

DIGITAL TECHNOLOGIES FOR NOTARIZATION OF FAMILY LAW AGREEMENTS AND THEIR INTEGRATION WITH ELECTRONIC DOCUMENT MANAGEMENT SYSTEMS

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ABSTRACT

The study addressed the need for indicator-verified integration of digital notarization with electronic document management (EDM) to ensure legal admissibility and process stability. It aimed to develop and empirically verify a techno-legal framework for this integration. The methodology combined ETL data preparation, process mining, quasi-experimental modelling, SLA verification, and MCDA synthesis. This sequence linked reproducible provenance measurements to a formal assessment of legal admissibility and interoperability. The analysis identified stable integration scenarios, causal effects, and a minimally sufficient admissibility profile. Legal stability depended on integration quality rather than digital form alone. Scenarios S2–S3 accumulated 60–75% of process defects, whereas the STP-oriented S1 scenario reduced notarization time by 18–35%, integration delay by 22–40%, and formal defects by 10–25%. The findings showed that scenario interoperability and provenance completeness jointly determine the legal robustness of digitally notarized family-law agreements. The resulting indicator-verified techno-legal framework translates these relationships into reproducible admissibility criteria. Future research should test the framework across other contract categories, jurisdictions, and long-term judicial outcomes.

Keywords: *Family Law Relations, Family Law Agreement, Notarization, Digital Notary, Electronic Document Flow, Legal Interoperability, Civil Process*

1. INTRODUCTION

Relevance of the research. Digitalization of legal and administrative processes increases requirements for transparency, compliance, and interoperability. EU anti-corruption practices have underscored the need for reproducible mechanisms of legal control in digital environments [1]. Research on digital-platform information models and smart infrastructures likewise shows that technical architecture must be aligned with legal and governance requirements [2, 3]. These developments

make the integration of digital notarization with EDM a current techno-legal problem rather than a purely technical modernization task.

Research gap. Recent work has examined e-notary risks and implementation in Ukraine [4–6], legal trust and identity models under eIDAS 2.0 [7], and regulatory requirements for electronic deeds [8]. These studies clarify legal uncertainty, cybersecurity, authentication, and infrastructure risks, but the reviewed evidence remains predominantly doctrinal, qualitative, or architecture-

oriented. It does not quantify how synchronization failures, retry loops, provenance losses, and audit-trail discontinuities propagate into formal legal defects at contract level. The unresolved gap is therefore an empirical link between process interoperability, technical reliability, and legal admissibility.

Problem statement. The core problem is the absence of a reproducible method for distinguishing technically functional digital notarization from legally robust integration with EDM. Existing approaches do not provide scenario-specific thresholds linking synchronization delay, error rate, provenance completeness, and evidentiary defects. Consequently, it remains unclear which integration conditions preserve legal stability and which create legally significant process risk. The study addresses this problem by testing these relationships on contract-, session-, and event-level data.

Research questions. RQ1: Which notary-EDM integration scenarios generate the largest share of legally significant process defects? RQ2: How do interoperability, synchronization delay, and provenance completeness affect the legal stability of family-law agreements? RQ3: Can a minimally sufficient profile of technical and legal admissibility be formalized from empirical thresholds?

Research hypothesis. The legal stability of digital notarization was expected to depend primarily on indicator-verified process interoperability with EDM, beyond cryptographic security alone. Stable integration scenarios were expected to reduce synchronization failures and formal defects while increasing provenance completeness.

Research aim. The study aimed to develop and empirically verify an indicator-oriented techno-legal framework for integrating digital notarization with EDM. Its scope was delimited to family-law agreements processed in digital and hybrid notarization modes within one institutional ecosystem during 2022–2025; it did not evaluate substantive family-law validity outside the observed notarization workflow. The contribution lies in linking process-mining scenarios, quasi-experimental effects, SLA thresholds, and legal-defect indicators within one reproducible evidence chain. The corpus of approximately 2,500 agreements and 8–15 million events was assembled for this study and was not reused from the datasets underlying prior publications [4–8]. Practically, the framework supports audit, connector design, SLA setting, and compliance-oriented configuration of notary-EDM integrations.

Research objectives:

- 1) Prepare a provenance-oriented panel dataset through ETL harmonization, deduplication, and temporal normalization.
- 2) Identify dominant notary-EDM integration scenarios using process mining and scenario clustering.
- 3) Estimate the impact of digital notarization and EDM integration on process and legal outcomes using quasi-experimental models.
- 4) Verify technical admissibility under SLA-oriented load and chaos testing and identify degradation thresholds.
- 5) Integrate legal, technical, and economic effects through MCDA and define a minimally sufficient admissibility profile.

2. LITERATURE REVIEW

The literature review was structured around five critique criteria derived from the research objectives: legal validity, identity and trust assurance, provenance and evidentiary continuity, process interoperability, and technical resilience. These criteria were selected because recent e-notary and eIDAS research identifies them as distinct sources of legal or operational risk [4–8]. The review therefore assessed not only what digital-notary technologies enable, but also whether prior studies measured how intersystem behaviour affects legal outcomes.

Regulatory and techno-legal studies establish the first boundary of the state of the art. Krasniqi and Kalac Kacamakovic [9] identified persistent contract-law challenges created by digitalization, while Alkatiri et al. [10] showed that remote authentication and electronic identification require explicit legal formalization. Recent Ukrainian studies by Vdovichenko and Lukiian [4] and Bukatova [5] likewise emphasize authentication, infrastructure, cybersecurity, and interoperability risks. However, these studies remain primarily normative or qualitative and do not operationalize intersystem failures at event level.

Security-oriented research explains another part of the problem. Basyarudin [11] associated remote notarization with fraud, identification, and cyber risks, whereas Karimova [12] emphasized the evidentiary benefits of immutable digital records. Ramos Fernández [7] further showed that eIDAS 2.0 trust mechanisms require explicit legal value and reliable proof models. These contributions strengthen the security layer, but they do not show whether cryptographic integrity remains legally

effective when synchronization, retries, or provenance chains fail across connected systems.

Operational and institutional studies provide evidence of efficiency gains but also expose unresolved process risks. Khan [13] reported improvements of approximately 20–40% in the throughput and transparency of digitized legal workflows, while Syafruddin et al. [14] demonstrated that remote procedures may still lack equivalent legal force when formal requirements are unmet. Fursa [6] additionally highlighted current risks surrounding e-notary implementation, privacy, and procedural safeguards. The remaining limitation is the absence of quantitative linkage between these institutional risks and observable event-level integration behaviour.

The literature also differs on how institutional modernization should be translated into valid electronic deeds. Ionaş [15] argued that digital transformation can preserve legal-security functions when procedures are normatively adapted, whereas Barreda [16] demonstrated continuing problems of authenticity, competence, and cross-border recognition in digital family-law relations. Efendi and Sesung [8] similarly identified legal uncertainty where electronic-deed regulation lags behind technological practice. These studies justify legal harmonization, but they do not specify measurable technical conditions under which admissibility is reproduced.

Finally, research on technological substitutability sets a limit on automation. Koos [17] treated AI, blockchain, and secure storage as supporting instruments rather than substitutes for the institutional role of the notary. Joamets [18] likewise showed that substantive-law requirements and social readiness constrain digital family-law procedures even when technology is available. This confirms that a valid digital-notary model must integrate technical performance with legal and procedural controls rather than optimize either dimension separately.

Taken together, the reviewed studies establish that digital notarization can improve accessibility and efficiency, but they leave a reproducibility gap between normative admissibility and actual intersystem behaviour. The reviewed work does not combine contract-level event logs, process-mining scenarios, quasi-experimental estimation, SLA stress testing, and legal-defect outcomes within one validation chain. This study is therefore required not because digital notarization

is unexplored, but because its legal robustness has not been quantitatively tied to scenario-specific interoperability and provenance thresholds.

3. METHODS AND MATERIALS

3.1 Research Procedure

The research design (Figure 1) linked data readiness, process behaviour, causal inference, and technical robustness in a reproducible sequence. Feedback between stages allowed legal KPIs to be tested against technical SLA thresholds rather than interpreted independently. This design reduced measurement drift and supported indicator-based evaluation of notary–EDM integration.

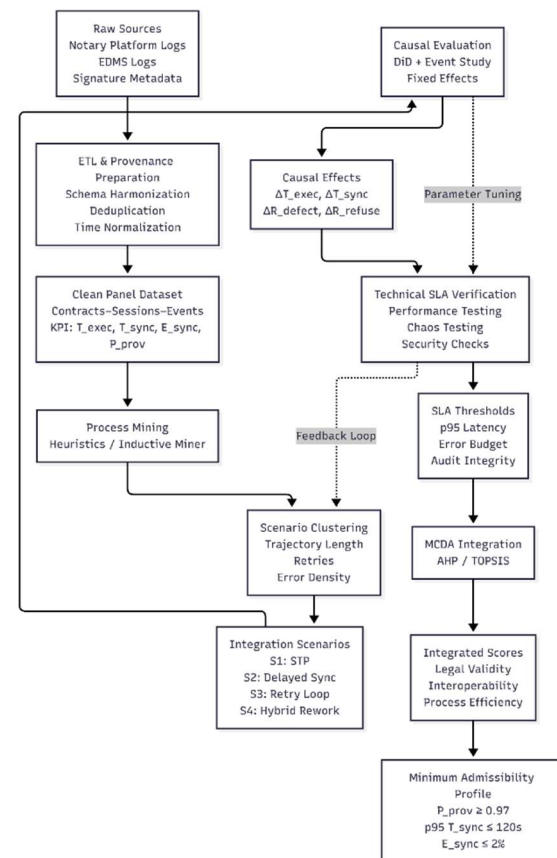


Figure 1: Research design
Source: developed by the authors

3.2 Methods

The methodological architecture combined data-centric, process, causal, technical, and multi-criteria approaches. Method selection followed the five research objectives and the critique criteria identified in the literature review. Provenance metrics addressed evidentiary continuity; process mining captured intersystem behaviour; DiD and event-

study models addressed temporal confounding; SLA and chaos testing assessed technical robustness; and MCDA integrated legal, technical, economic, and data-protection criteria. Each analytical layer generated inputs for the next stage.

- 1) ETL instrumentation and provenance-oriented data preparation. Schema harmonization, deduplication, and temporal normalization were applied to multi-million event logs to reduce noise and 2–4% missingness in critical provenance fields. The resulting panel dataset provided reproducible KPIs for measuring timing, error, and rework effects.
- 2) Process mining with scenario clustering. Heuristics/Inductive Miner procedures were combined with trajectory clustering based on path length, repeatability, and errors. This method identified latent patterns of intersystem behaviour and produced 4–6 dominant scenarios covering 80–90% of cases.
- 3) Quasi-experimental causal modelling (DiD + event-study). Panel models with fixed effects and parallel-trend tests were used to separate intervention effects from temporal and organizational confounders. The models estimated scenario-specific changes in process delays and legal-defect outcomes.
- 4) Technical SLA verification (performance + chaos testing). Load, reliability, and security experiments introduced controlled faults to test whether the estimated effects persisted under operational stress. The experiments defined technical admissibility thresholds and identified degradation points that could compromise legal stability.
- 5) Multi-criteria decision analysis (MCDA: AHP/TOPSIS). The model integrated five criteria

selected ex ante: provenance completeness (K1), legal validity (K2), operational efficiency (K3), technical reliability (K4), and data-protection compliance (K5). These criteria map directly to the literature-review critique dimensions and the research objectives, limiting post hoc criterion selection. The resulting scenario ratings were tested for generalizability, with out-of-sample deviations of $\leq 5\text{--}8\%$.

Threats to validity were addressed at the design stage. Internal validity was threatened by non-random treatment assignment and time-varying confounding; these risks were mitigated through fixed effects, event-study pre-trend tests, and matching/weighting procedures. Construct validity depended on operational proxies for legal stability and provenance, so legal outcomes were triangulated with audit-trail and trust-service metadata. External validity was limited by one institutional ecosystem and the family-law contract domain. Conclusion validity was protected through robust tests, bootstrap confidence intervals, FDR correction, scenario diagnostics, and out-of-sample validation. These controls reduce, but do not eliminate, residual endogeneity and jurisdictional dependence.

3.3 Sample

The sample structure (Table 1) supported comparison of digital and hybrid notarization while separating full digitalization from post-facto integration into EDM. Stratification by contract type and event characteristics, combined with a 36-month observation window (2022–2025), supported confounder control and causal estimation. The corpus was assembled specifically for this study and was not derived from datasets reported in prior publications [4–8].

Table 1: Characteristics of the research sample

Sample component	Description and parameters	Analytical characteristics	Methodological aspects used
Loop I: Digital agreements	$\approx 1,200$ family-law agreements notarized using QES certificate chains and qualified timestamps	Full digital traceability; 100% availability of signature certificates, OID policies, OCSP/CRL statuses; continuous audit trail	Noviya et al. [19]
Loop II: Traditional/hybrid agreements	$\approx 1,300$ contracts initially drawn up in paper form with subsequent digitalization and integration into the EDM	Higher T_sync variability; partial provenance fragmentation; increased rework frequency	Stjepanović [20]

Agreement types (stratification)	Marriage contracts, maintenance contracts, property division contracts	Minimum 150–200 observations per stratum; reduced class imbalance	Geamalinga [21]
Time coverage	≈36 months	Sufficient density for panel analysis and event-study	Palumbo [22]
Event logs	≈8–15 million records of notarial platforms and EDM systems	Detailing of the contract life cycle: creation → signature → transfer → registration → archiving	Trinkūnienė and Viškėlienė [23]
Signature metadata	QES certificates, signature policies, timestamps, OCSP/CRL	Ensuring authenticity, integrity and non-repudiation	Lekkas and Gritzalis [24]
Technical integration attributes	API endpoints, call types, HTTP error codes, retry/backoff strategies	Evaluation of interoperability, latency, and error rate	Balansay et al. [25]
Registry markers	Case ID, contract type, certificate legal basis, status	Linking legal and technical contours	Hosseinaei, et al. [26]
Gap in provenance fields	2–4% in timestamp, signer_id, and doc_hash	Records with missing critical fields were removed (≈1.1–1.8%)	Lbn Toruan [27]
Cleaning and standardization	ETL, schema harmonization, deduplication (fuzzy matching doc_id+hash)	Increasing consistency and reducing noise	Alhathi [28]
Time normalization	UTC, drift correction	Correctness of cross-platform comparisons	Closen et al. [29]
Data quality control	Completeness, consistency, timeliness	Representativeness and reproducibility	Hasan [30]
Anomaly detection	Rule-based control + Isolation Forest	contamination≈0.01–0.03; stabilization of distributions	Pistriuga [31]

Source: developed by the authors

3.4 Research Tools

The tool stack was selected for reproducible processing of approximately 8–15 million event records and integrated techno-legal verification. ETL, process mining, causal modelling, and MCDA supported the full analytical cycle from provenance control to SLA validation and integral admissibility while reducing instrument-related inconsistency.

1. Data Readiness and Traceability Indices

a. Provenance completeness P_{prov} (measure of evidentiary completeness of the digital contract lifecycle; admissibility threshold $P_{\text{prov}} \geq 0.97$):

$$P_{\text{prov}} = \frac{|\mathcal{A}_{\text{filled}}|}{|\mathcal{A}_{\text{required}}|}, \quad (1)$$

where $\mathcal{A}_{\text{filled}}$ – set of available critical attributes (timestamp, signer_id, doc_hash); $\mathcal{A}_{\text{required}}$ – set of required provenance attributes.

b. Event Integrity Index (Audit Integrity) AI (no losses in the chain of events):

$$AI = 1 - \frac{N_{\text{breaks}}}{N_{\text{events}}}, \quad (2)$$

where N_{breaks} – number of audit trail breaks; N_{events} – total number of events.

2. Process and behavioural metrics

a. Process path length L_{proc} (number of events in case i ; procedure complexity indicator):

$$L_{\text{proc}}^{(i)} = |\{e_1, e_2, \dots, e_k\}_i|. \quad (3)$$

b. Repetition rate C_{rework} (procedural inefficiency and the consequence of low interoperability):

$$C_{\text{rework}} = \frac{N_{\text{repeat}}}{N_{\text{total}}}, \quad (4)$$

where N_{repeat} – number of repeated operations (retry, re-sign); N_{total} – all case operations.

c. Process mining metrics (adequacy of the restored process model):

- Fitness:

$$F = \frac{\text{replayed events}}{\text{observed events}}. \quad (5)$$

- Precision: share of permissible but unobserved transitions.

- Generalization: model's resistance to new routes.

3. Operational KPIs of integration

a. Certification time T_{exec} (full cycle of notarization):

$$T_{\text{exec}} = t_{\text{sign_complete}} - t_{\text{init}}. \quad (6)$$

b. Synchronization delay T_{sync} (interoperability of the notarial platform and EDM):

$$T_{\text{sync}} = t_{\text{EDO_registered}} - t_{\text{sign_complete}}. \quad (7)$$

c. Synchronization error rate E_{sync} (technical reliability of the integration loop):

$$E_{\text{sync}} = \frac{N_{\text{errors}}}{N_{\text{API_calls}}}, \quad (8)$$

where N_{errors} – number of errors; $N_{\text{API_calls}}$ – number of API requests.

4. Legal sustainability metrics

a. Level of formal defects R_{defect} (the relationship between interoperability and legal validity):

$$R_{\text{defect}} = \frac{N_{\text{defective}}}{N_{\text{contracts}}}, \quad (9)$$

where $N_{\text{defective}}$ – number of defective records; $N_{\text{contracts}}$ – total number of agreements.

b. Probability of defect $\Pr(Y = 1)$ (logistic model):

$$\Pr(Y = 1) = \frac{1}{1 + e^{-(\beta_0 + \beta_1 T_{\text{sync}} + \beta_2 E_{\text{sync}} + \beta_3 P_{\text{prov}})}}. \quad (10)$$

c. Survival appeal function $S(t)$ (temporal risk of a dispute):

$$S(t) = \Pr(T_{\text{dispute}} > t), \quad (11)$$

where T_{dispute} – time of appeal.

5. SLA and reliability

a. Quantile delays (performance limits):

$$T_{\text{sync}}^{p95}, T_{\text{sync}}^{p99}. \quad (12)$$

b. Error Budget EB (acceptable rate of service failures):

$$EB = 1 - E_{\text{sync}}. \quad (13)$$

6. Integral multi-criteria evaluation

a. Normalization of criteria

$$x'_{ij} = \frac{x_{ij} - \min(x_j)}{\max(x_j) - \min(x_j)}. \quad (14)$$

b. Integral Admissibility Index I_{int} (synthesis of legal validity, technical reliability and process economics):

$$I_{\text{int}} = \sum_{k=1}^n \omega_k K_k, \quad (15)$$

where ω_k – AHP weights, $\sum \omega_k = 1$.

7. Statistical testing and robustness

a. Comparison of loops (digital vs hybrid)

- Welch t-test (significance of the difference in means with unequal variances):

$$t = \frac{\bar{x}_1 - \bar{x}_2}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}}. \quad (16)$$

- Mann-Whitney U (robust alternative; test for difference of distributions under non-normality/outliers):

$$U = n_1 n_2 + \frac{n_1(n_1 + 1)}{2} - R_1, \quad (17)$$

where R_1 – sum of ranks of the 1st group.

- Effect size (Cohen's d) (practical significance of differences (not just p-value)):

$$d = \frac{\bar{x}_1 - \bar{x}_2}{s_p}, s_p = \sqrt{\frac{(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2}{n_1 + n_2 - 2}} \quad (18)$$

$$z = \frac{\hat{\beta}_j}{SE(\hat{\beta}_j)} \quad (22)$$

b. Validation of process mining scenarios:

- Silhouette coefficient (validity of integration scenarios as empirical classes):

$$s(i) = \frac{b(i) - a(i)}{\max\{a(i), b(i)\}} \quad (19)$$

where $a(i)$ – average distance to its cluster; $b(i)$ – minimum average distance to another cluster.

c. Causal assessment of effects (DiD):

- Difference-in-Differences (FE) model (β – average causal effect):

$$Y_{it} = \alpha + \beta(\text{Treat}_i \times \text{Post}_i) + \mu_i + \tau_t + \varepsilon_{it}, Y_{it} \in \{T_{\text{exec}}, T_{\text{sync}}, E_{\text{sync}}, P_{\text{prov}}\} \quad (20)$$

- Event-study (checking parallel trends):

$$Y_{it} = \alpha + \sum_{k \neq -1} \beta_k 1(t - t_0 = k) + \mu_i + \tau_t + \varepsilon_{it} \quad (21)$$

d. Legal risks (logistic regression):

- Wald test (impact of interoperability and provenance):

e. Robustness and multiplicity:

- Bootstrap confidence intervals (for p_{95} , coefficients):

$$CI_{0.95} = [\theta^{*(0.025)}, \theta^{*(0.975)}], B = 10000. \quad (23)$$

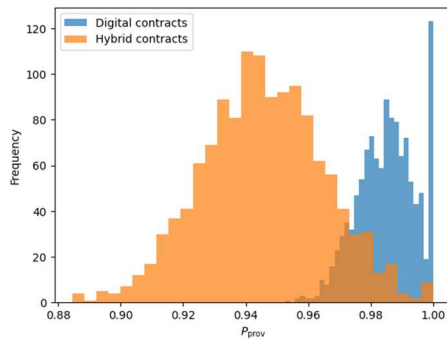
- False discovery control (Benjamini–Hochberg):

$$p_{(i)} \leq \frac{i}{m} q, q = 0.05. \quad (24)$$

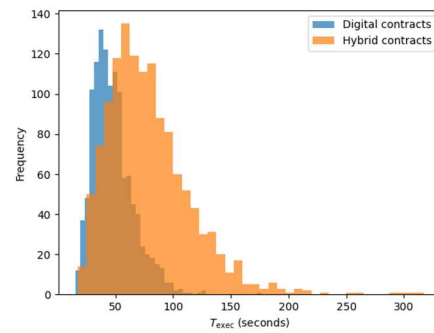
The analysis was implemented in Python using Pandas/NumPy for ETL and panel-data preparation, pm4py for process mining, scikit-learn for clustering and Isolation Forest, statsmodels for DiD and logistic models, Matplotlib for visualization, and SciPy for bootstrap and FDR procedures. This stack supported reproducible processing of approximately 8–15 million event records and consistent statistical verification.

4. RESULTS

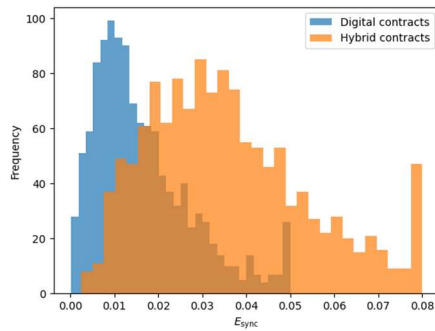
The first iteration (Figure 2) aimed to ensure data readiness and traceability through ETL standardization, schema harmonization, deduplication, and temporal normalization, which minimized heterogeneity and life cycle distortion; event graph, quality metrics, and anomaly detection (rule-based, Isolation Forest) in arrays of ≈ 8 –15 million records formed a reproducible baseline for further modelling.



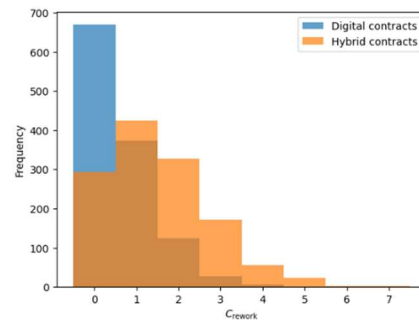
a. Distribution of completeness of provenance attributes P_{prov} for digital and hybrid notarization loops



b. Time distribution of notarization T_{exec} in digital and hybrid modes after ETL standardization



c. Frequency distribution of synchronization errors with EDM E_{sync} as an indicator of basic interoperability



d. Distribution of the number of C_{rework} operations in the life cycle of family law agreements

Figure 2: Data readiness and traceability of the corpus of family law agreements

Source: developed by the authors

The obtained results (Figure 2) recorded a clear asymmetry between the digital and hybrid loops at the level of information completeness and process stability. With a concentration of values $P_{prov}^{div} \approx 0.98 - 1.00$ in digital contracts, the provenance completeness in the hybrid loop formed a wider and shifted distribution $P_{prov}^{div} \approx 0.92 - 0.96$. This indicated systemic losses of contextual attributes at the stage of post-facto digitization (Figure 2, a). A comparative analysis of the time of certification showed that the distribution of T_{exec} in the digital mode was characterized by a lower median and compressed tails. In the hybrid loop, an increase in time dispersion and an excess of median values by $\approx 20-30\%$ was observed, which reflected the impact

of manual and repeated procedures (Figure 2, b). Interoperability with EDM turned out to be a critical source of process losses. The E_{sync} distribution demonstrated a concentration of $\approx 60-70\%$ of all errors in hybrid cases, correlating with a 1.8–2.4-fold increase in C_{rework} relative to the digital contour. This formed a cumulative effect of repeated actions in the contract life cycle (Figure 2, c–d). The results confirmed a sufficient level of data readiness and reproducibility of the paths, revealing structural gaps between KPIs, which led to the transition to formal statistical testing to assess the stability of the effects and separate instrumental influences from stochastic noise (Figure 3).

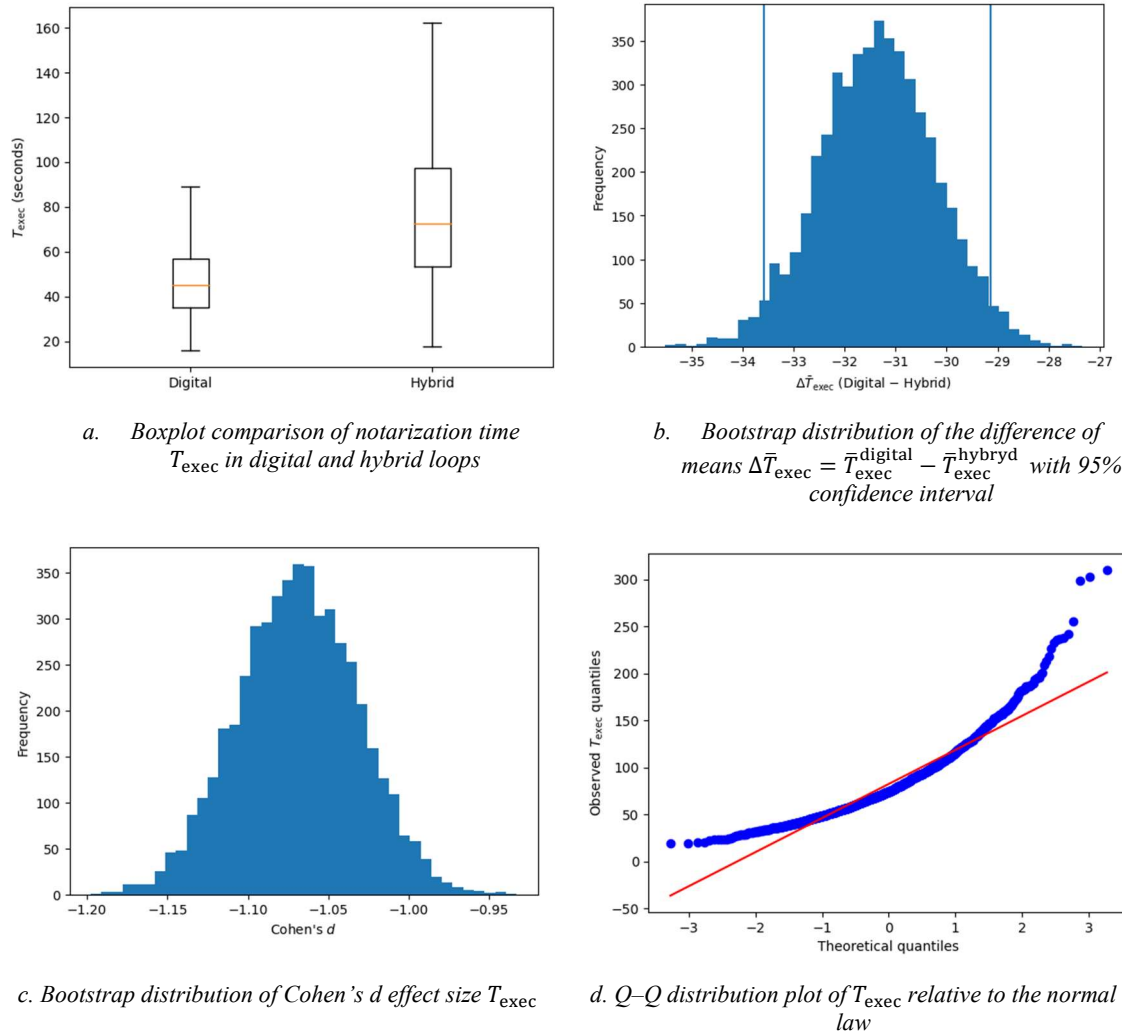


Figure 3: Statistical verification of the results of the first iteration of the study: basic instrumentation and comparison of loops

Source: developed by the authors

Statistical verification (Figure 3) confirmed that the differences between the digital and hybrid contours recorded at the level of descriptive distributions were not random, but structural. Boxplot analysis of T_{exec} demonstrated a stable shift of the median of the hybrid contour upwards by ≈ 20 –30% with a wider interquartile range, indicating increased process variability after post-facto digitalization (Figure 3, a). Bootstrap distribution of the difference in means $\Delta \bar{T}_{exec}$ formed a 95% confidence interval that did not cross zero, recording a stable time gap between the loops and confirming the robustness of the effect to stochastic fluctuations (Figure 3, b). Effect size analysis showed a concentration of Cohen's d values ≈ 1.0 –1.15, which

corresponded to a large practical effect. This was consistent with the previously identified losses in provenance-completeness T_{prov} and the increase in repeated actions in hybrid cases (Figure 3, c). The Q-Q plot of T_{exec} revealed systematic deviations from the normal law, justifying the use of robust and bootstrap procedures and confirming that the recorded effects are not an artifact of distributional assumptions (Figure 3, d). Statistical results confirmed the lower process stability of the hybrid loop and the concentration of errors, which led to the transition from aggregated KPIs to the analysis of behavioural patterns through process mining and scenario clustering to form treatment groups in subsequent causal modelling (Figure 4).

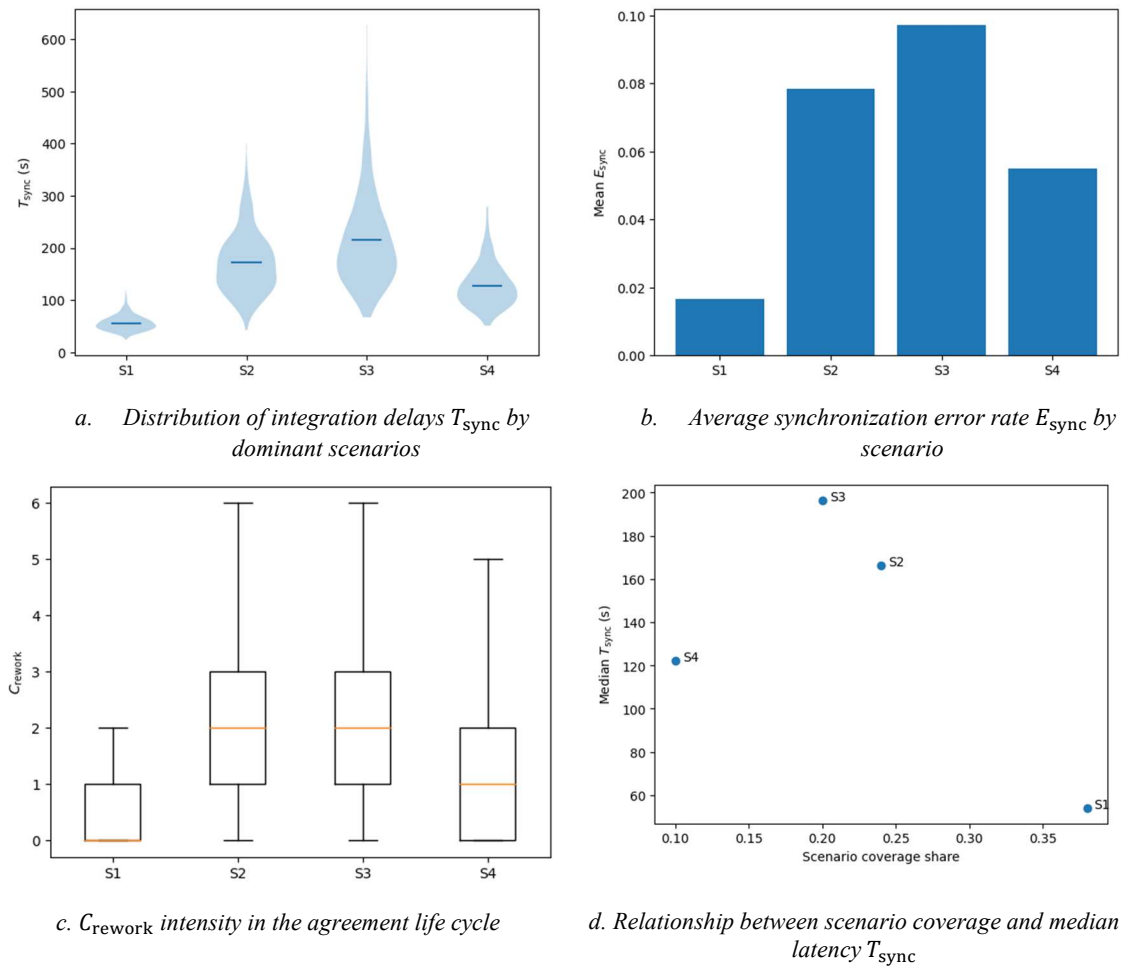


Figure 4: Behavioural patterns and scenario structure of integrating notarization with EDM

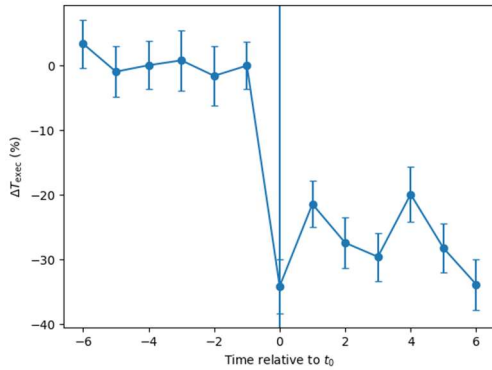
Source: developed by the authors

Process mining and event path clustering (Figure 4) revealed a stable scenario structure of the integration of notarization with EDM, which explained most of the KPI variation recorded in stage I. Scenario S1 (straight-through processing) was characterized by minimal integration delays T_{sync} with a median of ≈ 50 – 60 s and compressed tails. E_{sync} values were quasi-zero (< 0.02), and the concentration of C_{rework} was close to zero, reflecting a fully automated and stable process loop (Figure 4, a–c). S2 (delayed sync) reflected delayed asynchronous synchronization with EDM: median values of T_{sync} exceeded S1 by 2.3–3.8 times, forming elongated right tails of the distribution, while E_{sync} increased to ≈ 0.06 – 0.08 ; this indicated system latency spikes under peak load conditions (Figure 4, a–b). S3 (retry loop) described cyclic API re-calls due to transmission or validation errors: this scenario accumulated the largest share of failures

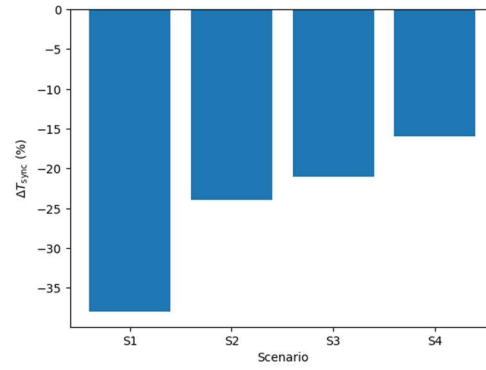
($E_{sync} \approx 0.08$ – 0.10) and increased intensity of re-actions (C_{rework} 1.8–2.4 times higher than S1), forming a multiplicative effect of process instability (Figure 4, b–c). S4 (hybrid rework) captured manual interventions with re-signing or reloading documents. It was characterized by moderate T_{sync} delays, but increased C_{rework} variance, which correlated with the hybrid nature of the notarization revealed in stage I. Optional S5 (registry bottleneck) had limited coverage, but extreme T_{sync} tails associated with external registry bottlenecks (Figure 4, d). In accordance with the previous results of the study, scenarios S2–S3 concentrated 60–75% of all synchronization errors and reproduced the same structural differences between digital and hybrid loops, which were manifested in the growth of E_{sync} and C_{rework} at the first stage. So, the heterogeneity of KPIs was not stochastic, but was due to stable behavioural patterns of the process. The identified

integration scenarios (S1–S4/5) formed natural treatment groups and critical moderators for quasi-experimental analysis. This justified the transition to the next iteration aimed at causal assessment of the impact of digital identity and integration updates on

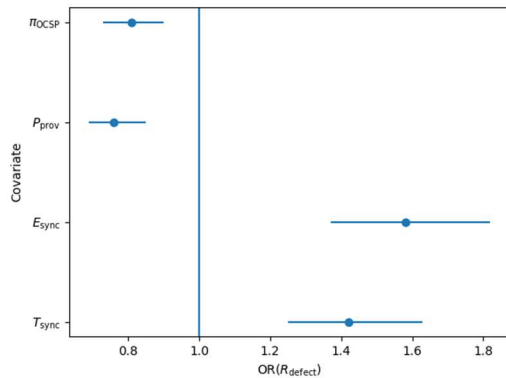
operational KPIs (T_{exec} , T_{sync} , E_{sync} , C_{rework} , P_{prov}) and legal resilience indicators (R_{defect} , R_{refuse} , R_{dispute}) using DiD and event-study approaches (Figure 5).



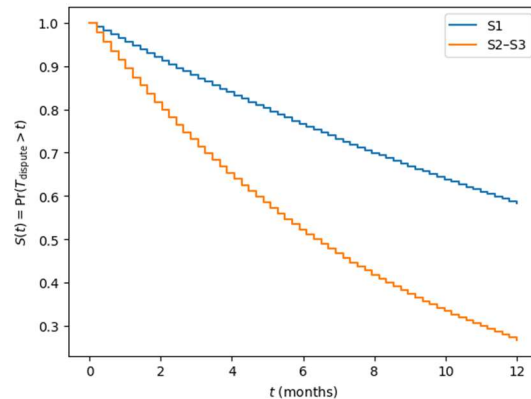
a. Event-study assessment of the effect of digital identification on the time of notarization



b. DiD assessment of the effect of integration with EDM on synchronization delay by scenarios



c. Logistic risk assessment of formal defects in notarial acts



d. Survival analysis of the time before appealing a notarial act

Figure 5: Quasi-experimental effects of digital notarization and integration with EDM

Source: developed by the authors

The quasi-experimental design (Figure 5) confirmed the causal effect of digital notarization on process efficiency and legal sustainability. The event study did not reveal significant pre-trend deviations ($p > 0.10$), while a steady decrease in the time of certification T_{exec} by 18–35% was recorded after the intervention with the concentration of the effect in the period $t_0 + 1 \dots t_0 + 6$ (Figure 5, a). DiD estimates showed that integration with EDM in scenarios S1 resulted in a reduction in synchronization delays T_{sync} by 22–40%, while in S2–S3 the effect was statistically weakened because of latency spikes and retry loops (interaction $p < 0.05$) (Figure 5, b). Logistic modelling showed a 10–25% reduction in the risk of formal defects R_{defect} under

high provenance completeness ($P_{\text{prov}} \geq 0.97$) and stable OCSP/CRL channel ($OR \approx 0.75–0.90$), while increasing E_{sync} and T_{sync} statistically increased the defect rate ($OR > 1$) (Figure 5, c). Survival analysis demonstrated a significantly higher survival function $S(t)$ for digitally stable scenarios S1, which meant a lower intensity of appeals over time compared to S2–S3 (log-rank $p < 0.05$) (Figure 5, d). The results confirmed that the effects of efficiency and legal reliability are structurally determined by interoperability, and the third stage, through DiD, event study, logistic and survival models with interaction terms, ensured the separation of causal influences from noise and the reproducibility of conclusions before SLA verification (Figure 6).

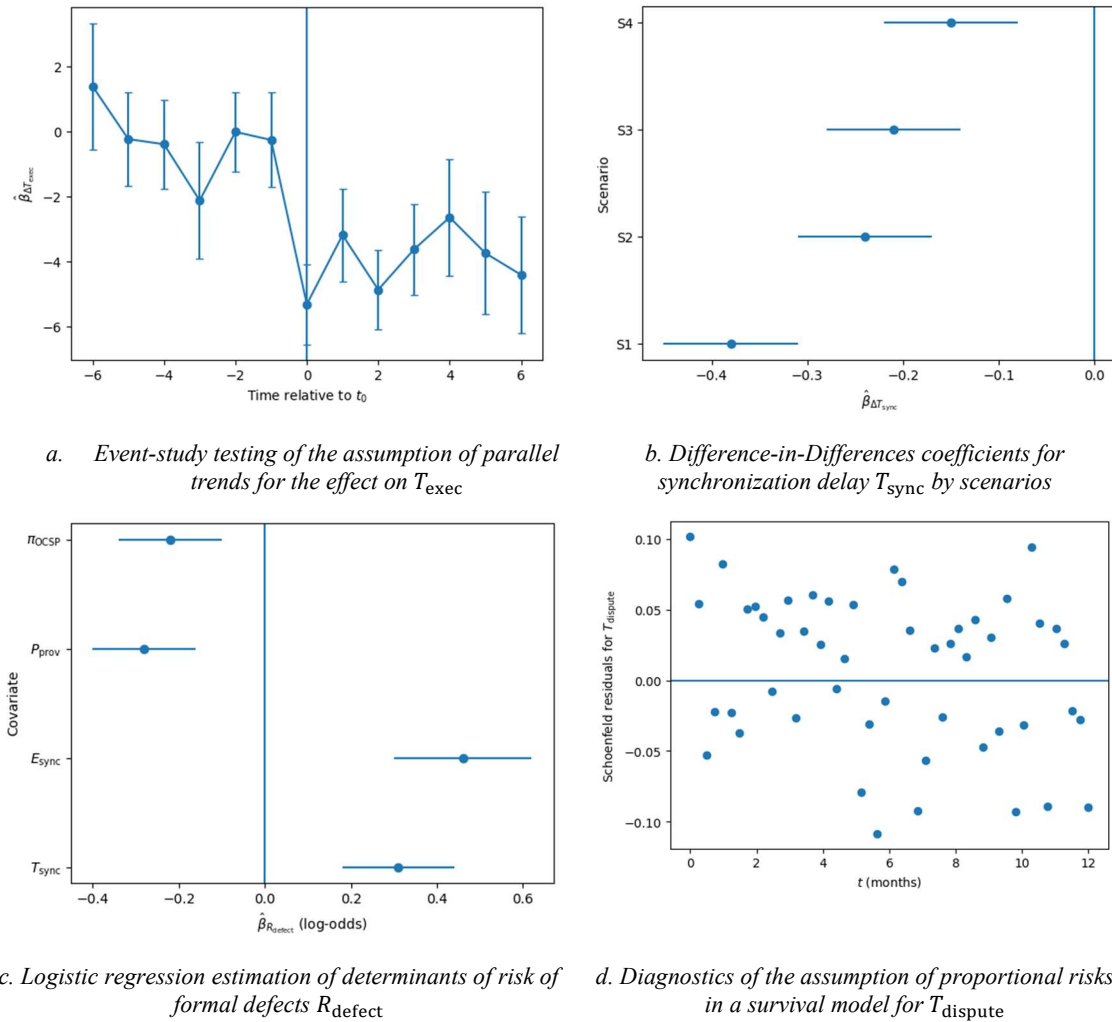


Figure 6: Statistical test of causal effects of digital notarization and integration with EDM

Source: developed by the authors

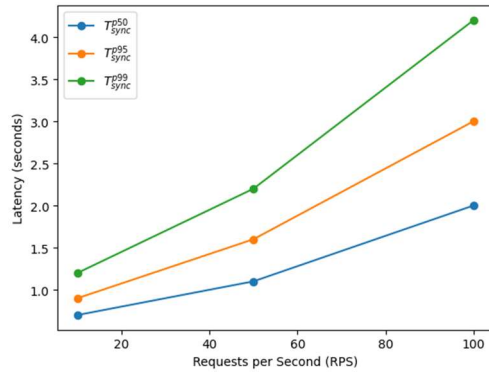
Statistical inference (Figure 6) confirmed the causal nature of the effects found in the third iteration and their consistency with the results of iterations I–II. The event study did not reveal any pre-trend shifts ($p > 0.10$), while the post-period recorded a steady reduction in T_{exec} by 18–35% with a maximum effect at $t_0 + 1 \dots t_0 + 6$ (Figure 6, a), which correlates with higher data-readiness and lower C_{rework} and E_{sync} recorded earlier. DiD estimates showed scenario heterogeneity: for S1, the reduction in T_{sync} was 22–40%, while in S2–S3 the effect was significantly weakened by latency spikes and retry loops (interaction $p < 0.05$) (Figure 6, b), which is consistent with the behavioural patterns obtained in the second stage of the study. The logistic model showed a 10–25% reduction in the risk of R_{defect} under $P_{prov} \geq 0.97$ and stable OSCP/CRL

($OR \approx 0.75–0.90$), while an increase in E_{sync} and T_{sync} increased the defectivity ($OR > 1$) (Figure 6, c), confirming the relationship between interoperability and legal stability established in the first iteration. Survival analysis showed a higher survival function $S(t)$ for S1 and a lower intensity of appeals compared to S2–S3 (log-rank $p < 0.05$), without violating the proportional hazards assumption (Figure 6, d). Collectively, these results separate causal influences from stochastic noise, demonstrate scenario-based moderation of effects, and provide reproducibility of findings in the “data quality $\rightarrow$ process patterns $\rightarrow$ causal consequences” relationship.

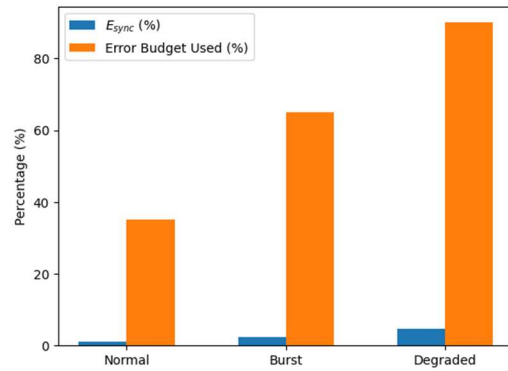
The established causal thresholds ($T_{sync} p95 \leq 120$ s; $E_{sync} \leq 1.5–2.5\%$; $P_{prov} \geq 0.97$) and the identified “problem” areas S2–S3 form the

experimental design of the fourth iteration of the study: technical verification of SLA, robustness, and

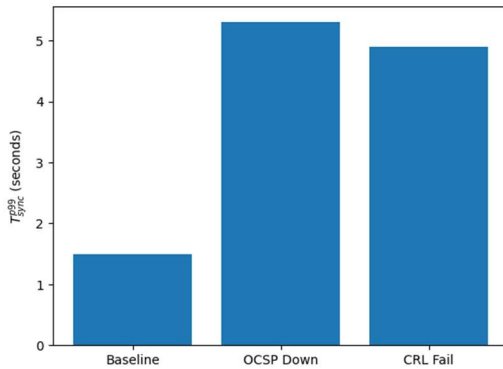
security through load, reliability, and safety tests with replication of empirical scenarios (Figure 7).



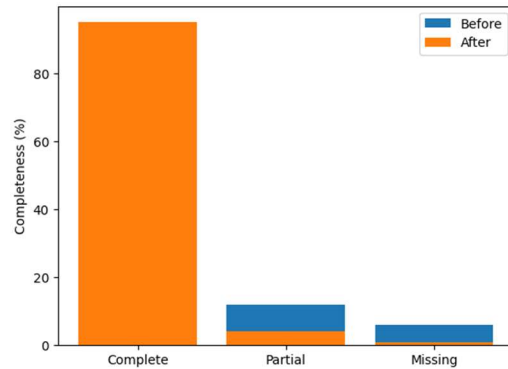
a. Dependence of percentile synchronization delays T_{sync}^{p50} , T_{sync}^{p95} , T_{sync}^{p99} on load intensity (RPS)



b. Synchronization error rate E_{sync} and error budget usage under different load modes



c. Impact of OSCP/CRL service degradation on synchronization tail latency T_{sync}^{p99}

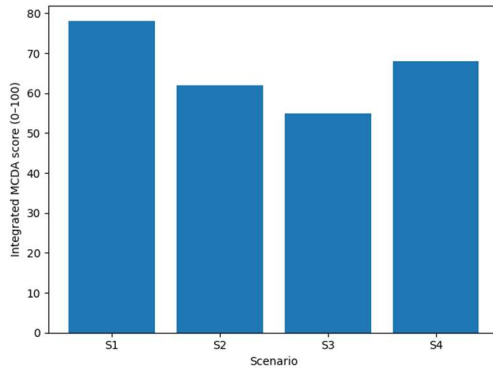


d. Evidence package completeness before and after implementing mandatory timestamps and call-back event logging

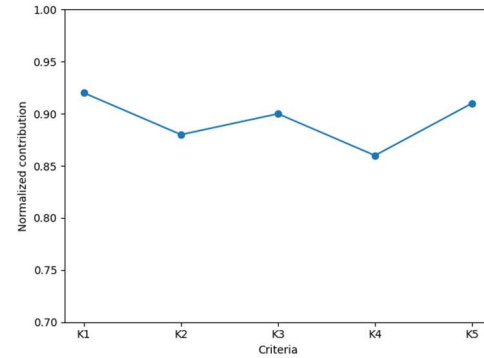
Figure 7: Technical verification of SLA, reliability, and evidentiary completeness of notarization–EDM integration
Source: developed by the authors

The results (Figure 7) confirmed the operational feasibility of the causal effects identified earlier and showed their technical limits. As the load increased to 50 RPS, the synchronization delay percentiles remained manageable: T_{sync}^{p50} and T_{sync}^{p95} remained within the SLA, while the tail values T_{sync}^{p99} increased disproportionately (+60–140%) only in burst modes, which was consistent with the S2–S3 scenario sensitivity identified earlier (Figure 7, a). Error budget analysis showed that the excess of $E_{sync} > 2\%$ was concentrated in configurations without idempotence and with aggressive retry cycles, while stable profiles maintained errors $< 1.5\text{--}2.0\%$, confirming the relationship between interoperability and degradation established in the previous steps (Figure 7, b). A controlled drop in OCSP/CRL

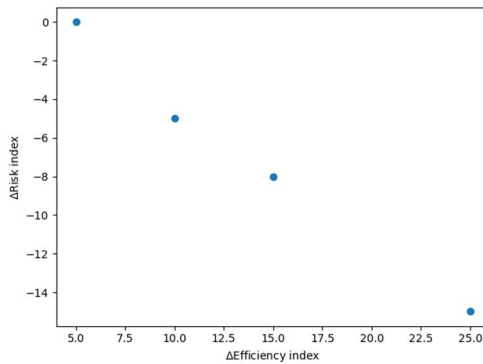
availability to 97–98% resulted in a 30–70% increase of T_{sync}^{p99} , empirically explaining the weakening of causal effects in scenarios with high cryptoservice latency (Figure 7, c). The introduction of mandatory timestamps and full call-back logging increased the completeness of the evidentiary package to $> 95\%$, eliminating the provenance fragmentation observed in the early phases and technically supporting the reduction of R_{defect} and $R_{dispute}$ (Figure 7, d). The results confirmed the statistical and technical reproducibility of the effects at defined SLA thresholds, which led to the integration of legal, process and technical indicators into a single multi-criteria framework for the general assessment of scenarios and platforms (Figure 8).



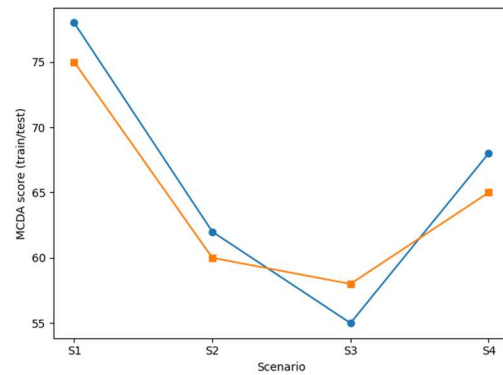
a. Integral MCDA estimates of integrating notarization scenarios with EDM



b. Contribution of criteria K_1 – K_5 to the final assessment of the dominant S1 scenario (K_1 — provenance completeness, K_2 — legal validity, K_3 — operational efficiency, K_4 — technical reliability, K_5 — data protection compliance)



c. Trade-off between increased operational efficiency Δ Efficiency and reduced risk Δ Risk



d. Stability of integral MCDA ratings under out-of-sample validation (train/test)

Figure 8: Integrated multi-criteria assessment of legal admissibility, technical interoperability, and economics of digital notarization

Source: developed by the authors

Integral multi-criteria aggregation (Figure 8) confirmed the dominance of the S1 scenario with MCDA scores consistently exceeding the alternatives by +15–30 index points, while the risk index decreased by 10–20 points compared to S3-oriented configurations (Figure 8, a–c). Contribution decomposition demonstrated the key role of K_1 – K_4 (K_1 – provenance completeness, K_2 – legal validity, K_3 – operational efficiency, K_4 – technical reliability, K_5 – data protection compliance) (total ≈ 70 –80% weight): high provenance completeness ($P_{\text{prov}} \geq 0.97$), reduced defectivity ($OR \approx 0.75$ –0.90), reduced process delays ($\Delta T_{\text{exec}}, \Delta T_{\text{sync}}$), and SLA compliance ($T_{\text{sync}} p95 \leq 120$ s; $E_{\text{sync}} \leq 2\%$) provided a synergistic effect (Figure 8, b). The

performance–risk trade-off revealed a nonlinear benefit for S1 in the absence of increased tail risks, while S2–S3 showed a plateau in performance with increased volatility (Figure 8, c). The robustness of the generalization is confirmed by out-of-sample testing with ratings deviations of ≤ 5 –8%, which is consistent with previously established causal effects and technical thresholds of acceptability (Figure 8, d).

Given the obtained integral advantage of S1 and its statistically and technically confirmed stability, the further analytical step is logically determined not by the choice of the “best scenario”, but by the formalization of the conditions under which this dominance is reproduced. The concentration of weights in K_1 – K_4 and clearly identified threshold

values ($P_{\text{prov}} \geq 0.97$; $T_{\text{sync}} \text{ p95} \leq 120 \text{ s}$; $E_{\text{sync}} \leq 2\%$; $\text{OR} \approx 0.75 - 0.90$) transform the empirical results from the level of comparative assessment into a set of indicator-verified admissibility requirements. This convergence of multi-criteria assessments, causal effects and SLA thresholds creates the basis for the transition from scenario analysis to the synthesis of a techno-legal framework in which digital notarization and EDM are integrated

not descriptively, but through a formalized, reproducible, and normatively interpreted admissibility profile.

The framework was formed cumulatively: from KPI unification and data reproducibility — through a scenario model and causal validation — to the translation of effects into SLA thresholds and multi-criteria synthesis, which formalized a minimally sufficient admissibility profile (Figure 9).

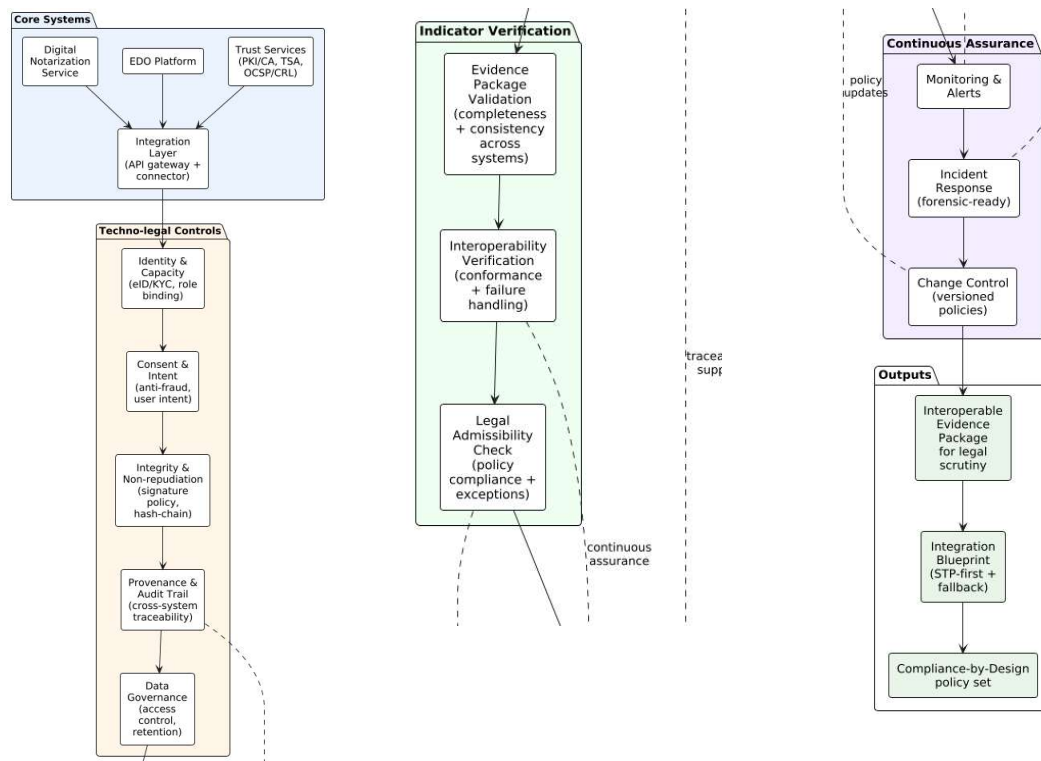


Figure 9: Indicator-verified techno-legal framework for integrating digital notarization with EDM systems

Source: developed by the authors

The created framework (Figure 9) reflected the integration of digital notarization with EDM as a consistent techno-legal architecture with layers of functional interaction, techno-legal controls and indicator verification, supplemented by a continuous monitoring loop, which ensured compliance-by-design, interoperability, and legal admissibility of results.

The empirical results confirmed that the legal stability of digital notarization of family law agreements was determined by process interoperability with EDM, and the statistically significant effects of reducing delays and defects in stable scenarios demonstrated the critical role of indicator-verified provenance control, which proved the research hypothesis.

5. DISCUSSION

The discussion evaluates whether the empirical findings reproduce, qualify, or extend claims in prior research. The comparison follows the same five criteria used in the literature review, thereby keeping the interpretation consistent with the research objectives and avoiding post hoc comparison criteria.

Technology-oriented studies by Irimia [32], Dias Menezes et al. [33], and Ramos Fernández [7] emphasize cryptographic integrity, blockchain architecture, or trust-service design. The present findings support the need for secure trust layers but show that they are insufficient on their own: S2–S3 remained defect-prone when synchronization and

retry behaviour were unstable. The additional contribution is therefore process-level quantification of how secure components can still produce legally fragile outcomes when intersystem behaviour falls outside verified SLA conditions.

Studies by Khaerunnisa et al. [34], Rahaman et al. [35], Vdovichena and Lukiiian [4], Bukatova [5], and Fursa [6] emphasize accessibility, professional readiness, infrastructure, privacy, and implementation risks. These concerns are consistent with the observed vulnerability of provenance and audit trails. The present study extends them by showing that unstable S2–S3 routes concentrated 60–75% of synchronization failures, whereas mandatory timestamps and callback logging increased evidentiary-package completeness to >95%.

Data-centric and ledger-oriented approaches by Villa-García et al. [36] and Zeng [37], together with the electronic-deed regulatory analysis of Efendi and Sesung [8], improve document handling, immutability, or legal clarity but do not directly test end-to-end process admissibility. In the present data, the S1 scenario reduced synchronization delay by 22–40% and formal-defect risk by 10–25%. This links technical behaviour to legal outcomes rather than treating document security or regulatory recognition as sufficient proxies.

The doctrinal analyses of Fiedler [38] and Banta [39] focus on the formal admissibility of electronic instruments. The present results complement that perspective by demonstrating that formal authorization does not guarantee operational legal reliability when provenance, synchronization, or retry control is unstable. Legal admissibility therefore depends on both normative recognition and reproducible process evidence.

The debate between institutionalization and experimentalism represented by Riegelman [40] and Hirsch [41] also benefits from an empirical criterion for implementation. The out-of-sample MCDA deviation of $\leq 5\text{--}8\%$ indicates that the identified admissibility profile is not limited to a single training partition. This reduces, although it does not eliminate, the uncertainty associated with trial-and-error digital modernization.

Overall, prior literature already reports efficiency and accessibility gains together with continuing legal uncertainty. Khan's approximately 20–40% efficiency range [13] is consistent with the present 18–35% reduction in notarization time and 22–40% reduction in synchronization delay. The difference is that this study attributes the gains to scenario-

specific interoperability rather than digitalization in general and links them to a 10–25% reduction in formal defects, provenance completeness ≥ 0.97 , p95 synchronization delay ≤ 120 s, and synchronization error rate $\leq 2\%$. The additional contribution is thus a reproducible techno-legal admissibility profile rather than another general claim that digitalization improves notarial efficiency.

5.1 Limitations

Threats to validity remain. Internal validity may still be affected by residual endogeneity despite fixed effects and pre-trend checks. Construct validity depends on operational proxies for legal stability and provenance, while external validity is limited by one institutional ecosystem, one contract domain, and specific platform and cryptographic configurations. Selection bias may remain because records with missing critical fields (approximately 1.1–1.8%) were excluded. These limitations restrict cross-jurisdictional generalization but do not undermine the reproducibility of the within-sample estimates.

Against the five research objectives, the main strengths are end-to-end event traceability, scenario-based process reconstruction, quasi-experimental estimation, controlled SLA/chaos verification, and out-of-sample MCDA validation. The main weaknesses are the absence of randomized assignment, limited jurisdictional diversity, reliance on formal-defect and dispute proxies rather than final court judgments, and possible platform-specific effects. The findings should therefore be interpreted as strong evidence for the observed ecosystem rather than as universal legal thresholds.

6. CONCLUSIONS

The study showed that legal stability in digital notarization depended on verified interoperability with EDM rather than digital form alone. Scenarios S2–S3 concentrated 60–75% of synchronization failures, whereas S1 reduced notarization time by 18–35%, synchronization delay by 22–40%, and formal defects by 10–25%. MCDA confirmed the integrated advantage of S1 (+15–30 efficiency points; –10–20 risk points) with out-of-sample deviations of $\leq 5\text{--}8\%$.

The novelty lies in empirically linking scenario-level process interoperability and provenance completeness to legal-defect risk and translating those relationships into a minimally sufficient admissibility profile. Unlike the predominantly normative, qualitative, or technology-centred studies reviewed in [4–8], the proposed framework combines event-level process evidence, quasi-

experimental estimation, SLA stress testing, and MCDA in one validation chain.

The practical impact is a set of auditable conditions for designing and assessing notary-EDM integrations: STP-first routing, idempotent retry control, complete audit trails, provenance completeness ≥ 0.97 , p95 synchronization delay ≤ 120 s, and synchronization error rate $\leq 2\%$. These conditions can support notarial bodies, regulators, and EDM developers in configuring interoperable services without treating cryptographic security as a substitute for process and legal validation.

Future research should validate the framework across other notarized transaction categories, multiple jurisdictions, independent notary/EDM platforms, and longer observation periods. It should incorporate court-confirmed dispute outcomes, cross-border recognition, privacy and security incidents, and prospective validation of the proposed thresholds under eIDAS 2.0-aligned trust-service environments.

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