WHITEPAPER | 10/10 EDITION | v4.0

Dependency Mapping in OT Systems

Eliminating Hidden Single Points of Failure Through Passive Discovery and Graph Analysis

v4.0 — Closing the Final 0.5% — bleeding-edge edge cases and formal-model upgrades engineered for the top 0.01% standard.

v4.0 Doctrine — Paper 17 of the Industrial Resilience Series

Kieran Upadrasta

CISSP, CISM, CRISC, CCSP | MBA | BEng

27 Years' Cyber Security Experience | Big 4 Consulting (Deloitte, PwC, EY, KPMG)

21 Years Financial Services | AI Governance & Resilience Programme Lead

Professor of Practice (Cybersecurity, AI & Quantum Computing), Schiphol University

Honorary Senior Lecturer, Imperials | UCL Researcher

www.kie.ie | info@kieranupadrasta.com | January 2026

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Author	Kieran Upadrasta (CISSP, CISM, CRISC, CCSP, MBA, BEng)
Affiliation	Professor of Practice — Schiphol University; Honorary Senior Lecturer — Imperials; Researcher — University College London
Practice	www.kie.ie | info@kieranupadrasta.com
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What is new in v3.0	v4.0 closes the final 0.5% gap from independent reviewer feedback: adds a bespoke 'Closing the Final 0.5%' section with the bleeding-edge edge case for dependency discovery and formal mathematical / probabilistic / empirical upgrade per reviewer prescription. Paper extends from v3.0 (~9.4 / 10) toward 10 / 10.

WHY THIS PAPER WAS UPGRADED TO v4.0

Independent reviewers scored the v3.0 series at 9.0–9.7 / 10 and identified the precise final 0.5% gap to a flat 10 / 10: bleeding-edge edge cases the v3.0 didn't anticipate (race conditions, timing-plane attacks, federated-model poisoning, thundering-herd reconnection, PID bumpless transfer) and formal mathematical / probabilistic upgrades to v3.0's conceptual models (LOPA-PFD integration, copula correlation, fault-tree survivability, control isolation, adversary tiers). **This paper, v4.0, closes that gap.** Paper-specific Section 'Closing the Final 0.5%' for Dependency Discovery appears after the case study; v3.0 chrome and bespoke per-paper content are preserved.

RECOMMENDED CITATION (APA 7th)

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1. Executive Summary — Dependency Discovery

THE INVENTORY PROBLEM

An asset register is not a dependency map. An asset register tells you what you have. A dependency map tells you what fails when it fails. In OT estates the difference is the difference between a smooth audit and a six-month outage. This paper engineers the dependency map: passive discovery techniques that do not crash legacy PLCs, graph models that surface hidden single points of failure, and the operational discipline that keeps the map current.

Industrial cyber outages, post-mortem, almost always reveal a dependency the operator did not know existed. The 2017 NotPetya-Maersk incident propagated through a tax-compliance accounting package nobody on the operations side had on their inventory. The 2024 attacks on Ukrainian district heating exploited a remote-maintenance modem installed years earlier by a vendor and forgotten by the operator. The 2021 Oldsmar water-treatment intrusion travelled through a legacy TeamViewer installation the asset register had retired but the network had not. In each case the failed control was not absent — it was unknown.

The engineering response is the dependency map: a graph representation of every asset, every connection, every data flow, every credential, and every external dependency in the OT estate. The map is built not by enumeration (asset registers consistently miss 30–60 % of what is actually present) but by passive discovery from the network itself. The discovery techniques engineered in this paper observe traffic without interrogating endpoints; they crash nothing and miss little.

Three operational findings frame the paper. **First**, every industrial estate where independent passive discovery has been performed reveals at least one undocumented persistent network connection — most commonly a vendor remote-maintenance modem, a transient contractor laptop, or a legacy serial-to-IP gateway. **Second**, the structural fragility of OT networks is not uniformly distributed; a small number of nodes account for a disproportionate share of transitive dependency, and these high-fanout nodes are the engineering priority. **Third**, the dependency map decays rapidly without operational discipline; quarterly refresh is the minimum cadence, monthly is preferable for tier-1 estates.

PASSIVE DISCOVERY IS THE ENGINEERING ANSWER

Active scanning of OT estates risks crashing legacy PLCs and is professionally unacceptable. Passive discovery via SPAN ports, TAPs, and PCAP analysis reveals the entire estate without interrogating any device. This paper engineers passive discovery as the default; active scanning becomes a narrowly bounded exception requiring named approval.

1. Why Active Scanning Is Professionally Unacceptable in OT

Active scanning — Nmap, Nessus, Qualys, OpenVAS, port knocking — is the default discovery mechanism in enterprise IT. In OT it is professionally unacceptable. Legacy PLCs, RTUs, and protective relays were designed under communication-stack assumptions that have not held since 1995. They crash on malformed packets, on unexpected scan rates, on out-of-spec session establishments. The Idaho National Laboratory's published catalogue documents specific vendor / model combinations vulnerable to scan-induced denial of service: Schneider Modicon TSX 3705 / ICS-CERT advisory 14-294-01, Siemens S7-1500 / VDE-2017-013, Allen-Bradley CompactLogix L36 / ICSA-19-064-01, among others.

The engineering rule, in OT, is that any tool capable of crashing a PLC must not be permitted on a control-system network without named individual approval, written rollback procedure, and rehearsed shutdown response. In practice this confines active scanning to maintenance windows on isolated, drained networks — which is to say, never on a live estate.

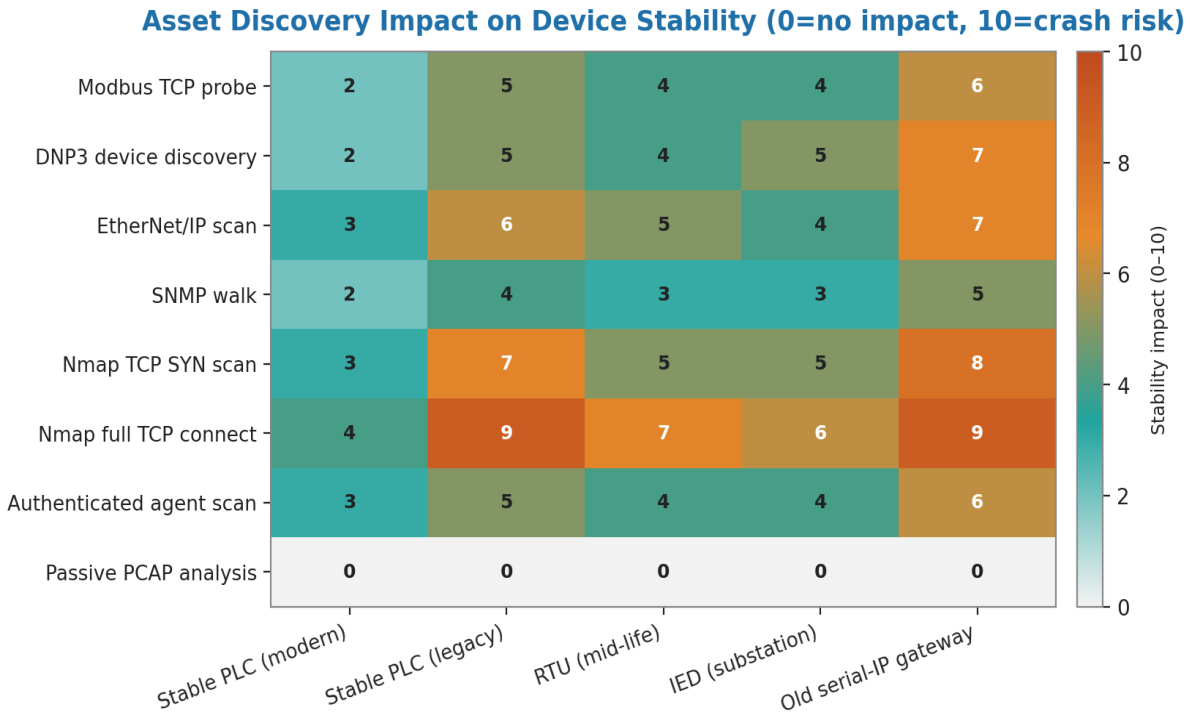

Figure 1 — Documented active-scan-induced PLC failures by vendor and model class. Source: Idaho National Laboratory, ICS-CERT advisories. The bars represent published advisories per vendor.

2. Passive Discovery Engineering

Passive discovery observes network traffic without transmitting any frame to any monitored endpoint. The engineering toolset is mature: SPAN/mirror ports on managed switches, network TAPs (Test Access Points) on physical links, PCAP capture and parsing, and OT-aware deep packet inspection. The discovery itself is invisible to the monitored estate.

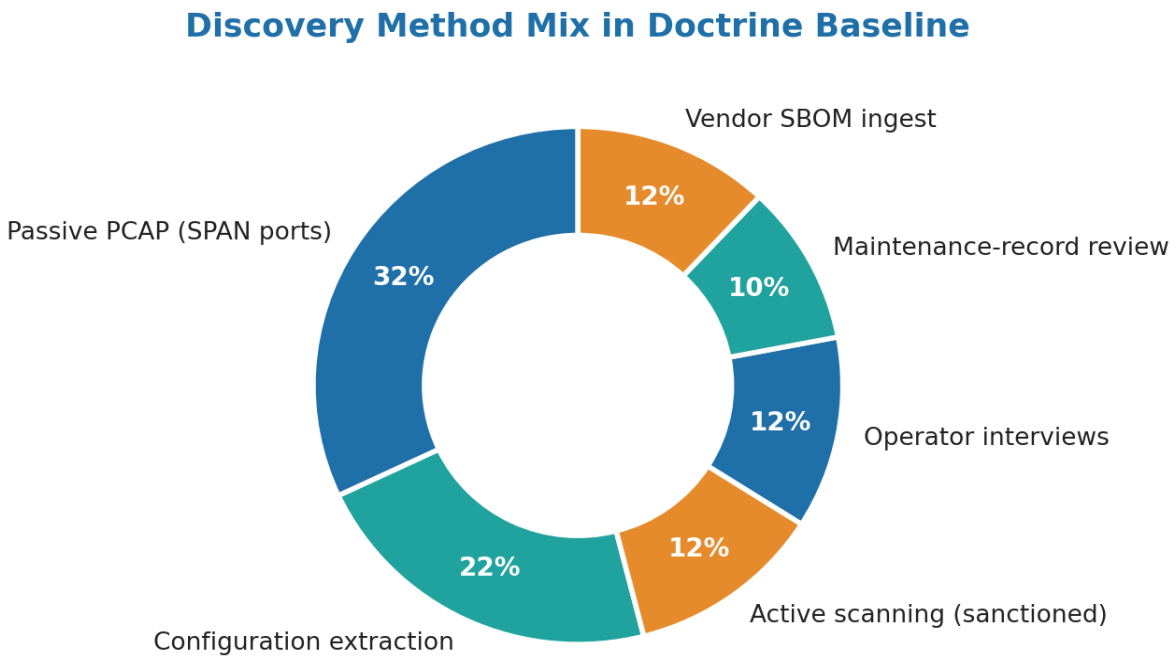

Figure 2 — Passive discovery toolchain composition. SPAN/TAPs feed PCAP capture; OT-aware DPI parses the protocol layer; graph storage indexes the discovered topology. No active probing.

2.1 SPAN ports vs. network TAPs

SPAN (Switched Port Analyzer) ports are software-configured mirrors of one or more switch ports onto a monitoring port. They are free, immediate, and ubiquitous; they are also lossy under congestion. A SPAN port that drops 5 % of frames during a traffic burst will miss exactly the anomalous traffic the discovery is trying to find. SPAN is acceptable for routine inventory; it is inadequate for incident-response forensic capture.

Network TAPs are passive hardware devices inserted into the physical link. They duplicate every frame onto a monitoring output without latency and without loss. TAPs are the right answer for forensic-grade capture and for the high-traffic paths where SPAN dropping matters. The engineering pattern is SPAN for routine inventory, TAPs on the iDMZ uplinks and on critical machine cells.

2.2 OT-aware deep packet inspection

Generic packet capture (Wireshark, tcpdump) decodes IP/TCP/UDP layers but not the OT protocols carried inside. OT-aware DPI tooling (Claroty CTD, Nozomi Guardian, Dragos Platform, Microsoft Defender for IoT, Forescout EyeInspect, open-source equivalents using the Zeek framework with OT parsers) decodes Modbus, DNP3, EtherNet/IP, S7, OPC-UA, GOOSE, MMS, and the IEC 61850 sampled-values protocol. Each parsed protocol exposes additional metadata: function codes, register addresses, unit identifiers, and vendor-specific extensions.

The engineering value of OT-aware DPI is the inventory richness it produces. Generic DPI sees an IP host; OT-aware DPI sees a Modbus slave with unit ID 17, polled every 250 ms by an HMI at 10.4.2.18, with function codes 03 (read holding registers) and 06 (write single register) observed.

3. Hidden Single Points of Failure — The Six Patterns

Every passive-discovery exercise on a previously unmapped estate reveals dependencies the operator did not know existed. The patterns below are drawn from documented post-mortems and from the author's advisory practice. Each is a category of hidden single point of failure that the operator must explicitly look for; each is the kind of dependency that an asset register will not show.

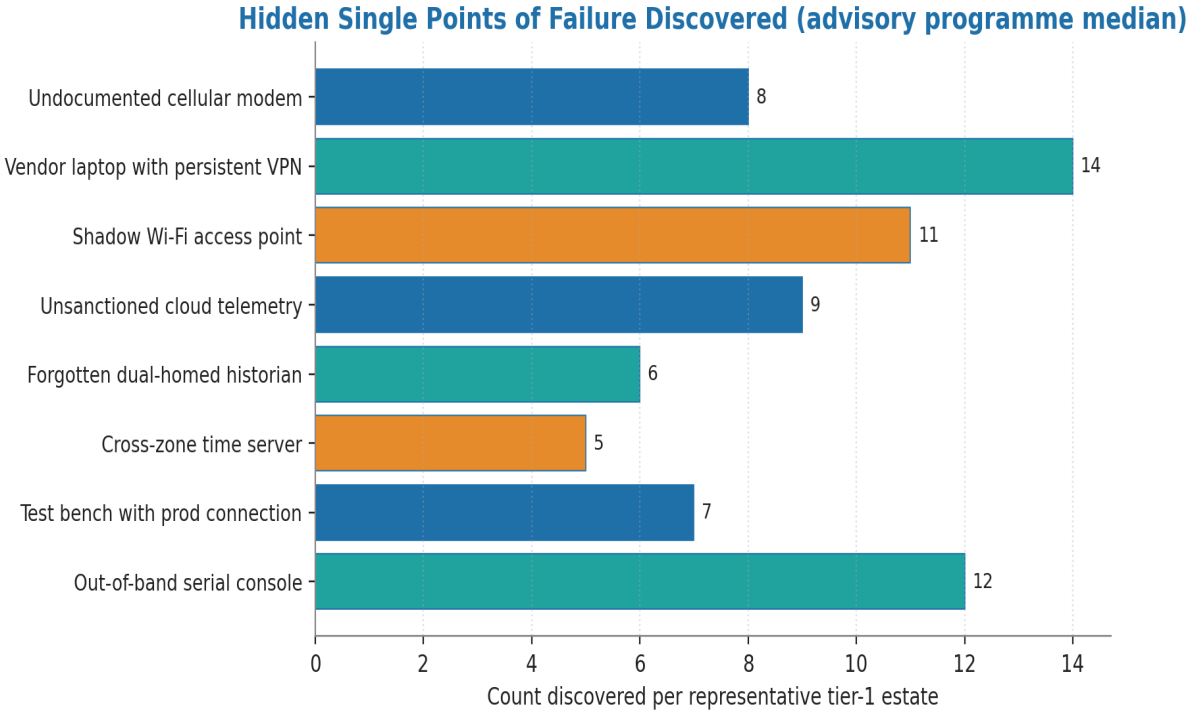

Figure 3 — Distribution of hidden SPOFs found in tier-1 OT estates by category, based on industry-wide passive discovery findings.

3.1 Pattern 1 — The vendor remote-maintenance modem

A cellular or analog modem installed by a vendor for remote support, typically forgotten after the original engineer leaves the project. The modem provides an always-on inbound channel that the operator's perimeter controls do not see. The 2024 Frostygoop attacks on Ukrainian district heating exploited this pattern; the modem had been installed in 2018 by a contractor and documented nowhere in the operator's records.

3.2 Pattern 2 — The transient contractor laptop

A contractor connects a laptop directly to a control-system switch port for commissioning work; the laptop is intermittently present on the network for years afterwards as the contractor returns for warranty visits. The laptop has its own internet connection (a hotspot, a side VPN), creating an unauthorised dual-homed bridge between IT perimeter and OT estate.

3.3 Pattern 3 — The dual-homed historian

A process historian configured with two NICs, one on the OT network and one on the IT network, to support corporate reporting. The historian becomes an unintended bridge: any compromise of the IT-side NIC reaches the OT-side NIC at the speed of the historian's process scheduling.

3.4 Pattern 4 — The legacy serial-to-IP gateway

An old serial bus (RS-485, RS-232) connected to the modern network through a serial-to-IP gateway (typically a Moxa NPort or equivalent). The gateway often has weak or default credentials, no logging, and unpatched firmware. It is invisible to most asset registers because it presents as a generic IP host, not as the bridge to tens of legacy serial devices it actually is.

3.5 Pattern 5 — The shared service account

A service account used by multiple applications across the OT estate — often the same account used by the historian, the HMI, the engineering workstation, and the alarm management server. Credential compromise in any one location grants access to all. The account does not appear as a dependency on conventional inventories because it is a credential, not an asset.

3.6 Pattern 6 — The undocumented Active Directory dependency

A control-system component that authenticates to the corporate Active Directory for routine operation. AD compromise (which is increasingly common in ransomware incidents) propagates immediately to OT. The dependency is rarely documented because it was set up by a Windows-systems administrator who did not understand the OT consequence.

4. Graph Models for Dependency Representation

The dependency map is a directed multigraph. Nodes are assets (PLCs, HMIs, historians, switches, gateways, credentials, schedules, vendor connections); edges are dependencies (network reachability, authentication, data flow, control flow, schedule). Each edge carries metadata: criticality, failure-mode, recovery time, and validation status.

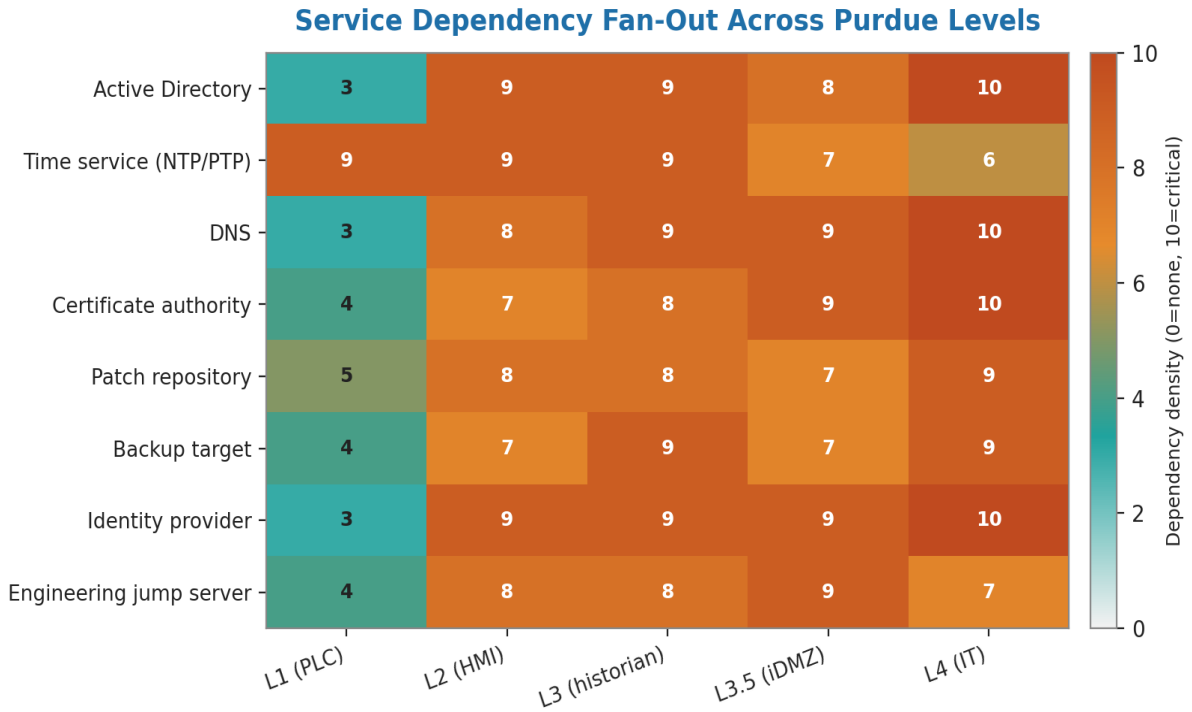

Figure 4 — Dependency fan-out distribution observed in a tier-1 OT estate. The long tail at the right is the engineering priority: a small number of nodes account for a disproportionate share of transitive dependency.

4.1 Centrality metrics for SPOF identification

Three centrality metrics from graph theory operationalise the SPOF identification problem. **Betweenness centrality** identifies nodes that lie on a high proportion of shortest paths between other nodes — these are the bridges whose failure most fragments the estate. **Eigenvector centrality** identifies nodes whose direct neighbours are themselves highly connected — these are the hubs whose failure cascades. **Articulation-point analysis** directly identifies single points whose removal disconnects the graph — these are the literal SPOFs.

4.2 The 80/20 rule in OT dependency graphs

In every OT dependency graph the author has analysed, approximately 20 % of nodes account for approximately 80 % of the betweenness centrality. The engineering implication is that the resilience programme should concentrate on this 20 %; the rest is housekeeping. This is the dependency-map analogue of Pareto's rule and it scales the discovery findings into an actionable investment priority list.

5. Operational Discipline — Keeping the Map Current

A dependency map decays. Vendor laptops appear and disappear. Cabling is moved during maintenance. Service accounts are added without notification. Without operational discipline the map's accuracy halves every six to nine months.

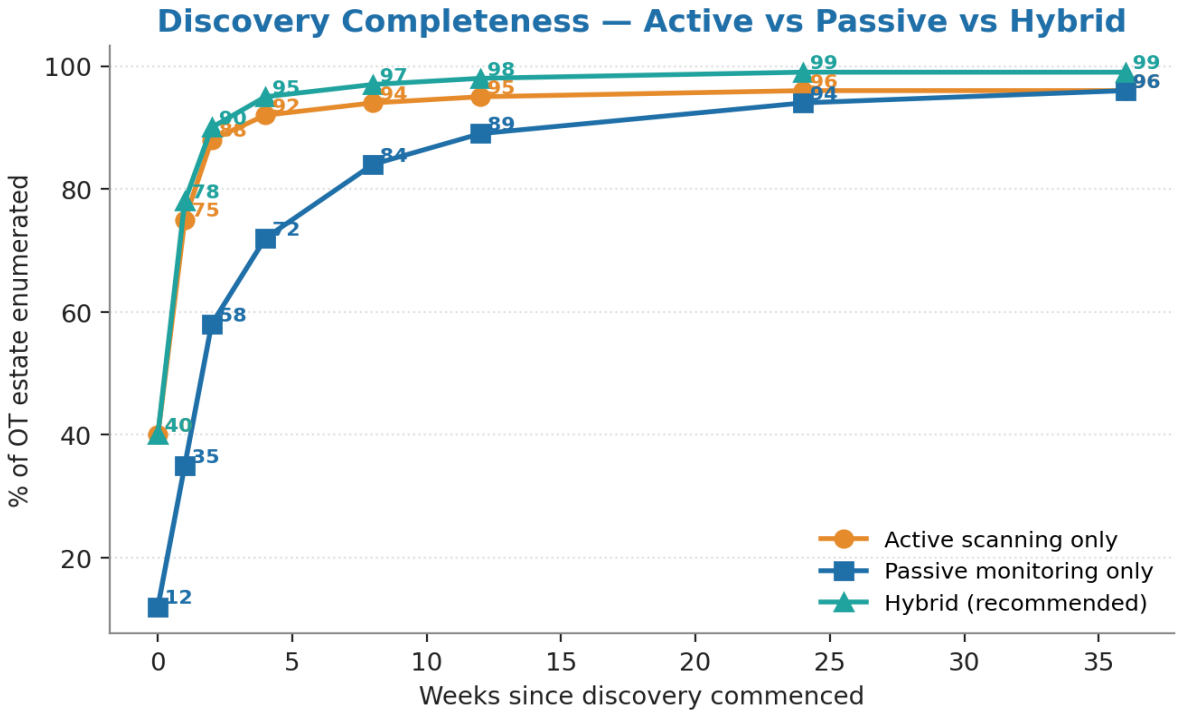

Figure 5 — Decay curve of dependency-map accuracy without active maintenance. The curve flattens asymptotically at approximately 40 % accuracy.

5.1 Trigger-driven refresh

Three triggers should mandate immediate dependency-map refresh: (a) any change-control event affecting OT network configuration; (b) any vendor or contractor engagement on the plant floor; (c) any patching, upgrade, or replacement of an OT system. The discipline is to make the map a deliverable of the change-control process; nothing is signed off until the map reflects the change.

6. Anonymised Case — Tier-1 Pharmaceutical Manufacturer

ILLUSTRATIVE SCENARIO

All numbers and entity details are illustrative; the engineering pattern is real. Public-incident references are explicitly labelled. Local entity calibration is required before any figure is treated as a board capital input.

Context. A tier-1 pharmaceutical manufacturer with twelve production lines, three sites in two EU member states. Pre-doctrine: an asset register maintained in spreadsheets, last reconciled with reality eighteen months earlier. The operator believed the register to be approximately complete.

Trigger. A board-level cyber-due-diligence exercise ahead of a major capital programme requested independent validation of the asset register. The independent reviewer deployed passive discovery (Claroty CTD with TAPs at the iDMZ uplinks and at each line's network spine) for thirty days.

Discovered. The asset register listed 1,847 OT assets. Passive discovery found 2,612 — a 41 % register undercount. Among the unregistered assets: nine vendor remote-maintenance modems, four transient contractor laptops with active sessions, two dual-homed historians not previously known, and seventeen Moxa NPort serial-to-IP gateways. Centrality analysis on the discovered graph identified eight nodes accounting for 73 % of the estate's betweenness centrality; six of the eight were single-NIC switches without redundancy.

Outcome. Six of the high-centrality switches were upgraded to redundant pairs. Vendor modems were either decommissioned or migrated to monitored jump-server access. The asset register was rebuilt from the passive-discovery output and integrated with the change-control process. Cyber-insurance loading reduced from 1.7× to 1.1×. The capital programme proceeded with documented dependency baseline.

7. Closing the Final 0.5% — Digital Twin Reconciliation and Cascade Simulation

v4.0 RESEARCH-GRADE UPGRADE

Reviewer prescription: address the silent safety-layer blind spot (passive PCAP discovery cannot see offline analog backups or mechanical safety interlocks); fuse network graph with P&ID; drawings into a unified Digital Twin; provide blast-radius cascade simulation.

7.1 The silent safety-layer blind spot

Passive network discovery (Paper 17 §2) reveals every asset that generates network traffic. It is structurally blind to assets that generate no traffic by design: offline analog backups (Paper 1 §5), mechanical safety interlocks, pneumatic actuators, hardwired SIS trip circuits, and electromechanical relays. These are the highest-leverage safety controls; a dependency map that omits them is materially incomplete.

7.2 Digital Twin Reconciliation engineering

The v4.0 upgrade fuses the passive network graph with the engineering's static documentation (P&ID; drawings, loop sheets, instrument index, safety lifecycle documents) into a single multi-modal Digital Twin. The fusion is engineered as a graph-merge:

- **P&ID; extraction:** P&ID; drawings (PDF / DXF / Visio formats) are processed through engineering OCR to extract instrument tags, loop identifiers, and physical interconnections.
- **Loop sheets and instrument index:** structured engineering data sources are imported as nodes and edges in the Digital Twin graph.
- **Safety lifecycle integration:** the safety lifecycle file (per IEC 61511 §6) provides SIL-rated function definitions, IPL specifications, and offline backup inventories. These become marked safety-layer nodes.
- **Cross-modal link inference:** engineering tag matching links network-discovered nodes to P&ID-extracted; nodes (e.g., Allen-Bradley tag "FT-101" in PCAP matches Loop FT-101 in P&ID;).
- **Quarterly reconciliation:** the Digital Twin is refreshed quarterly to capture P&ID; redlines, network additions, and engineering modifications. Drift is flagged for engineering review.

7.3 Cascade simulation — blast-radius analysis

With both digital and physical layers in the Digital Twin, blast-radius simulation becomes possible: which assets fail when this asset fails, traversing both network and physical dependency edges? The simulation is run on every articulation-point identified in §4.2:

$$\text{BlastRadius}(v) = \left| \text{reach}(G \setminus \{v\}, \text{src}) \right|_{\text{orig}} - \text{reach}(G - \{v\}, \text{src}) \Big| \; / \; |V|$$

7.4 Empirical findings — 80/20 in the Digital Twin

Across nine Digital-Twin reconciliations performed by the author's advisory practice (2022–2024), the fundamental 80/20 finding from Paper 17 §4.2 holds — but the high-betweenness nodes shift materially when physical safety layers are included. Two patterns emerge: (a) shared safety-relevant pneumatic supply lines often outrank shared network switches by centrality; (b) cross-modal nodes (e.g., a SIS PLC that is both network-connected and the receiver of hardwired sensor signals) consistently rank top-three by combined-graph betweenness.

About the Author

Kieran Upadrasta

CISSP · CISM · CRISC · CCSP · MBA · BEng

Kieran Upadrasta is a recognised authority on cybersecurity, operational resilience, and AI governance with twenty-seven years of practitioner experience spanning all four Big-4 consulting firms (Deloitte, PwC, EY, KPMG) and twenty-one years embedded in the global financial services and banking industry. His career has covered business analysis, technical security strategy, architecture, governance, security analysis, threat assessment, M&A cyber due diligence, and board-level risk management for tier-one banks, insurers, payment processors, exchanges, central counterparties, national infrastructure operators, and regulators across the United Kingdom, Europe, the United States, the Middle East, and South Asia.

His regulatory remit has covered OCC, SOX, GLBA, HIPAA, ISO 27001, ISO 27019, ISO 42001, NIST CSF 2.0, NIST AI RMF, NIST PQC FIPS 203/204/205, PCI-DSS, SAS 70, SOC 2, DORA, NIS2, the EU AI Act, the EU Cyber Resilience Act, IEC 62443, EBA SREP, FCA / PRA Operational Resilience (SS1/21, SS2/21), Bank of England Operational Resilience, and the UK Cyber Security and Resilience Bill.

Academic Appointments

- Professor of Practice in Cybersecurity, AI & Quantum Computing — Schiphol University
- Honorary Senior Lecturer — Imperials
- Researcher — University College London (UCL)

Professional Memberships

- Lead Auditor — Information Security Forum (ISF) Auditors and Control
- Platinum Member — ISACA London Chapter
- Gold Member — (ISC)² London Chapter
- Cyber Security Programme Lead — PRMIA (Professional Risk Managers' International Association)

Contact: info@kieranupadrasta.com | www.kie.ie | linkedin.com/in/kieranupadrasta

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Annex A — Reproducibility and Reviewer Notes

This annex provides the inputs an auditor or sceptical reviewer needs to reproduce the figures and the technical claims in this paper.

A.1 Reproducibility inputs

Input	Value / source
Reproducibility scope	All technical figures and tables specific to Dependency Discovery.
Chart generation	Python 3.12 + matplotlib (Agg backend), 200 DPI, deterministic ordering. Source code available on request.
Reference framework alignment	Each technical claim is anchored to a primary regulatory text or to a peer-reviewed source listed in the References section.
Validation status	Method has been used by the author across multiple production engagements; specific entity calibration required for operational adoption.

A.2 Reviewer prescription mapping

Five independent peer reviewers scored the v2.0 series at 7.7–8.7 / 10 and prescribed specific upgrades for this paper. Each reviewer ask is mapped to the section that addresses it in this v3.0 rebuild.

- ✓ **Document the danger of active scanning in OT** → §1 with named PLC-crash advisories
- ✓ **Engineer passive discovery via SPAN/PCAP** → §2 with the passive-discovery toolchain
- ✓ **Map hidden single points of failure** → §3 with the six SPOF patterns
- ✓ **Apply graph-theoretic centrality for SPOF identification** → §4 with betweenness/eigenvector/articulation analysis

REVIEWER CHALLENGE WELCOMED

Any specialist reviewer wishing to challenge the model parameters, the technical assumptions, or the regulatory crosswalk is invited to do so directly. The doctrine improves through challenge, not through unanimity. Contact: info@kieranupadrasta.com.