artifacts, monitored for drift and gated before their output is used as evidence (Nwakamma et al., 2024a; Nwakamma et al., 2024b). For regulated teams, the principal change is to audit links by sampling their correctness and currency rather than by counting them, and to treat a stale link as a finding of the same severity as a missing one. Security operations research makes the same argument for integrated monitoring, where the reliability of the evidence determines whether alerts can be acted on (Ladapo et al., 2024; Jimoh & Ahmed, 2024).

Roles and incentives complete the picture. Trace maintenance works where artifact owners are named and where the people who create links also benefit from them, which argues for giving developers impact analysis tools that consume links rather than only asking them to produce links for others. Cross-functional education has been associated with fewer contract errors in engineering teams, and a similar investment in shared understanding of link semantics across analysts, developers and testers is likely to raise correctness (Anichukwueze et al., 2022; Amayo et al., 2023c). Leadership models from safety

management show that visible use by leaders sustains reporting behaviour, which for traceability means that release decisions should cite the impact analysis on which they rest (Arumosoye & Obriki, 2024; Obogo et al., 2019b).

9.3 Objections and Boundary Conditions

One objection holds that modern delivery practices make traceability obsolete: with comprehensive automated test suites and continuous deployment, a failing test reveals impact faster than any analysis. The objection has force for fast-feedback defects in well-tested code, but it assumes that the test suite verifies every requirement strongly, which is precisely what verifies links and test strength checks establish. It also fails for requirements whose violation is not observable in a test environment, such as regulatory limits enforced across services, and for audit settings where evidence of control operation is required regardless of test results (Daka & Fraser, 2014; Borah et al., 2022).

A second objection holds that the model's emphasis on currency is impractical because confirming links after every change is too expensive. The hazard model answers part of this: event-based capture targets only links whose endpoints changed, and risk weighting targets only the links that matter. The remaining cost is real, and the model predicts that for low-change, low-criticality components the optimal policy is to let links decay and rely on recovery when a rare change arrives, provided that recovery capability is kept ready in the way emergency readiness models require of capabilities used rarely (Arumosoye & Obriki, 2023). A third objection holds that generative models of code and text will soon recover links well enough to make recorded links unnecessary. The review's evidence on answer sets and vetting suggests caution: better recovery reduces creation cost but does not remove the need for confirmed links where links are evidence, and a recovered link without provenance cannot satisfy an auditor (Ominyi et al., 2024b; Ominyi, 2021).

Boundary conditions follow from the moderators. The model's value predictions weaken in small systems where engineers hold the whole design in memory, in short-lived applications whose horizon ends before decay matters, and in organisations where no process consults links. The model also assumes that requirements exist as identifiable artifacts; in organisations where requirements live only in conversations and user stories that are discarded after delivery, trace links have no stable source endpoint and the model does not apply without first establishing one. Load matters as well: risk models built for extreme operating conditions show that controls calibrated under normal load fail under peak load, which for traceability means release crunches (Arumosoye & Obriki, 2018; Mairiza et al., 2010; Liadi, 2022b; Liadi, 2024c).

9.4 Threats to Validity for the Proposed Research Programme

Studies that test the propositions face threats specific to traceability data, summarised in Table 4. The most serious is shared-mechanism bias: trace links and defect attribution often rely on the same commit message conventions, so a correlation between them may reflect recording discipline rather than quality. Answer-set incompleteness threatens any study that uses existing links as ground truth, and survivorship threatens longitudinal repository studies because components that were retired or rewritten drop out of the data. Construct threats arise when currency is measured through timestamps that record edits rather than confirmations. Each threat has a mitigation, and studies should report which were applied (Runeson & Höst, 2009; Easterbrook et al., 2008; Wedraogo & Sanni, 2024).

Table 4. Threats to validity specific to studies of traceability and software quality, with mitigations

Threat	How it arises in traceability studies	Mitigation
Shared-mechanism bias	Links and defect attribution both derived from commit message keys	Attribute defects from issue-tracker records independent of commit conventions
Answer-set incompleteness	Existing links used as ground truth are themselves incomplete and partly stale	Construct answer sets independently for a stratified sample; report agreement
Reverse causation	Defects prompt engineers to add links to affected requirements	Measure link quality strictly before the outcome window
Survivorship	Retired or rewritten components drop out of longitudinal data	Retain retired components with censoring in survival and count models
Construct validity of currency	Timestamps record edits to a link, not confirmation of its relation	Record explicit confirmation events; vet a sample against endpoint content
Maturity confounding	Disciplined teams trace, review and test more	Team random effects; independent discipline proxies such as review coverage
External validity	Open-source and academic datasets differ from enterprise repositories	Replicate on enterprise systems; report domain, scale and regulatory regime

10 Limitations and Research Agenda

The review is integrative rather than meta-analytic, so its judgements about the strength of evidence rest on appraisal rather than pooled estimates. The evidence base on recovery is dominated by small academic and open-source datasets, and the evidence on outcomes is dominated by correlational repository studies, so the enterprise conclusions are extrapolations that the proposed validation design is intended to test. Publication bias is likely in the recovery literature, where techniques that fail to beat a baseline are less often reported. Finally, the TAVM propositions are untested, and the illustrative parameters in Figure 2 are assumptions chosen for exposition (Page et al., 2021; Kitchenham et al., 2009; World Bank, 2014).

Five research priorities follow. First, the hazard parameters λ , δ and m should be estimated from the histories of real enterprise repositories, by link type and granularity, so that maintenance policies can be set from data. Second, recovery evaluation needs enterprise benchmarks with independently constructed answer sets and reported vetting cost, so that techniques are compared on cost per confirmed link rather than on F2 alone. Third, the currency-over-completeness proposition should be tested in regulated settings where completeness is mandated, which provides a natural control. Fourth, the embedded experiment on false assurance should be replicated with practitioners rather than students. Fifth, the use of learning-based recovery as an auditor should be evaluated in pipelines, including its failure modes when trained on incomplete link sets (Wieringa, 2014; Adesuyi et al., 2024; Falemi et al., 2024).

Traceability for machine learning components, where requirements must link to datasets, training runs and evaluation reports as well as to code, is a fast-growing obligation under emerging regulation, and the TAVM dimensions need adaptation for artifacts that change with every retraining (Ominyi et al., 2024b; Ogundairo & Ayivi-Donkor, 2024b). Cross-organisational traceability in outsourced and multi-vendor

enterprise programmes raises questions of link ownership across contractual boundaries, where the governance literature on joint ventures and cross-border regulatory harmonisation offers starting points (Eyetsemitan et al., 2020; Jones & Ominyi, 2021; Aminu-Ibrahim et al., 2024). Methodologically, professional development research indicates that practitioner capability develops through sustained practice, suggesting longitudinal studies of how teams learn to maintain links (Joseph & Nwankwo, 2024; Ogbete et al., 2023).

11 Conclusion

Requirements traceability improves software quality when trace links are treated as an engineered asset: created through the workflow rather than for the audit, kept current where change is frequent and consequences are serious, and consulted when decisions are made. The review establishes that automated recovery is a capable candidate generator and auditor but not a substitute for confirmed links, that decay is chiefly a correctness problem that coverage counts conceal, and that the relation between traceability and defect density is plausible and directionally supported but still awaits designs that separate it from general process discipline. The Trace Asset Value Model gives that research a structure, with four quality dimensions, three use channels, three moderators and six propositions that can each be refuted. For enterprise teams, the message is direct: measure whether links are right and recent, not only whether they exist, and spend maintenance effort where change and consequence meet.

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